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Assessment of the biological effectiveness of newly constructed fishways on the Murray Barrages, South Australia: Progress Report 2016

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

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SARDI Aquatics Sciences
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TABLE OF CONTENTS

ACKNOWLEDGEMENTS VII
EXECUTIVE SUMMARY 1
1. INTRODUCTION 5
1.1. Background 5
1.2. Objectives 7
2. METHODS 8
2.1. Study site 8
2.2. Fishways 9
2.3. Fishway sampling 16
2.4. Data analysis 18
3. RESULTS 20
3.1. Environmental conditions 20
3.2. Catch summary 21
3.3. Fishway use comparison 24
3.4. Fishway effectiveness 25
4. DISCUSSION 37
4.1. General catch and variability in fishway use 37
4.2. Fishway effectiveness 39
4.3. Overall fish passage at the Murray Barrages 43
5. CONCLUSION AND RECOMMENDATIONS 51
REFERENCES 54

LIST OF FIGURES

Figure 1. Map of the Coorong and Lower Lakes at the terminus of the River Murray, southern Australia, with the Murray Barrages presented as bold lines. The positioning of fishways constructed under the CLLMM Program are presented in green circles, namely: Goolwa large vertical-slot 2 (GVS2, constructed 2015), Goolwa small vertical-slot (GSVS, to be constructed in 2016), Mundoo dual vertical-slot (MVS, constructed 2016), Boundary Creek vertical-slot (BVS, constructed 2015), Ewe Island dual vertical-slot (EVS, constructed 2015) and Tauwitchere trapezoidal (TT, to be constructed 2016, subject to funding). The positioning of pre-existing fishways are indicated by red circles, namely: Goolwa large vertical-slot (GVS), Hunters Creek vertical-slot (Hunters), Tauwitchere vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS) and Tauwitchere rock ramp (TRR). 8

Figure 2. a) Plan and b) side views of the newly constructed Goolwa large vertical-slot 2 (GVS2) fishway. Entrance and exit trapping locations are indicated in the plan view, whilst vertical-slot aperture configuration is indicated in the side view. 12

Figure 3. Plan view of the newly constructed Ewe Island dual vertical-slot fishway and indication of entrance, and exit, trapping locations. 14

Figure 4. Plan view of the newly constructed Boundary Creek vertical-slot fishway and indication of entrance, and exit, trapping locations. 15

Figure 5. Fishway traps deployed at the exits of the a) Goolwa large vertical-slot (GVS2) and b) Boundary Creek small vertical-slot (BCVS). Note chains and lifting hook of mobile crane attached to GVS2 trap. 16

Figure 6. Discharge (ML.day^{-1}) and head loss data from the Murray Barrages in spring/summer 2015/16, specifically: a) total barrage daily discharge; b) daily discharge (black solid line), and daily minimum (blue dotted line) and maximum head loss (red dotted lined) at Goolwa Barrage; c) daily discharge (black solid line), and daily minimum (blue dotted line) and maximum head loss (red dotted lined) at Boundary Creek Barrage; and d) daily discharge (black solid line), and daily minimum (blue dotted line) and maximum head loss (red dotted lined) at Ewe Island Barrage. Arrows indicate sampling season at each barrage and associated fishway. 21

Figure 7. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages (entrance and exit samples pooled) sampled at the Goolwa large vertical-slot 2 (GVS2, solid triangles), Ewe Island dual vertical-slot (EVS, open triangles) and Boundary creek vertical-slot (BVS, open circles). 24

Figure 8. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most common species sampled at the entrance (shaded bar) and exit (open bar) of the new Goolwa

large vertical-slot 2 fishway in spring/summer 2015/16. Significant differences between entrance and exit abundance are indicated by asterisks. 26

Figure 9. Length-frequency distributions of a) congolli, b) common galaxias, c) flat-headed gudgeon and d) Australian smelt captured from the entrance (black bar) and exit (shaded bar) of the new Goolwa large vertical-slot fishway in spring/summer 2015/16. Sample sizes represent the number of fish measured for length, and those in brackets, represent the total number of fish sampled for each species. 27

Figure 10. Relationship between the total fish abundance (fish.hour^{-1}, all species pooled) sampled at the new Goolwa large vertical-slot 2 a) entrance and b) exit, and minimum head loss (m) experienced during trapping. 28

Figure 11. Comparison of mean relative abundance (number of fish. hour^{-1}.trap event^{-1}) of the most common species sampled at the entrance (shaded bar) and exit (open bar) of the Ewe Island dual vertical-slot fishway in spring/summer 2015/16. Significant differences between entrance and exit abundance indicated by asterisks. 29

Figure 12. Length-frequency distributions of a) congolli, b) common galaxias, c) flat-headed gudgeon and d) Australian smelt captured from the entrance (black bar) and exit (shaded bar) of the Ewe Island dual vertical-slot fishway in spring/summer 2015/16. Sample sizes represent the number of fish measured for length, and those in brackets, represent the total number of fish sampled for each species. 31

Figure 13. Relationship between the total fish abundance (fish . hour^{-1}, all species pooled) sampled at the Ewe Island dual vertical-slot a) entrance and b) exit, and minimum head loss (m) experienced during trapping 32

Figure 14. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most common species sampled at the entrance (shaded bar) and exit (open bar) of the Boundary Creek vertical-slot fishway in spring/summer 2015/16. Significant differences between entrance and exit abundance indicated by asterisks. 34

Figure 15. Length-frequency distributions of a) congolli, b) common galaxias, c) flat-headed gudgeon and d) Australian smelt captured from the entrance (black bar) and exit (shaded bar) of the Boundary Creek vertical-slot fishway in spring/summer 2015/16. Sample sizes represent the number of fish measured for length, and those in brackets, represent the total number of fish sampled for each species. 35

Figure 16. Relationship between the total fish abundance (fish.hour^{-1}, all species pooled) sampled at the Boundary Creek vertical-slot a) entrance and b) exit, and minimum head loss (m) experienced during trapping. 36

LIST OF TABLES

Table 1. Ecological objectives for fish passage and resulting overall passage requirements determined for each of the Murray Barrages. 10

Table 2. List of all current and 'to be constructed' fishways on the Murray Barrages, as of June 2016. Details include the barrage on which the fishways are situated, fishway design, abbreviation used throughout, construction year and hydraulic design parameters. 11

Table 3. Definitions of fish 'estuarine use' categories and guilds represented by fishes of the Coorong, following the approach of Potter et al. (2015). Examples of representative species from the Coorong are presented for each guild. 17

Table 4. Species, total number and length range of fish collected from the entrances and exits of the newly constructed Goolwa large vertical-slot 2, Boundary Creek vertical-slot and Ewe Island dual vertical-slot in spring/summer 2015/16. Species are grouped using the life history categories of Potter et al. (2015) 23

Table 5. Matrix adopted for determining fishway effectiveness. Fishway effectiveness is considered a product of 'relative attraction' and 'passage efficiency' and is categorised as ineffective, sub-optimal or optimal. 44

Table 6. Qualitative statements on fish migration and function of fishways on Goolwa Barrage for small-bodied (<100 in length) and large-bodied (>100 mm in length) fish under low flow and high flow scenarios, including: 1) Biomass: the likely biomass of fish accumulated below the barrage and attempting to migrate upstream (low, moderate, high); 2) Relative attraction: the relative proportion of fish attempting to migrate able to locate the entrance of the fishway (low, moderate, high); 3) Passage efficiency: the proportion of fish able to enter the fishway that are able to successfully ascend (based on empirical data from assessments, low (<25%), moderate (25–75%) or high (>75%)); and 4) Effectiveness: the product of 'relative attraction' and 'passage efficiency' following Table 4......45

Table 7. Qualitative statements on fish migration and function of fishways on Boundary Creek and Ewe Island barrages for small-bodied (<100 in length) and large-bodied (>100 mm in length) fish under low flow and high flow scenarios, including: 1) Biomass: the likely biomass of fish accumulated below the barrage and attempting to migrate upstream (low, moderate, high); 2) Relative attraction: the relative proportion of fish attempting to migrate able to locate the entrance of the fishway (low, moderate, high); 3) Passage efficiency: the proportion of fish able to enter the fishway that are able to successfully ascend (based on empirical data from assessments, low

(<25%), moderate (25–75%) or high (>75%)); and 4) Effectiveness: the product of 'relative attraction' and 'passage efficiency' following Table 4. 47

Table 8. Qualitative statements on fish migration and function of fishways on Tauwitchere Barrage in regards to small-bodied (<100 in length) and large-bodied (>100 mm in length) fish passage under low flow and high flow scenarios, including: 1) Biomass: the likely biomass of fish accumulated below the barrage and attempting to migrate upstream (low, moderate, high); 2) Relative attraction: the relative proportion of fish attempting to migrate able to locate the entrance of the fishway (low, moderate, high); 3) Passage efficiency: the proportion of fish able to enter the fishway that are able to successfully ascend (based on empirical data from assessments, low (<25%), moderate (25–75%) or high (>75%)); and 4) Effectiveness: the product of 'relative attraction' and 'passage efficiency' following Table 4. 50

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EXECUTIVE SUMMARY

Fishways are used to reinstate connectivity in fragmented river systems and partially mitigate the impact of barriers to fish movement. The Murray Barrages, at the terminus of Australia's longest river system, the Murray-Darling Basin (MDB), separate the estuarine waters of the Coorong and the freshwaters of the Lower Lakes, and represent significant barriers to movement of fishes between these environments. Recognition of the importance of fish movement at the Murray Barrages led to the construction of five fishways (varying vertical-slot and rock ramp designs) at Goolwa and Tauwitchere Barrages, and the Hunters Creek causeway, between 2003 and 2009. Whilst these fishways enhanced fish passage and promoted connectivity, assessments of their biological effectiveness and improved knowledge of fish migration at the Murray Barrages, indicated that additional fishways were needed to meet the movement requirements of fishes across the 7.6 km barrage network.

Under the *Coorong Lower Lakes and Murray Mouth Recovery Project*, construction of a further six technical fishways across the Murray Barrages was proposed from 2015 to 2016. This included inaugural fishways on Mundoo, Boundary Creek and Ewe Island barrages, and further fishways on Goolwa and Tauwitchere Barrages. The fishway designs were varied and tailored for target species, locations and hydrology in order to meet fish passage requirements at the Murray Barrages. The primary objective of the current project was to assess the biological effectiveness of the first three newly constructed fishways on the Murray Barrages: 1) Goolwa large vertical-slot 2 (at median water levels: max velocity 1.7 $m.s^{-1}$, maximum turbulence 23 $W.m^{-3}$, discharge 37 $ML.day^{-1}$); 2) Boundary Creek small vertical-slot (maximum velocity 1.7 $m.s^{-1}$, maximum turbulence 32 $W.m^{-3}$, discharge 15.6 $ML.day^{-1}$); and 3) Ewe Island dual vertical-slot (maximum velocity 0.92 $m.s^{-1}$, maximum turbulence 16 $W.m^{-3}$, discharge 3.1 $ML.day^{-1}$). Specifically, the project aimed to:

1. Undertake 'entrance and exit trapping' of each fishway and compare fish species composition, abundance and length distributions between entrance and exit samples to determine passage efficiency against fishway-specific objectives and design specifications;
2. Determine the influence of head loss on relative attraction and passage efficiency, and thus, biological effectiveness;

3. Qualitatively compare biological effectiveness (i.e. the species and size classes for which passage is facilitated) between the newly constructed fishways and with existing fishways on the Murray Barrages;
4. Provide comment on the contribution of the CLLMM fishway construction program to improving overall fish passage at the site;
5. Make recommendations for fishways still to be constructed; and
6. Make recommendations on future barrage/fishway operation in light of results of the current project and previous fishway assessments.

From 24 November 2015 to 4 March 2016, over 16 paired-day samples of the fishway entrances and exits, 21,691 fish (14 species) were sampled from the Goolwa large vertical-slot 2, 9935 fish (15 species) from the Boundary Creek small vertical-slot and 2719 fish (9 species) from the Ewe Island dual vertical-slot. The catch at all fishways was dominated by small-bodied fishes (i.e. length <100 mm), particularly the freshwater Australian smelt (*Retropinna semoni*), and juveniles of the catadromous congolli (*Pseudaphritis urvilii*) and common galaxias (*Galaxias maculatus*). Species composition was similar among fishways, but total fish (all species pooled) and species-specific abundance varied, likely as a result of varying discharge among the barrages; discharge at Ewe Island was typically lower (≤5 $ML.day^{-1}$) than at Goolwa and Boundary Creek Barrages (often ≥300 $ML.day^{-1}$), likely resulting in the attraction of fewer fish to the associated fishway.

At the Goolwa large vertical-slot 2 fishway, the abundances of the most common sampled species (congolli, common galaxias, Australian smelt and flat-headed gudgeon *Philypnodon grandiceps*) were significantly greater at the entrance than at the exit of the fishway, whilst a greater proportion of small (<40 mm in length) congolli and common galaxias were sampled at the entrance than at the exit. This indicates some obstruction of the passage of small-bodied fishes at this fishway; nonetheless, overall passage efficiency (~25%) at this fishway in 2015/16 was up to five times greater than at the original Goolwa large vertical-slot fishway during assessment in 2005/06 (~5%). Additionally, the mean number of fish sampled from the exit (20.2 ± 11.4 $fish.hour^{-1}$) was similar to that at the exit of the Boundary Creek small vertical-slot fishway (31.2 ± 10.5 $fish.hour^{-1}$), suggesting comparable absolute fish passage between these fishways in 2015/16. Furthermore, low flows during sampling in 2015/16 resulted in generally high head loss (>0.5 m 60% of the time) across the fishway. These conditions promote internal hydraulics in the fishway that may be unsuitable for the passage of small fish. Because of its design, greater passage efficiency is expected at this fishway under conditions of higher flow and lower head loss.

At the Boundary Creek small vertical-slot fishway, abundances of congolli, common galaxias and Australian smelt were similar between entrance and exit samples, whilst flat-headed gudgeon were significantly more abundant from the entrance, although this species was generally uncommon in the fishway (n = 121). Slightly greater proportions of small size classes (<40 mm) of common galaxias were sampled at the entrance (~40%) than the exit (~17%), but length distributions were generally similar between the entrance and exit for other species. As such, this fishway exhibited high passage efficiency for the species sampled. Although statistically not significant, there was an apparent trend of increasing minimum head loss during trapping events and greater total fish abundance in entrance samples. This suggests that during times of greater head loss and higher fishway discharge and velocities, greater numbers of fish are attracted into the fishway; this result is consistent with a head loss–abundance relationship previously observed at the Tauwitchere small vertical-slot fishway, which has a similar design.

At the Ewe Island dual vertical-slot fishway, the abundance of congolli, common galaxias and Australian smelt were similar between entrance and exit samples, but flat-headed gudgeon was more abundant at the entrance. Furthermore, length-frequency distributions were generally similar between entrance and exit samples, with the exception of a slightly greater proportion of small (<40 mm in length) common galaxias at the entrance. As such, this fishway exhibited high passage efficiency for the species sampled. Although statistically not significant, there was an apparent trend of decreasing total fish abundance in exit samples and increasing minimum head loss during trapping events. This suggests greatest passage efficiency for small-bodied fishes during periods of relatively low head loss.

The current fishway construction program has improved overall fish passage at the Murray Barrages. The fishways on Boundary Creek and Ewe Island Barrages have re-instated migratory pathways providing further locations across the barrage network for fish to access the Lower Lakes from the Coorong. Additionally, these fishways, together with the Goolwa large vertical-slot 2 fishway, have increased the capacity of the fishway network to pass a high biomass of fish, under all flow conditions. Completion of the remaining three fishways will result in the provision of fish passage on every barrage within the network, further improving the geographical spread of migration pathways and capacity to pass high biomasses of fish.

The key conclusions/recommendations of this report are:

- Each of the assessed fishways are operating to biological design objectives;

- Physical alterations to the new fishways are likely not required, but will be dependent upon wet commissioning to determine hydraulic characteristics (to be undertaken October 2016);
- No specific recommendations are provided for the remaining fishways to be constructed (i.e. proceed as designed); and
- We suggest the year-round operation of all fishways, but particularly June–January, and barrage operation that maximises attraction to fishway entrances (i.e. operation of barrage gates adjacent fishways).

