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Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2018/19

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

SARDI Publication No. F2011/000186-9
SARDI Research Report Series No. 1043

SARDI Aquatics Sciences
PO Box 120 Henley Beach SA 5022

December 2019

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This publication may be cited as:
Bice, C. M., Zampatti, B. P. and Fredberg, J. (2019). Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2018/19. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000186-9. SARDI Research Report Series No. 1043. 67pp.

SARDI Aquatic Sciences
2 Hamra Avenue
West Beach SA 5024

Telephone: (08) 8207 5400
Facsimile: (08) 8207 5415
http://www.pir.sa.gov.au/research

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SARDI Publication No. F2011/000186-9
SARDI Research Report Series No. 1043

Author(s): C. M. Bice, B. P. Zampatti and J. Fredberg

Reviewer(s): D. Schmarr (SARDI) and A. Rumbelow (DEW)

Approved by: A/Prof Q. Ye
Program Leader –Inland Waters and Catchment Ecology

Signed:

Date: 12 December 2019

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ACKNOWLEDGEMENTS

Thank you to Adrienne Rumbelow, Kirsty Wedge and Rebecca Turner (Department for Environment and Water, Lower Lakes, Coorong and Murray Mouth Icon Site) for facilitating funding and managing this project, and for ongoing support of aquatic ecosystem research in the Coorong and Lower Lakes. To Michael Shelton, Leigh Angus, Ray Maynard, Bryce Buchannan, Greg Bald, Dave Bishop, Arron Strawbridge, Ian Magraith and George Giatas, and all the other SA Water Barrage and SARDI staff who braved four seasons in one day to set and retrieve traps, and assist in processing fish, thanks for all your efforts. This project was funded by The Living Murray initiative of the Murray–Darling Basin Authority. The Living Murray is a joint initiative funded by the New South Wales, Victorian, South Australian, Australian Capital Territory and Commonwealth Governments, coordinated by the Murray–Darling Basin Authority. All sampling was conducted under an exemption (no. ME9902942) of section 115 of the *Fisheries Management Act 2007*. Thanks to David Schmarr and Gavin Begg (SARDI), and Adrienne Rumbelow (DEW) for reviewing this report

EXECUTIVE SUMMARY

The Lower Lakes and Coorong, at the terminus of the Murray–Darling Basin (MDB), are considered a wetland of international importance under the Ramsar Convention and an Icon Site under *The Living Murray Initiative*. The region supports a diverse fish assemblage of ecological, cultural and commercial importance. An understanding of variability in estuarine fish populations and assemblage structure in relation to freshwater inflow and antecedent conditions is fundamental to the management of estuarine ecosystems. Data on diadromous fish migration and estuarine fish assemblage structure has been collected since 2006 to inform against specific ecological objectives and targets within the Lower Lakes, Coorong and Murray Mouth Icon Site Management Plan.

The objective of this study in 2018/19 was to investigate the influence of freshwater inflows and connectivity between the Lower Lakes and Coorong on fish assemblage structure, and migration and recruitment of diadromous fish. By sampling fish attempting to move through the barrage fishways and inhabiting sites adjacent the barrages, we aimed to:

1. Determine the species composition and abundance of fish species immediately downstream of the barrages and/or attempting to move between the Coorong and Lower Lakes via the barrage fishways in 2018/19, and assess spatio-temporal variation in assemblage structure over the period 2006–2018;
2. Assess spatio-temporal variability in the recruitment and relative abundance of catadromous fish (congolli, *Pseudaphritis urvillii*, and common galaxias, *Galaxias maculatus*) attempting to migrate upstream at the Murray Barrages in 2018/19, and in relation to long-term data from 2006–2018;
3. Assess spatio-temporal variability in the relative abundance of anadromous fish (pouched lamprey, *Geotria australis*, and short-headed lamprey, *Mordacia mordax*) attempting to migrate upstream at the Murray Barrages in 2018/19, and in relation to long-term data from 2006–2018;
4. Utilise these data to inform on Ecological Targets associated with the Ecological Objective (F-1) – *'Promote the successful migration and recruitment of diadromous fish species in the Lower Lakes and Coorong'*; and
5. Inform operation of the barrages and implementation of the lakes and barrages operating strategies.

Hydrology in 2018/19 was characterised by low freshwater discharge (370 GL; maximum discharge during sampling = ~1,500 $ML.d^{-1}$), and in association, salinity below the barrages was brackish (7–31 $g.L^{-1}$). The fish assemblage sampled was diverse (36 species) and dominated by the marine estuarine-opportunist sandy sprat (*Hyperlophus vittatus*, 75.5% of total catch) and catadromous congolli (13.5%), whilst the semi-catadromous common galaxias (3%), and the freshwater Australian smelt (*Retropinna semoni,* 6.9%), redfin perch (*Perca fluviatilis*, 1.4%) and bony herring (*Nematalosa erebi,* 1%) were also common. The 2018/19 fish assemblage was generally similar to those of previous years of low freshwater discharge (annual discharge <500 GL), including 2006/07, and characterised by low overall abundance, but high diversity, and moderate abundances of catadromous species.

In 2018/19, the abundances of the catadromous congolli and common galaxias were high relative to 2006–2011, but were the lowest recorded since 2011/12. Nevertheless, >80% of all individuals sampled were newly recruited young-of-the-year (YOY). Annual recruitment of catadromous fishes appears influenced by two primary factors: 1) the abundance of reproductively mature adults (i.e. potential spawning biomass); and 2) hydrological connectivity between freshwater, estuarine and marine environments during the preceding winter/early spring, and subsequently, capacity for adult migration, spawning and survival of larvae/juveniles under brackish salinities. Recruitment and subsequent YOY abundance steadily increased from 2010/11 to 2014/15, following reinstatement of freshwater discharge and high levels of connectivity. A lack of connectivity and reduced recruitment of congolli and common galaxias from 2007–2010 may have resulted in a depleted population of reproductively mature adults. As such, while recruitment was enhanced following the resumption of freshwater flow in 2010/11, the number of juveniles produced may have been limited by the adult spawning biomass. Congolli mature at 3–4 years of age and thus, the adult spawning population post–2014 was likely abundant and comprised of fish that recruited and migrated into freshwater habitats from 2010/11 to 2014/15. Fluctuations in abundance of YOY post-2014, however, likely reflect variability in connectivity during the winter downstream migration period. Indeed, since 2014, a metric of connectivity we term ‘percentage of connected days’, which is the percentage of days over June–August when at least one barrage bay is open, fluctuates in synchrony with YOY abundance.

In 2018/19 a total of six pouched lamprey, and a single short-headed lamprey were sampled at the Murray Barrages. This was the first record of short-headed lamprey at the Murray Barrages since 2011. All pouched lamprey were sampled in winter (July–August), whilst the short-headed lamprey was sampled in October, reinforcing the peak migration period for these species as winter

and winter–spring, respectively, and the need to incorporate specific lamprey monitoring to adequately assess population status.

In 2018/19, congolli exhibited seasonal peaks in migration in December and January. For common galaxias, peaks in abundance differed between sites, and occurred in October, November and December. This general period of upstream migration (October–January) for catadromous species is consistent with previous years monitoring. Based on timing of upstream and downstream movements of diadromous species derived from fishway monitoring from 2006–2018, and allied projects, freshwater discharge and fishway operation should be facilitated at the barrages annually from at least June–January. This encompasses three key periods: 1) June–August to allow for downstream spawning migrations of congolli and common galaxias and upstream migrations of pouched lamprey; 2) August–November to allow for upstream migrations of short-headed lamprey; and 3) October–January to allow for the upstream migrations of juvenile congolli and common galaxias.

