Inland Waters &
Catchment Ecology

Salt Creek and Morella fishway assessment 2022/23

Q.Ye, L. Bucater, D. Short and C.M. Bice

SARDI Publication No. F2022/000401-2
SARDI Research Report Series No. 1214

SARDI Aquatic and Livestock Sciences
PO Box 120 Henley Beach SA 5022

April 2024

Report to the Department for Environment and Water

Government of South Australia
Department of Primary Industries and Regions

Government of South Australia
Department for Environment and Water

SARDI
SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE

Salt Creek and Morella fishway assessment 2022/23

Report to the Department for Environment and Water

Q.Ye, L. Bucater, D. Short and C.M. Bice

SARDI Publication No. F2022/000401-2
SARDI Research Report Series No. 1214

April 2024

The South Australian Research and Development Institute respects Aboriginal people as the state's first people and nations. We recognise Aboriginal people as traditional owners and occupants of South Australian land and waters. We pay our respects to Aboriginal cultures and to Elders past, present and emerging.

This publication may be cited as:
Ye, Q., Bucater, L., Short, D. and Bice, C.M. (2024). Salt Creek and Morella fishway assessment 2022/23. Report to the Department for Environment and Water. South Australian Research and Development Institute (Aquatic and Livestock Sciences), Adelaide. SARDI Publication No. F2022/000401-2. SARDI Research Report Series No. 1214. 41pp.

Author(s):	Q. Ye, L. Bucater, D. Short and C.M. Bice
Reviewer(s):	J. Earl (SARDI), A. Rumbelow (DEW), M. de Jong (Limestone Coast Landscape Board) and L. Vial (DEW)
Approved by:	S. Nayar Program Leader - Aquaculture
Signed:	
Date:	12 April 2024
Distribution:	Department for Environment and Water, SARDI Aquatic and Livestock Sciences, Parliamentary Library, State Library and National Library
Circulation:	OFFICIAL

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

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

This project was funded by the South Australian Department for Environment and Water (DEW) as part of its ongoing responsibilities for effective use and management of water for the environment in South Australia. The project was managed by Adrienne Rumbelow, Kirsty Wedge and Luke Vial (DEW). We acknowledge the people of the Ngarrindjeri Nation and First Nations of the South East as the traditional custodians of the land on which this study was undertaken. Thanks to Bill Wilson of the Ngarrindjeri Aboriginal Corporation (NAC) and Kirsty Wedge (DEW) for coordinating field work, and to Gordon Rigney, Jayden Rigney (Ngarrindjeri Nation), Uncle Doug Nicholls and Jack Campbell (First Nations of the South East) for working together with us on Country. The authors would like to thank Anthony Newbery (SARDI) for assistance with fieldwork and Brenton Zampatti (CSIRO) for helpful discussions on the results. Special thanks to Richard Palmer (South Eastern Water Conservation and Drainage Board) and Mark de Jong (South Australian Limestone Coast Landscape Board, SALCLB) for providing information on fishway design, construction history and modified fishway configurations, and their ongoing advice on hydrology, structure operation and assistance with fieldwork logistics. Also, thanks to Chrissie Bloss (DEW) for her support and Kimberley Williamson (DEW) for providing hydrology data for this project. Finally, we thank Adrienne Rumbelow (DEW), Luke Vial (DEW), Mark de Jong (SALCLB) and Jason Earl (SARDI) for constructive reviews of a draft of this report. The report was formally approved for release by Professor Mike Steer, Research Director, SARDI Aquatic and Livestock Sciences.

EXECUTIVE SUMMARY

The restoration of biological connectivity and facilitation of fish passage between the Coorong and South East is a key ecological objective of the *South East Flows Restoration Project* (SEFRP). In 2019, this included upgrades of the Salt Creek and Morella flow regulators and the construction of associated rock-ramp fishways. These fishways were designed to facilitate the passage of six key species: congolli (*Pseudaphritis urvillii*), common galaxias (*Galaxias maculatus*), yelloweye mullet (*Aldrichetta forsteri*), smallmouth hardyhead (*Atherinosoma microstoma*), bluespot goby (*Pseudogobius olorum*) and black bream (*Acanthopagrus butcheri*), anticipating that functional fishways for these indicator species would facilitate passage of the whole fish community in the region. The current study aimed to assess passage efficiency of both fishways and was the second formal monitoring of fish passage since the first monitoring in November 2021. Fish sampling was conducted at the entrance and exit of each fishway from 30 January to 10 February 2023 to compare fish species composition, and species-specific abundances and length distributions, with similarity in these parameters suggesting fish passage efficiency.

During this study, a total of 1,026,519 fish from eight species were captured across two fishways, comprising the majority of fishes that occur in the Coorong South Lagoon. At both fishways, catches were dominated (~99% by number) by smallmouth hardyhead. At Salt Creek fishway, more than half of the fishway was submerged due to high water levels in the South Lagoon (0.75–0.90 m Australian Height Datum (AHD) below Salt Creek regulator). The brackish salinity conditions (14.1–26.9 ppt ppt) within and below this fishway provided favorable habitat for many species. For catadromous species, common galaxias were sampled in similar abundances at the entrance and exit of the fishway with smaller sized fish ascending the fishway, suggesting effective passage. Congolli were sampled in greater abundance from the entrance, but a high proportion of smaller individuals (<130 mm total length, TL) passed the fishway, suggesting no size related obstruction of passage. However, passage efficiency was reduced for the small-bodied estuarine species, smallmouth hardyhead and bluespot goby, particularly smaller individuals (<30 mm TL), likely due to a combination of poor swimming ability, fishway internal hydraulics (e.g., high water velocities), and potentially, a lack of drive for upstream movement. Yelloweye mullet were considerably more abundant at entrance than exit in this season, however, this may reflect a lack of drive for upstream movements particularly given the favourable estuarine habitat and abundant food below the fishway. During sampling, water depth at the Salt Creek fishway exit (range = 0.22–0.29 m) and head loss (water level difference between fishway exit and entrance) across

the fishway (range = 0.19–0.35 m) were within the designed functional ranges. Nevertheless, as the majority (≥90%) of the Salt Creek flow (79–117 ML.day^{-1}) was discharged through the regulator, attractant flows at the inundated fishway entrance were minimal, likely resulting in minimal cues for fish to locate the fishway.

The Morella fishway generally provided effective fish passage for common galaxias, congolli and yelloweye mullet, although passage efficiency seemed compromised for smaller individuals (<50 mm TL) of smallmouth hardyhead. During sampling, water depth at the Morella fishway exit (range = 0.27–0.44 m) and head loss (range = 1.22–1.33 m) were largely within the designed functional range. The fishway entrance, however, was perched with the water level immediately downstream of the fishway ranging 2.76–2.95 m AHD. This was approximately 0.11 m lower (estimated based on the water levels at Crump Weir) than that during monitoring in November 2021 when the fishway entrance was largely submerged. Perching of the fishway entrance may have impacted the ability of certain species to enter the fishway and decreased the efficacy of entrance sampling.

Overall, fishway monitoring in 2023 suggested efficient passage for congolli and common galaxias (catadromous species), and to some extent for yelloweye mullet (marine-estuarine opportunistic species) at both fishways, but reduced passage efficiency for small-bodied estuarine species. Upstream movements of estuarine species are not driven by life history requirements. Rather, high abundance of these species at fishway entrances may reflect use of the rock-ramp fishways as habitat. Nonetheless, facilitating effective passage may be important for estuarine species to access upstream refuge habitats (e.g., lower salinities) when environmental condition deteriorates in the South Lagoon (e.g., increase to unfavourable salinities).

Future management of flow discharge through the regulators and associated fishways must consider fishway entrance conditions, including suitable attraction flows and appropriate water levels. The gauge boards established below the Salt Creek regulator and near the Morella fishway entrance since November 2022 collected useful water level/depth data during summer 2023, helping to improve understanding of the influence of discharge through regulators and associated fishways on downstream water levels, and better assess head loss. Additional data should be collected under different hydrological conditions to inform optimal flow management to improve fishway function. Moreover, some relatively minor modifications to the Morella and Salt Creek fishways could improve fish passage, for example, by addition of further rock and reconfiguring of existing rock to provide more diffuse flow through the fishways and limit substantial drops in water level across ridges.

Further monitoring of both fishways is required to assess passage efficiency under the full range of hydrological conditions (flow discharge and water levels) and seasons. This data, in conjunction with improved understanding of fish movement ecology (direction and timing for different species and life stages), will inform the regulator/fishway operations, potential structural modifications, and the development of flow management plans/guidelines to optimise fishway function, considering the broader context of ecological objectives for the Coorong and South East region.

Keywords: Fish passage, Coorong South Lagoon, Morella, connectivity, rock-ramp.

1. INTRODUCTION

1.1. Background

The South East Flows Restoration Project (SEFRP) was implemented to improve the health of the Coorong by managing salinity in the South Lagoon via the diversion of excess freshwater from the Upper South East of South Australia. As part of the SEFRP, two rock-ramp (or 'nature-like') fishways were designed and constructed in conjunction with regulator upgrades at the Salt Creek outfall and Morella Basin outlet (KBR 2019). These structures regulate upstream water levels and flows between the South East drainage system and the Coorong. Previous structures had no consideration for fish passage and were barriers to the upstream movement of fish from the Coorong into the South East drainage system and wetlands. Improved fish movement/migration will enhance population connectivity between the Coorong and South East, promoting population resilience and associated ecological (e.g., food webs) and cultural (e.g., culturally significant fishes) benefits.

A diverse range of fish species have been recorded from the Coorong (Bice et al. 2018), a subset of which, are commonly present in the hypersaline South Lagoon. This includes the solely estuarine smallmouth hardyhead (*Atherinosoma microstoma*) and bluespot goby (*Pseudogobius olorum*); marine-estuarine opportunist yelloweye mullet (*Aldrichetta forsteri*) and diadromous/catadromous[a] congolli (*Pseudaphritis urvillii*) (Ye et al. 2020). These species are commonly found in the vicinity of Salt Creek and may seek to move between the South Lagoon and South East drainage system in order to complete their lifecycle (i.e., congolli), or to access resources and low salinity refuge habitat when salinities in the South Lagoon are elevated (commonly during summer/autumn) and unfavourable. The aforementioned species, along with black bream (*Acanthopagrus butcheri*), a large-bodied estuarine species, and common galaxias (*Galaxias maculatus*), another diadromous/catadromous species, were included in the consideration of fishway design (KBR 2019). The primary biological design objective of the fishways was to effectively facilitate the passage of the catadromous species (i.e., congolli and common galaxias); and the secondary objective was to pass other species including marine-estuarine opportunist and estuarine species. It was anticipated that the six indicator species adequately represented fish passage needs of the broader fish assemblage

[a]Diadromous: This category is defined as those species that must migrate between freshwater and marine environments to complete their life cycles (Potter et al. 2015).
Catadromous: This guild refers to species whose adult life is spent in fresh water, prior to downstream migration into the marine environment for spawning (Potter et al. 2015). Larvae and juveniles develop in the ocean before migrating upstream into freshwater habitats.

in the region, and associated fishway design specifications would accommodate the passage of other species potentially present in this region.

The initial assessment of Salt Creek and Morella fishways in November 2021 indicated that both fishways were generally effective in facilitating the passage of congolli and yelloweye mullet under the conditions experienced (Ye et al. 2022). However, passage efficiency appeared reduced for the small-bodied estuarine species – smallmouth hardyhead and bluespot goby, particularly for smaller individuals (<40 mm total length, TL). This was likely due to a combination of poor swimming ability and fishway internal hydraulics (e.g., high water velocities), and potentially, lack of drive for upstream movement. During the monitoring, Salt Creek discharge was 50–95 ML.day^{-1} and the fishway exit water depth ranged 0.3–0.38 m (1.15–1.23 m AHD) and 0.35–0.46 m (4.05–4.16 m AHD) at Salt Creek and Morella fishways, respectively, which were near or slightly above the maximum of the designed optimal functional depth range of 0.1–0.4 m. From late January to mid-February 2023, further monitoring of the fishways was conducted to assess passage efficiency under different hydrological conditions (flow discharge and water levels) and seasons (summer vs spring). These data, in conjunction with improved understanding of fish movement ecology (direction and timing for different species and life stages), is informing future regulator/fishway operations, potential structural modifications and the development of flow management plans/guidelines to optimise fishway function, considering the broader context of ecological objectives for the Coorong and South East region.

1.2. Objectives

The overall aim of this project was to assess the effectiveness of Salt Creek and Morella rock-ramp fishways with a focus on fish passage efficiency. Specific objectives were to:

- Undertake ‘entrance and exit trapping’ of each fishway and compare data on fish species composition, abundance and length between entrance and exit samples to determine passage efficiency; and
- Inform future regulator/fishway operation to maximise fish passage.

2. METHODS

2.1. Description of the study region

2.1.1. South East drainage system

The South East drainage system extends from Blackford Drain in the south near Kingston SE, to the Salt Creek outfall in the north (Figure 2.1). The works for SEFRP commenced in 2019 and included excavation of approximately 93 km of open drains between the Blackford Drain and Salt Creek, and construction of several regulators to divert surface water in a northerly direction. This included the construction of new regulators and associated rock-ramp fishways at Salt Creek and Morella (Figure 2.2). The Salt Creek regulator and associated fishway are located in the vicinity of the outflow of Salt Creek into the Coorong South Lagoon, and the Morella regulator and associated fishway are approximately 3 km upstream and immediately downstream of the Morella Basin (Figure 2.2).