1. INTRODUCTION

1.1. Background

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

At the terminus of Australia's longest river system, the Murray-Darling, a series of low-level (~1.5 m above sea level) barrages separate the Coorong and Lower Lakes, regulate freshwater discharge to the Coorong and obstruct the movement of fishes between marine, estuarine and freshwater environments. A growing appreciation of the importance of fish movement at the Murray Barrages prompted the construction of three experimental fishways (two vertical-slot fishways and one rock ramp) in 2004 under the Murray-Darling Basin Authority's *The Sea to Hume Program* (Barrett and Mallen-Cooper 2006). Due to a paucity of scientific data on fish movement in the region, fishway designs were informed by local knowledge (e.g. anecdotal evidence from commercial fishers). Perceived importance of the movement of large-bodied species, including black bream (*Acanthopagrus butcherii*) and mulloway (*Argyrosomus japonicus*), resulted in the vertical-slot fishways on Goolwa and Tauwitchere Barrages being designed to pass large-bodied fish (i.e. >150 mm Total Length; TL), whilst the rock ramp fishway at Tauwitchere was designed to facilitate the passage of small-bodied fish (i.e. 40–150 mm TL).

Assessment of the effectiveness of the three experimental fishways from 2004–2006 (Stuart *et al.* 2005, Jennings *et al.* 2008) and long-term monitoring of fishway entrances from 2006–2016 (see Bice and Zampatti 2015) suggested the migratory fish assemblage was substantially different from that originally proposed from local ecological knowledge and used to inform original fishway design. Indeed, small-bodied fish (<100 mm TL), including young-of-the-year catadromous congolli (*Pseudaphritis urvillii*) and common galaxias (*Galaxias maculatus*), typically represented >95% of fish sampled at these fishways in any given year, with limited use of the fishways by large-bodied species, particularly black bream and mulloway. Assessment of the effectiveness of the vertical-slot fishways suggested the passage of small-bodied fish (<100 mm) was largely obstructed, particularly during years of low discharge from the barrages and consequently conditions of predominantly high head loss (the difference between water levels between upstream and downstream), whilst the rock-ramp fishway had a limited operational window (Lake Alexandrina water level >0.65 m Australian Height Datum (AHD) and Coorong water level >0.18 m AHD) due to the high variability in headwater and tailwater levels typical of the Murray Barrages.

An improved model of fish movement at the Murray Barrages, supported by scientific data, and enhanced knowledge of fishway function (Zampatti *et al.* 2010, 2012, Bice and Zampatti 2015), highlighted the need to improve fish passage on the Murray Barrages, particularly for small-bodied species. This prompted the construction of the Tauwitchere small vertical-slot and Hunters Creek vertical-slot fishway, which were both specifically designed (i.e. low velocity and turbulence) to facilitate the passage of small-bodied fishes. Additionally, alterations were made to the slot dimensions of the original Goolwa large vertical-slot fishway (i.e. reduced slot width and overall aperture) with the intention of reducing internal turbulence and thus, improving passage for small-bodied fishes. The Tauwitchere small vertical-slot and Hunters Creek vertical-slot were found to be effective at passing small-bodied fishes, whilst passage at the Goolwa large vertical-slot was improved (Zampatti *et al.* 2012).

Despite the construction of new fishways and improved function of the Goolwa large vertical-slot fishway, fish passage was still not provided at three barrages, namely Mundoo, Boundary Creek and Ewe Island. Furthermore, the large extent of both Goolwa and Tauwitchere Barrages, and contemporary operation of the Murray Barrages that prioritises discharge to these structures, suggests high biomasses of fish are likely to attempt to migrate at these barrages. Given the overall extent of the barrage network (collectively 7.6 km in length) and potential high biomass of fish attempting to migrate, further fishways were considered necessary to meet the movement requirements of fishes in this region.

Under the *Coorong Lower Lakes and Murray Mouth* (CLLMM) *Recovery Project*, construction of a further six fishways across the Murray Barrages was proposed for 2015–2016. This includes fishways on Mundoo, Boundary Creek and Ewe Island Barrages, and further fishways on Goolwa and Tauwitchere Barrages. The fishway designs are varied and tailored for target species, locations and hydrology in order to holistically meet fish passage requirements at the Murray Barrages. Fundamental to any fishway construction is assessment of the biological effectiveness of fishways against their design criteria. Such assessment can inform modifications required to improve passage and future fishway design.

1.2. Objectives

The primary objective of the current project was to assess the biological effectiveness of each of the newly constructed fishways on the Murray Barrages: Goolwa large vertical-slot 2; Goolwa small vertical-slot; Mundoo dual vertical-slot; Boundary Creek small vertical-slot; Ewe Island dual vertical-slot; and Tauwitchere trapezoidal fishway (should this be built). Specifically, the project aims to:

1. Undertake ‘entrance and exit trapping’ of each fishway and compare fish species composition, abundance and length distributions between entrance and exit samples to determine passage efficiency against fishway-specific objectives and design specifications;
2. Determine the influence of head loss on relative attraction and passage efficiency, and thus, biological effectiveness;
3. Qualitatively compare biological effectiveness (i.e. the species and size classes for which passage is facilitated) between the newly constructed fishways and with existing fishways on the Murray Barrages;
4. Provide comment on the contribution of the CLLMM fishway construction program to improving overall fish passage at the site;
5. Make recommendations for fishways still to be constructed; and
6. Make recommendations on future barrage/fishway operation in light of results of the current project and previous fishway assessments.

The current report presents data on the assessment of the Goolwa large vertical-slot 2 fishway, Boundary Creek small vertical-slot fishway and Ewe Island dual vertical-slot fishway in spring/summer 2015/16. The remaining fishways will be assessed and reported upon in 2016/17.

2. METHODS

2.1. Study site

This study was conducted at the Murray Barrages, the physical interface between the Coorong and Lower Lakes of the River Murray, in southern Australia (Figure 1). A series of five tidal barrages (Goolwa, Mundoo, Boundary Creek, Ewe Island and Tauwitchere), cumulatively spanning 7.6 km, separate the freshwater Lower Lakes (lakes Alexandrina and Albert) from the remnant Murray estuary and the Southern Ocean. Constructed in the 1930s, the barrages maintain a freshwater storage upstream by preventing saltwater intrusion and regulate freshwater discharge to the Murray estuary. Under natural conditions, mean annual discharge was ~12,233 GL, but there was strong inter-annual variation (Puckridge *et al.* 1998). Under regulated conditions, an average of ~4,723 $GL.y^{-1}$ reaches the sea (CSIRO 2008).

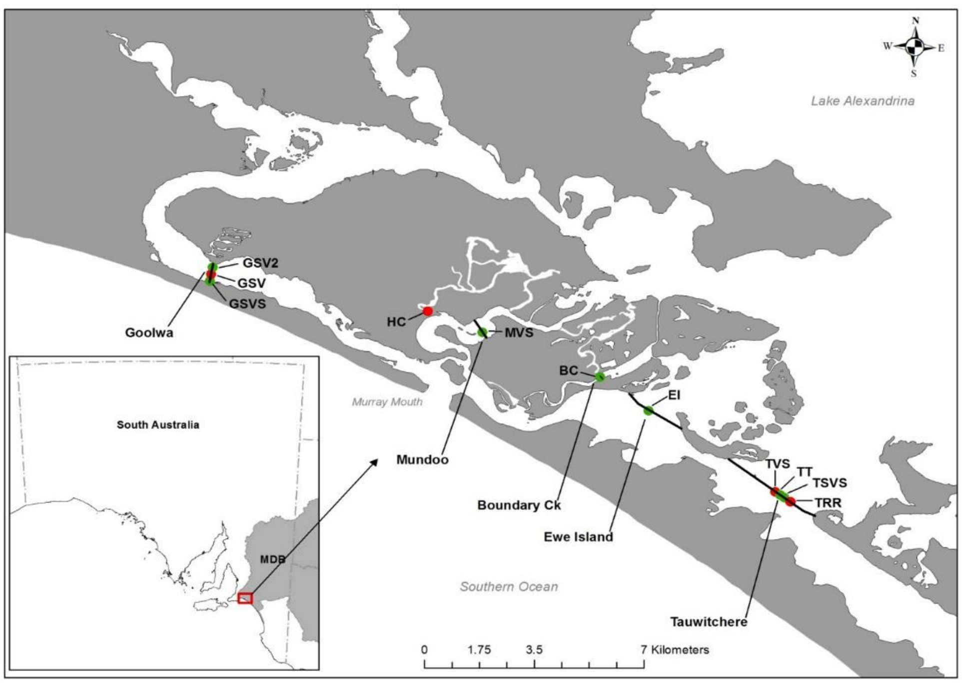

Figure 1. Map of the Coorong and Lower Lakes at the terminus of the River Murray, southern Australia, with the Murray Barrages presented as bold lines. The positioning of fishways constructed under the *CLLMM Program* are presented in *green circles*, namely: Goolwa large vertical-slot 2 (GVS2, constructed 2015), Goolwa small vertical-slot (GSVS, to be constructed in 2016), Mundoo dual vertical-slot (MVS, constructed 2016), Boundary Creek vertical-slot (BVS, constructed 2015), Ewe Island dual vertical-slot (EVS, constructed 2015) and Tauwitchere trapezoidal (TT, to be constructed 2016, subject to funding). The positioning of pre-existing fishways are indicated by *red circles*, namely: Goolwa large vertical-slot (GVS), Hunters Creek vertical-slot (Hunters), Tauwitchere vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS) and Tauwitchere rock ramp (TRR).

Water levels both upstream and downstream of the Murray Barrages exhibit hourly–seasonal fluctuations. The large surface area of Lake Alexandrina (~650 km^2) results in water levels upstream of the barrages being influenced by wind seiche as well as riverine flow. Downstream, water level is influenced by tide, freshwater inflows and wind seiche. In concert, these factors result in temporally variable head loss across the Murray Barrages, which typically range from 0 to 0.9 m, with occasional reverse (negative) head loss. The constricted nature of the river mouth, which connects the Coorong and Southern Ocean, means that during times of high river flow (e.g. >300 $GL.month^{-1}$), downstream water levels are generally elevated and tidal fluctuations are dampened, resulting in relatively low head loss (i.e. 0–0.5 m). Conversely, during times of low river flow, tidal fluctuation is maximised, resulting in variable head loss, but a greater frequency of periods with relatively high head loss (up to 1.1 m).

More than 80 species of fish have been recorded in the vicinity of the Murray Barrages representing freshwater, diadromous, estuarine and marine life history categories. A total of 33 species have been recorded attempting to migrate through the original vertical-slot fishways constructed on Goolwa and Tauwitchere Barrages (Zampatti *et al.* 2010, 2011, Bice *et al.* 2012), including two catadromous (congolli and common galaxias) and two anadromous species (short-headed lamprey, *Mordacia mordax,* and pouched lamprey, *Geotria australis*).

2.2. Fishways

Prior to the current construction program, five fishways existed on the Murray Barrages, specifically at Goolwa and Tauwitchere Barrages, and the Hunters Creek Causeway, comprising rock ramp and varying vertical-slot designs (Figure 1). All of these fishways have previously been assessed for biological effectiveness (Stuart *et al.* 2005, Jennings *et al.* 2008, Zampatti *et al.* 2012). As part of the current construction program, an expert working group – the 'Construction of Fishways Inter-agency Working Group' – comprised of fish ecologists, engineers, natural resource managers and river operators assessed the specific fish passage requirements on each of the Murray Barrages, with respect to the biomass and size classes of fish (i.e. small-bodied (<100 mm TL) and/or large-bodied (>100 mm TL) species) attempting to move at each structure, and the need for passage during periods of low discharge. Where possible, fish passage requirements were based on empirical data from previous fishway sampling (Stuart *et al.* 2005, Jennings *et al.* 2008, Zampatti *et al.* 2010, 2012, Bice and Zampatti 2015) and broader fish sampling within the Coorong (Noell *et al.* 2009, Ye *et al.* 2014, 2015) or otherwise based on expert opinion. Passage requirements were integrated with knowledge of function and effectiveness of existing fishways to determine new fishway designs likely to best meet passage requirements at individual structures and holistically across the barrage network.

Table 1. Ecological objectives for fish passage and resulting overall passage requirements determined for each of the Murray Barrages.

Barrage	Ecological objectives				Overall passage requirement
	Estimated overall biomass[1]	**Small-bodied fish passage[2]**	**Large-bodied fish passage[2]**	**Requirement for passage at low flows[3]**	
Goolwa	High	Yes	Yes	High	Small and large-bodied fishes over range of flows, and specifically small-bodied fish under low flows
Mundoo	Moderate	Yes	Potentially	Low	Small and large-bodied fishes over range of flows
Boundary Creek	Low	Yes	No	Moderate	Small-bodied fishes over range of flows
Ewe Island	Moderate	Yes	Potentially	Low	Small and large-bodied fishes over range of flows
Tauwitchere	High	Yes	Yes	High	Small and large-bodied fishes over range of flows, and specifically small-bodied fish under low flows

[1]Overall biomass was suggested to be either low/moderate/high. [2]A specific requirement for the passage of small- and large-bodied species was categorized as yes/no or 'potentially' where limited data existed. [3]Requirement for passage at low flows was categorised as high/moderate/low and based on typical operation of the barrages under such conditions (i.e. freshwater discharge is typically prioritized to Goolwa and Tauwitchere Barrages, followed by Boundary Creek, during conditions of low discharge)..

Under the current program, up to six new fishways are planned for construction across Goolwa, Mundoo, Boundary Creek, Ewe Island and Tauwitchere Barrages. Each fishway design considers the physical nature and typical operation of individual barrages, as well as predetermined fish passage ecological objectives at individual barrages and the site more broadly (Table 1). By November 2015, three fishways were completed (i.e. Goolwa large vertical-slot 2, Boundary Creek vertical-slot and Ewe Island dual vertical-slot) and were subsequently sampled in spring/summer 2015/16, with the remainder to be completed and sampled in spring 2016 (Table 2). At the conclusion of the construction program, up to 11 fishways will be in operation on the Murray Barrages.

Table 2. List of all current and 'to be constructed' fishways on the Murray Barrages, as of June 2016. Details include the barrage on which the fishways are situated, fishway design, abbreviation used throughout, construction year and hydraulic design parameters.

Fishway type	Abbrev.	Year constructed	Max velocity ($m.s^{-1}$)	Max turbulence ($W.m^{-3}$)	Discharge ($ML.day^{-1}$)
Goolwa Barrage					
Vertical-slot (large)	GVS	2004	1.7	26	40
Vertical-slot (large)	GVS2	2015	1.7	23	37
Vertical-slot (small)	GSVS	2016	-	-	-
Hunters Creek causeway					
Vertical-slot (small)	Hunters	2009	1.1	25	3
Mundoo Barrage					
Dual vertical-slot	MDVS	2016	-	-	-
Boundary Creek Barrage					
Vertical-slot (small)	BCVS	2015	0.92	20	2.2
Ewe Island Barrage					
Dual vertical-slot	EDVS	2015	1.7	40	32
Tauwitchere Barrage					
Vertical-slot (large)	TVS	2004	2.0	95	31
Rock ramp	TRR	2004	-	-	30
Vertical-slot (small)	TSVS	2009	0.75	26	2.4
Trapezoidal*	TT	2016	-	-	-

**Subject to availability of funds.*

Goolwa large vertical-slot 2 fishway (GVS2)

The Goolwa large vertical-slot 2 fishway was designed with the objective of passing both small-bodied and large-bodied fishes. The design is expected to work optimally for large-bodied fishes during both low flow and high flow conditions, but sub-optimally for small-bodied fishes under low flow, and optimally under high flows.

This fishway is located towards the northern end of Goolwa Barrage in bay 99. The fishway consists of four precast vertical-slot baffles installed within the piers of the barrage bay, resulting in three pools with dimensions 2.7 m long x 3.6 m wide (Figure 2). Baffle height is 3.6 m and mean water depth in the fishway is ~2.8 m. Vertical-slot widths are 200 mm and the hydraulic gradient of the fishway is created by decreasing slot height across the baffles from upstream to downstream (Figure 2b). At median headwater levels, the fishway discharges ~35 $ML.day^{-1}$ and head loss is 0.15 m between consecutive cells, resulting in a maximum velocity of 1.5 $m.s^{-1}$ and average turbulence of 22 $W.m^{-3}$ (calculated with a Coefficient of Discharge [Cd] of 0.7).