The results of this investigation highlight the influence of freshwater inflow and hydrological connectivity on fish assemblages of the Coorong. In general, the assemblage trended towards low abundance, but diverse, fish assemblages that characterise estuaries subject to low freshwater flow. Abundances of catadromous congolli and common galaxias were moderate, and the annual recruitment target was met for both species. While pouched lamprey and short-headed lamprey were both detected, limited numbers resulted in ecological targets relating to these species not being achieved. As such, the Ecological Objective (F-1) *'promoting the successful migration and recruitment of diadromous fish species in the Lower Lakes and Coorong'* was met for catadromous, but not anadromous fishes. Continued freshwater discharge and connectivity between the Lower Lakes and the Coorong is essential for the maintenance of populations of diadromous, estuarine and estuarine-dependent marine species and maintaining diversity in estuarine fish communities.

Keywords: estuarine, fishway, diadromous, *Galaxias*, *Pseudaphritis*, lamprey.

1. INTRODUCTION

1.1. Background

Estuaries form a dynamic interface and conduit between freshwater and marine ecosystems, supporting high levels of biological productivity and diversity (Day *et al.* 1989, Goecker *et al.* 2009). Freshwater flows to estuaries transport nutrients and sediments and maintain a unique mixing zone between freshwater and marine environments (Whitfield 1999). Throughout the world, however, anthropogenic modification of rivers has diminished freshwater flows to estuaries and threatens the existence of estuarine habitats (Gillanders and Kingsford 2002, Flemer and Champ 2006). In addition, structures that regulate flow may alter the longitudinal connectivity between estuarine and freshwater environments (Lucas and Baras 2001).

Estuaries support complex fish assemblages, characterised by a broad range of life history strategies (Whitfield 1999), and as such, fishes are key indicators of the impacts of altered freshwater inflows to estuaries and of barriers to connectivity (Gillanders and Kingsford 2002, Kocovsky *et al.* 2009). The interplay of temporally variable freshwater inflow and tidal cycle determines estuarine salinity regimes, influencing the structure of fish assemblages, which in turn are often characterised by a spatio-temporally variable mix of freshwater, estuarine and marine fish species (Kupschus and Tremain 2001, Barletta *et al.* 2005). Estuaries also represent critical spawning and recruitment habitats, and essential migratory pathways for diadromous fish (McDowall 1988, Beck *et al.* 2001). Consequently, changes to flow regimes and physical barriers to movement represent significant threats to estuarine dependent fishes, particularly diadromous species (Lassalle and Rochard 2009).

The Lower Lakes and Coorong estuary in south-eastern Australia lies at the terminus of Australia’s longest river system, the Murray–Darling, and the region is an icon site under *The Living Murray Initiative* (TLM). The river system is highly regulated and on average only ~39% (4723 GL) of the natural mean annual discharge (12,233 GL) now reaches the ocean (CSIRO 2008). Furthermore, the river now ceases to flow through the Murray Mouth 40% of the time compared to 1% under natural unregulated conditions (CSIRO 2008). The estuary is separated from the lower river by a series of tidal barrages that form an abrupt physical and biological barrier, and have reduced the extent of the historical estuary.

From 2006–2018, freshwater discharge to the Coorong was highly variable. Notably, over the period 2006–2010, a combination of reduced system-wide inflows and consumptive water use resulted in reduced flow to the Lower Lakes (<600 GL.y^{-1} in 2007 and 2008), causing a reduction in water level downstream of Lock 1 of >1.5 m and the cessation of freshwater flow to the Coorong estuary. Disconnection of the Coorong from the Lower Lakes resulted in increased salinities in the Coorong and a concomitant decrease in overall fish abundance and altered assemblage structure (Zampatti *et al.* 2010). Specifically, the abundance of freshwater, diadromous and estuarine species decreased and marine species became more common (Zampatti *et al.* 2010). Furthermore, catadromous congolli (*Pseudaphritis urvillii*) and common galaxias (*Galaxias maculatus*) exhibited significant declines in the abundance of young-of-the-year (YOY) migrants and contraction of migration and spawning periods (Zampatti *et al.* 2011), whilst the anadromous short-headed lamprey (*Mordacia mordax*) and pouched lamprey (*Geotria australis*), present in 2006/07, were absent through 2007–2010.

The following eight-year period (2010–2018), was characterised by contrasting hydrology; increased inflows in the Murray–Darling Basin (MDB) in 2010/11 resulted in large-scale flooding and the return of typical water levels to the Lower Lakes, and subsequently, the delivery of large volumes (12,498 GL) of freshwater to the Coorong, with further high volumes of freshwater in 2011/12 (8795 GL), and 2012/13 (5177 GL). Discharge declined, and was moderate during 2013/14 (1647 GL) and 2014/15 (984 GL), and low in 2015/16 (562 GL), before another high flow year in 2016/17 (6536 GL), and a return to low flow in 2017/18 (802 GL). Annual (650 GL) and three-year rolling average (2000 GL.yr^{-1}) targets for barrage discharge volumes established under the Icon Site Environmental Water Management Plan, were achieved in all years except 2015/16.

Increased discharge, relative to 2007–2010, was accompanied by significant changes in fish assemblage structure in the Murray Estuary. The fish assemblages in high flow years (2010/11, 2011/12 and 2016/17) were characterised by high species richness, and high abundance of freshwater species. Years of moderate discharge were characterised by high abundances of catadromous (congolli and common galaxias), and certain estuarine (e.g. lagoon goby, *Tasmanogobius lasti*) and marine migrant (sandy sprat *Hyperlophus vittatus*) species. Years of low flow (2015/16 and 2017/18), however, saw assemblages begin transitioning towards that observed in 2006/07, prior to the prolonged period of zero discharge (2007–2010). Nonetheless, throughout 2011–2018, the abundance of catadromous fishes has remained high, whilst pouched lamprey have been detected in six years, and short-headed lamprey in one year.

The year 2018/19, represented the ninth consecutive year of freshwater discharge to the Coorong and connectivity between the Coorong and Lower Lakes, post the Millennium drought (Van Dijk *et al.* 2013). This provided the opportunity to assess the continued response of fish assemblage structure, movement and recruitment to freshwater flow and connectivity. Such data are integral to the understanding of hydrologically mediated patterns in fish assemblage structure and movement. Ultimately, these data can be used to assess specific ecological targets (DEWNR 2017) and will aid future management of the system, including informing operating strategies for the Lower Lakes and barrages.

1.2. Objectives

The objective of this study was to investigate the influence of freshwater inflows and connectivity between the Lower Lakes and Coorong on fish assemblage structure and migration, and diadromous fish recruitment. Using the barrage fishways as a sampling tool we specifically aimed to:

1. Determine the species composition and abundance of fish immediately downstream of the barrages and/or attempting to move between the Coorong and Lower Lakes via the barrage fishways in spring–summer 2018/19, and assess spatio-temporal variation in assemblage structure in relation to 2006–2018;
2. Investigate spatio-temporal variability in the recruitment and relative abundance of catadromous fish (congolli and common galaxias) attempting to migrate upstream at the Murray Barrages in 2018/19, in relation to long-term data from 2006–2018;
3. Assess spatio-temporal variability in the relative abundance of anadromous fish (pouched lamprey and short-headed lamprey) attempting to migrate upstream at the Murray Barrages in 2018/19, and in relation to long-term data from 2006–2018;
4. Utilise these data to inform on Ecological Targets associated with the following revised Ecological Objective (F-1): *'Promote the successful migration and recruitment of diadromous fish species in the Lower Lakes and Coorong'* (Robinson 2014); and
5. Inform the implementation of lakes and barrages operating strategies.