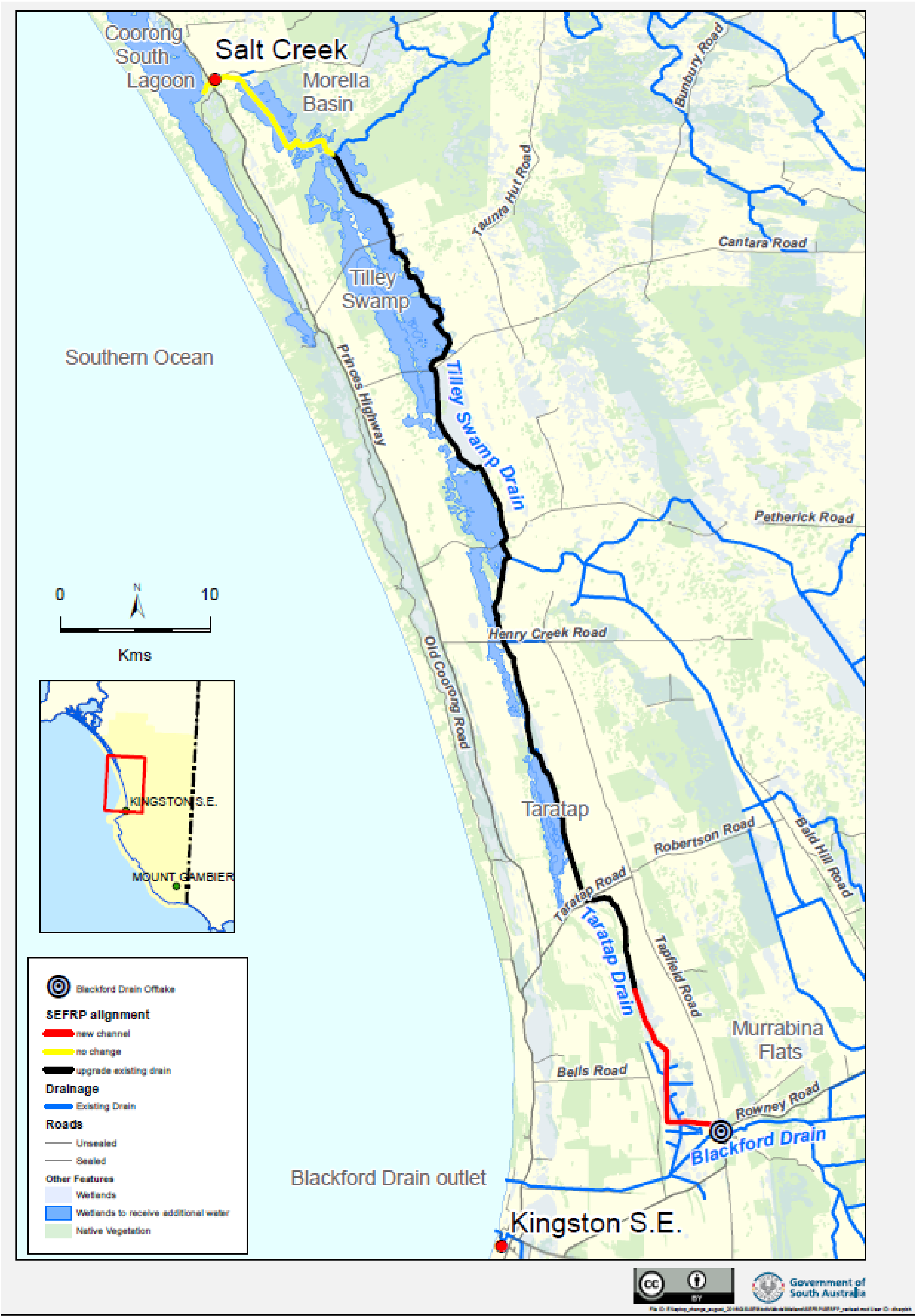


Figure 2.1. A map of the South East drainage system showing the existing, new and upgraded channels and drains between Blackford Drain and Salt Creek. South East Flows Restoration Project Alignment (DEW).

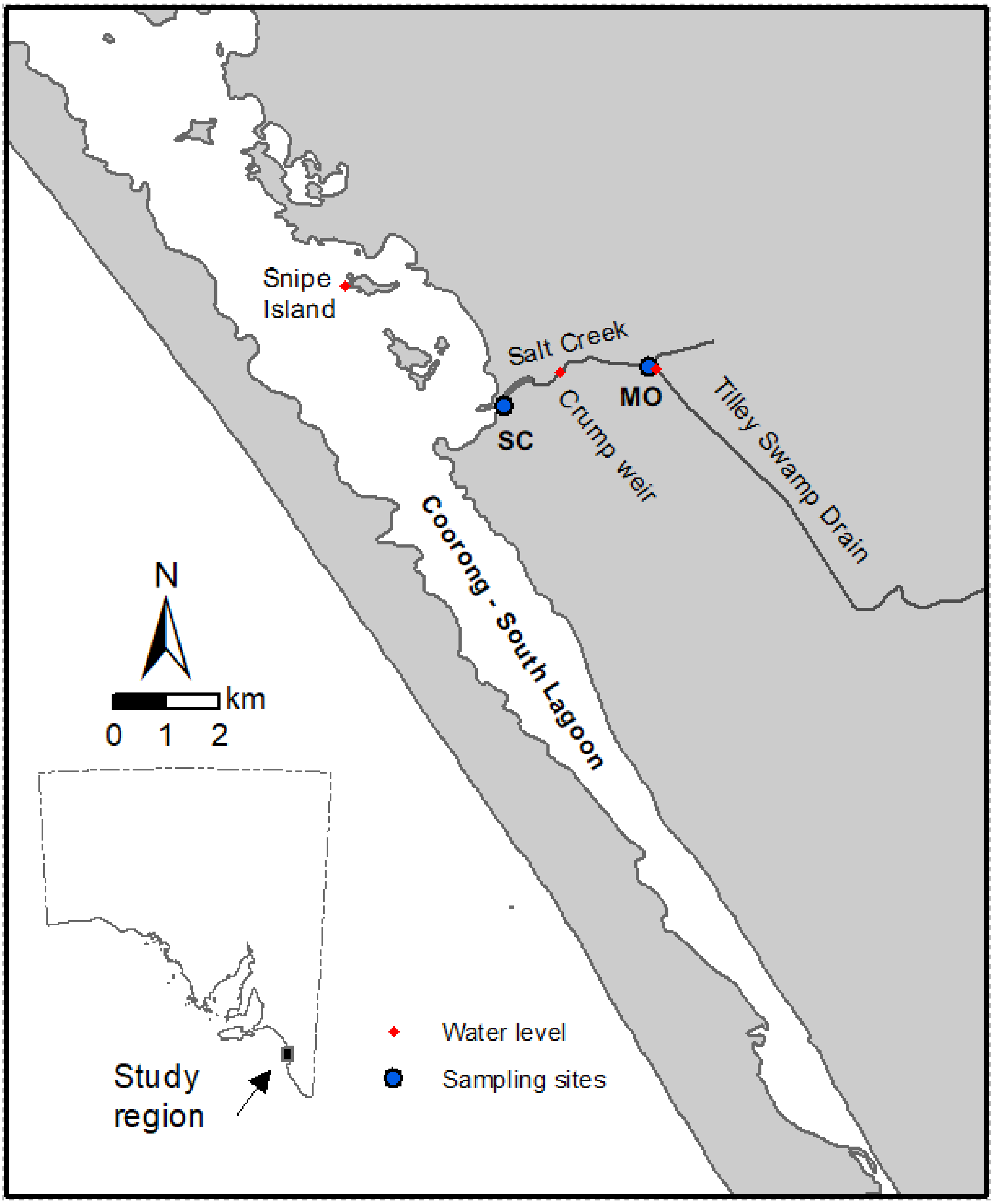
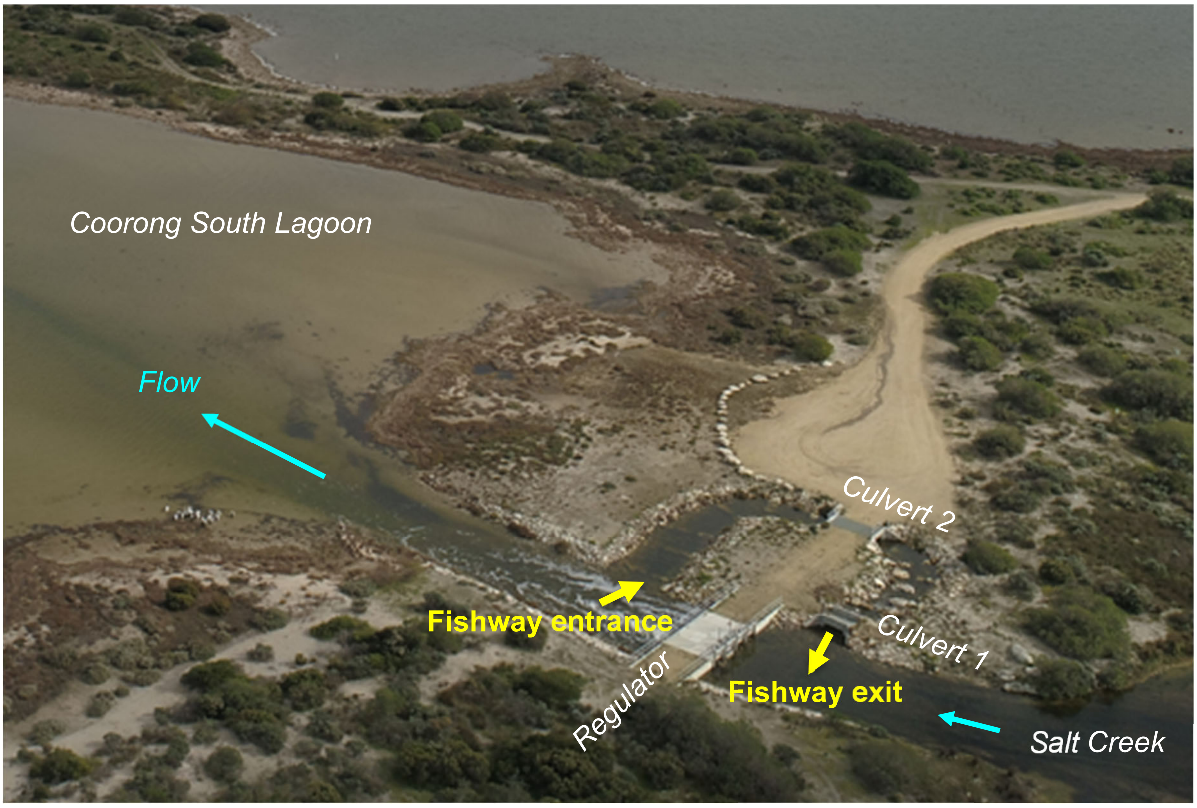


Figure 2.2. A map of the study sites including the location of the Salt Creek (SC) and Morella (MO) fishways and telemetered surface water level monitoring stations.

2.1.2. Fishways

The Salt Creek rock-ramp fishway bypasses the Salt Creek regulator and has a total length of ~55 m and base width of 3.2–5.3 m (Figure 2.3). It consists of a series of 12 pools separated by rock ridges. The rock ridges comprise of large boulders (height ~0.5–0.7 m), with small gaps (width ~0.2–0.35 m) in-between. Lengths of pools, including the rock ridges, range from 2.5–9.5 m with drops between the pools of ~25 mm, and overall fishway slope is ~1:67. There are two box culverts incorporated in the fishway: Culvert 1 at the fishway exit (width 2.1 m; length 2.4 m), and Culvert 2 at the mid-point of the fishway to allow vehicular traffic (width 2.1 m; length 4.8 m) (Figure 2.3).

The Morella rock-ramp fishway bypasses the Morella regulator and has a total length of ~43 m and base width of 3.4–6.5 m (Figure 2.3). It consists of 15 pools interspersed by rock ridges. The rock ridges comprise of large boulders (height ~0.5–0.7 m) with small gaps (width ~0.2–0.35 m) in-between. Lengths of pools range from 2–4 m including rock ridges with drops between the pools of ~75 mm, and overall fishway slope is ~1:39. The last section of the fishway incorporates a box culvert (width ~2.1 m; length ~6 m) with a penstock gate before fish enter a small side exit channel (see Figure 2.3) which leads to the Morella Basin proper. The penstock gate on the culvert can be operated to shut and dewater the fishway when required (i.e., when Morella Basin water level exceeds the operating range of the fishway, or for fishway maintenance work).