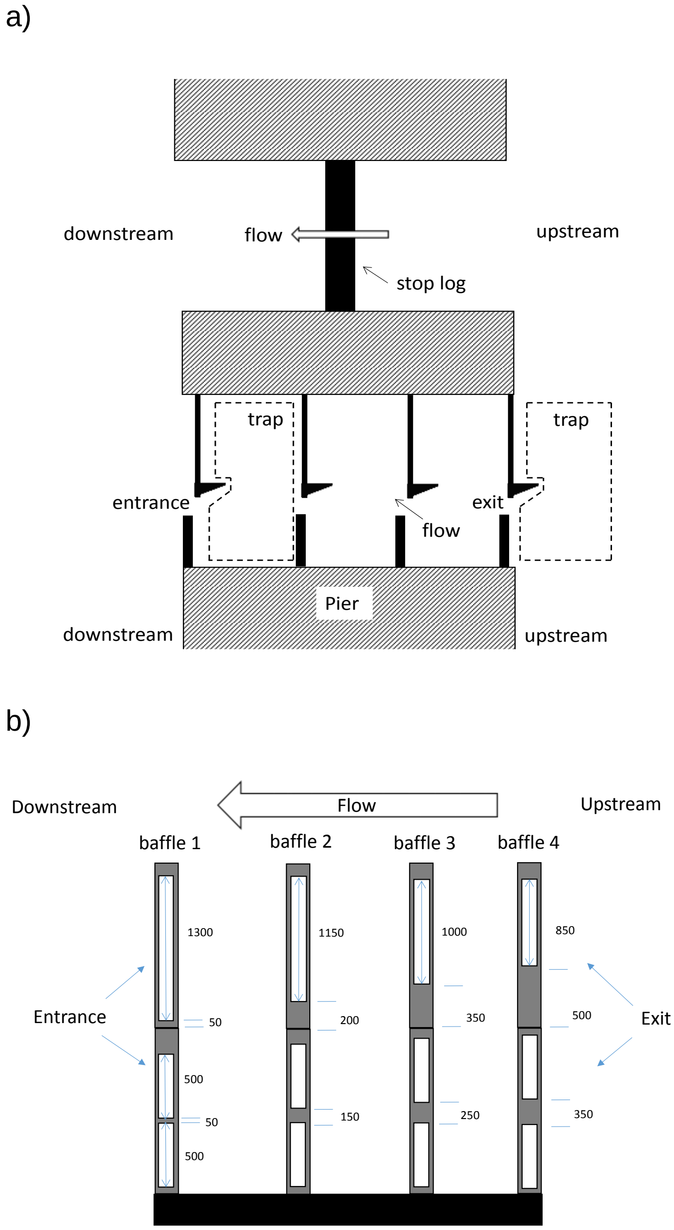

Figure 2. a) Plan and b) side views of the newly constructed Goolwa large vertical-slot 2 (GVS2) fishway. Entrance and exit trapping locations are indicated in the plan view, whilst vertical-slot aperture configuration is indicated in the side view.

The depth of this fishway necessitated the use of a ‘double trap’ configuration to sample fish, with two traps ~3.2 m long x ~1.9 m wide x ~1.8 m high, connected together one atop the other. A double cone-shaped entrance configuration was used on the ‘top trap’ (cone 1: 0.65 m high x 0.15 m wide, cone 2: 0.35 m high x 0.15 m wide) and a single cone-shaped entrance configuration used on the ‘bottom trap’ (1.15 m high x 0.15 m wide). The traps were clad with a combination of 3 mm perforated aluminum sheet and 6 mm knotless mesh. The same traps were used to sample the exit of the fishway.

Ewe Island dual vertical-slot fishway (EDVS)

This fishway was designed with the objective of passing both small- and large-bodied fishes under a range of flows. The design is expected to work optimally for large-bodied fishes during both low flow and high flow conditions, but optimally for small-bodied fishes under high flow, and sub-optimally under low flows.

This fishway is located in Bay 2 at the western end of Ewe Island Barrage. The fishway is a reinforced concrete channel, separated into three pools of equal dimension (3.6 m wide 2.5 m long) by four dual vertical-slot baffles (Figure 3). Slot widths are 150 mm and the hydraulic gradient of the fishway is created by decreasing slot height across the baffles from upstream to downstream. At median headwater levels (0.75 m AHD), the fishway discharges ~15 $ML.day^{-1}$ and head loss of ~0.145 m between consecutive cells, resulting in a maximum velocity of 1.7 $m.s^{-1}$ and average turbulence of 40 $W.m^{-3}$ (calculated with a Coefficient of Discharge [Cd] of 0.7). At Lake Alexandrina levels of 0.7 m AHD, turbulence is reduced to 30 $W.m^{-3}$. The sill of the vertical-slot on the most upstream baffle is set at 0.4 m AHD, meaning the fishway ceases to function at Lake Alexandrina levels <0.4 m AHD.

Two separate traps were constructed to sample the left- and right-hand side entrances of the fishway (Figure 3). The traps were mirror images of one another and approximately cuboid in shape, ~0.9 m long x ~0.6 m wide x ~1.5 m high. Single cone-shaped entrance configurations were used on both traps (1.06 m high x 0.11 m wide). The traps were clad with a combination of 3 mm perforated aluminum sheet and 6 mm knotless mesh. These traps were also used to sample the exit of the fishway.

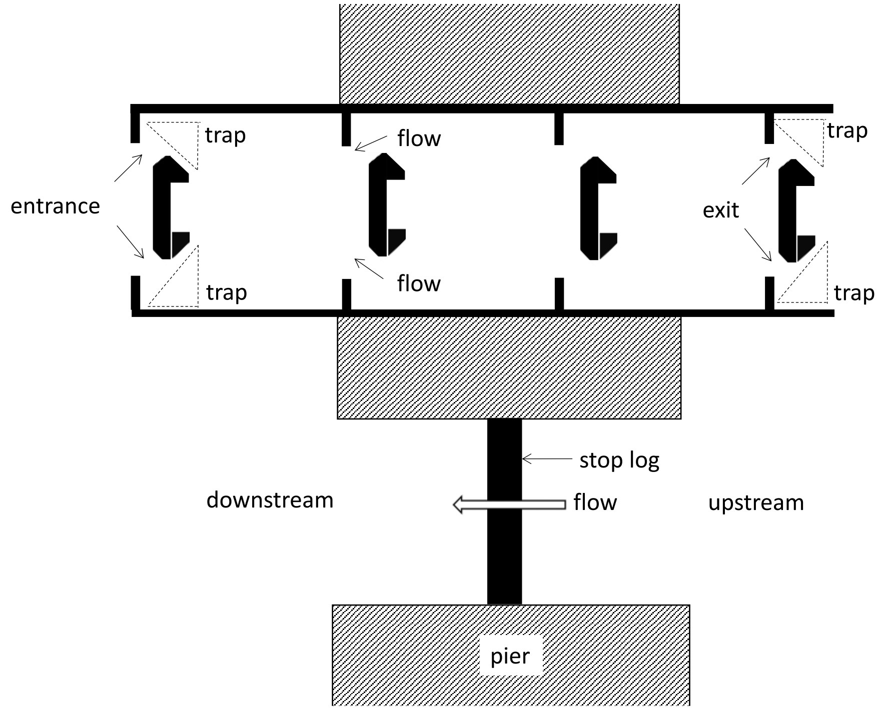

Figure 3. Plan view of the newly constructed Ewe Island dual vertical-slot fishway and indication of entrance, and exit, trapping locations.

Boundary Creek vertical-slot fishway and traps

This fishway was designed with the specific objective of passing small-bodied fishes. The design is expected to work optimally for small-bodied fishes under low flows and sub-optimally under high flows. It is expected to work sub-optimally for large-bodied species, particularly individuals >350 mm TL, under all flow conditions due to narrow slot widths (100 mm).

This fishway is located in Bay 2 of Boundary Creek Barrage. The fishway is a reinforced concrete channel, rectangular in cross-section, divided into 15 pools by 16 vertical-slot baffles, comprising six resting/turning pools (1.04 m wide x 2.35 m long) and nine regular pools (1.1 m wide x 1.1 m long) (Figure 4). Slot widths are 100 mm and the hydraulic gradient of the fishway is created by decreasing slot height across the baffles from upstream to downstream. At a design depth of 0.4 m, the fishway discharges ~2.2 ML.day^{-1} and head loss is ~0.043 m between consecutive pools, resulting in a maximum velocity of 0.92 m.s^{-1} and average turbulence of 20 W.m^{-3} (calculated with Coefficient of Discharge [Cd] of 0.7). The fishway has three different exits that can be manually ‘engaged’ with the aim of maintaining optimal velocity and turbulence. Nonetheless, only exit one was used in the current study. A specific ‘attraction gate’ was also manufactured and installed adjacent the fishway (Figure 4). This gate may be used to regulate discharge and thus, optimise entrance conditions and fish attraction.

A cuboid trap was used to sample both the entrance and exit of this fishway (Figure 4). The trap was 1.25 m high x 0.95 m long x 0.84 m wide and used a single cone-shaped entrance configuration 0.75 m high x 0.11 m wide. The trap was clad with a combination of 3 mm perforated aluminum sheet and 6 mm knotless mesh.

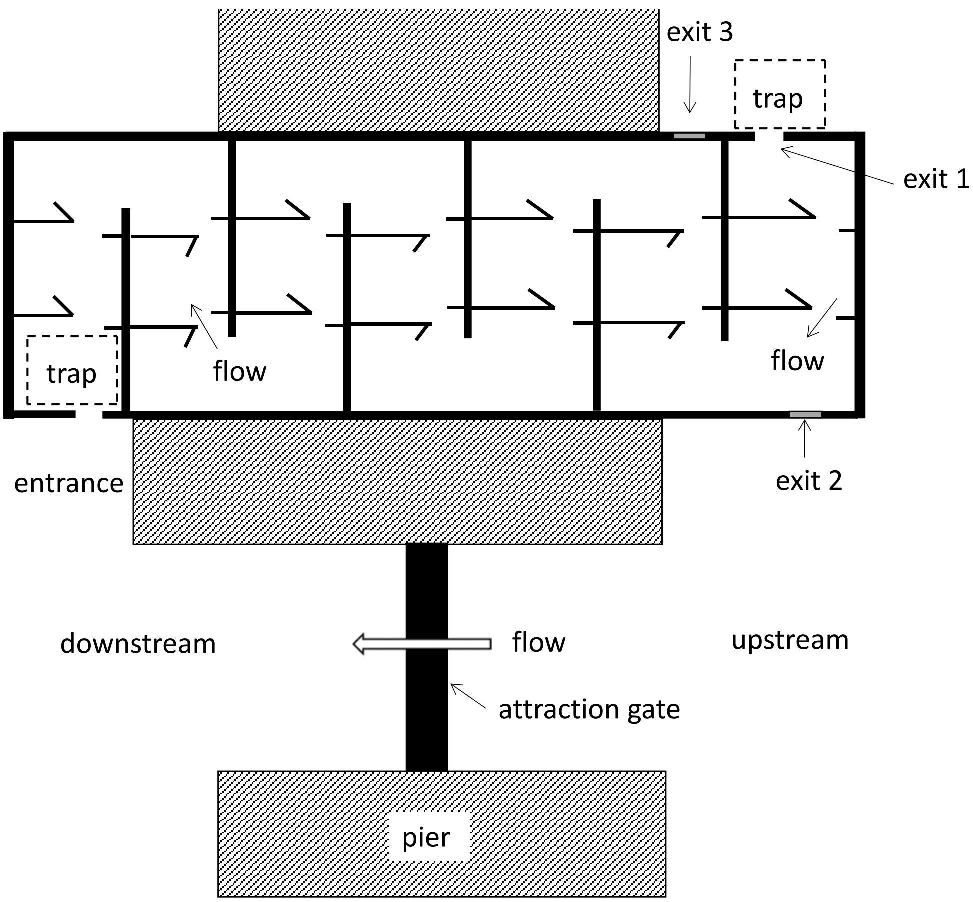

Figure 4. Plan view of the newly constructed Boundary Creek vertical-slot fishway and indication of entrance, and exit, trapping locations.

2.3. Fishway sampling

Fish were sampled from the fishways from 24 November 2015 to 4 March 2016. Assessment occurred during the austral spring/summer as this is the peak upstream migration period for juvenile catadromous fishes at the Murray Barrages (Zampatti *et al.* 2010). During each sampling event (Monday–Friday) the entrance and exits of the fishways were sampled consecutively, overnight for a period of ~24 hours; as such, entrances and exits were each sampled twice within each sampling week. A minimum of eight sampling events were conducted for the entrance and exit of each fishway and these sampling events are treated as replicates for subsequent statistical analyses.

At the Goolwa large vertical-slot 2 fishway, the cage traps were deployed and retrieved with a mobile crane and the assistance of SA Water staff (Figure 5a). At the Boundary Creek vertical-slot and Ewe Island dual vertical-slot fishways, cage traps were deployed and retrieved by hand (Figure 5b). All fish sampled were identified to species and enumerated, and length measurements (fork length (FL) or total length (TL) depending on tail morphology) taken for up to 50 individuals per species per trapping event. The estuarine use life history guilds of Potter *et al*. (2015) are adopted throughout (Table 3)

a) b)

Figure 5. Fishway traps deployed at the exits of the a) Goolwa large vertical-slot (GVS2) and b) Boundary Creek small vertical-slot (BCVS). Note chains and lifting hook of mobile crane attached to GVS2 trap.

Table 3. Definitions of fish 'estuarine use' categories and guilds represented by fishes of the Coorong, following the approach of Potter et al. (2015). Examples of representative species from the Coorong are presented for each guild.

Category and guild	Definition	Example
Marine category		
Marine straggler	Truly marine species that spawn at sea and only sporadically enter estuaries, and in low numbers.	King George whiting (*Sillaginodes punctatus*)
Marine estuarine-opportunist	Marine species that spawn at sea, but regularly enter estuaries in substantial numbers, particularly as juveniles, but use, to varying degrees, coastal marine waters as alternative nurseries.	Mulloway (*Argyrosomus japonicus*)
Estuarine category		
Solely estuarine	Species that complete their life cycles only in estuaries.	Small-mouthed hardyhead (*Atherinosoma microstoma*)
Estuarine and marine	Species represented by populations that may complete their life cycles only in estuaries, but also discrete populations that complete their lifecycle in marine environments.	Yellow-eyed mullet (*Aldrichetta forsteri*)
Diadromous category		
Anadromous	Most growth and adult residence occurs in the marine environment prior to migration into, spawning and larval/juvenile development in freshwater environments.	Pouched lamprey (*Geotria australis*)
Catadromous	Most growth and adult residence occurs in the freshwater environments prior to migration into, spawning and larval/juvenile development in marine environments.	Congolli (*Pseudaphritis urvillii*)
Semi-catadromous	As per catadromous species, but spawning run extends as far as downstream estuarine areas rather than the ocean.	Common galaxias (*Galaxias maculatus*)
Freshwater category		
Freshwater straggler	Truly freshwater species that spawn in freshwater environments and only sporadically enter estuaries, and in low numbers.	Golden perch (*macquaria ambigua ambigua*)
Freshwater estuarine-opportunist	Freshwater species found regularly and in moderate numbers in estuaries, and whose distribution can extend beyond low salinity zones of these system.	Bony herring (*Nematalosa erebi*)

2.4. Data analysis

2.4.1. Fishway use

Differing use of the three fishways, in regards to species identity and abundance (fish.hour^{-1}.trap event^{-1}, entrance and exit samples pooled), was investigated using multidimensional scaling (MDS) ordination and PERMANOVA (Permutational Anova), performed on Bray-Curtis similarity matrices, 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. An arbitrary 60% cumulative contribution cut-off was applied.

2.4.2. 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 >200 individuals were sampled over the study period) sampled at each fishway 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. >25 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.

2.4.3. Influence of head loss on fishway effectiveness

The influence of head loss (the difference in water level between the entrance and exit of each fishway) on attraction to the fishways and passage efficiency, and thus fishway effectiveness (fishway effectiveness can be viewed as the sum of attraction and passage efficiency), was assessed by investigating the relationship between the total fish abundance (fish.hr^{-1}, all species pooled) at the entrance and exit of the fishways and the minimum head loss experienced during each trapping event. Whilst we did not specifically assess attraction of individual fish from the areas immediately below the fishways (ideally done using telemetry, Cooke and Hinch 2013), the abundance of fish in entrance samples was considered to represent relative attraction (i.e. greater relative abundance in a given entrance sample is taken to signify greater relative attraction), whilst abundance in exit samples was considered to represent passage efficiency (i.e. greater relative abundance in a given exit sample is taken to signify greater relative passage efficiency).

Water level upstream and downstream of the barrages is recorded hourly by remote logging stations (DEWNR 2013) and hourly head loss for each fishway was calculated by subtracting downstream water level from upstream water level, and the minimum value determined for the course of each trapping event. Both linear and sigmoidal regression models were fitted to $Log_{10}(x + 1)$ transformed total fish abundance and minimum head loss data, with the relative support for each assessed by calculating Akaike's Information Criteria (AIC), corrected for small sample sizes (AIC_c) (Burnham and Anderson 1998). AIC_c values were rescaled as the difference between the two models. The likelihood of the models given the data was calculated as:

$$P(Mk|y) = e^{(-0.5a)}\left[\sum_{k=1}^{10} e^{(-0.5a)}\right] - 1$$

where P ($M_k|y$) if the likelihood of model M_k given data y (Hoeting et al. 1999) and a is ΔAIC_{ck}. The model (i.e. linear or sigmoidal) with the greatest likelihood was selected as the most appropriate for explaining the total fish abundance/minimum head loss relationships and assessed for significance using analysis of variance (ANOVA, $\alpha = 0.05$). Significant relationships would suggest minimum head loss during trapping was influencing (negatively or positively) relative attraction and/or relative passage efficiency, and thus, fishway effectiveness.