2. METHODS

2.1. Study area, hydrology and fishways

This study was conducted at the interface between the Coorong estuary and Lower Lakes of the River Murray, in southern Australia (Figure 2-1). The River Murray discharges into a shallow (mean depth 2.9 m) expansive lake system, comprised of Lakes Alexandrina and Albert before flowing into the Coorong and finally the Southern Ocean via the Murray Mouth.

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 ~4723 GL.y^{-1} reaches the sea, although from 1997–2010 this was substantially less and zero for a period of over three years (March 2007 – September 2010) (Figure 2-2). Discharge increased abruptly in September 2010 and annual discharges in 2010/11, 2011/12 and 2012/13 were approximately 12,500, 8800 and 5200 GL, respectively (Figure 2-2). Annual discharge continued to decrease in subsequent years, with low–moderate discharge in 2013/14 (~1600 GL), 2014/15 (~984 GL), 2015/16 (~562 GL), 2017/18 (802 GL) and 2018/19 (370 GL), interspersed by high discharge in 2016/17 (~6536 GL) (Figure 2-2).

The Coorong is a narrow (2–3 km wide) estuarine lagoon running southeast from the Murray Mouth and parallel to the coast for ~140 km (Figure 2-1). It consists of a northern and southern lagoon bisected by a constricted region that limits water exchange (Geddes and Butler 1984). The region was designated a Wetland of International Importance under the Ramsar Convention in 1985, based upon its unique ecological character and importance to migratory wading birds (Phillips and Muller 2006).

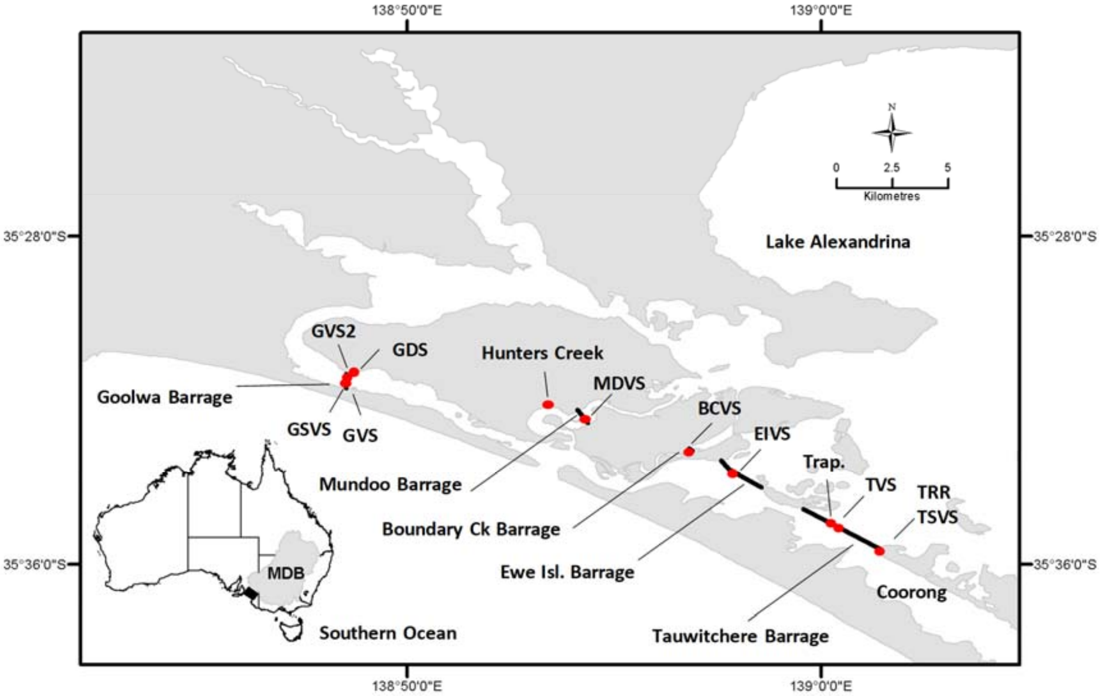

Figure 2-1. A map of the Coorong and Lake Alexandrina at the terminus of the River Murray, southern Australia showing the study area in the Coorong estuary, highlighting the Murray Barrages (bold lines). Barrages, fishways and fyke-net sampling sites (red dots); Goolwa vertical-slot (GVS), Goolwa vertical-slot 2 (GVS2), adjacent Goolwa Barrage (GDS), Hunters Creek vertical slot (Hunters Creek), Mundoo dual vertical-slot (MDVS), Ewe Island dual vertical-slot (EIVS), Boundary Creek vertical-slot (BCVS), Tauwitchere trapezoidal (Trap.), Tauwitchere large vertical-slot (TVS) and Tauwitchere small vertical-slot (TSVS) and rock ramp (TRR). Note: GVS2, MDVS and BCVS are sampled only during winter lamprey monitoring, while the Trapezoidal fishway was not sampled in the current study.

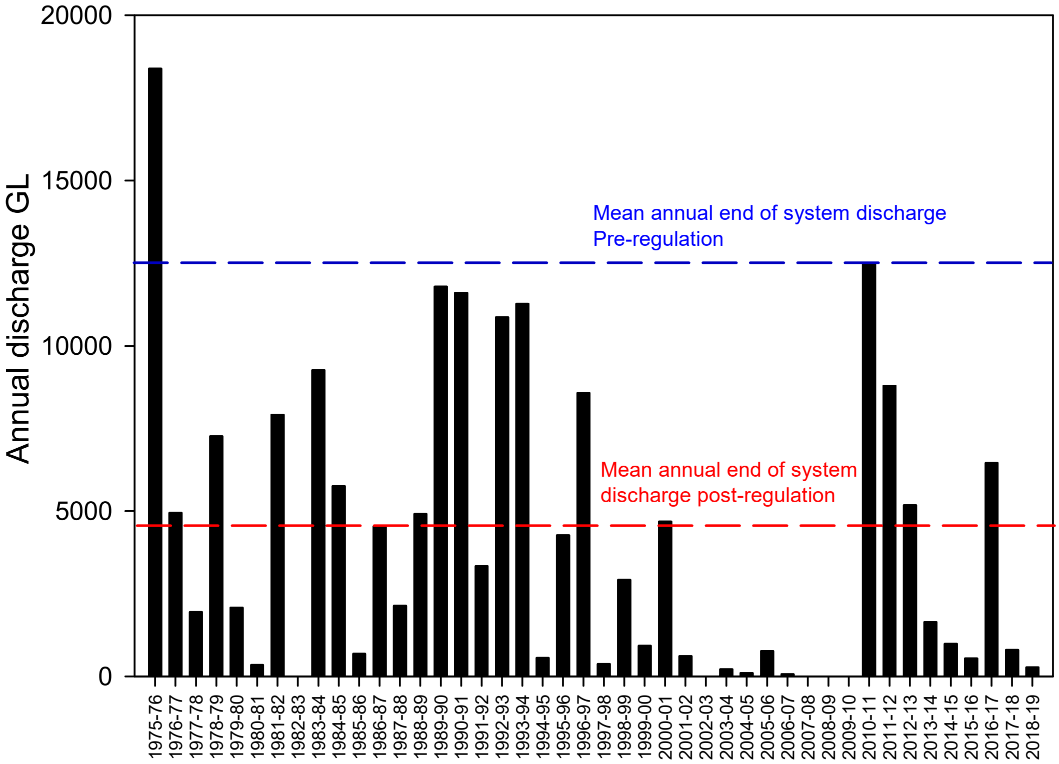

Figure 2-2. Annual freshwater discharge (GL) through the Murray Barrages into the Coorong estuary from 1975–June 2019. Dashed lines represent mean annual end of system discharge pre- (blue) and post-regulation (red).