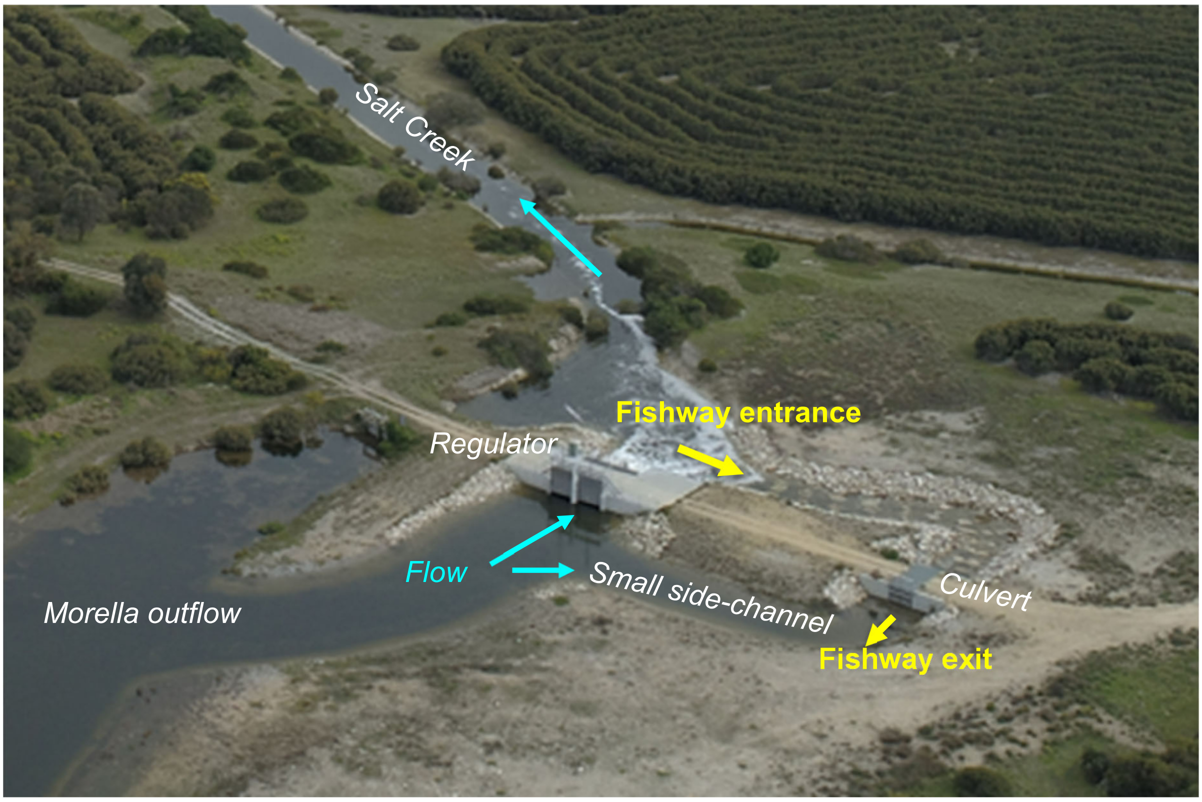


Figure 2.3. Drone photo of the Salt Creek rock-ramp fishway (top) and Morella rock-ramp fishway (bottom) (G. Bowman, SEWCDB).

2.1.3. Hydrology

The two rock-ramp fishways were designed to operate under limited hydrological scenarios, including optimum fishway discharge rates from 10–40 $ML.day^{-1}$, water depth at the fishway exit of 0.1–0.4 m (i.e., 3.84–4.14 m AHD at Morella; 0.95–1.25 m AHD at Salt Creek) and head loss (water level difference between fishway exit and entrance) of <1.3 m. The upstream water levels and discharge are managed by operation of the Morella and Salt Creek regulators. At times, all flow can be delivered through the fishways or discharge can be shared between the fishways and regulator structures (i.e., through lay-flat gates at Morella and penstock gates at Salt Creek). Operational scenarios have an influence on headwater and tailwater levels, and therefore, fishway hydraulics and function.

From 2000–2023, annual discharge from Salt Creek was highly variable, ranging between 0–45 $GL.year^{-1}$ (mean 15.9 $GL.year^{-1}$); daily discharge was generally <400 $ML.day^{-1}$ and salinity in Salt Creek varied from fresh to hypersaline (~3–46 ppt) (Figure 2.4). Flows are seasonal, with peak discharges typically occurring from July–October (winter–spring). In 2021/22 and 2022/23, the South East region received high rainfall in winter–spring, which contributed to increased flows from Salt Creek to the Coorong, with above average annual discharge estimated at 31.9 and 37.2 GL, respectively. However, daily flow patterns differed among years. In 2021/22, discharge was highest during winter–spring, with flow peaking at 796 $ML.day^{-1}$ in late August 2021, but was otherwise <100 $ML.day^{-1}$. Contrastingly, in 2022/23, the Morella regulator was operated to maintain daily discharge at <70 $ML.day^{-1}$ during winter–early summer. The operation aimed to minimise inflow to the Coorong given the already high water levels in the South Lagoon, and to raise storage levels in Morella to 5.1 m AHD in spring 2022. Higher releases to the Coorong (e.g., >100 $ML.day^{-1}$) did not occur until May and June 2023.

During 2022/23, the Morella fishway was operational from 30 January–30 June 2023 while water level at Morella remained above 3.74 m AHD (i.e., Morella fishway exit depth >0 m). The Salt Creek fishway was operational throughout 2022/23. To optimise fishway function, the regulators at both sites were operated to adjust the split of discharge through regulator gates and associated fishways (approximately twice monthly), attempting to maintain optimal water depths at both fishway exits (0.1–0.4 m) (Richard Palmer 2023, personal comm.). The estimated discharge rates via each regulator and fishway from 30 January to 28 February 2023 are presented in Table 2.1. Fishway monitoring was conducted between 30 January and 10 February 2023, with the timing aligned with the commencement of Morella fishway operation in this season and the aim to assess fish passage through both fishways during summer (vs previous monitoring in spring 2021) under different hydrological conditions.

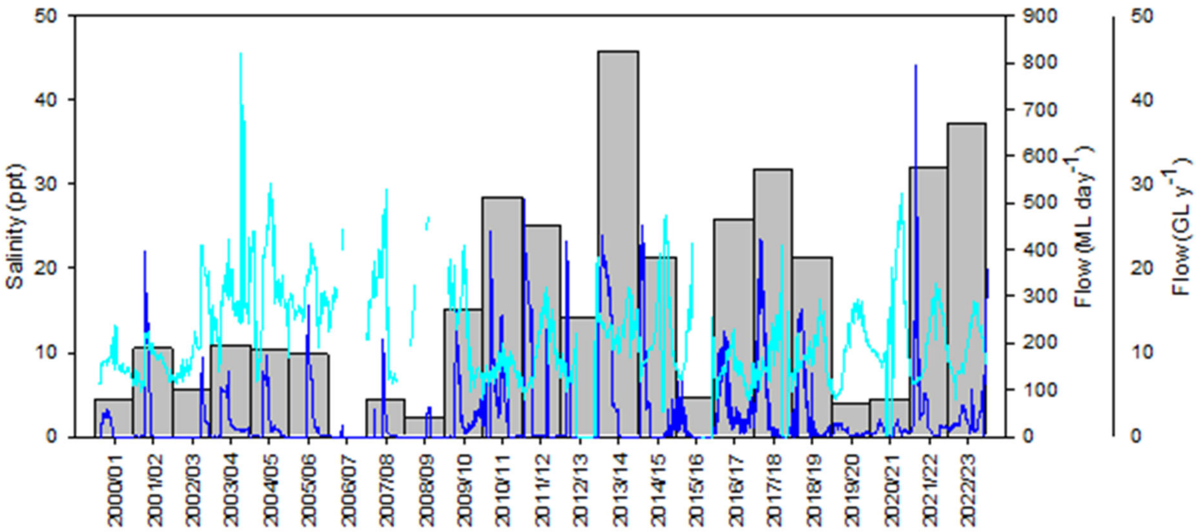


Figure 2.4. Estimated annual (grey bar; GLyear^{-1}) and daily (blue line; MLday^{-1}) discharge through the Salt Creek outfall to the Coorong, with salinity levels at Crump Weir in Slat Creek (cyan line; ppt) from July 2000 to June 2023 (Water Data SA, Station A2390568, DEW 2023). Note: For salinity, a data point of zero would indicate the site is dry and not recording a value.

Table 2.1. Estimates of the split of daily flow discharge through the regulator and associated fishway at Salt Creek and Morella from 30 January to 28 February 2023 (Richard Palmer 2023, personal comm.). Note: Gauging was taken on 6,10 and 27 February 2023; Morella flows were taken from automated gate flow meter and correlate well with manual flow gauging measurements.

Date	Total Flow	Salt Creek			Morella		
	(ML.day^{-1})	Regulator	Fishway	%fishway	Regulator	Fishway	% fishway
30/01/2023	117	108	9	8%	68	49	42%
31/01/2023	115	107	8	7%	66	49	43%
1/02/2023	115	107	8	7%	66	49	43%
2/02/2023	110	102	8	7%	61	49	45%
3/02/2023	82	74	8	10%	37	45	55%
4/02/2023	82	75	8	9%	52	30	37%
5/02/2023	82	75	8	9%	52	30	37%
6/02/2023	82	75	7	9%	52	30	37%
7/02/2023	83	76	7	8%	55	28	34%
8/02/2023	93	86	7	8%	67	26	28%
9/02/2023	81	74	7	9%	59	22	27%
10/02/2023	79	72	7	9%	57	22	28%
11/02/2023	70	64	6	9%	50	20	29%
12/02/2023	70	64	6	9%	50	20	29%
13/02/2023	47	42	6	12%	27	20	43%
14/02/2023	54	49	6	10%	34	20	37%
15/02/2023	68	63	6	8%	48	20	29%
16/02/2023	68	63	6	8%	48	20	29%
17/02/2023	12	9	3	25%	0	12	100%
18/02/2023	12	9	3	25%	0	12	100%
19/02/2023	12	9	3	25%	0	12	100%
20/02/2023	12	9	3	25%	0	12	100%
21/02/2023	10	7	3	30%	0	10	100%
22/02/2023	10	7	3	30%	0	10	100%
23/02/2023	8	6	2	24%	0	8	100%
24/02/2023	8	6	2	24%	0	8	100%
25/02/2023	8	6	2	24%	0	8	100%
26/02/2023	8	6	2	24%	0	8	100%
27/02/2023	8	6	2	24%	0	8	100%
28/02/2023	8	6	2	24%	0	8	100%

2.2. Data collection

2.2.1. Fish sampling

Specifically designed traps were used to sample the fish assemblage at the entrance and exit of each fishway (Figure 2.5). For the Salt Creek fishway, two different fyke net designs were employed to sample the entrance and exit. At the entrance, a double wing fyke was used, which had a 3.5 m long body with five hoops, two funnels and 6 m wings, and 4 mm mesh. The wings and entrance of the fyke net were 0.7 m high to sample the entire water column within the fishway. At the fishway exit, a wingless fyke net was used with the same dimensions as above. An aluminum frame was fitted to the mouth of the fyke net body, which was subsequently set abutting the exit of Culvert 1 (Figure 2.3). This covered the entire fishway exit and replaced the need for the fyke wings.

For the Morella fishway, a double wing fyke net was employed to trap the entrance of the fishway. It had a 4 m long body with five hoops, two funnels and 6 m wings, and 4 mm mesh. The wings and entrance of the fyke net were 1.1 m high to sample the entire water column within the fishway. Similar to Salt Creek, the Morella fishway exit was trapped using a wingless fyke net with an aluminum frame fitted to the mouth of the fyke net body. It was set abutting the culvert and covering the entire fishway exit. The fyke net dimensions were the same as that used at the Salt Creek fishway exit.

Trapping involved undertaking paired replicate samples of the fishway entrances and exits, each for an overnight period of ~20–25 hours (see Appendix A). Entrance and exit trapping allowed for a comparison between the species, abundance and size range of fish that entered the fishway (entrance trapping) with those that successfully ascended (exit trapping). Fishway trapping was conducted over two weeks from 30 January–10 February 2023. This resulted in a total of four entrance and four exit trapping events for both fishways. Prior to undertaking trapping, SARDI staff consulted with the water managers and operators from the Department for Environment and Water (DEW) and South East Water Conservation and Drainage Board (SEWCDB) to gain contextual information about the regulator/fishway operations.

Upon retrieval of each fyke net, all trapped fish were removed from nets and placed in aerated holding tubs, before being identified to species and counted. A sub-sample of fish (up to 50 individuals per species per trapping event) were measured for total length (mm, TL) to generate a representative size structure from the sampled population at the fishway entrance and exit.

Figure 2.5. Fish trapping at the Salt Creek rock-ramp fishway entrance (top left) and exit (top right) and the Morella rock-ramp fishway entrance (bottom left) and exit (bottom right).

2.2.2. Environmental data

Water quality parameters (i.e., salinity, temperature, pH and dissolved oxygen (DO)) were recorded using a TPS water quality meter. Measurements were taken at the entrance and exit of both fishways when traps were retrieved.

2022/23 data were obtained from Water Data SA (DEW 2023), including estimates of daily flow discharge from Morella/Salt Creek (ML.day^{-1}) at Crump Weir (Station A2390568) and daily average water levels (m AHD) immediately upstream the Morella regulator (Station A2391274), at Salt Creek Crump Weir, and at Snipe Island (Station A4261165) in the Coorong South Lagoon. Because the estimates of flows at the Crump Weir may not be accurate due to siltation, additional daily discharge data from Salt Creek were provided by Richard Palmer (SEWCDB) based on field measurements on 6, 10 and 27 February 2023 and subsequent estimates for other dates during the period between 30 January and 28 February 2023 (i.e., during and after fishway monitoring). During fishway monitoring, water levels (AHD) at the entrance and exit of each fishway were recorded by SARDI staff, which provided an estimate of head loss.

2.3. Data analysis

Fish passage efficiency at the Salt Creek and Morella fishways was assessed by comparing fish assemblage structure, species-specific abundance and length-frequency distributions between entrance and exit trapping events. Similarity in fish assemblages, with regards to species composition and abundance ($fish.hour^{-1}.trap\ event^{-1}$), among entrance and exit samples was assessed using multidimensional scaling (MDS) ordination and a single-factor (trap position) PERMANOVA (Permutational Multivariate Analysis of Variance) ($\alpha = 0.05$). These analyses were performed on Bray-Curtis similarity matrices in the software package PRIMER v. 6.12 and PERMANOVA+ (Anderson et al. 2008). When difference occurred, Similarity of Percentages (SIMPER) analysis was used to determine species contributing to differences in assemblages (a 70% cumulative contribution cut-off was applied). Species-specific passage efficiency was assessed for the most abundant species (>10 individuals) at each fishway by comparing relative abundance ($fish.hour^{-1}.trap\ event^{-1}$) between entrance and exit samples using uni-variate PERMANOVA, performed on Euclidean Distance similarity matrices. Due to low numbers of permutations in some instances, *p* values were compared with the Monte Carlo *p* values (*p* MC), where the real data were compared against 5000 runs of randomised data (Dufrene and Legendre 1997). Nonetheless, there were no differences in statistical results, and thus we presented *p* values. Fish relative abundance data were fourth-root transformed prior to all analyses.