3. RESULTS

3.1. Environmental conditions

Annual freshwater discharge from the Murray Barrages in 2015/16 (562 GL) was considerably less than the long-term post-regulation average (~4723 GL). Over the spring/summer sampling season, total barrage discharge peaked at ~3000 $ML.day^{-1}$ in mid-November, before declining to <100 $ML.day^{-1}$ throughout December and January, and gradually increasing to 2000–3000 $ML.day^{-1}$ through late-February and early-March (Figure 6a). Temporal patterns of discharge varied among Goolwa, Boundary Creek and Ewe Island Barrages (Figure 6b–d). Discharge at Goolwa and Boundary Creek barrages was approximately 300 $ML.day^{-1}$ at the initiation of trapping in November, but all gates were shut and discharge confined to the fishways by the start of December and for the remainder of the study (Figure 6b and c). Discharge at Ewe Island was ≤5 $ML.day^{-1}$ throughout the study, reflecting the absence of gate opening and confinement of discharge to the fishway (Figure 6d). Increases in 'total barrage discharge' in February and March reflected increased discharge from Tauwitchere Barrage, which is not presented here.

Head loss ranged from -0.35 to 1.08, -0.46 to 1.02 and -0.47 to 1.03 m at Goolwa, Boundary Creek and Ewe Island barrages, respectively (Figure 6 b–c). Nonetheless, conditions of negative and low head loss (i.e. ≤0.2 m) were rare, with head loss ranging from 0.2 to 0.9 m for ≥90% of the time at all barrages. A trend of slightly decreasing head loss through spring/summer was also apparent at all barrages.

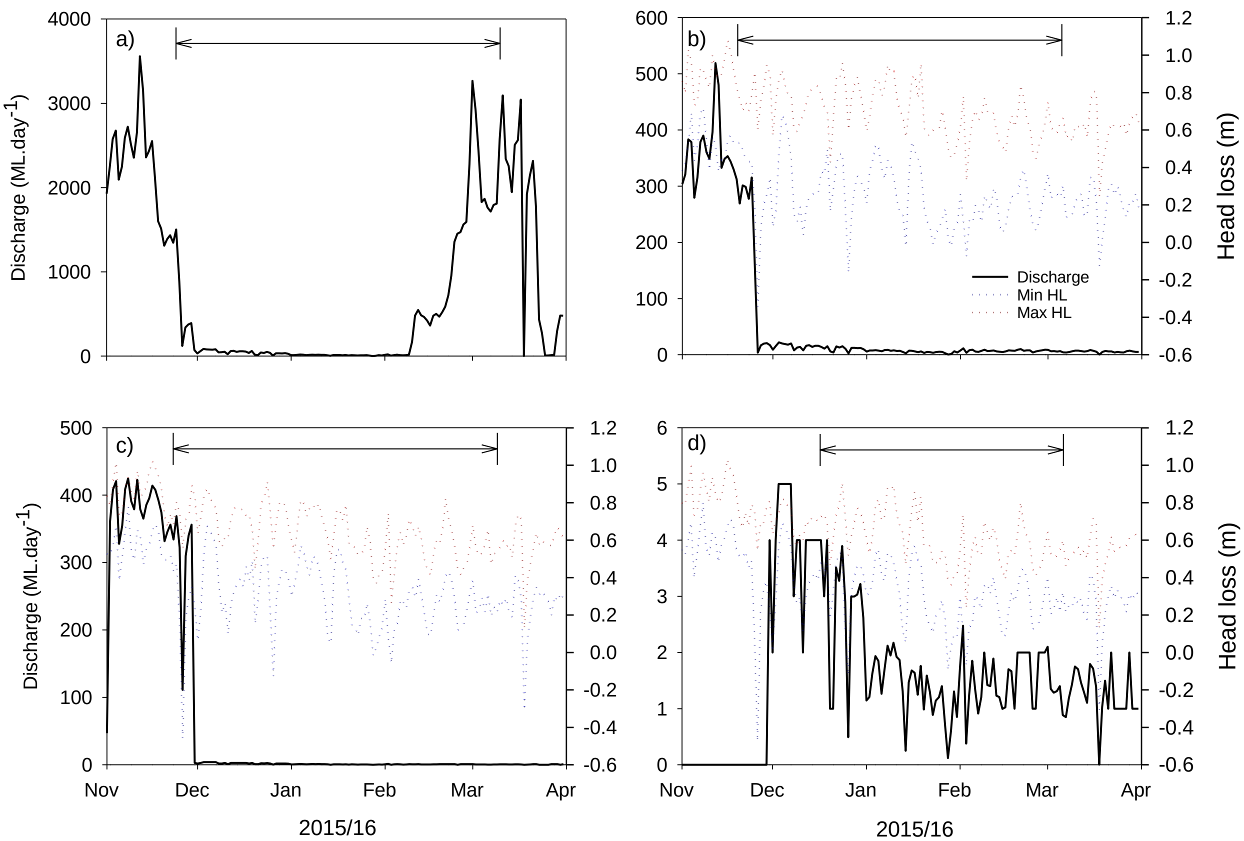

Figure 6. Discharge (ML.day-1) and head loss data from the Murray Barrages in spring/summer 2015/16, specifically: a) total barrage daily discharge; b) daily discharge (*black solid line*), and daily minimum (blue dotted line) and maximum head loss (*red dotted lined*) at Goolwa Barrage; c) daily discharge (*black solid line*), and daily minimum (blue dotted line) and maximum head loss (*red dotted lined*) at Boundary Creek Barrage; and d) daily discharge (*black solid line*), and daily minimum (blue dotted line) and maximum head loss (*red dotted lined*) at Ewe Island Barrage. Arrows indicate sampling season at each barrage and associated fishway.

3.2. Catch summary

In spring/summer 2015/16, a total of 34,345 fish from 17 species were collectively sampled from the three fishways (Table 4). The overall catch was dominated by the small-bodied freshwater Australian smelt (*Retropinna semoni*) and catadromous congolli (*Pseudaphritis urvillii*), which comprised ~39% and ~35% of the total catch, respectively, with smaller contributions from the catadromous common galaxias (*Galaxias maculatus*, 7.9%), freshwater flat-headed gudgeon (*Philypnodon grandiceps*, 5.4%), 'marine-estuarine opportunist' sandy sprat (*Hyperlophus* *vitattus*, 5.5%) and 'marine and estuarine' yelloweye mullet (*Aldrichetta forsteri,* 5.1%). The remaining 11 species collectively comprised <1.5% of the total catch.

Table 4. Species, total number and length range of fish collected from the entrances and exits of the newly constructed Goolwa large vertical-slot 2, Boundary Creek vertical-slot and Ewe Island dual vertical-slot in spring/summer 2015/16. Species are grouped using the life history categories of Potter *et al.* (2015)

		Boundary Creek			**Ewe Island vertical-slot**			**Goolwa large vertical-slot 2**			**Total**
Common name	**Scientific Name**	**entrance**	**exit**	**Length range**	**entrance**	**exit**	**Length range**	**entrance**	**exit**	**Length range**	
	Sampling events	8	8		8	8		10	8		
	No. of species	13	7		8	8		14	8		
Freshwater species											
Australian smelt	*Retropinna semoni*	990	279	20–69	43	327	27–71	9251	2651	20–68	**13,541**
Bony herring	*Nematalosa erebi*	62	0	25–125	5	181	26–95	1	0	24	**249**
Flat-headed gudgeon	*Philypnodon grandiceps*	110	21	17–81	318	72	15–67	1272	68	12–72	**1,861**
Dwarf flat-headed gudgeon	*Philypnodon macrostomus*	1	0	31	0	0	-	2	0	16–19	**3**
Carp gudgeon	*Hypseleotris* spp	1	1	22–29	0	0	-	0	0	-	**2**
Common carp	*Cyprinus carpio**	0	11	467–640	0	0	-	0	0	-	**11**
Redfin perch	*Perca fluviatilis**	0	5	89–136	0	20	57–90	12	14	44–132	**51**
Eastern gambusia	*Gambusia holbrooki**	1	0	25	0	0	-	0	0	-	**1**
Semi-catadromous species											
Common galaxias	*Galaxias maculatus*	188	90	29–97	232	287	28–101	1349	576	22–76	**2,722**
Congolli	*Pseudaphritis urvillii*	3248	4891	27–67	902	311	26–131	2436	303	28–159	**12,091**
Estuarine species											
Small-mouthed hardyhead	*Atherinosoma microstoma*	17	0	32–48	0	0	-	4	0	31–38	**21**
Tamar River goby	*Afurcagobius tamarensis*	2	0	27–32	5	3	18–32	4	1	21–56	**15**
Blue-spot goby	*Pseudogobius olorum*	9	0	28–43	2	0	31–38	3	0	30–36	**14**
Lagoon goby	*Tasmanogobius lasti*	7	0	21–43	5	6	21–38	78	0	17–26	**96**
River garfish	*Hyperhamphus regularis*	0	0	-	0	0	-	1	0	22	**1**
Marine species											
Yelloweye mullet	*Aldrichetta forsteri*	0	0	-	0	0	-	1757	1	17–63	**1,758**
Sandy sprat	*Hyperlophus vittatus*	1	0	38	0	0	-	1903	4	20–56	**1,908**
	Total	**4637**	**5298**		**1512**	**1207**		**18,073**	**3618**		**34,345**

**Denotes non-native species*

3.3. Fishway use comparison

The number of species and total number of fish sampled from the Ewe Island dual vertical-slot (9 species, 2719 fish) was considerably lower than that sampled from both the Boundary Creek vertical-slot (15 species, 9935 fish) and Goolwa large vertical-slot 2 fishways (14 species, 21,691 fish). MDS ordination of fish assemblage data suggested weak grouping of trapping events by fishway and the ordination exhibited poor stress (0.22) (Figure 7). Nonetheless, PERMANOVA, indicated assemblages were significantly different among fishways ($Pseudo\text{-}F_{2,\ 49}$ = 4.11, $p <$ 0.001). Pairwise comparisons indicated fish assemblages were significantly different between each fishway ($p < 0.05$ for all comparisons).

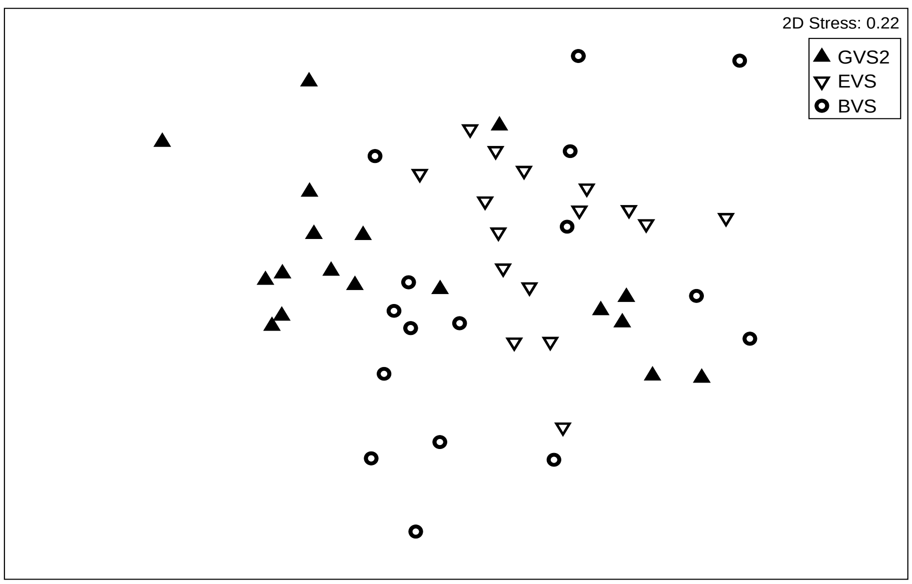

Figure 7. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages (entrance and exit samples pooled) sampled at the Goolwa large vertical-slot 2 (GVS2, *solid triangles*), Ewe Island dual vertical-slot (EVS, *open triangles*) and Boundary creek vertical-slot (BVS, *open circles*).

Nine species were sampled from all three fishways, but species-specific abundance varied substantially. SIMPER indicated differences in fishway use between the Goolwa large vertical-slot 2 and Ewe Island dual vertical-slot were primarily driven by greater relative abundance of the freshwater Australian smelt and flat-headed gudgeon, and the catadromous congolli and common galaxias at the Goolwa large vertical-slot 2, but greater abundance of bony herring (*Nematalosa erebi*) at the Ewe Island dual vertical-slot. Similarly, differences between the Goolwa large vertical-slot 2 and Boundary Creek vertical-slot were driven by greater abundance of Australian smelt, flat-headed gudgeon and common galaxias at Goolwa, but greater abundance of congolli at Boundary Creek. Differences between assemblages at Ewe Island and Boundary Creek were driven by greater abundance of flat-headed gudgeon and bony herring at Ewe Island, but greater abundance of Australian smelt and congolli at Boundary Creek.

3.4. Fishway effectiveness

3.4.1. Goolwa large vertical-slot 2

Passage efficiency

A total of 14 species were sampled from the entrance of this fishway and 8 from the exit (Table 4). Fishes that did not successfully ascend the fishway included the freshwater bony herring and dwarf flat-headed gudgeon (*Philypnodon macrostomus*) and the estuarine species small-mouthed hardyhead (*Atherinosoma microstoma*), blue-spot goby (*Pseudogobius olorum*) and river garfish (*Hyperhamphus regularis*), but all were sampled in low numbers at the entrance ($n \leq 4$). Conversely, the estuarine lagoon goby ($n = 78$), yelloweye mullet ($n = 1757$) and marine sandy sprat ($n = 1903$) were sampled in high abundance from the entrance of the fishway, but few from the fishway exit ($n = 0–4$).

Numbers of fish entering the fishway ranged from 9 to 130 fish.hour^{-1} (mean ± SE = 81.5 ± 15.3 fish.hour^{-1}), whilst numbers of fish successfully ascending the fishway ranged from 1 to 84 fish.hour^{-1} (mean ± SE = 20.2 ± 15.3 fish.hour^{-1}). This resulted in an overall passage efficiency (the abundance of fish that successfully ascended as a proportion of those that attempted to ascend the fishway) across the sampling period of ~25%. Comparison of abundance between entrance and exit trapping events for the most abundant species indicated no significant difference for common galaxias ($Pseudo\text{-}F_{1, 17} = 3.97$, $p = 0.071$), but significantly higher abundances of congolli ($Pseudo\text{-}F_{1, 17} = 14.56$, $p < 0.001$), flat-headed gudgeon ($Pseudo\text{-}F_{1, 17} = 12.38$, $p = 0.006$) and Australian smelt ($Pseudo\text{-}F_{1, 17} = 5.26$, $p = 0.040$) at the entrance than at the exit of the fishway (Figure 8).

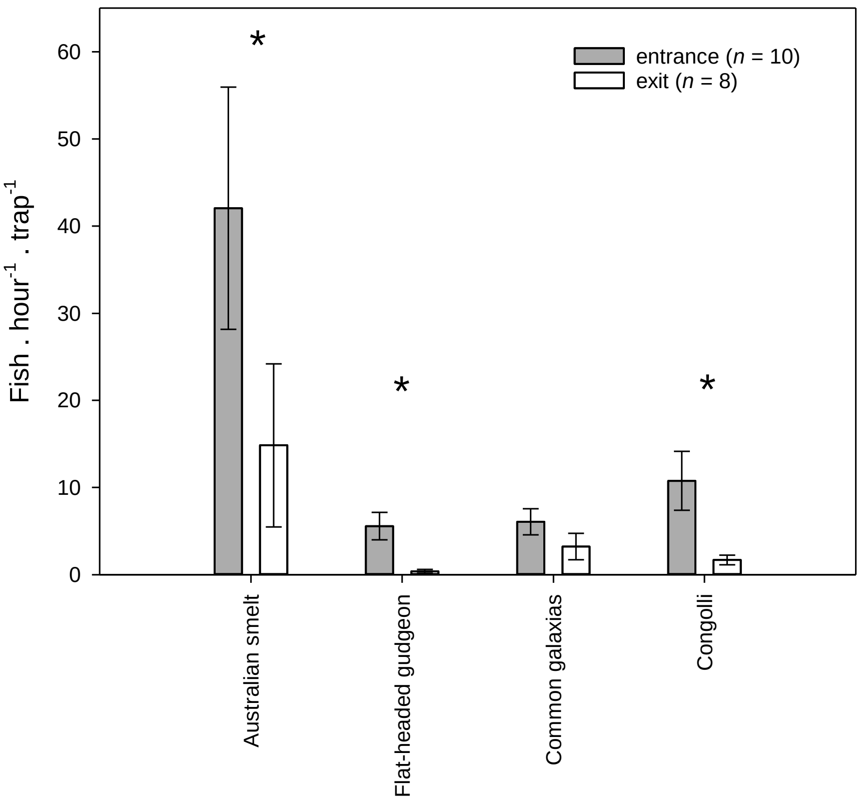

Figure 8. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most common species sampled at the entrance (*shaded bar*) and exit (*open bar*) of the new Goolwa large vertical-slot 2 fishway in spring/summer 2015/16. Significant differences between entrance and exit abundance are indicated by asterisks.