In the 1940s, five tidal barrages with a total length of 7.6 km were constructed to prevent saltwater intrusion into the Lower Lakes and maintain stable freshwater storage for consumptive use (Figure 2-1). The construction of the barrages dramatically reduced the extent of the estuary, creating an impounded freshwater environment upstream and an abrupt ecological barrier between estuarine/marine and freshwater habitats. Pool level upstream of the barrages is typically regulated for most of the year at an average of 0.75 m AHD (Australian Height Datum), but in recent years has been varied to meet ecological objectives.

Following construction of the barrages, an increased frequency of years without freshwater discharge to the estuary and reduced tidal incursion has contributed to a reduction in estuary depth and the prevalence of hypersaline (>40 g.L^{-1}) salinities (Geddes 1987, Walker 2002). During times of low freshwater discharge, salinity ranges from marine (30–35 g.L^{-1}) near the Murray Mouth to hypersaline (>100 g.L^{-1}) at the south end of the Southern Lagoon (Geddes and Butler

1984). During periods of high freshwater discharge, salinities near the Murray Mouth and in the Northern Lagoon are typically brackish (i.e. 5–30 g.L^{-1}) (Geddes 1987).

In 2004, three fishways (2 x large vertical-slots and 1 x rock ramp) were constructed on the Murray Barrages (Barrett and Mallen-Cooper 2006) with the aim of facilitating fish movement between the Coorong and Lower Lakes. The two large vertical slot fishways (slope ~13.6%), located on Goolwa and Tauwitchere Barrages, were designed to pass fish >150 mm total length (TL) and discharge approximately 30–40 ML.d^{-1} (Mallen-Cooper 2001). Assessments of these fishways indicated they were effective in passing fishes >150 mm in length, but the passage of small-bodied species and small life stages (<100 mm TL), which predominated catches, was partly obstructed (Stuart *et al.* 2005, Jennings *et al.* 2008). The rock ramp fishway (slope ~4%) constructed on Tauwitchere Barrage aimed to pass fish 40–150 mm in length. Nevertheless, this fishway was found to have a limited operational window with function influenced by downstream tidal level and upstream water levels (Jennings *et al.* 2008).

In 2009, additional small vertical-slot fishways (slope ~3%) were constructed on Tauwitchere Barrage and the Hunters Creek causeway. These new fishways were designed with internal hydraulics (low headloss, velocity and turbulence) that were considered favourable for the upstream passage of small-bodied fish and to operate with low discharge (<5 ML.d^{-1}). Both fishways effectively facilitate the passage of small-bodied fish (Zampatti *et al.* 2012). Furthermore, from 2014 to 2018, a further seven fishways were constructed as part of the *Coorong, Lower Lakes and Murray Mouth Program* (Bice *et al.* 2017). These fishways are likely to greatly enhance fish passage at the Murray Barrages, but are only episodically monitored under the current program.

2.2. Fish sampling

In 2018/19, fish sampling occurred in distinct periods in winter (July–August) and spring–summer (October–January). During spring–summer, samples of fish were collected from the entrances of four vertical-slot fishways on Tauwitchere and Goolwa Barrages, and the Hunters Creek causeway as well as a site adjacent to the rock ramp fishway at the southern end of Tauwitchere Barrage and a site adjacent the Hindmarsh Island abutment of the Goolwa Barrage (hereafter 'adjacent Goolwa Barrage') (Figure 2-1 and Table 2-1). Winter sampling occurred principally to capture lamprey during the key upstream migration season and involved trapping of the aforementioned fishways, as well as the second large vertical-slot fishway at Goolwa, the dual vertical-slot fishways on Mundoo and Ewe Island barrages, and the small vertical-slot fishway on Boundary Creek Barrage.

Table 2-1. Details of fishways and fyke-net sampling sites at the Murray Barrages, including site name, abbreviated name used throughout and the barrage associated with site, as well as latitude and longitude.

Name	Abbreviation	Barrage	Latitude	Longitude
Tauwitchere large vertical-slot	TVS	Tauwitchere	35°35’09.35’’S	139°00’30.58’’E
Tauwitchere small vertical-slot	TSVS	Tauwitchere	35°35’23.44’’S	139°00’56.23’’E
Tauwitchere rock ramp	TRR	Tauwitchere	35°35’23.60’’S	139°00’56.30’’E
Tauwitchere trapezoidal	Trap.	Tauwitchere	35°35’08.74’’S	139°00’29.34’’E
Goolwa vertical-slot	GVS	Goolwa	35°31’34.44’’S	138°48’31.12’’E
Goolwa vertical-slot 2	GVS2	Goolwa	35°31’26.48’’S	138°48’32.89’’E
Goolwa small vertical-slot	GSVS	Goolwa	35°31’37.65’’S	138°48’30.57’’E
Adjacent Goolwa Barrage	GDS	Goolwa	35°31’24.16’’S	138°48’33.79’’E
Hunters Creek vertical-slot	Hunters	Hunters Creek causeway	35°32’07.08’’S	138°53’07.48’’E
Mundoo dual vertical-slot	MDVS	Mundoo	35°32’27.59’’S	138°54’16.97’’E
Ewe Island dual vertical-slot	EIVS	Ewe Island	35°33’48.25’’S	138°57’51.63’’E
Boundary Creek small vertical-slot	BCVS	Boundary Creek	35°33’13.05’’S	138°56’48.42’’E

The entrances of the vertical-slot fishways were sampled using aluminium-framed cage traps, designed to fit into the first cell of each fishway (Tauwitchere large vertical-slot: 2.3 m long x 4.0 m wide x ~2.0 m depth and 0.3 m slot widths; Tauwitchere small vertical-slot: 1.2 m long x 1.6 m wide x ~1.0 m depth and 0.2 m slot widths; Goolwa large vertical-slot and large vertical-slot 2: 2.6 m long x 3.6 m wide x ~3.6 m depth, 0.3 m slot widths (baffle modified to include three 200 mm wide x 500 mm deep orifices); Hunters Creek: 1.6 m long x 1.6 m wide x ~0.6 m depth and 0.1 m slot widths; Mundoo dual vertical-slot: 2.8 m long x 3.1 m wide x ~2 m depth and 0.15 m slot widths; Boundary Creek small vertical-slot: 1.1 m long x 1.1 m wide x ~0.4 m depth and 0.1 m slot widths) (Figure 2-3a). Traps for the large vertical-slot fishways at Tauwitchere and Goolwa, and the Mundoo and Ewe Island dual vertical-slot fishways, were covered with 6 mm knotless mesh and featured a double cone–shaped entrance configuration (each 0.39 m high x 0.15 m wide) to maximise entry and minimise escapement. Traps for the small vertical-slot fishways were covered with 6 mm knotless mesh and perforated aluminum, with single cone–shaped entrances (each 0.75 m high x 0.11 m wide).