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

3. RESULTS

3.1. Environmental conditions

Salt Creek discharge was <70 ML.day^{-1} from July 2022–January 2023 (Figure 3.1). There was a small flow pulse, peaking at ~117 ML.day^{-1} on 30 January 2023 (Richard Palmer 2023, personal comm.), but then a rapid decline to <10 ML.day^{-1} in late-February 2023. Discharge remained <18 ML.day^{-1} until mid-April, when it steadily increased, reaching approximately 100 ML.day^{-1} during May 2023. In June 2023, flow increased rapidly to >350 ML.day^{-1}. During the period of fishway monitoring (30 January–10 February 2023), Salt Creek flow ranged between 79–117 ML.day^{-1} (mean = 93 ML.day^{-1}), with discharge through both regulators and fishways (Richard Palmer 2023, personal comm.). The percentage of overall flow that passed through the Salt Creek fishway ranged 7–10% and 27–55% at the Morella fishway (Table 2.1).

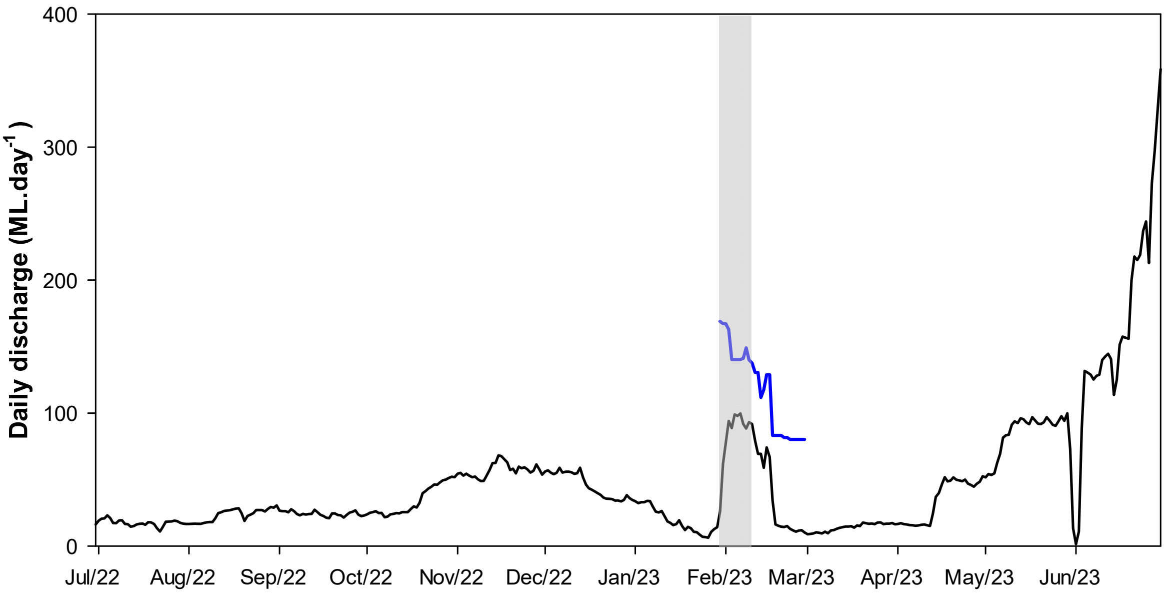


Figure 3.1. Estimated daily flow discharge from Morella/Salt Creek (ML.day^{-1}) for 2022/23 (Water Data SA, DEW 2023) (black line) and in field measurements (blue line) by Richard Palmer (SEWCDB) during and after the monitoring period (grey bar).

During 2022/23, water levels ranged 3.84–4.92 m AHD upstream of the Morella regulator, 1.72–2.70 m AHD at the Salt Creek Crump Weir (Figure 3.2), and 0.16–1.06 m AHD in the Coorong South Lagoon (Snipe Island) (Figures 1.2 and 3.3). Specifically, during fishway monitoring, water depth immediately below the entrance of Morella fishway ranged 0.13–0.32 m (2.76–2.95 m AHD) (noting fishway entrance was perched) and at the exit of the fishway ranged 0.27–0.44 m (4.01–4.18 m AHD), resulting in a head loss of 1.22–1.33 m. At the Salt

Creek fishway, water depth ranged 0.72–0.87 m (0.75–0.90 m AHD) at the entrance and 0.22–0.29 m (1.07–1.14 m AHD) at the exit, resulting in a head loss of 0.19–0.35 m. (Figure 3.3).

Figure 3.2. Crump Weir gauging station for water levels within Salt Creek.

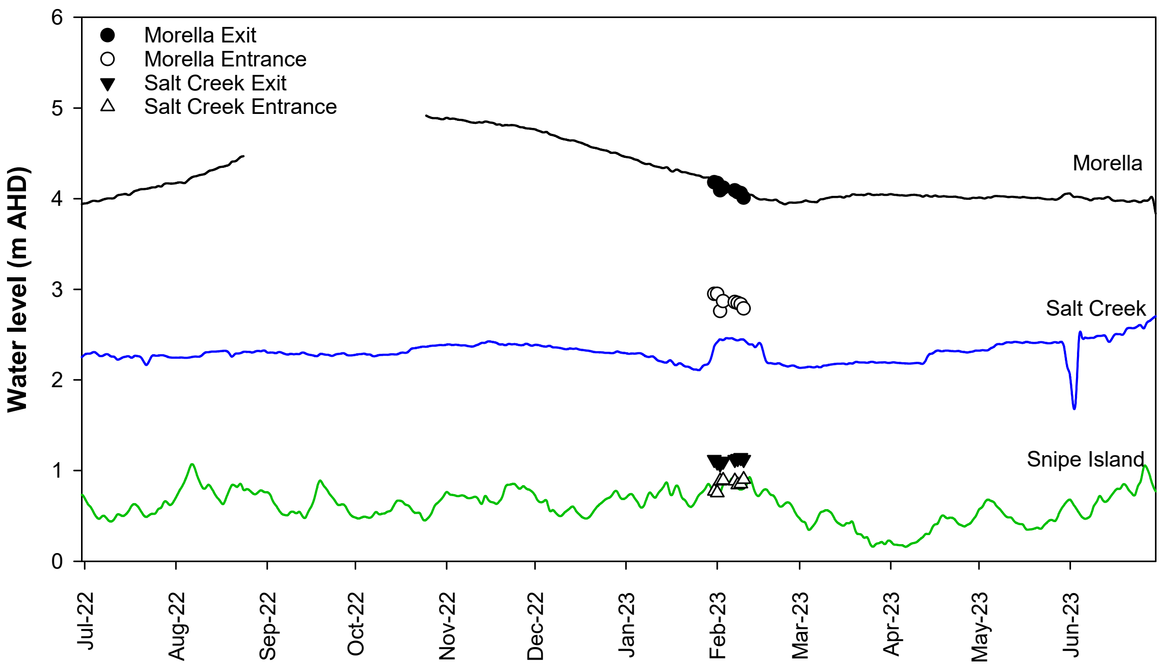


Figure 3.3. Daily average water levels (m AHD) immediately upstream the Morella regulator (A2391274), at Salt Creek Crump Weir (A2390568), and at Snipe Island (A4261165) in the Coorong South Lagoon from 1 July 2022 to 30 June 2023 (data Source: DEW), and gauge board measurements by SARDI staff at the entrances and exits of the Salt Creek and Morella fishways during trapping between 31 January and 10 February 2023.

Water quality parameters during fish sampling are presented in Table 3.1. The maximum salinity at the Salt Creek fishway entrance was much higher than the other three sites, while the ranges of temperature, DO and pH were similar across all sites, with minor variations likely due to the times of the day when measurements were taken.

Table 3.1. The ranges of water quality parameters during fishway trapping at the Salt Creek and Morella fishways from 31 January–10 February 2023.

	Morella Fishway		Salt Creek Fishway	
Water parameters	**Entrance**	**Exit**	**Entrance**	**Exit**
Salinity (ppt)	13.8–14.1	13.4–14.0	14.1–26.9	13.8–14.1
Temperature (°C)	14.7–22.7	19.2–20.9	15.7–23	20.3–21.0
Dissolved oxygen (mg.L^{-1})	6.3–8.6	7.0–8.5	4.6–9.9	5.5–7.4
pH	6.9–9.1	7.6–9.0	8.0–9.0	8.9–9.1

3.2. Catch summary

A total of 1,026,519 fish from eight species were sampled collectively from the Salt Creek and Morella fishways (Table 3.2). The overall catch was numerically dominated by the small-bodied estuarine smallmouth hardyhead (99.9% of total catch). The next three most abundant species were the small-bodied catadromous common galaxias, medium-bodied catadromous congolli, and the small-bodied estuarine bluespot goby (collectively ~0.04%). These four species as well as the medium-bodied marine-estuarine opportunist yelloweye mullet and freshwater-estuarine opportunist flat-headed gudgeon (*Philypnodon grandiceps)*, were present at both fishways. The large-bodied estuarine black bream was sampled only at the entrance of the Salt Creek fishway, whereas the freshwater exotic eastern gambusia (*Gambusia holbrooki*) (one individual) was only collected at the exit of the Morella fishway.

Table 3.2. Species, total numbers and total length (TL, mm) range of fish sampled during the Salt Creek and Morella fishway monitoring in January-February 2023. FG = Functional group, E = Estuarine, C = Catadromous, FO = freshwater-estuarine opportunist, FE = freshwater exotic and MO = Marine-estuarine opportunist. Definitions of each functional group are provided in Potter et al. 2015.

				Salt Creek fishway			Morella fishway			
Common name	**Scientific name**	**FG**	**Body Size**	**Entrance (*n*)**	**Exit (*n*)**	**TL range (mm)**	**Entrance (*n*)**	**Exit (*n*)**	**TL range (mm)**	**Total (*n*)**
	Sampling events			4	4		4	4		
	No. of species			7	6		3	7		**8**
Smallmouth hardyhead	*Atherinosoma microstoma*	E	Small	1,007,969	4,133	21–104	10,092	3,763	31–117	**1,025,957**
Bluespot goby	*Pseudogobius olorum*	E	Small	94	43	20–57		1	36	**138**
Black bream	*Acanthopagrus butcheri*	E	Large	32		116–303				**32**
Common galaxias	*Galaxias maculatus*	C	Small	40	21	39–68		87	45–89	**148**
Congolli	*Pseudaphritis urvillii*	C	Medium	76	8	88–147	5	58	16–233	**147**
Flat-headed gudgeon	*Philypnodon grandiceps*	FO	Small	29	1	28–74		2	34–70	**32**
Eastern gambusia	*Gambusia holbrooki*	FE	Small					1	45	**1**
Yelloweye mullet	*Aldrichetta forsteri*	MO	Medium	40	3	94–348	10	11	118–375	**64**
Total				**1,008,280**	**4,209**		**10,107**	**3,923**		**1,026,519**

3.3. Passage efficiency

3.3.1. Salt Creek fishway

At the Salt Creek fishway, a total of 1,008,280 fish from seven species were sampled at the entrance, and 4,209 fish from six species at the exit (Table 3.2). Black bream was sampled exclusively at the entrance (*n* = 32), whilst the remaining six species were sampled at both the entrance and exit. PERMANOVA indicated that fish assemblages from the entrance and exit trap samples were significantly different (Pseudo-$F_{1, 7}$ = 21.346, *p* = 0.023, Table 3.2). This was supported by MDS ordinations of fish assemblage data, which exhibited a strong separation of samples from entrance and exit trapping (Figure 3.4). SIMPER suggested that the assemblages differed primarily (67.3%) due to greater abundances of smallmouth hardyhead sampled at the entrance (Figure 3.5; Appendix B).

Relative abundances were significantly higher at the fishway entrance than exit for smallmouth hardyhead (Pseudo-$F_{1, 7}$ = 15.249, *p* = 0.029), yelloweye mullet (Pseudo-$F_{1, 7}$ = 8.5929, *p* = 0.034), congolli (Pseudo-$F_{1, 7}$ = 75.327, *p* = 0.026) and flat-headed gudgeon (Pseudo-$F_{1, 7}$ = 22.292, *p* = 0.029). However, for common galaxias (Pseudo-$F_{1, 7}$ = 1,6868, *p* = 3.06) and bluespot goby (Pseudo-$F_{1, 7}$ = 3.8721, *p* = 0.145), no significant differences were detected in abundances between the entrance and exit (Figure 3.5).