Fish sampled at the entrance of this fishway ranged from 12 to 159 mm in length, whilst those that successfully ascended the fishway ranged from 16 to 133 mm in length. Length-frequency distributions were significantly different between entrance and exit samples for congolli ($D_{440,\ 197}$ = 0.162, p = 0.001), common galaxias ($D_{336,\ 184}$ = 0.276, p < 0.001) and flat-headed gudgeon ($D_{409,\ 66}$ = 0.206, p = 0.014). Greater proportions of congolli and common galaxias <40 mm, and flat-headed gudgeon <20 mm TL, were sampled from the entrances of the fishways (Figure 9a–c). Length-frequency distributions were similar for Australian smelt ($D_{414,\ 165}$ = 0.078, p = 0.461).

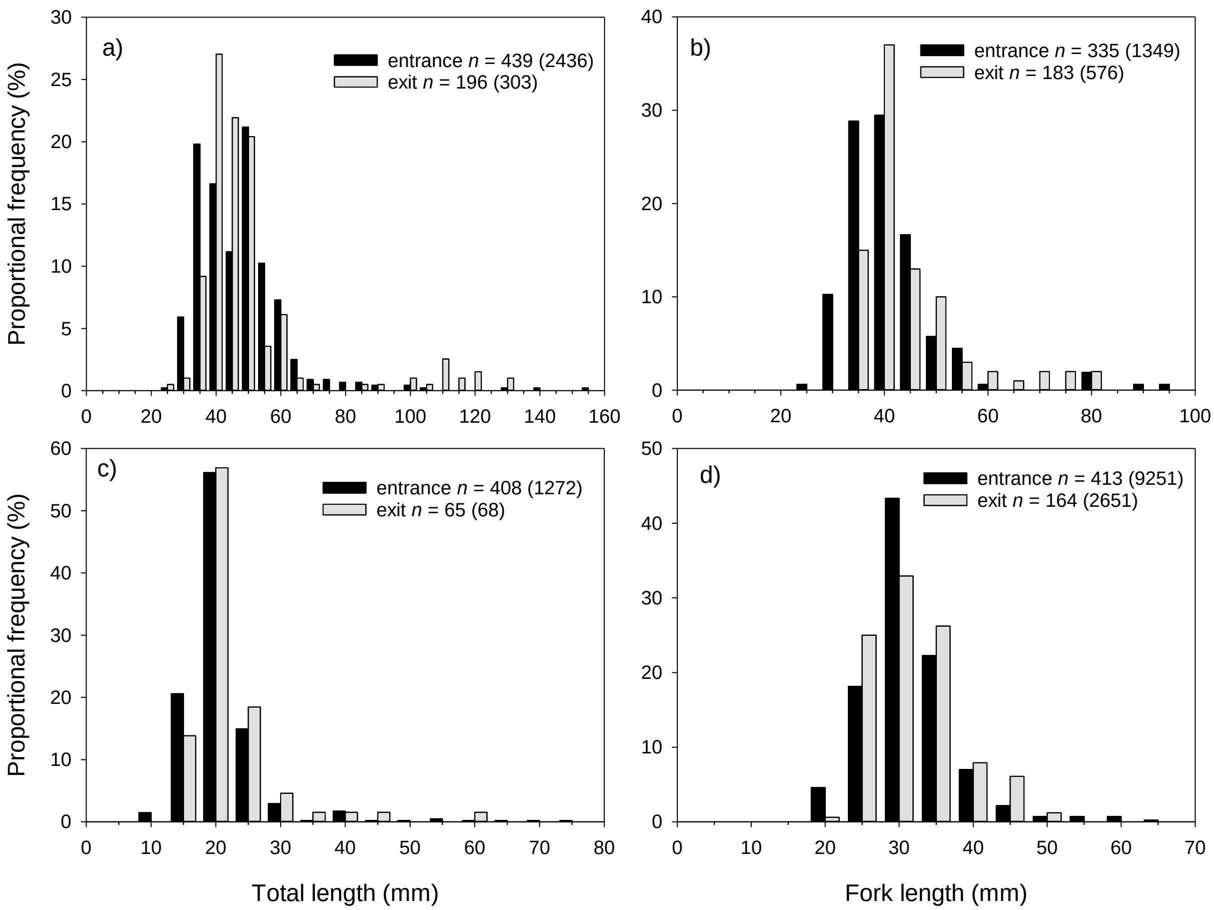

Figure 9. Length-frequency distributions of a) congolli, b) common galaxias, c) flat-headed gudgeon and d) Australian smelt captured from the entrance (*black bar*) and exit (*shaded bar*) of the new Goolwa large vertical-slot fishway in spring/summer 2015/16. Sample sizes represent the number of fish measured for length, and those in brackets, represent the total number of fish sampled for each species.

Influence of head loss on fishway effectiveness

Based on change in AIC_C, linear models received more support (>95%) than sigmoidal models for explaining the relationship between head loss and total fish abundance at the entrance and exit of the fishway. Nonetheless, these relationships were non-significant at the entrance (F = 0.253, p =0.628) and exit (F = 0.033, p =0.862), suggesting variation in head loss had little influence on relative attraction and passage efficiency over the range of head loss experienced (Figure 10).

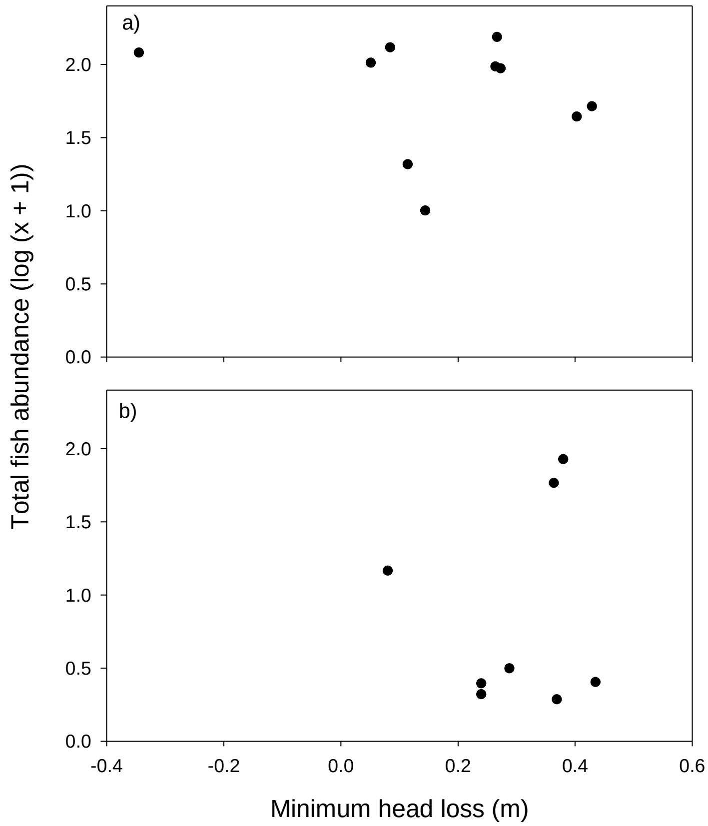

Figure 10. Relationship between the total fish abundance ($fish.hour^{-1}$, all species pooled) sampled at the new Goolwa large vertical-slot 2 a) entrance and b) exit, and minimum head loss (m) experienced during trapping.

3.4.2. Ewe Island dual vertical-slot

Passage efficiency

Eight species were sampled from the entrance of the Ewe Island dual vertical-slot fishway and all except the estuarine blue-spot goby, were also sampled at the exit (Table 4). Conversely, the freshwater redfin perch was sampled from the exit, but not the entrance.

Numbers of fish entering the fishway ranged from 3 to 20 $fish.hour^{-1}$ (mean ± SE = 8.3 ± 1.9 $fish.hour^{-1}$), whilst numbers of fish successfully ascending the fishway ranged from 5 to 12 $fish.hour^{-1}$ (mean ± SE = 6.9 ± 0.9 $fish.hour^{-1}$). This resulted in an overall passage efficiency across the sampling period of ~87%. Whilst apparent differences between entrance and exit abundance occurred for congolli, Australian smelt and bony herring, high variability resulted in these differences being non-significant (Congolli: *Pseudo-*$F_{1, 15}$ = 2.10, p = 0.168; Australian smelt: *Pseudo-*$F_{1, 15}$ = 1.48, p = 0.242; bony herring: *Pseudo-*$F_{1, 15}$ = 3.08, p = 0.101). Additionally, the abundance of common galaxias was similar between entrance and exit traps (*Pseudo-*$F_{1, 15}$ = 1.28, p = 0.260) (Figure 11). Alternatively, significantly higher abundances of flat-headed gudgeon (*Pseudo-*$F_{1, 15}$ = 7.03, p = 0.025) were sampled from the entrance than the exit of the fishway.

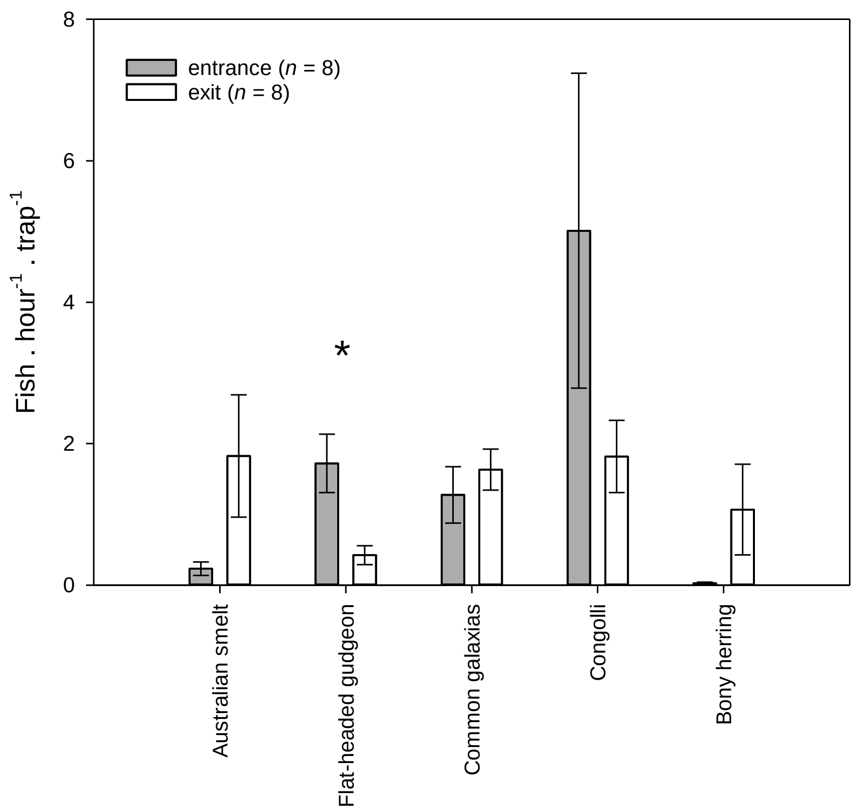

Figure 11. Comparison of mean relative abundance (number of fish. $hour^{-1}$.trap $event^{-1}$) of the most common species sampled at the entrance (*shaded bar*) and exit (*open bar*) of the Ewe Island dual vertical-slot fishway in spring/summer 2015/16. Significant differences between entrance and exit abundance indicated by asterisks.

Fish sampled at the entrance of this fishway ranged from 15 to 116 mm in length, whilst those that successfully ascended the fishway ranged from 17 to 131 mm in length. Length-frequency distributions for congolli ($D_{408, 310}$ = 0.067, p < 0.401) and Australian smelt ($D_{43, 266}$ = 0.119, p = 0.648) were similar between entrance and exit samples (Figure 12a and d). Conversely, length-frequency distributions of common galaxias ($D_{206, 280}$ = 0.156, p = 0.005) and flat-headed gudgeon

($D_{284, 72}$ = 0.310, $p < 0.001$) were significantly different between entrance and exit samples (Figure 12b and c). For flat-headed gudgeon, a greater proportion of fish 20–24 mm TL were sampled from the exit (~58%) than the entrance (~28%), whilst the reverse was true for fish 25–29 mm TL (entrance ~35%, exit ~8%) (Figure 12c). For common galaxias, a greater proportion of fish <40 mm FL were sampled from the entrance (~12%) than the exit (~3%) (Figure 12b).

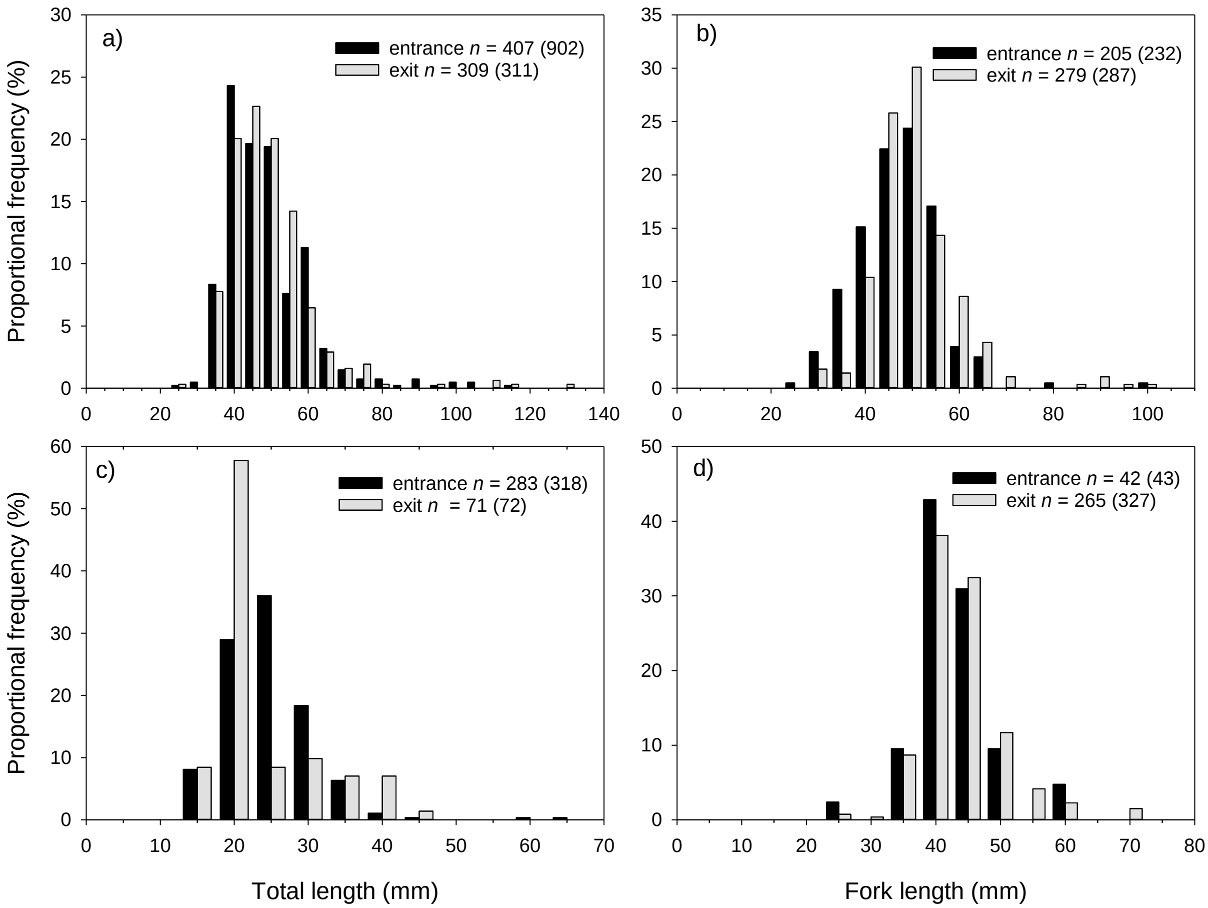

Figure 12. Length-frequency distributions of a) congolli, b) common galaxias, c) flat-headed gudgeon and d) Australian smelt captured from the entrance (*black bar*) and exit (*shaded bar*) of the Ewe Island dual vertical-slot fishway in spring/summer 2015/16. Sample sizes represent the number of fish measured for length, and those in brackets, represent the total number of fish sampled for each species.