Large double-winged fyke nets (6.0 m long x 2.0 m wide x 1.5 m high with 8.0 m long wings) covered with 6 mm knotless mesh were used to sample the immediate area downstream of Tauwitchere Barrage at the rock ramp fishway and downstream Goolwa Barrage (Figure 2-3b). At both locations, the net was set adjacent to the barrage to capture fish utilising this area.

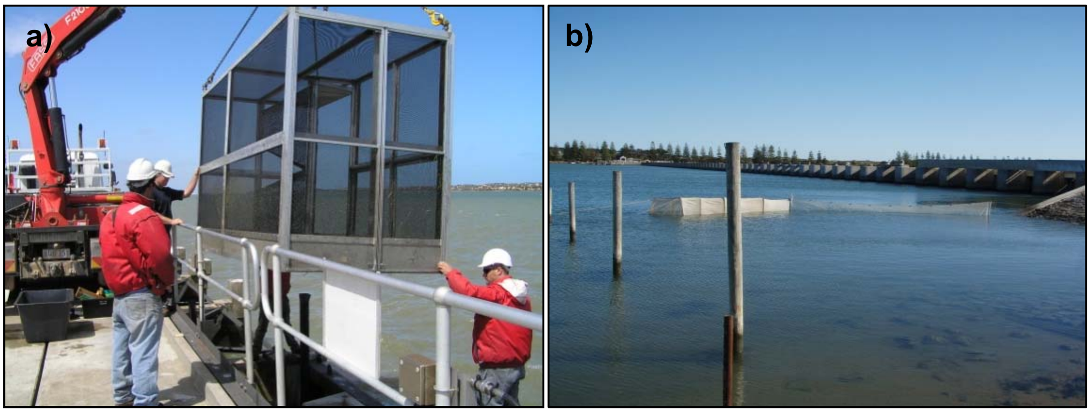

Figure 2-3 a) Cage trap used to sample the Tauwitchere and Goolwa vertical-slot fishways and b) large fyke net used to sample adjacent Goolwa Barrage. A net of the same dimensions was also used to sample adjacent to the Tauwitchere rock ramp.

Three weeks of sampling were undertaken in winter (10 July–9 August 2018) and four weeks in spring–summer (16 October 2018–11 January 2019). The sites adjacent the Tauwitchere rock ramp and Goolwa Barrage were sampled once overnight during each sampling week. All vertical-slot fishway sites were sampled overnight 1–3 times per sampling week. Cage traps at the large vertical-slot fishways were deployed and retrieved using a mobile crane (Figure 2-3a). All trapped fish were removed and placed in aerated holding tanks. During winter sampling, pouched lamprey and short-headed lamprey were identified and counted, whilst during spring–summer sampling, all fish were identified to species and counted. For catadromous congolli and common galaxias, during each trapping event a random sub-sample of up to 50 individuals were measured to the nearest mm (total length, TL) to represent the size structure of the population.

Salinity and estimated daily barrage discharge data were obtained from the Department for Environment and Water (DEW).

2.3. Data analysis

Temporal variability in fish assemblages

Temporal variability in fish assemblages was investigated by assessing changes in total fish abundance (all species combined), species richness and diversity, and fish assemblage structure (i.e. species composition and individual species abundance). Differences in the relative abundance (fish.hour^{-1}.trap event^{-1}) of fish (all species combined) sampled between years at each site were analysed using uni-variate single-factor PERMANOVA (permutational ANOVA and MANOVA), in the software package PRIMER v. 6.1.12 and PERMANOVA+ (Anderson *et al.* 2008). These analyses were performed on fourth-root transformed relative abundance data. This routine tests the response of a variable (e.g. total fish abundance) to a single factor (e.g. year) in a traditional ANOVA (analysis of variance) experimental design using a resemblance measure (Euclidean distance) and permutation methods (Anderson *et al.* 2008). Unlike ANOVA, PERMANOVA does not assume samples come from normally distributed populations or that variances are equal. Changes in species richness and diversity were qualitatively assessed by comparing total species richness (number of species sampled across all sampling sites) and the contribution of species from different estuarine-use categories and guilds (as defined by Potter *et al.* 2015 and classified for species of the Coorong and Lower Lakes by Bice *et al.* 2018a) between years (Table 2.2). Data from the Tauwitchere small-vertical slot and Hunters Creek vertical-slot were excluded from these analyses as they have only been sampled since 2010.

The composition of fish assemblages sampled at each location was assessed between all sampling years (i.e. 2006–2019). Non-Metric Multi-Dimensional Scaling (MDS) trajectory plots generated from Bray-Curtis similarity matrices of fourth-root transformed relative abundance data (number of fish.hour^{-1}.trip^{-1}) were used to graphically represent the transition of assemblages between years in two dimensions. PERMANOVA, based on the same similarity matrices, was used to detect differences in assemblages among years. CLUSTER analysis was then used to group assemblages among years based on similarity (an arbitrary 75% similarity level was applied to groupings). Differences in assemblages among clusters were then described in two ways. Firstly, similarity of percentages (SIMPER) analysis was undertaken to identify species contributing to these differences, and a 40% cumulative contribution cut-off was applied. Secondly, indicator species analysis (ISA) (Dufrene and Legendre 1997) was then used to calculate the indicator value (site fidelity and relative abundance) and determine species that characterised the cluster groups at each site using the package PCOrd v 5.12 (McCune and Mefford 2006). A perfect indicator remains exclusive to a particular group or site and exhibits strong site fidelity during sampling (Dufrene and Legendre 1997). Statistical significance was determined for each species indicator value using the Monte Carlo (randomisation) technique ($\alpha = 0.05$).

Table 2-2. Definitions of fish 'estuarine use' categories and guilds represented by fishes of the Coorong, following the approach of Potter et al. (2015), and designated by Bice et al. (2018). 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.	Bridled goby (*Arenogobius bifrenatus*)
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*)
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*)

Intra-annual spatial variability in fish assemblages

Spatial variation in fish assemblages between sampling locations in 2018/19 was also investigated using MDS, PERMANOVA and ISA. Due to differences in sampling methods, spatial variation was assessed separately for the vertical-slot fishway sites and the two sites sampled with the large fyke net (i.e. the Tauwitchere rock ramp and adjacent Goolwa Barrage). MDS plots generated from Bray-Curtis similarity matrices were used to graphically represent assemblages from different locations in two dimensions and PERMANOVA was used to detect differences in assemblages between locations. ISA was then used to determine what species characterised assemblages at the different sampling locations in 2018/19.

Spatio-temporal variability in diadromous species abundance

Inter-annual (2006–2019) differences in the standardised abundance (fish.hour^{-1}.trap event^{-1}) of pouched lamprey and short-headed lamprey were qualitatively assessed. Inter-annual differences in the standardised abundance of common galaxias and congolli (fish.hour^{-1}.trap event^{-1}) sampled at all six sites were analysed using uni-variate single-factor PERMANOVA (Anderson *et al.* 2008). Intra-annual (monthly) differences in the standardised abundance (fish.hour^{-1}.trap event^{-1}) of common galaxias and congolli sampled at all sites in 2018/19 were qualitatively described.