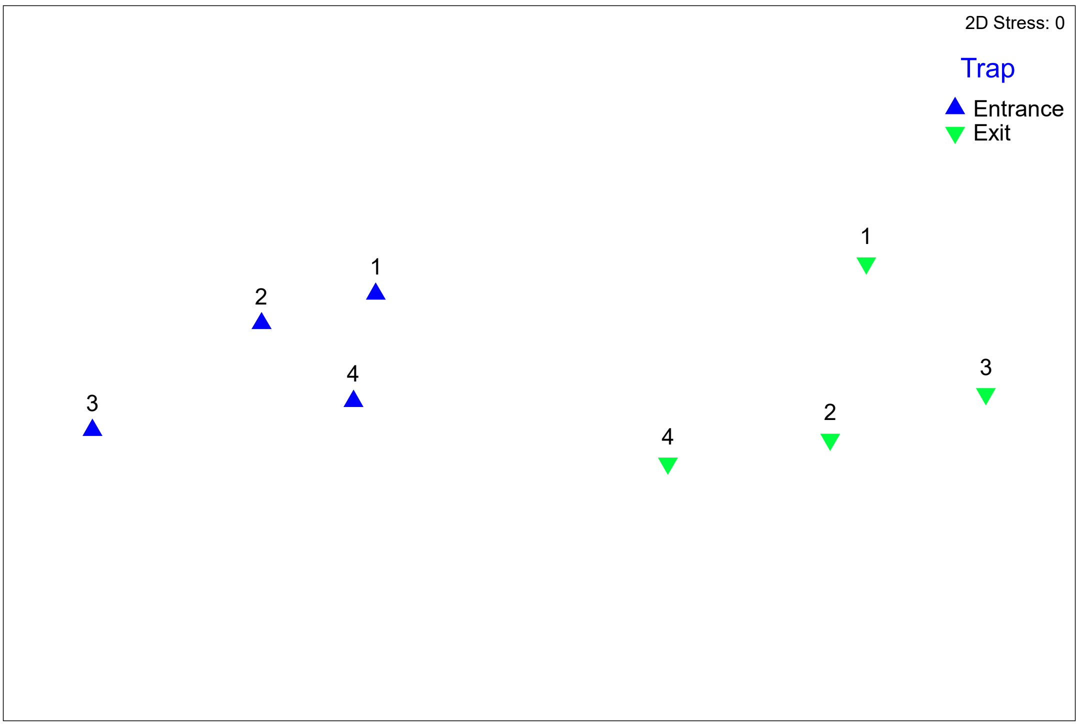


Figure 3.4. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages from each of the entrance and exit samples at the Salt Creek rock-ramp fishway.

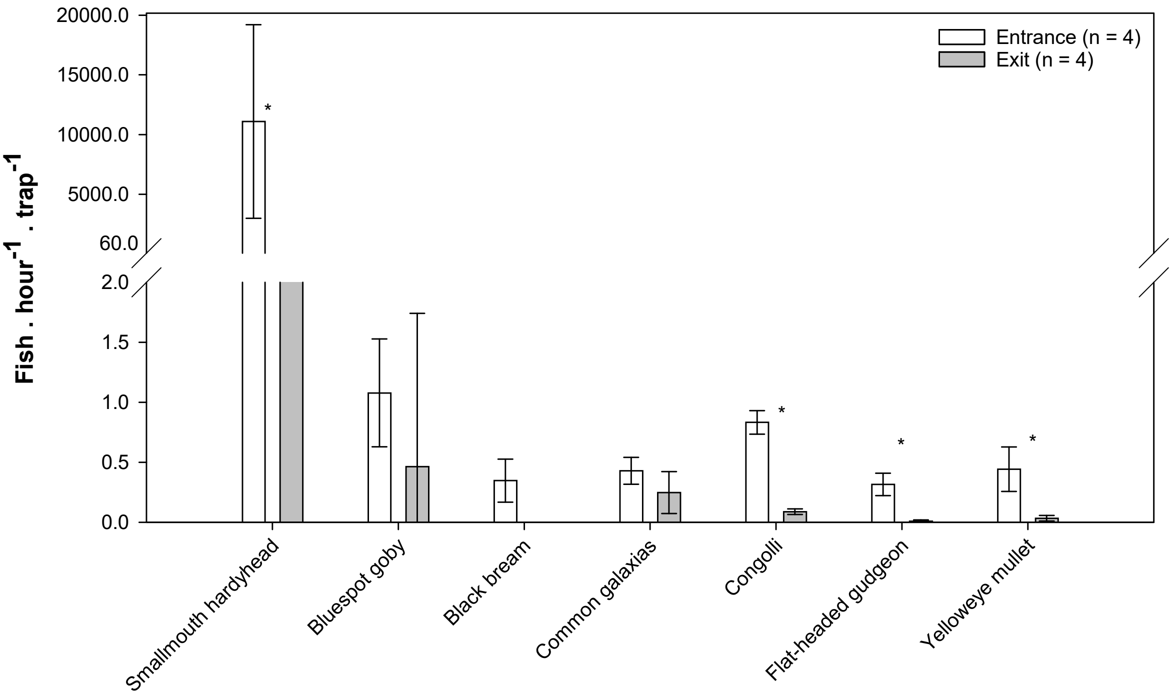


Figure 3.5. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1} ± standard error) of the species sampled at the entrance (white bar) and exit (grey bar) of the Salt Creek rock-ramp fishway during January-February 2023. Significant differences between entrance and exit abundances are indicated by asterisks.

Fish sampled at the entrance of the Salt Creek fishway ranged from 20–303 mm in TL, whilst those sampled at the exit ranged from 24–348 mm in TL (Figure 3.6). The length-frequency distributions for smallmouth hardyhead ($D_{200, 200}$ = 0.450, *p* <0.001) were significantly different between the fishway entrance and exit; there was a greater proportion of smaller individuals 20–39 mm TL sampled from the entrance (78%) than the exit (45%), whilst larger individuals (60–109 mm TL) represented 20% of the fishway exit samples compared to 4% of the entrance samples (Figure 3.6d). For bluespot goby ($D_{94, 43}$ = 0.881, *p* <0.001), the length-frequency distributions also showed a significant difference between the entrance and exit (Figure 3.6e), with a slightly greater proportion (45%) of smaller individuals (20–29 mm TL) sampled at the entrance than at the exit (35%) and a greater proportion (63%) of larger individuals (30–39 mm TL) sampled at the exit than at the entrance (47%).

There were insufficient numbers of yelloweye mullet, common galaxias, congolli and flat-headed gudgeon sampled to enable statistical comparison of size structures between the fishway entrance and exit. However, the length-frequency distributions showed a higher proportion of smaller yelloweye mullet (120–149 mm TL) sampled at the fishway entrance than at the exit (Figure 3.6c). For common galaxias, although the size mode of fish was slightly larger (at 50–59 mm TL) for samples from the exit than entrance, the smallest size class (30–

39 mm TL) was present at the exit (Figure 3.6g). For congolli, the proportion of fish <130 mm TL was greater at the fishway exit than entrance, whereas fish >150 mm TL were only detected at the entrance (Figure 3.6f).

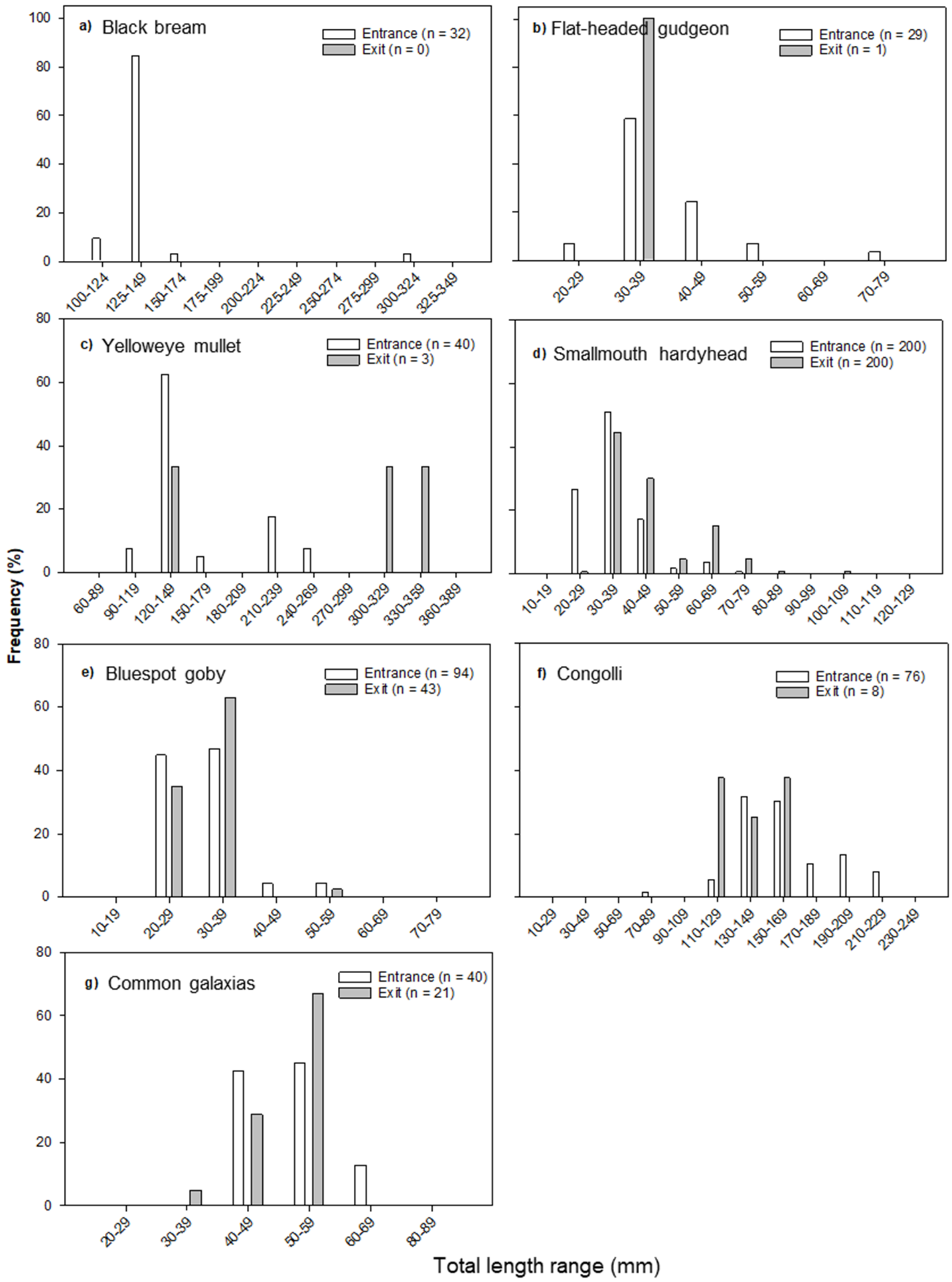


Figure 3.6. Length-frequency distributions seven fish species captured from the entrance (white) and exit (grey) of the Salt Creek rock-ramp fishway during January-February 2023. Sample sizes (*n*) represent the number of fish measured for total length for each species. Note: plots have varying axis scaling.

3.3.2. Morella fishway

At the Morella fishway, a total of 10,107 fish from three species were sampled from entrance trapping, and 3,923 fish from seven species from exit trapping (Table 3.2). The species exclusively sampled at the exit were common galaxias (n = 87), flat-headed gudgeon (n = 2), bluespot goby (n = 1) and eastern gambusia (n = 1). PERMANOVA indicated that fish assemblages from entrance and exit trap samples differed significantly ($Pseudo\text{-}F_{1,\,7}$=4.8617, p = 0.021, Table 3.2). This was supported by MDS ordinations of fish assemblage data, which exhibited a separation of samples from entrance and exit trapping (Figure 3.7). SIMPER suggested that the difference in assemblages was primarily (78%) due to the presence of common galaxias solely at the exit, and greater abundances of smallmouth hardyhead sampled at the entrance and congolli at the exit (Figure 3.8; Appendix B).

The relative abundance of congolli was significantly higher at the fishway exit than at the entrance ($Pseudo\text{-}F_{1,\,7}$ = 14.714, p = 0.023). No significant differences in the abundance of smallmouth hardyhead ($Pseudo\text{-}F_{1,\,7}$ = 1.1127, p = 0.358) and yelloweye mullet ($Pseudo\text{-}F_{1,\,7}$ = 0.00093, p = 1) were detected between the entrance and exit (Table 3.2; Figure 3.8).

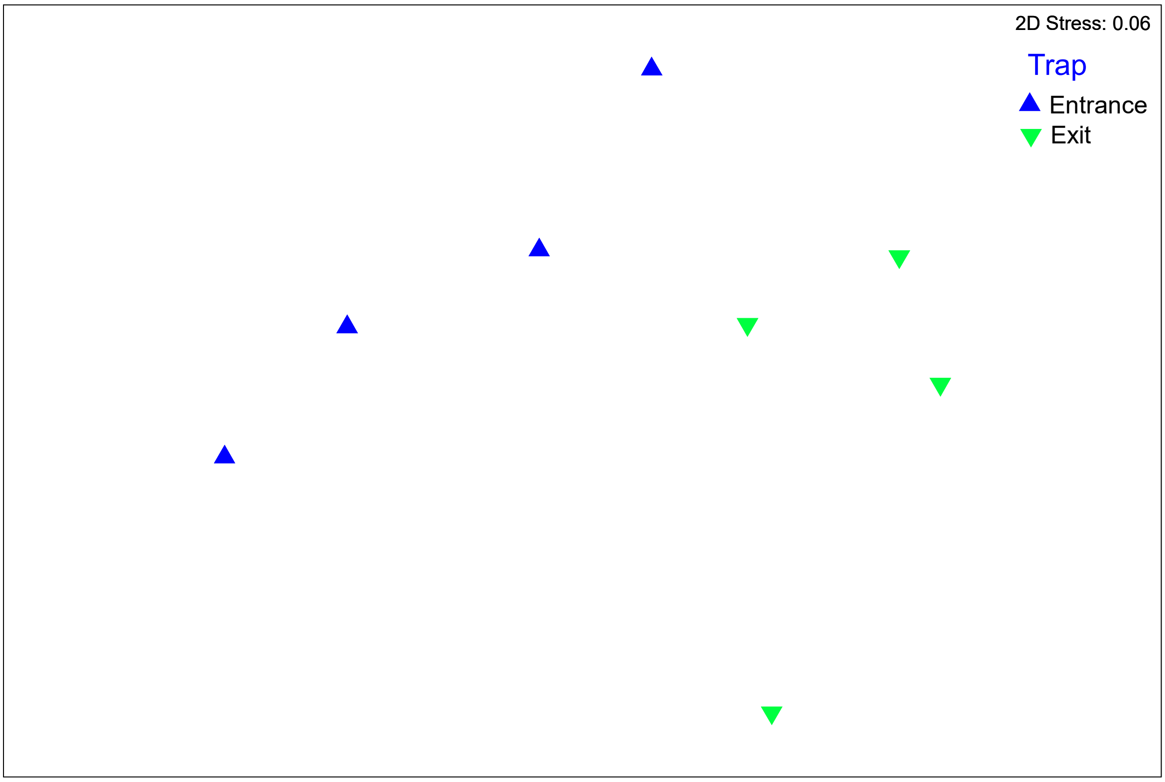


Figure 3.7. Non-metric multi-dimensional scaling (MDS) ordination of fish assemblages from each of the entrance and exit samples at the Morella Creek rock-ramp fishway.