Influence of head loss on fishway effectiveness

Based on change in AIC_C, linear models received more support (≥97%) than sigmoidal models when applied to head loss–total fish abundance data for both entrance and exit trapping events. At the entrance of the fishway, total fish abundance was similar across the range of head loss experienced and the linear relationship was non-significant (F = 0.003, p = 0.957) (Figure 13a). The linear relationship between total fish abundance and minimum head loss at the exit was also non-significant (F = 0.067, p = 0.805), but this relationship may be influenced by two outliers. Relatively low total fish abundance was observed during sampling events with minimum head loss 0.1–0.2 m (Figure 13b); if these data points were removed a trend of decreasing total fish abundance with increasing minimum head loss becomes apparent.

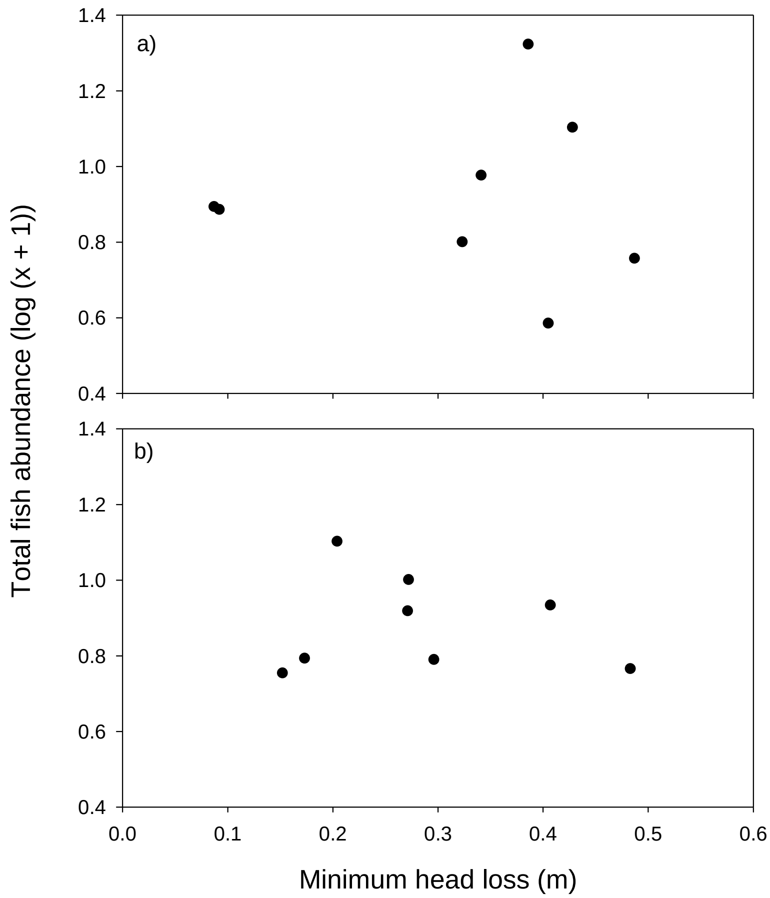

Figure 13. Relationship between the total fish abundance (fish . hour^{-1}, all species pooled) sampled at the Ewe Island dual vertical-slot a) entrance and b) exit, and minimum head loss (m) experienced during trapping

3.4.3. Boundary Creek vertical-slot

Passage efficiency

A total of 13 species were sampled from the entrance of the Boundary Creek vertical-slot fishway compared to seven from the exit (Table 4). The freshwater dwarf flat-headed gudgeon and eastern gambusia (*Gambusia holbrooki*), the estuarine species small-mouthed hardyhead, blue-spot goby, Tamar River goby (*Afurcagobius tamarensis*) and lagoon goby (*Tasmanogobius lasti*), and the marine sandy sprat were sampled in low numbers from the entrance (n = 1–17), but were absent from exit trapping. Additionally, the freshwater bony herring was sampled in moderate numbers from the entrance (n = 62), but was absent from exit trapping, although 85% of the fish sampled at the entrance were captured during a single trapping event. Alternatively, common carp and redfin perch were only sampled from the exit of the fishway.

Numbers of fish entering the fishway ranged from 3 to 60 fish.hour^{-1} (mean ± SE = 25.6 ± 8.1 fish.hour^{-1}), whilst numbers of fish successfully ascending the fishway ranged from 1 to 82 fish.hour^{-1} (mean ± SE = 31.2 ± 10.5 fish.hour^{-1}). This resulted in an overall passage efficiency across the sampling period of 100%. Comparison of abundance between entrance and exit trapping events for the most abundant species suggested no significant difference for common galaxias ($Pseudo\text{-}F_{1,15}$ = 2.04, p = 0.179), congolli ($Pseudo\text{-}F_{1,15}$ = 0.27, p = 0.597) and Australian smelt ($Pseudo\text{-}F_{1,15}$ = 0.82, p = 0.386), but significantly higher abundances of flat-headed gudgeon ($Pseudo\text{-}F_{1,15}$ = 11.11, p = 0.006) at the entrance than the exit of the fishway (Figure 14).

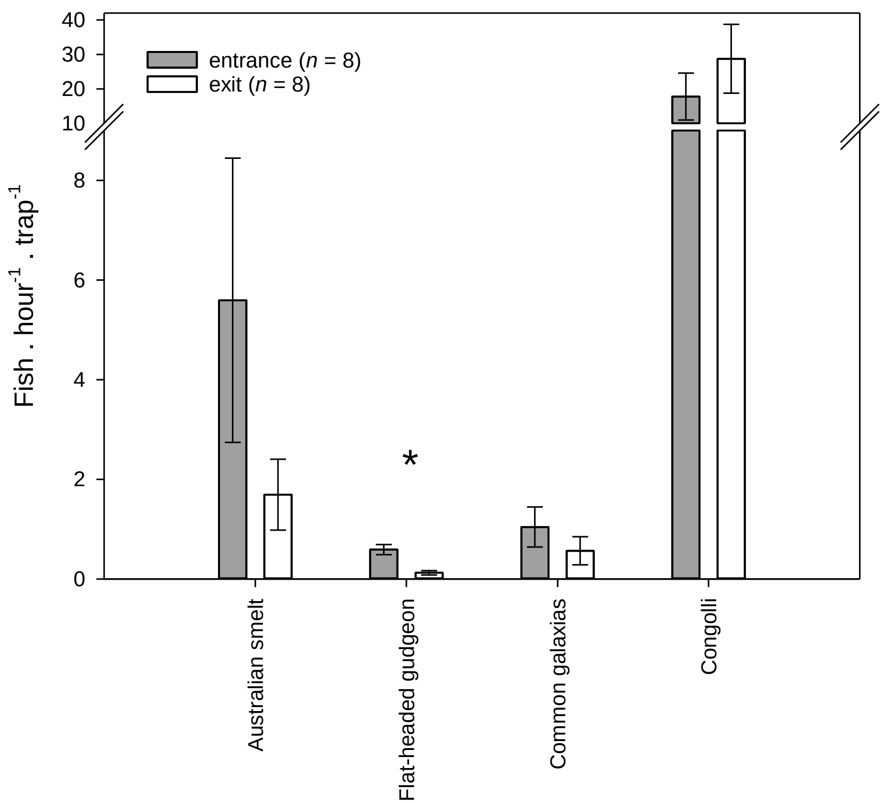

Figure 14. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1}) of the most common species sampled at the entrance (*shaded bar*) and exit (*open bar*) of the Boundary Creek vertical-slot fishway in spring/summer 2015/16. Significant differences between entrance and exit abundance indicated by asterisks.

Fish sampled from the entrance of this fishway ranged from 17 to 125 mm, whilst those that successfully ascended the fishway ranged from 19 to 640 mm in length. Difference in length ranges was due to the capture of 11 adult common carp (467–640 mm FL) in the exit trap over two occasions in November and December. Comparison of length-frequency distributions between entrance and exit trapping events for the most abundant species suggested significant differences for congolli ($D_{407, 354}$ = 0.107, p = 0.024) and common galaxias ($D_{157, 88}$ = 0.271, p < 0.001), but not for Australian smelt ($D_{236, 180}$ = 0.107, p = 0.181) and flat-headed gudgeon ($D_{110, 21}$ = 0.271, p = 0.124) (Figure 15). Despite statistical significance, differences for congolli were minor, with slightly greater proportions of fish <45 mm TL and smaller mean length (47.57 ± 0.36 mm) at the entrance, than at the exit (48.96 ± 0.39 mm) (Figure 15a). Differences between entrance and exit trapping events were more marked for common galaxias, with a greater proportion of fish ≤39 mm FL sampled from the entrance (~40%) than the exit (~17%), and a shorter mean length (entrance = 43.15 ± 0.81 mm, exit = 47.19 ±1.20 mm) (Figure 15b).

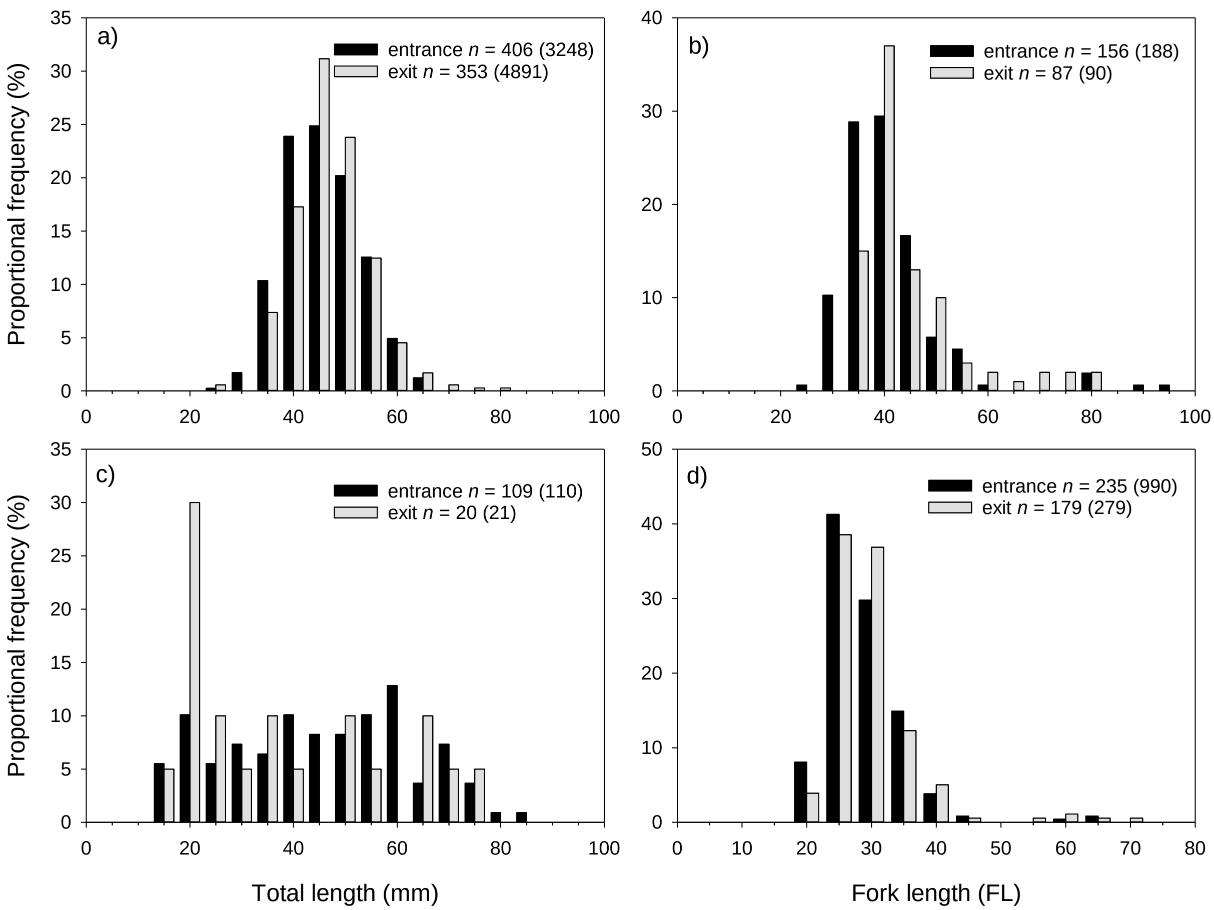

Figure 15. Length-frequency distributions of a) congolli, b) common galaxias, c) flat-headed gudgeon and d) Australian smelt captured from the entrance (*black bar*) and exit (*shaded bar*) of the Boundary Creek vertical-slot fishway in spring/summer 2015/16. Sample sizes represent the number of fish measured for length, and those in brackets, represent the total number of fish sampled for each species.

Influence of head loss on fishway effectiveness

Change in AIC_C again indicated linear models had more support (≥99%) than sigmoidal models when applied to head loss–total fish abundance data for both entrance and exit trapping events. At the entrance of the fishway, total fish abundance increased with increasing minimum head loss (Figure 16a), but the linear relationship was non-significant (F = 3.632, p =0.105), most likely due to low sample size. At the fishway exit, there was no relationship between total fish abundance and minimum head loss (F = 0.136, p =0.725) (Figure 16b).

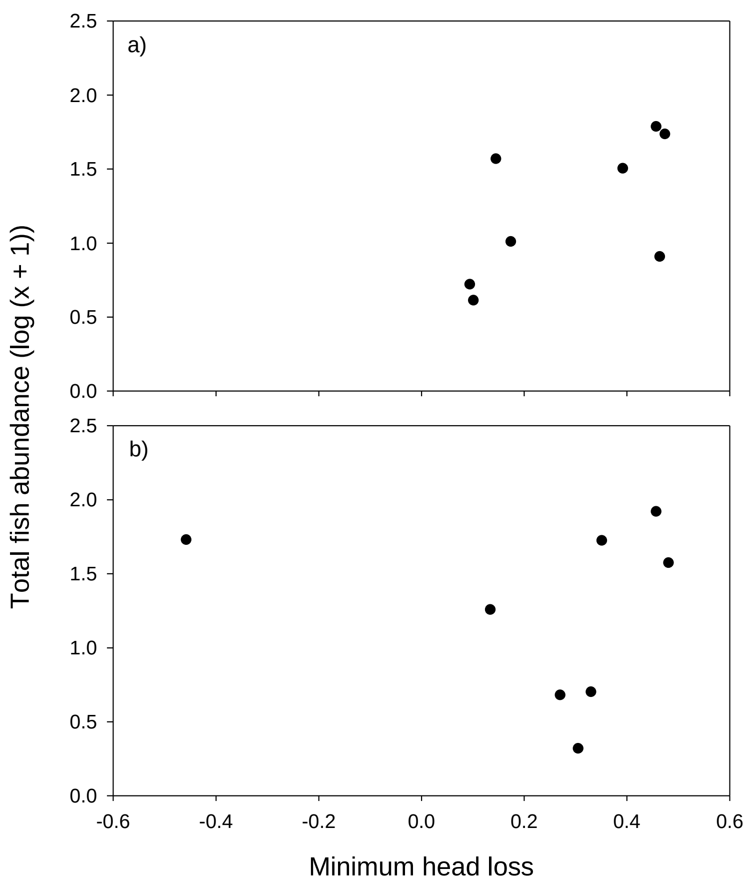

Figure 16. Relationship between the total fish abundance (fish.hour^{-1}, all species pooled) sampled at the Boundary Creek vertical-slot a) entrance and b) exit, and minimum head loss (m) experienced during trapping.

4. DISCUSSION

Since 2003, the Murray Barrages have been the subject of substantial investment in fish passage. Most recently, under the *Coorong Lower Lakes and Murray Mouth* (CLLMM) *Recovery Project*, construction of a series of six technical fishways across the Murray Barrages was proposed for 2015–2016. This includes new fishways on all five of the Murray Barrages (i.e. Goolwa, Mundoo, Boundary Creek, Ewe Island and Tauwitchere). The fishway designs were varied and tailored for target species, location and hydrology in order to complement existing fishways on the Murray Barrages and holistically meet fish passage requirements. Fundamental to the construction program, is assessment of the biological effectiveness of the fishways against their design criteria.

The aim of the current study is to assess the biological effectiveness of the new fishways. Three fishways were completed and assessed in spring/summer 2015/16 (present report), with a further three scheduled for assessment in spring 2016. The effectiveness of these fishways is discussed in the context of previous assessments of existing fishways and overall improvements to fish passage at the barrages. Ultimately, this work will inform future operation of the barrages and fishways, and the contribution of the CLLMM fishway construction program to overall fish passage objectives in the region.