2.4. Assessment against TLM Ecological Targets

A specific Ecological Objective (F-1), in the revised Lower Lakes, Coorong and Murray Mouth Icon Site Condition Monitoring Plan (Robinson 2014) is to – *'Promote the successful migration and recruitment of diadromous fish species in the Lower Lakes and Coorong'*. The achievement of this objective is determined by the assessment of three ecological targets. These targets were developed from empirical data collected from 2006 to 2014 and relate specifically to the migration and recruitment of congolli and common galaxias, and the migration of short-headed and pouched lamprey:

1. The annual abundance of upstream migrating YOY congolli is ≥ the lower confidence bound of the recruitment reference value (i.e. lower bound 22.67 YOY.hr^{-1});
2. The annual abundance of upstream migrating YOY common galaxias is ≥ the lower confidence bound of the recruitment reference value (i.e. lower bound 3.12 YOY.hr^{-1}); and
3. Pouched lamprey and short-headed lamprey are sampled from ≥60% of the vertical-slot fishway sites sampled in any given year.

Ecological Target 1

This target is assessed by calculating an annual recruitment index for congolli, derived by calculating overall site abundance of upstream migrating YOY (i.e. fish.hr^{-1}) during the period November to January and comparing that to a predetermined reference value and associated confidence intervals. Annual recruitment index is calculated using equation 1:

Equation 1 $RI = (S_1(mean((r{*}A_{Nov})\ )+(r{*}A_{Dec})+(r{*}A_{Jan}))\ +\ S_2(mean((r{*}A_{Nov})+(r{*}A_{Dec})+(r{*}A_{Jan}))\ldots..S_n)$

where S = site, A = abundance (fish hour^{-1}) and r = the percentage of the sampled population comprised of YOY (i.e. <60 mm in length). The annual recruitment index (RV) ± half confidence interval = 44.26 ± 21.78 YOY.hr^{-1}.

Ecological Target 2

This target is assessed by calculating an annual recruitment index for common galaxias, derived by calculating overall site abundance of upstream migrating YOY (i.e. fish.hr^{-1}) during the period October to December and comparing that to a predetermined reference value and associated confidence intervals. Annual recruitment index is calculated using equation 1:

Equation 2 $RI = (S_1(mean((r{*}A_{Oct})\ )+(r{*}A_{Nov})+(r{*}A_{Dec}))\ +\ S_2(mean((r{*}A_{Oct})+(r{*}A_{Nov})+(r{*}A_{Dec}))\ldots..S_n)$

where S = site, A = abundance (fish hour^{-1}) and r = the percentage of the sampled population comprised of YOY (i.e. <60 mm in length). The annual recruitment index (RV) ± half confidence interval = 6.12 ± 3.00 YOY.hr^{-1}.

Ecological Target 3

The achievement of this target is assessed by determining a migration index for both pouched lamprey and short-headed lamprey. The annual migration index is calculated as the percentage of fishway sites from which these species were sampled in a given year, against the percentage of sites from which these species were sampled in a predetermined reference year:

Equation 3 $\boldsymbol{Short - headed\ lamprey\ MI(year)} = \frac{\textbf{Percentage of sites where detected}}{\textbf{Percentage of sites where detected in 2006/07}}$

Equation 4 $\boldsymbol{Pouched\ lamprey\ MI(year)} = \frac{\textbf{Percentage of sites where detected}}{\textbf{Percentage of sites where detected in 2011/12}}$

This provides a value of *MI* of ≤1.0 and an arbitrary tolerance of 0.4 is adopted, i.e. *MI* ≥ 0.6 is taken to suggest achievement of target. These indices are calculated from all monitoring undertaken at the Murray Barrages in a given year, including annual spring/summer monitoring and specific lamprey monitoring during winter, which has occurred in 2011, 2013 and 2015–2019. Whilst this influences comparability of data between years it is necessary for these rare species. As such, inter-annual variability in sampling effort needs to be considered during interpretation of results.

3. RESULTS

3.1. Hydrology

Freshwater discharge to the Coorong and salinity were highly variable over the period 2005–2019. Generally, sampling years could be grouped based upon hydrology as follows: 1) no discharge (0 GL; 2007–2010); 2) low–moderate discharge (63–1600 GL; 2006/07, 2013–2016 and 2017–2019); and high discharge (5200–12,500 GL; 2010–2013 and 2016/17).

Prior to sampling in 2006, low-volume freshwater flows of 1000–12,000 $ML.d^{-1}$ were consistently released into the Coorong through barrage 'gates', but by September 2006 discharge was confined to fishways (Tauwitchere: 20–40 $ML.d^{-1}$, Goolwa: ~20 $ML.d^{-1}$) (Figure 3-1a). Low inflows from the River Murray and receding water levels in the Lower Lakes resulted in the closure of fishways in March 2007 (Figure 3-1a) and persistent drought in the MDB resulted in no freshwater being released to the Coorong until September 2010. Significant inflows to the Lower Lakes in late 2010 saw the fishways reopened and the release of large volumes of freshwater to the Coorong throughout the 2010/11 sampling season. Cumulative flow across the barrages peaked at >80,000 $ML.d^{-1}$ with a mean daily discharge (± SE) of 49,955 ± 1396 $ML.d^{-1}$ over the 2010/11 sampling period (Figure 3-1a). High-volume freshwater flows continued throughout the 2011/12 sampling season (range 800–34,600 $ML.d^{-1}$; mean daily discharge = 10,823 ± 657 $ML.d^{-1}$) and 2012/13 (range 220–69,000 $ML.d^{-1}$; mean daily discharge = 12,617 ± 948 $ML.d^{-1}$), although no sampling was conducted in 2012/13 (Figure 3-1a). Low–medium volume flows occurred throughout 2013/14 with flow during the sampling season ranging 20–18,020 $ML.d^{-1}$ and a mean daily discharge of 1617 ± 217 $ML.d^{-1}$. Discharge continued to decrease through 2014/15 (range 8–2950 $ML.d^{-1}$; mean = 1547 ± 67 $ML.d^{-1}$) and 2015/16 (range 1–1503 $ML.d^{-1}$; mean = 128 ± 28 $ML.d^{-1}$), before increasing substantially in 2016/17, with cumulative flow across the barrages peaking at >80,000 $ML.d^{-1}$ and a mean daily discharge (± SE) of 36,851 ± 2277 $ML.d^{-1}$ over the sampling period. Flow had decreased during sampling in 2017/18, with a mean of 3340 ± 270 $ML.d^{-1}$ and range 0–12,498 $ML.d^{-1}$, and decreased further in 2018/19, with a mean of 1013 ± 65 $ML.d^{-1}$ and range 0–1502 $ML.d^{-1}$.

During sampling in 2006/07, salinity below Tauwitchere and Goolwa Barrages fluctuated 20–34 $g.L^{-1}$ (mean = 28.42 ± 0.18 $g.L^{-1}$) and 11–29 $g.L^{-1}$ (mean = 21.93 ± 0.29 $g.L^{-1}$), respectively (Figure 3-1b). Following the cessation of freshwater releases in March 2007, salinities at Tauwitchere increased and ranged 30–60 $g.L^{-1}$ until September 2010. Salinities at Goolwa