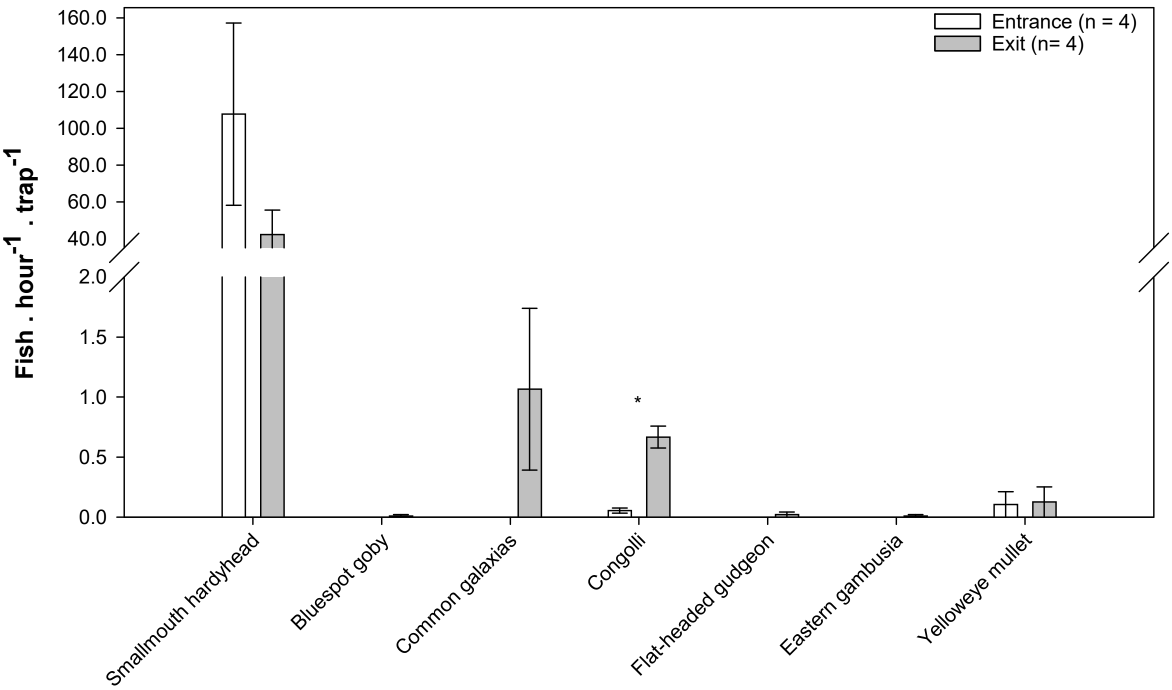


Figure 3.8. Comparison of mean relative abundance (number of fish.hour^{-1}.trap event^{-1} ± standard error) of the species sampled at the entrance (white bar) and exit (grey bar) of the Morella rock-ramp fishway during January-February 2023. Significant differences between entrance and exit abundances are indicated by asterisks.

Fish sampled at the entrance of the Morella fishway ranged from 35–375 mm TL, whilst those sampled at the exit ranged from 16–242 mm TL (Figure 3.9). The length-frequency distributions for smallmouth hardyhead ($D_{200, 199} = 0.169$, $p < 0.007$) were significantly different between the fishway entrance and exit, with the proportion of individuals <50 mm TL slightly higher from the entrance (17%) than exit (10.5%) (Figure 3.9b). For yelloweye mullet and congolli, there were insufficient numbers sampled to enable statistical comparison. Size distributions of yelloweye mullet, however, indicated that the proportion of individuals <150 mm TL was approximately 50% greater at the fishway entrance than the exit (Figure 3.9a). For congolli, the smallest size classes (10–29 mm, 30–49 mm and 70–89 mm TL) were sampled at the fishway exit, whereas larger fish were more abundant at the entrance.

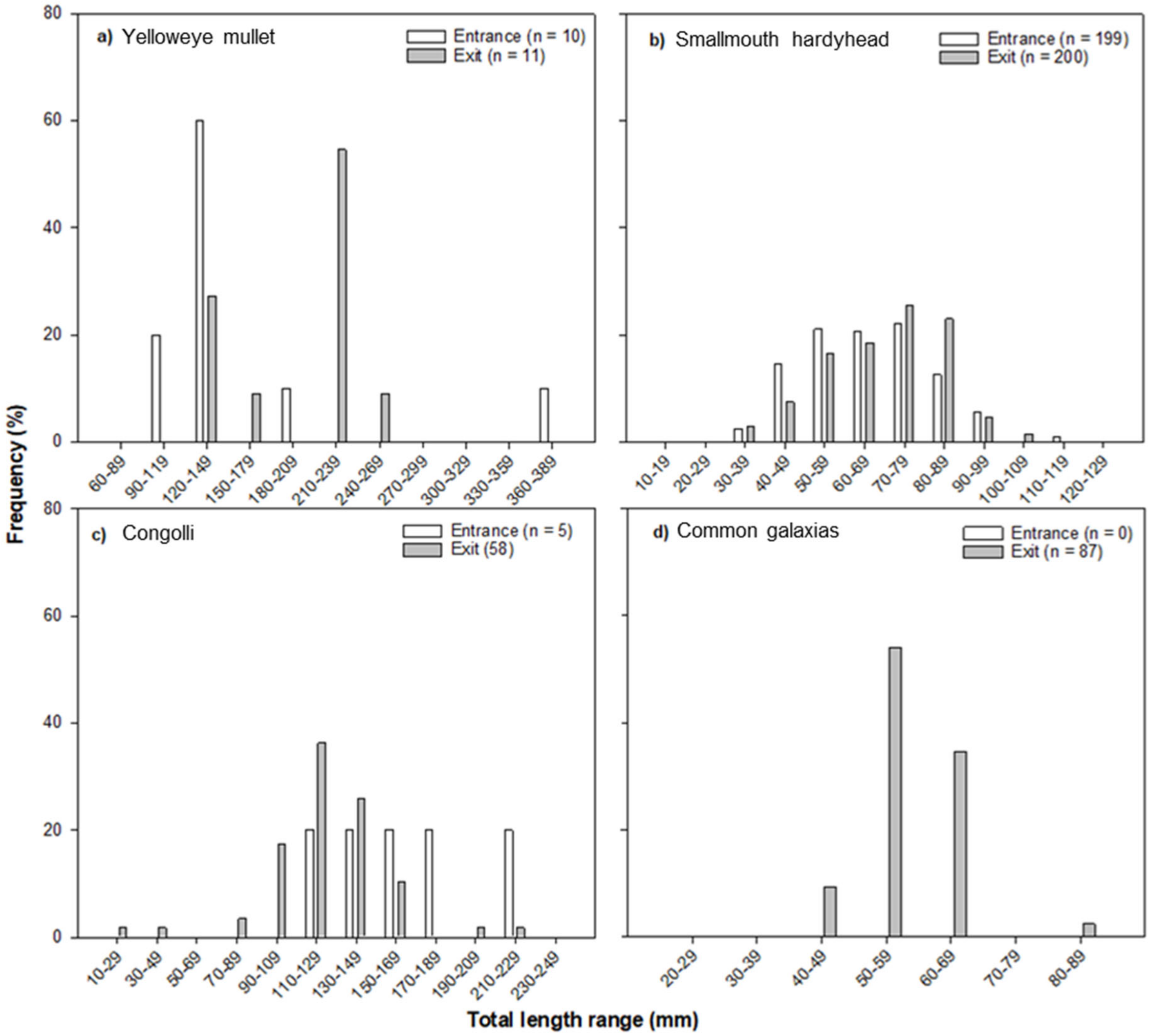


Figure 3.9. Length-frequency distributions of four fish species captured from the entrance (white) and exit (grey) of the Morella rock-ramp fishway during January–February 2023. Sample sizes (*n*) represent the number of fish measured for length for each species. Note: plots have varying x axis scaling.

4. DISCUSSION

The Salt Creek and Morella rock-ramp fishways were constructed as part of the SEFRP, in conjunction with regulator upgrades at these sites, and aimed to improve fish passage and biological connectivity between the Coorong and the South East drainage system. The first round of fishway monitoring was undertaken during spring (November) 2021 and provided an initial assessment of passage efficiency following high winter–spring discharge from Salt Creek (Ye et al. 2022). The present study involved additional fishway monitoring during late summer (late January–mid February) 2023 and followed relatively low Salt Creek discharge from winter–summer, albeit coinciding with high flows from the Murray Barrages and relatively low salinity and high water levels in the Coorong South Lagoon. Assessments involved fish trapping at the entrance and exit of each fishway and data comparisons with regards to fish species compositions, abundances and sizes able to successfully ascend fishways. Advice is provided on future operation of these regulators and associated fishways and potential structure improvements to facilitate fish passage, and further investigations.

4.1. Catch summary

The seven native fish species sampled from the Salt Creek and Morella fishways during summer 2023 were also sampled during fishway monitoring in November 2021 except for common galaxias (see Appendix C) (Ye et al. 2022). These species are common in the Coorong (Ye et al. 2020), with six being the indicator species expected to use these fishways (KBR 2019).

In the current study, two catadromous species, congolli and common galaxias, were sampled. These species migrate between freshwater and marine environments to complete their life cycle (Potter et al. 2015) and are regularly encountered using fishways on coastal streams in southeastern Australia (e.g., Bice et al. 2023). At the nearby Murray Barrage fishways, high numbers of juvenile congolli and common galaxias have been detected migrating upstream from the Murray Estuary to the freshwaters of the lower River Murray during spring–early summer following winter spawning in the sea (Bice et al. 2020). In summer 2023, common galaxias were reasonably abundant at both Salt Creek and Morella fishways, but were not detected during fishway monitoring in November 2021 (Ye et al. 2022). Common galaxias have a lower salinity tolerance than congolli (McNeil et al. 2013; SARDI unpublished data). Monitoring of fish assemblages in the Coorong indicated that during years with low barrage flows, the distribution of common galaxias was restricted to the Murray Estuary region (below the barrages proper), whereas in high flow years (e.g., 2016/17, 2022/23), their distribution expanded at least into the North Lagoon (Ye et al. 2020; SARDI unpublished data). Indeed, sustained high barrage flows in 2021/22 and 2022/23 resulted in much lower salinities in the North and South lagoons in summer 2023 compared to spring 2021 (DEW Water Data SA), likely leading to southward movement and distribution expansion of common galaxias, and hence their presence in Salt Creek and Morella fishways. This demonstrated improved biological connectivity between the Coorong and South East drainage system during 2022/23, facilitated by substantially increased flows from the River Murray. An adult shortfin eel (1,070 mm TL), a further catadromous species, was encountered at Salt Creek fishway exit during monitoring in spring 2021 (Ye et al. 2022) but was not detected in the present study. Shortfin eel is a rare species in South Australia (Hammer et al. 2009), although was likely more common in the lower River Murray prior to the construction of the Murray Barrages (Waite 1923; Scott et al. 1974).

Three solely estuarine species (i.e., fishes that can complete entire life cycle in estuaries (Potter et al. 2015)) were sampled during fishway monitoring in this study. Smallmouth hardyhead, a small-bodied estuarine species, was highly abundant at both fishways. This member of the Atherinidae family commonly occurs in estuaries, coastal embayment/wetlands, and hypersaline lagoons in high abundance throughout southern Australia (McDowall 1980) and can tolerate a broad range of salinities from 3–108 ppt (Lui 1969). It has been the most abundant species in the Coorong South Lagoon over at least the past two decades (Ye et al. 2020), and is also abundant in Salt Creek (Ye et al. 2022). Bluespot goby was the other small-bodied estuarine species detected in both fishways, although numbers were orders of magnitude lower than smallmouth hardyhead. Bluespot goby commonly occur in the South Lagoon during high flow years (Ye et al. 2020). Black bream, a large-bodied estuarine species, was sampled only at the entrance of the Salt Creek fishway with both adults and juveniles detected. These fish were likely attracted by Salt Creek inflows and resulting favourable brackish conditions (salinity 14.1–26.9 ppt) as well as abundant food resource (prey fish) concentrated in or below the rock-ramp fishway. Adults may have also been attracted to the salt wedge to spawn (Williams et al. 2013), given the fishway monitoring period (late January–mid February) was within the reproductive season of black bream in this region (spring–summer) (Ye et al. 2019).