4.1. General catch and variability in fishway use

A total of 17 species were sampled from the fishways in the current study, representing most species that are expected to use fishways on the Murray Barrages based on previous sampling (Stuart *et al.* 2005, Jennings *et al.* 2008, Zampatti *et al.* 2010, 2012, Bice and Zampatti 2015). A notable exception was the absence of the anadromous short-headed and pouched lamprey; peak upstream migration of these species occurs in winter/early spring, which was prior to the commencement of monitoring in the current study. Nevertheless, previous monitoring at the existing vertical-slot fishways on Goolwa and Tauwitchere Barrages (Bice and Zampatti 2015), suggests the new fishways are likely to be used by lampreys during their migration season.

The overall catch of fish utilising the fishways was dominated by small-bodied freshwater species (Australian smelt, flat-headed gudgeon and juvenile bony herring) and juvenile upstream migrants of catadromous species (i.e. congolli and common galaxias), and is indicative of recent freshwater discharge and salinity in the Coorong. Freshwater discharge in 2015/16 was historically low and throughout the sampling period salinity in the Murray estuary downstream of the fishways was mostly brackish (i.e. 20–35 $g.L^{-1}$). All three freshwater species are highly tolerant of elevated salinity and commonly encountered in the Coorong, even during periods of low flow. Similar dominance of fishway catches by freshwater species tolerant of elevated salinities and juveniles of catadromous species has been observed during previous low-flow conditions (e.g. 2006/07) (Zampatti *et al.* 2010).

Young-of-the-year congolli and common galaxias were sampled from the fishways in high abundances relative to previous sampling (Jennings *et al.* 2008, Zampatti *et al.* 2010, Bice and Zampatti 2015). In particular, congolli was the second most abundant species, likely reflecting consistent increases in the abundance of this species over the past six years, coincident with prolonged connectivity between the Lower Lakes, Coorong and Southern Ocean over this period (Bice and Zampatti 2015). Connectivity between these environments is critical in the life history of catadromous fishes and, subsequently, fishway construction on the barrages has emphasised the passage of these species. The capture of high abundances of these species is encouraging in regards to the ecological function of the fishways and provides a positive indication of population status.

Total fish and species-specific abundances differed among fishways, likely due to varying discharge from the different barrages and habitat downstream, and upstream, of the structures. Throughout sampling, freshwater discharge from Ewe Island Barrage was limited to the fishway (≤5 $ML.day^{-1}$, i.e. no discharge through gate openings) and likely resulted in lower attraction of fish, and subsequent lower species richness and total fish abundance, than at Boundary Creek and Goolwa Barrages, where freshwater discharge was occasionally greater (300–500 $ML.day^{-1}$). Differences between catches at the Goolwa and Boundary Creek vertical-slot fishways were driven by greater abundance of freshwater species and the catadromous common galaxias at Goolwa, but greater abundance of the catadromous congolli at Boundary Creek. Goolwa Barrage is commonly a site with a high biomass of migrating fish, relative to other barrages, particularly pelagic species like Australian smelt and common galaxias, but also congolli (Bice and Zampatti 2015). High relative abundances of congolli from the Boundary Creek vertical-slot, and dominance of overall catches at this fishway (>80% of total catch), suggest the construction of this fishway has potentially reinstated an important migratory pathway for this species.

4.2. Fishway effectiveness

4.2.1. Goolwa large vertical-slot 2

A total of eight species successfully ascended the Goolwa large vertical-slot 2 fishway comprising freshwater, catadromous, estuarine and marine life histories. Nevertheless, lower numbers of fish were sampled from the exit than the entrance of the Goolwa large vertical-slot 2 fishway suggesting a degree of obstruction of passage under the conditions assessed and/or potential differences in migratory motivation among species. The four most abundant species had catadromous (congolli and common galaxias) and freshwater life histories (Australian smelt and flat-headed gudgeon) and were likely undertaking motivated obligate upstream migrations to freshwater habitats, with all but common galaxias, sampled in significantly greater abundance at the entrance of the fishway, suggesting partially obstructed passage. Alternatively, migrations of estuarine and marine species into freshwater habitats is often viewed as a facultative process and thus, migration through fishways may occur with less motivation than for catadromous and freshwater species, which may account for low passage efficiency for several species from these guilds in the current study. Fish <20 mm in length successfully ascended the fishway, but the passage of small size-classes of congolli (<40 mm), common galaxias (<40 mm) and flat-headed gudgeon (<20 mm) was partially obstructed, likely due to insurmountable internal hydraulics.

The presence of high abundances of lagoon goby, yelloweye mullet and sandy sprat at the fishway entrance but low abundance or absence of these species ascending the fishway may be a result of incidental occurrence in the lower part of the fishway, likely coincident with reverse/low head loss conditions, and/or may indicate that passage through the fishway was often aborted. These species have estuarine and marine life histories and may show behavioural aversion to the rapid changes in salinity (35 $g.L^{-1}$ to <1 $g.L^{-1}$ over distances of <5 m) that often occur at fishways on the Murray Barrages during periods of low discharge. Migrations of these species into truly freshwater habitats are likely facultative rather than obligate, and such movements may not occur with great motivation. Contrary to the results of the current study, lagoon goby were recorded moving through fishways on Tauwitchere Barrage in considerable numbers during conditions of high discharge and minimal change in salinity between the Coorong and Lower Lakes (SARDI unpublished data), suggesting such conditions may be more conducive to movement of these species.

Despite restricted passage efficiency at this fishway, absolute passage, as indicated by the number of fish that successfully ascended the fishway and were captured during exit trapping events (mean = 20.2 ± 11.4 $fish.hour^{-1}$), was similar to that at the Boundary Creek vertical-slot (mean = 31.2 ± 10.5 $fish.hour^{-1}$), and greater than that at the Ewe Island dual vertical-slot (6.9 ± 0.9 $fish.hour^{-1}$). Furthermore, passage efficiency was substantially greater than at the original Goolwa large vertical-slot prior to slot modifications (Jennings *et al.* 2008).

Assessment of the original vertical-slot fishway at Goolwa in 2005/06, under conditions of similar discharge and head loss to the current study, found this fishway to be largely ineffective for small-bodied fishes, with overall passage efficiency (the abundance of fish that successfully ascended as a proportion of those that attempted to ascend the fishway) of ~5% (Jennings *et al.* 2008). Pre-fabricated aluminium inserts were subsequently added to the fishway to reduce slot widths (from 300 to 200 mm) and overall slot aperture, and thus, reduce internal turbulence (from 54 to 30 $W.m^{-3}$). Trapping of the fishway in 2010/11, whilst unable to quantify passage efficiency, suggested enhanced passage of small-bodied fish relative to the previous configuration (Zampatti *et al.* 2012). Excepting shallower depth, the new Goolwa large vertical-slot 2 fishway has the same pool dimensions as the original Goolwa large vertical-slot fishway, and similar aluminium inserts were applied to the vertical-slots; correspondingly overall passage efficiency was ~25%, whilst fish <20 mm in length, at times, successfully ascended the fishway.

Analyses of head loss/fish abundance relationships (ANOVA) suggested the range of head loss experienced in the current study had no influence on relative attraction and passage efficiency. We propose, however, that passage efficiency at this fishway would be greater during periods of high discharge and generally lower head loss. Previous analysis of head loss/fish abundance relationships at the original Tauwitchere large vertical-slot fishway showed a significant negative sigmoidal relationship between total fish abundance at the exit and head loss, with relative passage efficiency greater at lower head loss (SARDI unpublished data). We suggest such a relationship likely exists at the new Goolwa large vertical-slot 2 fishway, but was not detected due to low sample size (n = 8) and predominating conditions of high head loss throughout sampling (e.g. >0.5 m >60% of the time).

Despite some limitation to passage efficiency, the Goolwa large vertical-slot 2 fishway could be considered to be operating to design specifications. Considerable abundances of small-bodied fish, particularly 40–80 mm in length, were able to ascend the fishway, and whilst large-bodied fishes were uncommon, successful passage could be assumed considering smaller fish with weaker swimming abilities were able to ascend. Overall passage of small-bodied fishes during conditions of low discharge and generally high head loss should be improved at this barrage upon the construction of the Goolwa small vertical-slot fishway in 2016, whilst the large vertical-slot should pass greater numbers of small-bodied fish under conditions of higher discharge.

4.2.2. Ewe Island dual vertical-slot

All species detected at the entrance of this fishway, with the exception of the estuarine blue-spot goby, ascended the fishway, although slightly lower numbers of fish at the exit than the entrance of the fishway suggest a level of restricted passage efficiency. Flat-headed gudgeon, in particular, were sampled in significantly greater abundance from the entrance. Abundances of congolli were also higher at the fishway entrance, but not significantly greater ($\alpha = 0.05$) than at the fishway exit. Similar abundances of common galaxias were sampled from the entrance and exit, but fish <40 mm were partially restricted. Alternatively, abundances of bony herring and Australian smelt were greater at the exit, albeit without statistical significance, whilst length-frequency distributions were similar. Whilst this likely indicates optimal passage efficiency for these species, it also may indicate aversion to entering the fishway when the entrance trap was in place. Similar trap 'shyness' during entrance trapping of fishways has been observed for other species in the MDB, although has been more typical of large-bodied species like silver perch (*Bidyanus bidyanus*) (Baumgartner and Harris 2007).

The head loss–fish abundance relationship at the fishway exit was non-significant, but there was a trend of decreasing passage efficiency with increasing minimum head loss. Similar to the Goolwa large vertical-slot 2 fishway, and the original Tauwitchere large vertical-slot, a degree of reduced passage efficiency at high head loss was expected. At head loss >0.6 m, turbulence in this fishway may increase to ~50 $W.m^{-3}$, which would likely preclude many small-bodied fishes. Nonetheless, this effect was minor when compared to the large vertical-slot fishway at Tauwitchere (SARDI unpublished data). Also as expected, the head loss–fish abundance relationship at the fishway entrance was non-significant. This dual vertical-slot fishway, and the dual vertical-slot at Mundoo (yet to be assessed), were designed to discharge relatively large volumes of water (~30 $ML.day^{-1}$), and therefore provide a high degree of fish attraction across a range of head loss conditions, whilst retaining relatively benign hydraulics for the passage of small-bodied fish. As such, this fishway is expected to operate well in regards to both relative attraction and passage efficiency during high discharge. No improvements to this fishway are currently recommended, but will be subject to wet commissioning (i.e. analyses of fishway hydraulics).

6.2.4. Boundary Creek vertical-slot

A total of seven species successfully ascended this fishway, comprising species with freshwater and catadromous life histories. Six estuarine and marine species were also detected in low numbers at the fishway entrance and not at the fishway exit, indicating poor passage for these species or their incidental presence in the fishway entrance. Abundances of Australian smelt, congolli and common galaxias were similar between the fishway entrance and exit, whilst differences in length-frequency distributions were minor, indicating optimal passage efficiency for these species. Bony herring were sampled in greater numbers from the entrance, but this was largely the result of one relatively large catch of bony herring from the entrance. Given the strong swimming ability of bony herring, it is unlikely that passage is impeded at this fishway. The design of the Boundary Creek small vertical-slot fishway was modelled on the Tauwitchere small vertical-slot fishway, and as expected, similar results were yielded from the assessment of these fishways. Both were specifically designed to facilitate the passage of small-bodied fishes and are characterised by benign internal hydraulics (i.e. low velocity and turbulence), and both exhibited high passage efficiency.

The capture of common carp up to 640 mm FL at the exit of the fishway was somewhat unexpected given the narrow slot widths (100 mm) at this fishway. The capture of carp in this fishway coincided with closure of barrage gates and increasing salinity downstream of the fishway, likely prompting common carp to return to freshwater habitats. This data suggests large-bodied fishes may use small vertical-slot fishways when undertaking motivated migrations.

Whilst the head loss–fish abundance relationship at the entrance of the Boundary Creek vertical-slot was non-significant, there was a trend of greater relative attraction to this fishway with increasing minimum head loss, which has also been demonstrated at the Tauwitchere small vertical-slot fishway (SARDI unpublished data). As such, these fishways operate optimally under conditions of low barrage discharge and high head loss, when fishway discharge and velocity is maximised and relative attraction enhanced. Alternatively, conditions of high discharge and generally low head loss, may result in lower fishway discharge and velocity, and thus, lower relative attraction. We propose, however, that this effect is likely to be less at Boundary Creek Barrage than Tauwitchere Barrage, owing to the smaller size of Boundary Creek Barrage and typically lower volumes of freshwater discharge. In essence, discharge through the fishway at Boundary Creek represents a greater proportion of total barrage discharge than discharge through the small vertical-slot at Tauwitchere, and subsequently, there should be less ‘masking’ of fishway discharge by total barrage flows. Additionally, the incorporation of an attraction gate and the capacity to 'fine-tune' entrance conditions should support greater attraction. The operation of alternate exit gates that 'shorten' the fishway, increasing head loss across the fishway and water velocities (Figure 4) should partially improve attraction at both the Boundary Creek and Tauwitchere small vertical-slot fishways under low head loss conditions, but was not assessed in the current study. Ultimately, guidelines for engaging alternate exits need to be determined and incorporated into operational guidelines for barrage operators (SA Water). No improvements to this fishway are currently recommended, but will be subject to wet commissioning (i.e. analyses of fishway hydraulics).

4.3. Overall fish passage at the Murray Barrages

The construction of new fishways on the Murray Barrages has improved opportunities for fish passage at individual structures and collectively across the barrage network. Here we compile qualitative statements on the effectiveness of each of the new and pre-existing fishways for both small- (<100 mm length) and large-bodied (>100 mm length) fishes, to present a measure of overall effectiveness of fish passage on each barrage under scenarios of low and high barrage discharge. Quantitative comparisons are not possible due to individual fishways being assessed in different years and are thus subject to variability in the migratory fish assemblage present in any given year.

Under low discharge (e.g. 5–2000 ML.day^{-1} for Goolwa, Tauwitchere and Ewe Island barrages), water level in the Coorong is dictated by weather and tide, resulting in frequent periods of high head loss (>0.5 m) across the barrages. This maximises fishway discharge, which in turn represents a large proportion or, at times, 100% of barrage discharge. Alternatively, during high discharge (e.g. total barrage discharge >10,000 ML.day^{-1}), tidal fluctuation is dampened, resulting in generally lower head loss across the barrages. This reduces fishway discharge, which consequently represents a small proportion of total barrage discharge.

Qualitative statements are provided in regards to: 1) the biomass of fish potentially migrating (low, moderate, high); 2) relative attraction of fish to each fishway (low, moderate, high); 3) passage efficiency of each fishway (the ability of fish to ascend the fishway once the entrance is located; low (<25%), moderate (25–75%), high (80–100%); and 4) the effectiveness of each fishway. The effectiveness of each fishway under each scenario is assessed by combining both relative attraction and passage efficiency, and is categorised as ineffective, sub-optimal or optimal (Table 5). Qualitative statements on biomass, relative attraction, passage efficiency and effectiveness are based upon empirical data from monitoring of sites adjacent the Murray Barrages (Bice and Zampatti 2015) and previous assessments of fishway effectiveness (Stuart *et al.* 2005, Jennings *et al.* 2008, SARDI unpublished data), including from the current project.

Table 5. Matrix adopted for determining fishway effectiveness. Fishway effectiveness is considered a product of 'relative attraction' and 'passage efficiency' and is categorised as ineffective, sub-optimal or optimal.

Fishway effectiveness		**Passage efficiency**		
		low	**moderate**	**high**
Relative attraction	**Low**	Ineffective	Sub-optimal	Sub-optimal
	Moderate	Ineffective	Sub-optimal	Optimal
	High	Ineffective	Sub-optimal	Optimal

4.3.1. Goolwa Barrage

Two large vertical-slot fishways of similar design now operate on Goolwa Barrage. At low flows, both are expected to provide high relative attraction with moderate and high passage efficiency for small-bodied and large-bodied fishes, respectively. This results in sub-optimal effectiveness for small-bodied fishes and optimal effectiveness for large-bodied fishes at each fishway, and across Goolwa Barrage. Alternatively, under high flows, both fishways are expected to provide moderate attraction and high passage efficiency, resulting in optimal effectiveness for both small- and large-bodied species. Goolwa Barrage is a site typically characterised by a high biomass of migrating fish and whilst the effectiveness of the Goolwa large vertical-slot 2 is similar to that of the original Goolwa large vertical-slot fishway, its construction provides an additional access point for fishes migrating upstream, and enhances the biomass of fish passed at the barrage. This is likely to be of particular importance during times of high flow when diffuse freshwater discharge is likely to promote aggregation of fish across a broad area below the barrage.

The provision of passage for small-bodied species under low flow conditions requires improvement at Goolwa Barrage. This is a specific objective of construction and operation of a small vertical-slot fishway (GSVS) on Goolwa Barrage that will be constructed and assessed in spring or summer 2016/17.