Barrage, between March 2007 and September 2010, also increased, ranging from 26–37 g.L^{-1}. Following significant increases in freshwater releases to the Coorong in September 2010, salinities over the 2010/11 sampling period ranged 0.3–25 g.L^{-1} at Goolwa Barrage and 0.2–27 g.L^{-1} at Tauwitchere Barrage; however, mean salinities were significantly reduced at both Goolwa (2 ± 0.3 g.L^{-1}) and Tauwitchere (3.8 ± 0.3 g.L^{-1}) (Figure 3-1b). During 2011/12 sampling, salinity was more variable, ranging 0.3–32 g.L^{-1} at Goolwa (mean = 10.4 ± 0.8 g.L^{-1}) and 3–26 g.L^{-1} (mean = 12.7 ± 0.4 g.L^{-1}) at Tauwitchere (Figure 3-1b). In 2012/13, salinity fluctuated over a similar range to 2011/12, but no sampling was conducted. During sampling in 2013/14, decreasing freshwater flows resulted in increased salinity relative to the three previous years; nevertheless, conditions remained ‘brackish’ with salinity ranging 0.5–30 g.L^{-1} (mean = 13.5 ± 0.9 g.L^{-1}) at Goolwa and 5–22 g.L^{-1} (mean = 10.4 ± 0.8 g.L^{-1}) at Tauwitchere. Further decreases in freshwater discharge were associated with increases in salinity in 2014/15 (Goolwa: range 7–32 g.L^{-1}; mean = 18.7 ± 0.6 g.L^{-1}. Tauwitchere: range 15–32 g.L^{-1}; mean = 22.3 ± 0.4 g.L^{-1}) and 2015/16 (Goolwa: range 21–31 g.L^{-1}; mean = 27 ± 2.9 g.L^{-1}. Tauwitchere: range 19–34 g.L^{-1}; mean = 27.8 ± 3.2 g.L^{-1}). A substantial increase in discharge in 2016/17 was associated with reduced salinities, similar to 2010/11, ranging 0.2–26 g.L^{-1} at Goolwa Barrage and 0.2–20 g.L^{-1} at Tauwitchere Barrage. Mean salinities were substantially reduced relative to 2014–2016 at both Goolwa (3.5 ± 0.7 g.L^{-1}) and Tauwitchere (5 ± 0.5 g.L^{-1}). In 2017/18, salinity was generally ‘brackish’ downstream of both Goolwa (range 4–24 g.L^{-1}; mean = 13 ± 0.4 g.L^{-1}) and Tauwitchere Barrages (range 7–32 g.L^{-1}; mean = 16 ± 0.7 g.L^{-1}). Again in 2018/19, salinity was generally brackish downstream of Goolwa (range 7–31 g.L^{-1}; mean = 21 ± 0.6 g.L^{-1}) and Tauwitchere Barrages (range 7–31 g.L^{-1}; mean = 18 ± 0.6 g.L^{-1}).

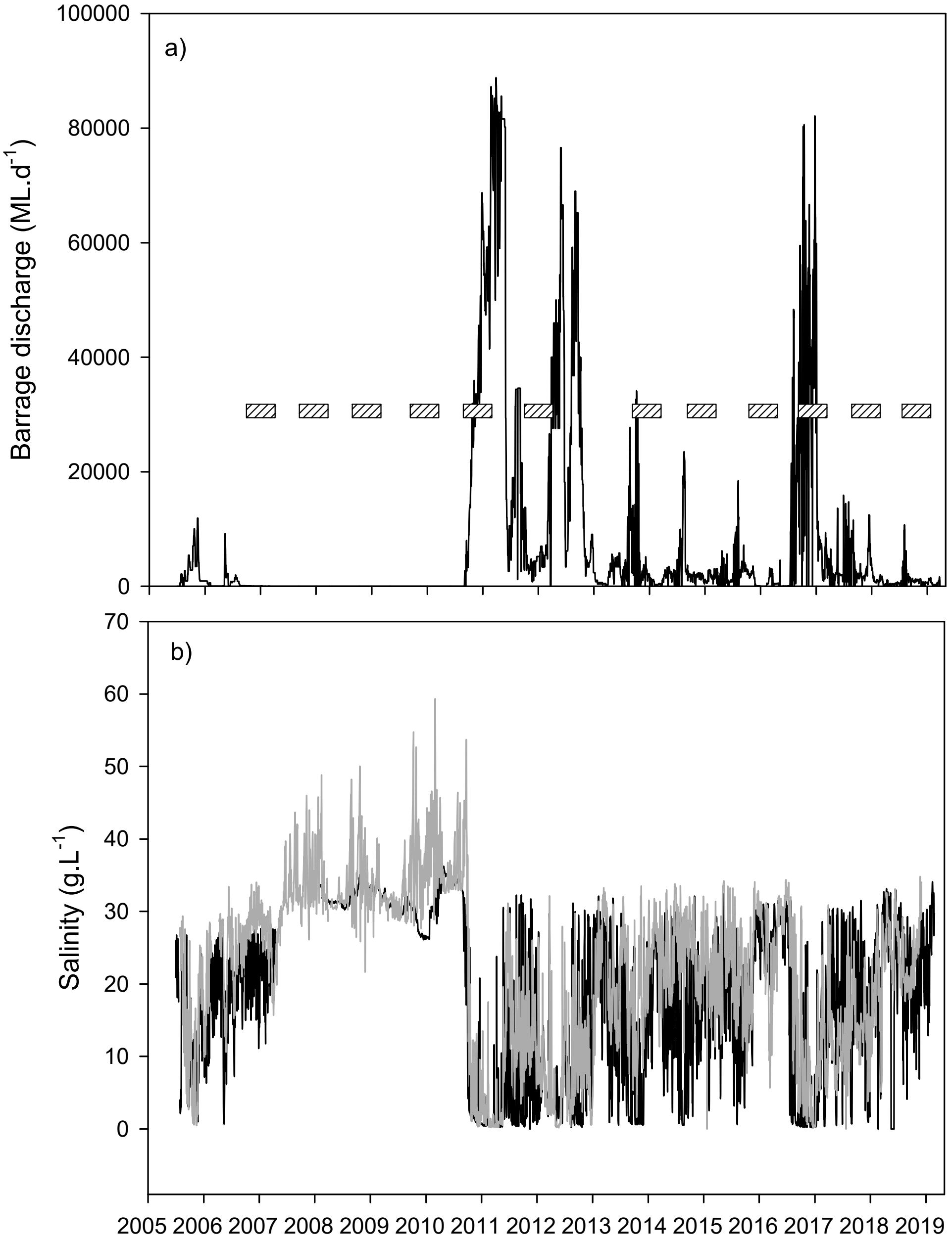

Figure 3-1. a) Mean daily flow (ML.d^{-1}) to the Coorong through the Murray Barrages (all barrages combined) from July 2005–March 2019 and b) Mean daily salinity (g.L^{-1}) of the Coorong below Tauwitchere (grey line) and Goolwa (black line) barrages from July 2005–February 2019. Sampling periods are represented by hatched bars. Barrage discharge data was sourced from DEW, whilst salinity data was sourced from water quality monitoring stations immediately below Tauwitchere and Goolwa Barrages (DEW 2019).

3.2. Catch summary

A total of 312,042 fish from 36 species were sampled in spring–summer 2018/19 (Table 3-1). The marine estuarine-opportunist sandy sprat (75.5%) and catadromous congolli (13.5%) dominated the total catch, whilst the semi-catadromous common galaxias (3.1%), freshwater Australian smelt (*Retropinna semoni*, 3%), redfin perch (*Perca fluviatilis*, 1.4%) and bony herring (*Nematalosa erebi,* 1%), were also abundant. The remaining 30 species collectively comprised <2.5% of the total catch.

Table 3-1. Summary of species and total number of fish sampled from the entrances of the Tauwitchere large vertical-slot, Tauwitchere small vertical-slot, Goolwa vertical-slot and Hunters Creek vertical-slot, and from the Tauwitchere rock-ramp and adjacent Goolwa Barrage in spring–summer 2018/19. Species are categorised using estuarine use guilds from Potter et al*.* (2015) and designations presented by Bice et al. (2018).