A marine-estuarine opportunist species (i.e., marine fishes that enter estuaries regularly, in substantial numbers, often as juveniles, (Potter et al. 2015)), yelloweye mullet, was sampled in both fishways during this study. This species is commonly found using fishways in low–moderate abundance in coastal streams of southeastern Australia (e.g., O'Connor et al. 2019;

Bice et al. 2021). It can tolerate elevated salinities (LC_{50} 82 ppt at 23°C, McNeil et al. 2013) and is usually a more abundant medium-bodied fish in the Coorong South Lagoon even under predominantly hypersaline conditions (salinities 60–100 ppt) (Ye et al. 2020). The reduction in salinities to 49–60 ppt in the South Lagoon in early 2023 (Water Data SA, DEW) provided more favourable conditions for this and many other species in the Coorong.

A small-bodied native freshwater fish, the flat-headed gudgeon, was present at both fishways. As a freshwater-estuarine opportunist (i.e., freshwater species that commonly use estuarine habitats in substantial numbers), this species often enters the Murray Estuary via the Murray Barrages (Bice et al. 2018), with high numbers often found immediately downstream of the barrages during high flow years (Ye et al. 2020; Dittmann et al. 2022). Although flat-headed gudgeon prefer salinities <5 ppt (SARDI unpublished data), they can tolerate salinities up to 24 ppt (LC_{50}) via direct transfer and 40 ppt via slow acclimation (Ye et al. 2010). During this study, salinity in Salt Creek and Morella fishways ranged from 13.4–26.9 ppt, which is within the tolerance range of the species.

Finally, one individual of eastern gambusia was collected at the exit of Morella fishway during this study. This small-bodied freshwater exotic species was introduced to Australia for mosquito control in 1925, and it is now widely spread (Rowe et al. 2008). Although there is no immediate concern regarding the finding of this species in the Morella fishway, as it has been established in the Murray-Darling Basin (Lintermans 2023) and the South East regions of South Australia (Hammer 2002; Whiterod and Gannon 2017), this species does pose threats on native fauna, particularly through trophic resource competition with native small-bodied fish (Macdonald and Tonkin 2008; Rowe et al. 2008).

4.2. Fishway use

4.2.1. Salt Creek fishway

At the Salt Creek rock-ramp fishway, smallmouth hardyhead overwhelmingly dominated the overall catch (99.97% by number) during monitoring in summer 2023. There was a significant difference in fish assemblages, and greater relative abundances of smallmouth hardyhead, congolli, yelloweye mullet and flat-headed gudgeon sampled from the entrance compared to the exit of the fishway. This may suggest potentially compromised passage efficiency for these species, but in this unique season, larger aggregations of fish species at the base of the fishway were more likely due to the presence of favourable conditions (i.e. brackish salinities 14.1–26.9 ppt ppt, rock-ramp habitat, abundant prey). Therefore, these species, may be present below or in Salt Creek fishway but not necessarily driven to move upstream.

Furthermore, throughout this season, about two-thirds of Salt Creek fishway was submerged due to high water levels in the Coorong South Lagoon, and there were minimal attractant flows to cue fish upstream movement. Nevertheless, length-frequency distribution comparison showed that smaller smallmouth hardyhead (20–29 mm TL) dominated the sampled population at the entrance, suggesting the smaller individuals may have been obstructed. For yelloweye mullet, samples at the fishway entrance also appeared smaller sized, although only three individuals were collected at the fishway exit. In general, small juvenile fish have inherently weaker swimming abilities than their larger conspecifics (Beamish 1978), and therefore, tend to be the individuals with greatest potential for compromised fish passage. In contrast, almost all larger congolli (170–260 mm TL) were collected at the fishway entrance, whereas a greater proportion of the smaller size class (110–129 mm TL) was found at the fishway exit. This suggests generally effective upstream passage for this catadromous species, meeting the primary fishway-specific biological objective (KBR 2019).

For common galaxias and bluespot goby, there was no significant difference in abundance between the entrance and exit of Salt Creek fishway. Furthermore, similar size compositions of common galaxias for samples from the fishway entrance and exit and the presence of the smallest size class (30–39 mm TL) at the exit suggested unimpeded fish passage for this catadromous species, also meeting the primary fishway biological objective of passing catadromous species. For bluespot goby, however, a slightly greater proportion of smaller (20–29 mm TL) individuals from the entrance suggested their passage efficiency may have been compromised as they are likely weaker swimmers (Beamish 1978).

Overall, the Salt Creek rock-ramp fishway was functioning to meet its primary biological design objective, effectively facilitating the passage of the catadromous common galaxias and congolli. This was evident despite the monitoring being conducted at the later period (summer 2023) of juvenile upstream migration/recruitment season (Bice et al. 2023). At the time of monitoring, Salt Creek flow discharge was 79–117 $ML.day^{-1}$ with 7–9 $ML.day^{-1}$ passing through the fishway. The water depth at the fishway exit ranged 0.22–0.29 m, which was within the designed optimal range for fishway function (depths 0.1–0.4 m). With relatively high water levels in the Coorong South Lagoon, head loss across the fishway was 0.19–0.35 m in this study, much less than the estimated head loss (0.78–1.14 m) during fishway monitoring in November 2021. The ranges of head loss in both years are within the specified operating range for this fishway (<1.3 m). For yelloweye mullet, although their passage did not appear as efficient during summer 2023, this may be a result of seasonal difference as they were found to pass through Salt Creek fishway effectively during the monitoring in spring 2021 (Ye et al. 2022).

The results of this study indicated that the secondary objective of passing small-bodied estuarine species may not be fully met, as indicated by the passage obstruction of smaller sized smallmouth hardyhead and bluespot goby. Nevertheless, with low head loss (0.19–0.35 m), the Salt Creek fishway appeared to be adequately functioning, enabling passage of some small individuals of both species (e.g., 0.30–0.39 m TL smallmouth hardyhead; 0.20–0.29 m TL bluespot goby). Movements of estuarine species from estuaries to freshwater systems are likely facultative, and their motive of upstream movement is not driven by life history requirements, but rather opportunistic use of upstream habitats. As such, greater abundances of these species at the entrance, may reflect use of the fishway as habitat, rather than driven attempts at upstream movement. This is particularly so when more than half of the rock-ramp fishway was inundated with brackish water in this season. However, the upstream movement for estuarine species may become important when hypersaline conditions in the South Lagoon intensify and become unfavourable for residence (typically in late summer/autumn during low flow years).

4.2.2. Morella fishway

Smallmouth hardyhead also dominated the catch (98.8% by number) at the Morella rock-ramp fishway. Although there was a significant difference in overall fish assemblages between entrance and exit samples, no significant difference in smallmouth hardyhead abundances between these locations. However, a slightly greater proportion of smallmouth hardyhead <50 mm TL were sampled at the entrance, suggesting the passage of smaller individuals may have been compromised for this species. For yelloweye mullet, relative abundance was not significantly different between the fishway entrance and exit, suggesting efficient passage. Although there appeared to be a greater proportion of smaller (<150 mm TL) individuals at the fishway entrance, the number of yelloweye mullet collected was low at both entrance and exit.

Common galaxias was exclusively sampled at the exit and congolli was significantly more abundant at the exit. This suggests efficient passage for these two catadromous species, yet, this result may also reflect compromised sampling efficiency at the fishway entrance due to imperfect fit of fyke net trap on the rocky structure (e.g., potential escapees under the fyke net wings). This could also explain the exclusive presence of flat-headed gudgeon, eastern gambusia and bluespot goby at the exit of this fishway. Sampling the entrance of rock ramp fishways represents a common challenge in assessing passage through this fishway type. Interestingly, during 2023 sampling, small congolli (10–29 mm and 50–69 mm TL) were detected at the exit of Morella fishway but were not detected at either the exit or entrance of Salt Creek fishway. Given the life history of congolli, which includes marine spawning, these individuals must have passed the Salt Creek fishway and/or regulator prior to reaching the Morella fishway, and thus, must have done so prior to the commencement of fishway monitoring in summer 2023.

At the time of assessment, the Morella rock-ramp fishway appeared to be meeting its biological design objectives, particularly for the passage of catadromous species (common galaxias and congolli) and marine-estuarine opportunistic species (yelloweye mullet). Although the passage efficiency for small-bodied estuarine species (smallmouth hardyhead <50 mm TL) seemed compromised, their upstream movements to Morella Basin are likely facultative. During this study, discharge through the Morella fishway was 22–49 ML.day^{-1}, whilst that through the regulator was 0–68 ML.day^{-1}. Water depth at the fishway exit (range = 0.27–0.44 m) and head loss across the fishway (range = 1.22–1.33 m) were largely within the specified operating ranges (exit depth 0.1–0.4 m; head loss <1.3 m). Comparatively, during the monitoring in November 2021, water depth at the fishway exit was greater (range = 0.35–0.46 m) but the estimated downstream water level was also greater near the fishway entrance, suggesting a similar head loss range for the two years. Relative to spring 2021 monitoring suggested a moderate improvement in passage efficiency during summer 2023 despite perching fishway entrance. Nevertheless, this could be due to a sampling artifact as the sampling was somewhat comprised at the perched fishway entrance and sampling efficiency was improved at the fishway exit.

4.3. Recommendations

All six indicator species that underpinned the design of the Salt Creek and Morella rock-ramp fishways (KBR 2019) were present during the monitoring in summer 2023. The results of fishway assessments generally indicated effective passage although species-specific passage efficiency varied between the two fishways.

The Salt Creek fishway was effective in facilitating the passage of catadromous common galaxias and congolli, but passage efficiency may have been slightly compromised for the two small-bodied estuarine species, particularly for smaller individuals (<30 mm TL smallmouth hardyhead and bluespot goby). This was likely due to a combination of poor swimming ability, fishway internal hydraulics (e.g., high water velocities), and potentially, a lack of drive for upstream movement. Furthermore, low discharge through the Salt Creek fishway relative to the regulator, high water levels in the Coorong South Lagoon, and thus a lack of attractant flows at the Salt Creek fishway entrance likely contributed to its reduced performance for all species during this study. In addition to fish passage efficiency, attraction efficiency, which is the ability of fish attempting to migrate to locate the fishway entrance (Cooke and Hinch 2013) is an important aspect of fishway function. Reliably assessing attraction efficiency typically involves mark-recapture or telemetry studies. This is challenging when assessing small-bodied species and those not undertaking obligate migrations, such as the smallmouth hardyhead in this study. Hence in the absence of empirical data on attraction efficiency, future flow management must better consider discharge through regulator gates and associated fishways in a way that creates/maintains favourable entrance conditions at both fishways. This includes maintaining integrity of fishway entrance discharge.

To better assess the performance of the Salt Creek fishway under a full range of hydrological conditions, future monitoring is recommended, particularly when the fishway exit water depth is <0.2 m and head loss is between 0.4–0.8 m. Additionally, monitoring during late summer–autumn, particularly when salinities in the South Lagoon are elevated and approaching unfavourable levels, will help to understand if upstream passage improves when there is a stronger biological drive (i.e., to access low salinity refuge) for estuarine species, and if the fishway effectively facilitates this movement. Nonetheless, inspections of the Salt Creek fishway including the drops between resting pools and the hydraulic conditions during both monitoring seasons suggest some modifications to the placement of ridges (boulders/gaps) could be undertaken to improve fishway function.

The Morella rock-ramp fishway was generally effective in facilitating the passage for common galaxias, congolli and yelloweye mullet, although passage efficiency may have been compromised for small (<50 mm TL) smallmouth hardyhead. Key context for interpreting catches from this fishway was the fact the fishway entrance was perched (Figure 2.5) for part of the sampling when the water level downstream the fishway entrance ranged 2.76–2.95 m AHD. This was approximately 0.11 m lower (estimated based on the water levels at Crump Weir) than that during the monitoring in November 2021 when the fishway entrance was largely submerged under water. Perching of the fishway entrance may have impacted the ability of certain species to enter the fishway and decreased the efficacy of entrance sampling. As such, future management of discharge through the Morella and Salt Creek regulators and fishways, where possible, should consider providing flow to promote desired tailwater levels and limit perching, and to optimise fishway entrance conditions. The gauge board established near the Morella fishway entrance since November 2022 measured water depths/levels, which have helped to improve understanding of the influence of discharge through the Morella regulator and fishway on downstream water levels, particularly near the fishway entrance, and better assess head loss during summer 2023. Further collection of such data under different hydrological conditions will be required to inform optimal flow management to improve the function of the Morella fishway.

In light of the results of fishway assessments and visual inspection, it appears that modifications to the Morella and Salt Creek fishways could improve fish passage. Both fishways could benefit from addition of further rock and reconfiguring of existing rock to provide more diffuse flow through the fishways and limit substantial drops in water level across ridges. In addition, at the Morella fishway, the fishway exit is via a long (6 m) box culvert, which provides little roughness and promotes laminar flow, may present an impediment to fish to successfully ascending the fishway. Hydraulic assessment of this pool at different flow rates and water levels may inform required actions, and roughness elements could be introduced (e.g., rocks, baffling), which can increase the heterogeneity in water velocities and improve fish passage (Magaju et al. 2020). Furthermore, in addition to flow management that promotes higher tailwater levels, modification of the entrance of the Morella fishway (e.g., installing an extended rock ramp) to alleviate ‘perching’ of the entrance under certain conditions should be considered.