Table 6. Qualitative statements on fish migration and function of fishways on Goolwa Barrage for small-bodied (<100 in length) and large-bodied (>100 mm in length) fish under low flow and high flow scenarios, including: 1) Biomass: the likely biomass of fish accumulated below the barrage and attempting to migrate upstream (low, moderate, high); 2) Relative attraction: the relative proportion of fish attempting to migrate able to locate the entrance of the fishway (low, moderate, high); 3) Passage efficiency: the proportion of fish able to enter the fishway that are able to successfully ascend (based on empirical data from assessments, low (<25%), moderate (25–75%) or high (>75%)); and 4) Effectiveness: the product of 'relative attraction' and 'passage efficiency' following Table 4.

			Goolwa Barrage			
			Biomass	**Relative attraction**	**Passage efficiency**	**Effectiveness**
Low flow	*GVS 1*					
		Small-bodied fish	High	High	Moderate	Sub-optimal
		Large-bodied fish	Low	High	High	Optimal
	GVS 2					
		Small-bodied fish	High	High	Moderate	Sub-optimal
		Large-bodied fish	Low	High	High	Optimal
	*GSVS**					
		Small-bodied fish	TBC	TBC	TBC	TBC
		Large-bodied fish	TBC	TBC	TBC	TBC
	Overall					
		Small-bodied fish				Sub-optimal
		Large-bodied fish				Optimal
*High flow^*	*GVS 1*					
		Small-bodied fish	High	Moderate	High	Optimal
		Large-bodied fish	Moderate	Moderate	High	Optimal
	GVS 2					
		Small-bodied fish	High	Moderate	High	Optimal
		Large-bodied fish	Moderate	Moderate	High	Optimal
	*GSVS**					
		Small-bodied fish	TBC	TBC	-	
		Large-bodied fish	TBC	-	-	
	Overall					
		Small-bodied fish				Optimal
		Large-bodied fish				Optimal

TBC = to be constructed. *denotes a fishway for which assessments have not been conducted. ^denotes conditions under which assessments have not been conducted and fishway characteristics are inferred.

4.3.2. Boundary Creek Barrage

The Boundary Creek small vertical-slot fishway is the first fishway to be constructed on this barrage, and as such has generally improved fish passage at Boundary Creek; however, fishway function is likely to vary with hydrology. At low flows, the small vertical-slot fishway on Boundary Creek provides high relative attraction with high and moderate passage efficiency for small- and large-bodied fishes, respectively (Table 7). Passage efficiency is deemed to be moderate for large-bodied species due to the narrow slot widths (100 mm) potentially precluding some large-bodied fishes (e.g. >350 mm length). This results in optimal effectiveness for small-bodied species and sub-optimal effectiveness for large-bodied species. Nonetheless, the biomass of large-bodied fishes migrating at this barrage is likely to be low, and the fishway was specifically designed with the objective of facilitating passage of small-bodied fishes at low flows.

Whilst this fishway has not been assessed under high flow conditions, inferences are made based upon expert opinion and function of the similar Tauwitchere small vertical-slot. At high flows, relative attraction at the Boundary Creek small vertical-slot is likely to be reduced (from high to moderate), due to masking of low volume fishway discharge (~2 $ML.day^{-1}$) by diffuse barrage discharge. Nonetheless, reductions in relative attraction are likely to be less than at the Tauwitchere small vertical-slot due to the small size of Boundary Creek Barrage and thus, greater proportion of overall barrage flow that is passed through the fishway. Under such conditions, high and moderate passage efficiency can be expected for small- and large-bodied fishes, resulting in optimal and sub-optimal fishway effectiveness for small- and large-bodied fishes.

Table 7. Qualitative statements on fish migration and function of fishways on Boundary Creek and Ewe Island barrages for small-bodied (<100 in length) and large-bodied (>100 mm in length) fish under low flow and high flow scenarios, including: 1) Biomass: the likely biomass of fish accumulated below the barrage and attempting to migrate upstream (low, moderate, high); 2) Relative attraction: the relative proportion of fish attempting to migrate able to locate the entrance of the fishway (low, moderate, high); 3) Passage efficiency: the proportion of fish able to enter the fishway that are able to successfully ascend (based on empirical data from assessments, low (<25%), moderate (25–75%) or high (>75%)); and 4) Effectiveness: the product of 'relative attraction' and 'passage efficiency' following Table 4.

		Boundary Creek Barrage			
		Biomass	**Relative attraction**	**Passage efficiency**	**Effectiveness**
Low flow	*BCVS 1*				
	Small-bodied fish	Moderate	High	High	Optimal
	Large-bodied fish	Low	High	Moderate	Sub-optimal
	Overall				
	Small-bodied fish				Optimal
	Large-bodied fish				Sub-optimal
*High flow^*	*BCVS 1*				
	Small-bodied fish	High	Moderate	High	Optimal
	Large-bodied fish	Moderate	Moderate	Moderate	Sub-Optimal
	Overall				
	Small-bodied fish				Optimal
	Large-bodied fish				Sub-optimal
		Ewe Island Barrage			
		Biomass	**Relative attraction**	**Passage efficiency**	**Effectiveness**
Low flow	*EIDVS*				
	Small-bodied fish	Moderate	High	High	Optimal
	Large-bodied fish	Low	High	High	Optimal
	Overall				
	Small-bodied fish	Moderate	High	High	Optimal
	Large-bodied fish	Low	High	High	Optimal
*High flow^*	*EIDVS*				
	Small-bodied fish	High	High	High	Optimal
	Large-bodied fish	Moderate	High	High	Optimal
	Overall				
	Small-bodied fish	High	High	High	Optimal
	Large-bodied fish	Moderate	High	High	Optimal

^denotes conditions under which assessments have not been conducted and fishway characteristics are inferred.

4.3.3. Ewe Island Barrage

The Ewe Island dual vertical-slot fishway is the first fishway to be constructed on this barrage, and as such has generally improved fish passage at Ewe Island Barrage; however, fishway function is likely to vary with hydrology. Relative attraction of fish to the Ewe Island dual vertical-slot fishway is likely to be high under both low and high flow conditions due to the considerable volumes of water discharged by the fishway. Furthermore, passage efficiency for small-bodied species was high under low flow conditions, and could thus be expected to be high under high flow conditions when head loss, and therefore internal turbulence and velocity, are reduced. Whilst few large-bodied species were sampled during assessment in 2015/16, successful passage of small-bodied species, which possess inherently weaker swimming abilities, and the application of slot widths of 150 mm, suggest large-bodied fish passage efficiency is likely to be high. Consequently, the effectiveness of this fishway could be viewed as optimal under both low and high flows (Table 7).

4.3.4. Tauwitchere Barrage

A new trapezoidal fishway is planned for construction in late-2016 to complement the existing small and large vertical-slot fishways, and rock ramp fishway, on Tauwitcherre Barrage. Currently, under low flow conditions, high relative attraction is exhibited by all three existing fishways, but passage efficiency, and thus effectiveness, varies (Table 8). The large vertical-slot fishway exhibits low passage efficiency for small-bodied fishes (Stuart *et al.* 2005, Jennings *et al.* 2008), suggesting that it is ineffective for these species, whilst passage efficiency is high for large-bodied species, resulting in optimal effectiveness (Table 8). Passage efficiency at the rock ramp is considered to be moderate and low for small- and large-bodied fishes, respectively. The construction of the Tauwitchere small vertical-slot fishway in 2009 necessitated the partial disassembly of this fishway, resulting in a concrete sill obstructing upstream fish passage during periods of low tailwater level. Additionally, in its original configuration, passage efficiency was partially limited for all species due to the limited operating window of this fishway (Lake Alexandrina water level >0.65 m AHD, Coorong water level > 0.2 m AHD), and further limited for large-bodied fishes under low flows, as the physical construction of the fishway likely limits passage of larger individuals (e.g. >350 mm length) (Jennings *et al.* 2008). As such, under low flows, at least one fishway provides optimal effectiveness for small- or large-bodied fishes. Nonetheless, given the large size of Tauwitchere Barrage and high biomass of small-bodied fishes that undertake migrations at this structure (Bice and Zampatti 2015), a further fishway will better meet passage requirements during low flows at this structure.

Under conditions of high flow, water levels in the Coorong are typically elevated and head loss across the barrage reduced, resulting in substantially different relative attraction, passage efficiency and effectiveness (Table 8). Relative attraction likely remains high at both the large vertical-slot and rock ramp fishways, but is reduced (to low) at the small vertical-slot due to the comparatively lower volumes of water discharged (2.2 v >30 $ML.day^{-1}$). Lower head loss across the large vertical-slot fishway results in more benign internal hydraulics (i.e. lower velocities and turbulence) and consequently, high passage efficiency and effectiveness for small-bodied fishes (Bice *et al.* In Review). At the rock ramp fishway, passage efficiency is improved for both small-bodied (i.e. from moderate to high) and large-bodied fishes (i.e. low to moderate), as the fishway is generally within its operational window due to relatively high water levels upstream and downstream of the barrage, whilst higher tail water levels, relative to low flow, likely facilitates greater movement of large fish through the structure (Jennings *et al.* 2008). Alternatively, whilst passage efficiency remains unchanged, relative to low flows, at the small vertical-slot fishway, relative attraction is hindered due to the low volume of discharge from this fishway as a proportion of overall barrage discharge. These changes in attraction and passage efficiency result in optimal effectiveness for small-bodied fishes at the large vertical-slot and rock ramp fishways, but sub-optimal effectiveness at the small vertical-slot fishway, whilst for large-bodied fishes, effectiveness is optimal at the large vertical-slot fishway, and sub-optimal at both the small vertical-slot and rock ramp fishways. As such, under high flows, at least one fishway provides optimal effectiveness for small- or large-bodied fishes, but as per low flow conditions, given the large size of Tauwitchere Barrage and high biomass of small-bodied fishes that undertake migrations at this structure (Bice and Zampatti 2015), a further fishway will better meet passage requirements. The trapezoidal fishway planned for Tauwitchere Barrage is designed to facilitate the passage of both small- and large-bodied fishways under a range of flows, and maintain high levels of relative attraction during high flow conditions.

Table 8. Qualitative statements on fish migration and function of fishways on Tauwitchere Barrage in regards to small-bodied (<100 in length) and large-bodied (>100 mm in length) fish passage under low flow and high flow scenarios, including: 1) Biomass: the likely biomass of fish accumulated below the barrage and attempting to migrate upstream (low, moderate, high); 2) Relative attraction: the relative proportion of fish attempting to migrate able to locate the entrance of the fishway (low, moderate, high); 3) Passage efficiency: the proportion of fish able to enter the fishway that are able to successfully ascend (based on empirical data from assessments, low (<25%), moderate (25–75%) or high (>75%)); and 4) Effectiveness: the product of 'relative attraction' and 'passage efficiency' following Table 4.

			Tauwitchere Barrage			
			Biomass	**Relative attraction**	**Passage efficiency**	**Effectiveness**
Low flow	*TVS*					
		Small bodied fish	High	High	Low	Ineffective
		Large bodied fish	Low	High	High	Optimal
	TRR					
		Small bodied fish	High	High	Moderate	Sub-optimal
		Large bodied fish	Low	High	Low	Ineffective
	TSVS					
		Small bodied fish	High	High	High	Optimal
		Large bodied fish	Low	Moderate	Moderate	Sub-optimal
	Trapez.					
		Small bodied fish	High	-	-	
		Large bodied fish	Low	-	-	
	Overall					
		Small bodied fish				Optimal
		Large bodied fish				Optimal
High flow	*TVS*					
		Small bodied fish	High	High	High	Optimal
		Large bodied fish	Moderate	High	High	Optimal
	TRR					
		Small bodied fish	High	High	High	Optimal
		Large bodied fish	Moderate	High	Moderate	Sub-optimal
	TSVS					
		Small bodied fish	High	Low	High	Sub-optimal
		Large bodied fish	Moderate	Low	Moderate	Sub-optimal
	Trapez.					
		Small bodied fish	High	-	-	-
		Large bodied fish	Moderate	-	-	-
	Overall					
		Small bodied fish				Optimal
		Large bodied fish				Optimal

5. CONCLUSION AND RECOMMENDATIONS

This study aimed to assess the biological effectiveness of six fishways recently constructed (2015–2016) on the Murray Barrages under the *Coorong Lower Lakes and Murray Mouth Recovery* (CLLMM) *Project*. The project also aimed to compare effectiveness with existing fishways, to provide a measure of overall fish passage at the Murray Barrages, and the contribution of the CLLMM program in meeting fish passage objectives. Ultimately, the project aims to inform future barrage and fishway operation. The current report details the assessment of the first three new fishways, with the assessment of the remaining fishways scheduled for spring 2016, after which the above objectives will be re-evaluated.

Each of the assessed fishways are considered to be operating to ecological objectives. As such, physical alterations to these structures are unlikely to be needed. Nonetheless, wet commissioning of all fishways is still required to determine that hydraulic characteristics of the constructed fishways meet designed criteria.

The current fishway construction program has contributed greatly to overall fish passage at the Murray Barrages. The fishways on Boundary Creek and Ewe Island Barrages have re-instated migratory pathways through these barrages, providing further locations across the barrage network for fish to access the Lower Lakes from the Coorong. Both fishways were found to be effective in facilitating the passage of small-bodied species, which dominate the migratory fish assemblage at the Murray Barrages. Additionally, these fishways, together with the Goolwa large vertical-slot 2 fishway, have increased the capacity of the fishway network to pass a high biomass of fish, under all flow conditions. Completion of the remaining three fishways will result in the provision of fish passage on every barrage within the network, further improving the geographical spread of migration pathways and capacity to pass high biomasses of fish.

The effectiveness of each of the fishways on the Murray Barrages is influenced by barrage operations. Migrating fish use rheotactic and salinity cues, amongst others, to guide their upstream movements, and consequently, to maximise fishway effectiveness, freshwater must be discharged through barrage gates in a way that maximises attraction to fishway entrances. Typically, this involves confining discharge to gates immediately adjacent to fishways; whereas discharge of water through barrage gates that are removed from fishway locations will result in attraction and accumulation of fishes at positions on the barrage where passage is not facilitated, compromising the effectiveness of fishways.

The provision of fishways on every barrage provides for flexibility in barrage operation in the future. Prior to the current construction program, barrage operation in regards to maximising fish passage and reducing the risk of fish accumulations, has prioritised discharge to barrages with fishways that provide effective fish passage (i.e. Goolwa and Tauwitchere; Bice and Zampatti 2015). Water may now be discharged from any of the five barrages with minimal risk of fish accumulations, if fishways and adjacent gates are operated effectively.

An allied project that has monitored fish migration at the Murray Barrages since 2006, provides evidence of peak seasons for movement and passage that should inform prioritisation of releases and fishway operations (Bice and Zampatti 2015). We suggest year-round operation of all fishways on the Murray Barrages, in particular from June–January to: 1) allow for downstream spawning migrations of congolli and common galaxias and upstream migrations of pouched lamprey from June to August; 2) allow for upstream migrations of short-headed lamprey from August to November; and 3) allow for the upstream migrations of young-of-the-year congolli and common galaxias (and other species) from October to January. In addition to fishway operation, the operation of barrage gates, particularly in winter, is likely to better facilitate downstream spawning migrations of catadromous species, and attraction of anadromous species.

The current program has included the construction of fishways that discharge only low volumes of water (e.g. Boundary Creek, <3 $ML.day^{-1}$). Subsequently, under dry conditions and limited water availability for freshwater releases from the barrages, such fishways may provide the opportunity to maintain connectivity between the Coorong and Lower Lakes, whilst discharging little water. Whilst we support the continuous operation of all fishways, a prioritisation scheme for the closure of high-discharge fishways, but maintenance of low-discharge structures, may be developed as a contingency.

Ultimately, upon the completion and biological assessment of the remaining three fishways, an operating plan should be developed for the Murray Barrages that enhances opportunities for fish migration. Such a plan would not dictate barrage operations, but provide a guide, that when considered with other objectives of barrage operations (e.g. Murray Mouth scouring, salt export from the Goolwa Channel), would maximise fish passage at the Murray Barrages under all hydrological conditions.

The CLLMM fishway construction program is greatly improving connectivity and the capacity for fishes to move freely between the Coorong and Lower Lakes. Such movements are critical in the life history of many native species and as such, fishway construction is contributing greatly to the sustainability of fish populations in the region.

To summarise, the key recommendations of this report are:

- Each of the assessed fishways are operating to biological design objectives;
- Physical alterations to the new fishways are likely not required, but will be dependent upon wet commissioning to determine hydraulic characteristics (to be undertaken October 2016);
- No specific recommendations are provided for the remaining fishways to be constructed (i.e. proceed as designed); and
- We suggest the year-round operation of all fishways, but particularly June–January, and barrage operation that maximises attraction to fishway entrances (i.e. operation of barrage gates adjacent fishways).

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