Finally, improved understanding of the movement ecology of key species, particularly timing and direction of movement of various life stages, is required. For instance, a study on the movements of adult female congolli has been initiated using acoustic telemetry to understand their movement dynamics between the South East and the Coorong during autumn–winter 2023 (Bice et al. 2024). Such knowledge for congolli and other catadromous species, along with the results of fishway assessment across broad hydrological conditions, will inform the development of guidelines to optimise regulator/fishway operations and flow management to improve biological connectivity between the Coorong and South East drainage system. Importantly, the broader ecological context needs to be considered and a holistic approach adopted when developing flow management plans given there are multiple ecological objectives in this region. These include managing water levels, including the ability to surcharge Morella to inundate fringing vegetation; drawdowns to provide mudflat habitat and food resources for waterbird populations in the Morella Basin; and the effects of Salt Creek flows (both benefits and potential risks) on the Coorong ecosystem.

5. CONCLUSION

All fish species commonly occurring in the Coorong South Lagoon that are expected to undertake movements between the Coorong and South East were captured from the Salt Creek and Morella fishways during the monitoring in 2023, and the fishways were generally performing to biological design objectives. Common galaxias and congolli were most successful in ascending both fishways, whilst smaller individuals of smallmouth hardyhead (<30 mm TL at Salt Creek fishway and <50 mm TL at Morella fishway) had limited passage efficiency. Although upstream movements for estuarine species are not driven by life history requirements, like the obligate migrations of diadromous species, providing un-obstructed passage for estuarine fishes could provide access to upstream refuge habitats when environmental condition deteriorates (e.g., salinity increases to unfavourable levels for species in the South Lagoon).

Further monitoring of fish movement at the Salt Creek and Morella fishways will inform on passage efficiency under different hydrological conditions (flow discharge and water levels) and seasonal variability. These data, in conjunction with improved understanding of fish movement ecology (direction and timing for different species and life stages), will inform future regulator/fishway operations, potential structural modifications, and the development of flow management plans/guidelines to optimise fishway function, considering the broader context of ecological objectives for the Coorong and South East region.

REFERENCES

Anderson, M. J., Gorley, R. N. and Clarke, K. R. (2008). "PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods, PRIMER-E: Plymouth, UK.".

Beamish, F. W. H. (1978). Swimming capacity. In ‘Fish Physiology’. Eds. Hoar, W.S. and Randall, J. D. New York, Academic Press, Inc. Vol 7, 101–187.

Bice, C. M., Hammer, M. P., Wedderburn, S. D., Ye, Q. and Zampatti, B. P. (2018). Fishes of the Lower Lakes and Coorong: An Inventory and Summary of Life History, Population Dynamics and Management. In: Mosley, L., Ye, Q., Shepherd, S., Hemming, S., Fitzpatrick, R. (eds) Natural History of the Coorong, Lower Lakes, and Murray Mouth Region (Yarluwar-Ruwe). Royal Society of South Australia, Adelaide. pp 371-399.

Bice, C. M., Schmarr, D. W., Zampatti, B. and Fredberg, J. (2020). Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2019/20. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000186-10. SARDI Research report Series No. 1081. 66pp.

Bice, C. M., Schmarr, D. W., Zampatti, B. P. and Fredberg, J. (2021). Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2020/21. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000186-11. SARDI Research report Series No. 1117. 66pp.

Bice, C. M., Ye, Q., Fredberg, J., Gannon, R. and Zampatti, B. P. (2024). Movement of adult female congolli (*Pseudaphritis urvillii*) in the Tilley Swamp Drain. Report to the Department for Environment and Water. South Australian Research and Development Institute (Aquatic and Livestock Sciences), Adelaide.

Bice, C. M.1, Zampatti, B. P.2 and Fredberg, J.1 (2023). Condition monitoring of fish movement and recruitment 2022/23. South Australian Research and Development Institute (Aquatic and Livestock Sciences), Adelaide. SARDI Publication No. F2011/000186-11. SARDI Research Report Series No. 1117. 64pp.

Cooke, S. J. and Hinch, S. G. (2013). Improving the reliability of fishway attraction and passage efficiency estimates to inform fishway engineering, science and practice. *Ecological Engineering* 58, 123–132.

Dittmann, S., Ye, Q., Furst, D., Newbery, A., Nitschke, J., Bucater, L., Pyke, W., Kent, J., Schroder, L., Henkens, J., Baring, R., Lam-Gordillo, O., Brookes, J. and Short, D. (2022). Food resource availability, energy content and nutritional value of major food sources for key fish and waterbird species under varying environmental conditions in the Coorong. Goyder Institute for Water Research Technical Report Series No. 22/12.

Dufrene, M., & Legendre, P. (1997). Species assemblages and indicator species: the need for a flexible asymmetrical approach. *Ecological monographs*, *67*(3), 345-366.

Hammer, M., 2002. The South East fish inventory: distribution and conservation of freshwater fishes of south east South Australia, p. 53. Native Fish Australia (SA) Inc., Adelaide, South Australia.

Hammer, M., Wedderburn, S. and van Weenen, J. (2009). Action Plan for South Australian Freshwater Fishes. Native Fish Australia, Adelaide.

KBR (2019). Design Report - Morella Basin Outlet Structure and Salt Creek Outfall Structure & Fishway. South East Flows Restoration Project. A report prepared for the Department of Planning, Transport and Infrastructure. Adelaide, South Australia.

Lintermans, M., 2023. Fishes of the Murray-Darling Basin, Second Edition. Australian Rivers Restoration Centre, Canberra, Australia.

Lui, L. C. (1969). Salinity tolerance and osmoregulation in *Taenomembrus microstomus* (Gunther, 1861) (Pisces: Mugiliformes: Atherinidae) from Australian salt lakes. Australian *Journal of Marine and Freshwater Research* 20, 157–162.

Macdonald, J. and Tonkin, Z. (2008). A review of the impact of eastern gambusia on native fishes of the Murray-Darling Basin. Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Heidelberg, Victoria.

Magaju, D., Montgomery, J., Franklin, P., Baker, C. and Friedrich, H. (2020). A new framework for assessing roughness elements in promoting fish passage at low-head instream structures. *Journal of Ecohydraulics* 5 (2), 152 –164.

McDowall, R. M. (1980). Freshwater fishes of South-eastern Australia (A H & A W Reed Pty Ltd, Sydney).

McNeil, D. G., Westergaard, S., Cheshire, K. J. M., Noell, C. J. and Ye, Q. (2013). Effects of hypersaline conditions upon six estuarine fish species from the Coorong and Murray Mouth. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2009/000014-4. SARDI Research Report Series No. 700. 27pp.

O'Connor, J., Pickworth, A., Fanson, B. and Lovric, D. (2019). Assessment of a vertical slot fishway in south-eastern Australia designed to pass numerous species and size classes of fish. *Ecological Management and Restoration* 20 (2), 151-155.

Potter, I. C., Tweedley, J. R., Elliott, M. and Whitfield, A. K. (2015). The ways in which fish use estuaries: A refinement and expansion of the guild approach. *Fish and Fisheries* 16, 230-239. https://doi.org/10.1111/faf.12050.

Rowe, D. K., Moore, A., Giorgetti, A., Maclean, C., Grace, P., Wadhwa, S. and Cooke, J. (2008). Review of the impacts of gambusia, redfin perch, tench, roach, yellowfin goby and streaked goby in Australia. Report prepared for the Australian Government Department of the Environment, Water, Heritage and the Arts, Canberra.

Scott, T. D., Glover, C. J. M. and Southcott, R. V. (1974). The Marine and Freshwater Fishes of South Australia. 2nd Edition. Government Printer: Adelaide.

Waite, E. R. (1923). The Fishes of South Australia. Government Printer: Adelaide.

Williams, J., Jenkins, G.P., Hindell, J.S. and Swearer, S.E. (2013). Linking environmental flows with the distribution of black bream *Acanthopagrus butcheri* eggs, larvae and prey in a drought affected estuary. *Marine Ecological Progress Series* 483, 273–287.

Whiterod, N. and Gannon, R. (2017). Assessing the risks of Eastern Gambusia invasion into the Drain L Catchment associated with SEFRP Augmentation: fish survey and management recommendations. A report for the South Australian Department of Environment, Water and Natural Resources. Aquasave – Nature Glenelg Trust, Goolwa Beach.

Ye, Q., Bucater, L. and Short, D. (2015). Coorong fish condition monitoring 2008–2014: Black bream (*Acanthopagrus butcheri*), greenback flounder (*Rhombosolea tapirina*) and smallmouthed hardyhead (*Atherinosoma microstoma*) populations. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000471-4. SARDI Research Report Series No. 836. 105pp.

Ye, Q., Bucater, L., Short, D. and Bice, C.M. (2022). Salt Creek and Morella fishway assessment 2021-22. Report to the Department for Environment and Water. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2022/000401-1. SARDI Research Report Series No. 1164. 35pp.

Ye, Q., Bucater, L., Lorenz, Z., Giatas, G. and Short, D. (2019). Monitoring salt wedge conditions and black bream (*Acanthopagrus butcheri*) recruitment in the Coorong during 2017-18. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2018/000425-1. SARDI Research Report Series No. 1012. 42pp.

Ye, Q., Giatas, G., Dittmann, S., Baring, R., Bucater, L., Deane, D., Furst, D., Brookes, J., Rogers, D. and Goldsworthy, S. (2020). A synthesis of current knowledge of the food web and food resources for waterbird and fish populations in the Coorong. Goyder Institute for Water Research Technical Report Series No. 20/11.

APPENDIX

Appendix A. Sampling regime for fishway entrance and exit trapping at the Salt Creek and Morella fishways during January and February 2023.

Fishway	Trap	Rep	Set Time	Retrieve Time	Hours Trapped
Morella	Exit	1	30/01/2023 15:30	31/01/2023 11:15	19.7
Salt Creek	Exit	1	30/01/2023 16:00	31/01/2023 12:40	20.7
Morella	Exit	2	31/01/2023 12:15	1/02/2023 10:00	21.8
Salt Creek	Exit	2	31/01/2023 13:15	1/02/2023 12:40	23.4
Morella	Entrance	1	1/02/2023 12:30	2/02/2023 10:30	22.0
Salt Creek	Entrance	1	1/02/2023 13:30	2/02/2023 14:30	25.0
Morella	Entrance	2	2/02/2023 11:00	3/02/2023 10:30	23.5
Salt Creek	Entrance	2	2/02/2023 15:45	3/02/2023 11:15	19.5
Salt Creek	Exit	3	6/02/2023 14:00	7/02/2023 10:30	20.5
Morella	Exit	3	6/02/2023 14:30	7/02/2023 12:00	21.5
Salt Creek	Exit	4	7/02/2023 11:15	8/02/2023 10:25	23.2
Morella	Exit	4	7/02/2023 12:15	8/02/2023 11:45	23.5
Salt Creek	Entrance	3	8/02/2023 11:15	9/02/2023 10:15	23.0
Morella	Entrance	3	8/02/2023 12:30	9/02/2023 12:30	24.0
Salt Creek	Entrance	4	9/02/2023 12:00	10/02/2023 10:30	22.5
Morella	Entrance	4	9/02/2023 13:00	10/02/2023 12:15	23.3

Appendix B. SIMPER analysis for fish assemblage comparisons between entrance and exit traps placed at the Salt and Morella fishways. Mean abundance is number of fish trapped per hour. CR (consistency ratio) indicates the consistency of differences in abundance between the different traps, with larger values indicating greater consistency. The contribution (%) indicates the proportion of difference between traps attributable to individual species. A cumulative cut-off of 70% was applied. Mean dissimilarity is expressed as a percentage ranging between 0% (identical) and 100% (totally dissimilar).

	Mean abundance			**Mean dissimilarity = 51.02**	
Salt Creek	**Entrance**	**Exit**	**CR**	**Contrib%**	**Cum.%**
Smallmouth hardyhead	8.92	2.46	3.44	67.27	67.27
Flat-headed gudgeon	0.73	0.11	2.33	6.86	74.14
	Mean abundance			**Mean dissimilarity = 33.51**	
Morella Creek	**Entrance**	**Exit**	**CR**	**Contrib%**	**Cum.%**
Common galaxias	0	0.88	2.61	31.65	31.65
Smallmouth hardyhead	2.97	2.48	1.31	27.64	59.29
Congolli	0.39	0.9	2.13	18.34	77.64

Appendix C. Comparison of fish catch summary during Salt Creek and Morella fishway monitoring in spring 2021 and summer 2023.

	Spring 2021					Summer 2023				
	Salt Creek fishway		Morella fishway			Salt Creek fishway		Morella fishway		
Common name	**Entrance (*n*)**	**Exit (*n*)**	**Entrance (*n*)**	**Exit (*n*)**	**Total (*n*)**	**Entrance (*n*)**	**Exit (*n*)**	**Entrance (*n*)**	**Exit (*n*)**	**Total (*n*)**
Sampling events	7	7	6	6		4	4	4	4	
No. of species	5	5	4	3	**7**	7	6	3	7	**8**
Common galaxias						40	21	0	87	**148**
Congolli	21	73	6	14	**114**	76	8	5	58	**147**
Smallmouth hardyhead	25,990	753	31,840	2,511	**61,094**	1,007,969	4,133	10,092	3,763	**1,025,957**
Bluespot goby	43	4	7	0	**54**	94	43	0	1	**138**
Black bream	3	0			**3**	32	0			**32**
Shortfin eel	0	1			**1**					
Yelloweye mullet	50	42	0	2	**94**	40	3	10	11	**64**
Flat-headed gudgeon			1	0	**1**	29	1	0	2	**32**
Eastern gambusia*								0	1	**1**
Total	**26,107**	**873**	**31,854**	**2,527**	**61,361**	**1,008,280**	**4,209**	**10,107**	**3,923**	**1,026,519**

**Exotic species*