			Tauwitchere large vertical-slot	**Tauwitchere small vertical-slot**	**Tauwitchere rock ramp**	**Goolwa vertical-slot**	**Adjacent Goolwa Barrage**	**Hunters Creek**	**Total**
Common name	**Scientific Name**	**Guild**							
		Sampling events	9	11	4	12	4	12	
		No. of species	15	6	25	15	25	12	
Australian smelt	*Retropinna semoni*	Freshwater estuarine opportunist	545	3,995	2,966	1500	326	2	**9,334**
Bony herring	*Nematalosa erebi*	Freshwater estuarine opportunist	108	17	1,769	871	197	9	**2,971**
Flat-headed gudgeon	*Philypnodon grandiceps*	Freshwater estuarine opportunist	702	3	116	447	32	20	**1,320**
Dwarf flat-headed gudgeon	*Philypnodon macrostomus*	Freshwater straggler	0	0	0	0	3	0	**3**
Carp gudgeon	*Hypseleotris* spp	Freshwater straggler	6	0	0	0	0	1	**7**
Golden perch	*Macquaria ambigua*	Freshwater straggler	1	0	0	0	2	0	**3**
Common carp	*Cyprinus carpio**	Freshwater straggler	11	0	18	6	10	2	**47**
Goldfish	*Carassius auratus**	Freshwater straggler	0	0	5	0	0	0	**5**
Redfin perch	*Perca fluviatilis**	Freshwater straggler	940	5	3,058	49	302	11	**4,365**
Oriental weatherloach	*Misgurnus angiullicandatus*	Freshwater straggler	1	0	0	0	0	0	**1**
Unspecked hardyhead	*Craterocephalus fulvus*	Freshwater straggler	0	0	1	0	0	0	**1**
Short-headed lamprey	*Mordacia mordax*	Anadromous	0	0	0	1	0	0	**1**
Common galaxias	*Galaxias maculatus*	Semi-catadromous	3,376	2,873	371	2,764	78	143	**9,605**
Congolli	*Pseudaphritis urvillii*	Catadromous	790	2,967	9,570	12,138	11,214	5,315	**41,994**

denotes introduced species

Table 3-1 continued.

Common name	Scientific Name	Guild	Tauwitchere large vertical-slot	Tauwitchere small vertical-slot	Tauwitchere rock ramp	Goolwa vertical-slot	Adjacent Goolwa Barrage	Hunters Creek	Total
Black bream	*Acanthopagrus butcheri*	Solely estuarine	1	0	1	0	0	0	**2**
Small-mouthed hardyhead	*Atherinosoma microstoma*	Solely estuarine	13	0	293	7	14	519	**846**
Tamar River goby	*Afurcagobius tamarensis*	Solely estuarine	13	0	135	23	1,092	4	**1,267**
Blue-spot goby	*Pseudogobius olorum*	Solely estuarine	1	0	50	0	22	0	**73**
Lagoon goby	*Tasmanogobius lasti*	Solely estuarine	981	0	1,601	20	13	0	**2,595**
River garfish	*Hyporhamphus regularis*	Solely estuarine	0	0	4	0	0	0	**4**
Bridled goby	*Arenogobius bifrenatus*	Estuarine & marine	0	0	262	1	53	0	**316**
Soldier fish	*Gymnapistes marmoratus*	Estuarine & marine	0	0	6	2	47	5	**55**
Yelloweye mullet	*Aldrichetta forsteri*	Marine estuarine-opportunist	0	0	18	1,372	45	0	**1,435**
Australian salmon	*Arripis trutta*	Marine estuarine-opportunist	0	0	19	0	1	0	**20**
Mulloway	*Argyrosomus japonicus*	Marine estuarine-opportunist	0	0	101	2	8	0	**111**
Greenback flounder	*Rhombosolea tapirina*	Marine estuarine-opportunist	0	0	7	0	13	0	**20**

Table 3-1 continued.

Common name	Scientific Name	Guild	Tauwitchere large vertical-slot	Tauwitchere small vertical-slot	Tauwitchere rock ramp	Goolwa vertical-slot	Adjacent Goolwa Barrage	Hunters Creek	Total
Long-snouted flounder	*Ammosetris rostratus*	Marine estuarine-opportunist	0	0	2	0	3	0	**5**
Flat-tailed mullet	*Liza argentea*	Marine estuarine-opportunist	0	0	0	7	0	0	**7**
Sandy sprat	*Hyperlophus vittatus*	Marine estuarine-opportunist	305	0	8,076	206,869	20,344	0	**235,594**
Smooth toadfish	*Tetractenos glaber*	Marine estuarine-opportunist	0	0	2	0	6	1	**9**
Beaked salmon	*Gonorynchus greyi*	Marine straggler	0	0	0	0	1	0	**1**
Blue sprat	*Spratelloides robustus*	Marine straggler	0	0	1	0	0	0	**1**
Sea mullet	*Mugil cepahalus*	Marine straggler	0	0	0	0	1	0	**1**
Sea sweep	*Scorpis aequipinnis*	Marine straggler	0	0	1	0	0	0	**1**
Bridled leatherjacket	*Acanthaluteres spilomelanurus*	Marine straggler	0	0	0	0	1	0	**1**
Six-spined leatherjacket	*Meuschenia freycineti*	Marine straggler	0	0	1	0	0	0	**1**
		Total	**7,794**	**9,860**	**28,454**	**226,079**	**33,828**	**6,033**	**312,042**

3.3. Temporal variation in fish assemblages

Total fish abundance, species richness and diversity

The mean number of fish (all species combined) sampled per trap event varied significantly among years from 2006/07 to 2018/19 (Figure 3-2) at the Tauwitchere rock ramp ($Pseudo\text{-}F_{11, 69} = 9.84$, $p < 0.001$), Tauwitchere vertical-slot ($Pseudo\text{-}F_{11, 59} = 7.60$, $p < 0.001$), Goolwa vertical-slot ($Pseudo\text{-}F_{10, 59} = 2.69$, $p = 0.015$), but not at the Tauwitchere small vertical-slot ($Pseudo\text{-}F_{7, 41} = 0.57$, $p = 0.777$), adjacent Goolwa Barrage ($Pseudo\text{-}F_{9, 49} = 1.96$, $p = 0.076$) or Hunters Creek vertical-slot ($Pseudo\text{-}F_{7, 41} = 2.06$, $p = 0.078$). Temporal variability in total fish abundance at the Tauwitchere vertical-slot, Tauwitchere rock ramp and Goolwa vertical-slot exhibited similar patterns, with low total abundance during the period of no freshwater discharge and disconnection through 2007–2010, and generally high total abundance from 2010–2018 (Figure 3-2). In 2018/19, however, total abundances at the Tauwitchere vertical-slot and Tauwitchere rock ramp were the lowest since 2009/10. Whilst not of statistical significance, total abundance adjacent Goolwa Barrage was the lowest since 2008/09. In contrast, total abundance at the Goolwa vertical-slot was highest recorded throughout the study; nonetheless high abundance was driven by a single trapping event during a reverse flow event when >200,000 sandy sprat were sampled (~90% of fish sampled from this fishway and ~65% of all fish sampled in the project in 2018/19). If this event was removed, total abundance at this fishway was also the lowest since the Millennium Drought. Total fish abundance has been generally consistent across years at the Tauwitchere small vertical-slot and Hunters Creek vertical-slot since the commencement of monitoring at these fishways in 2010/11; nonetheless, abundances in 2018/19 were at the lower end of this range.

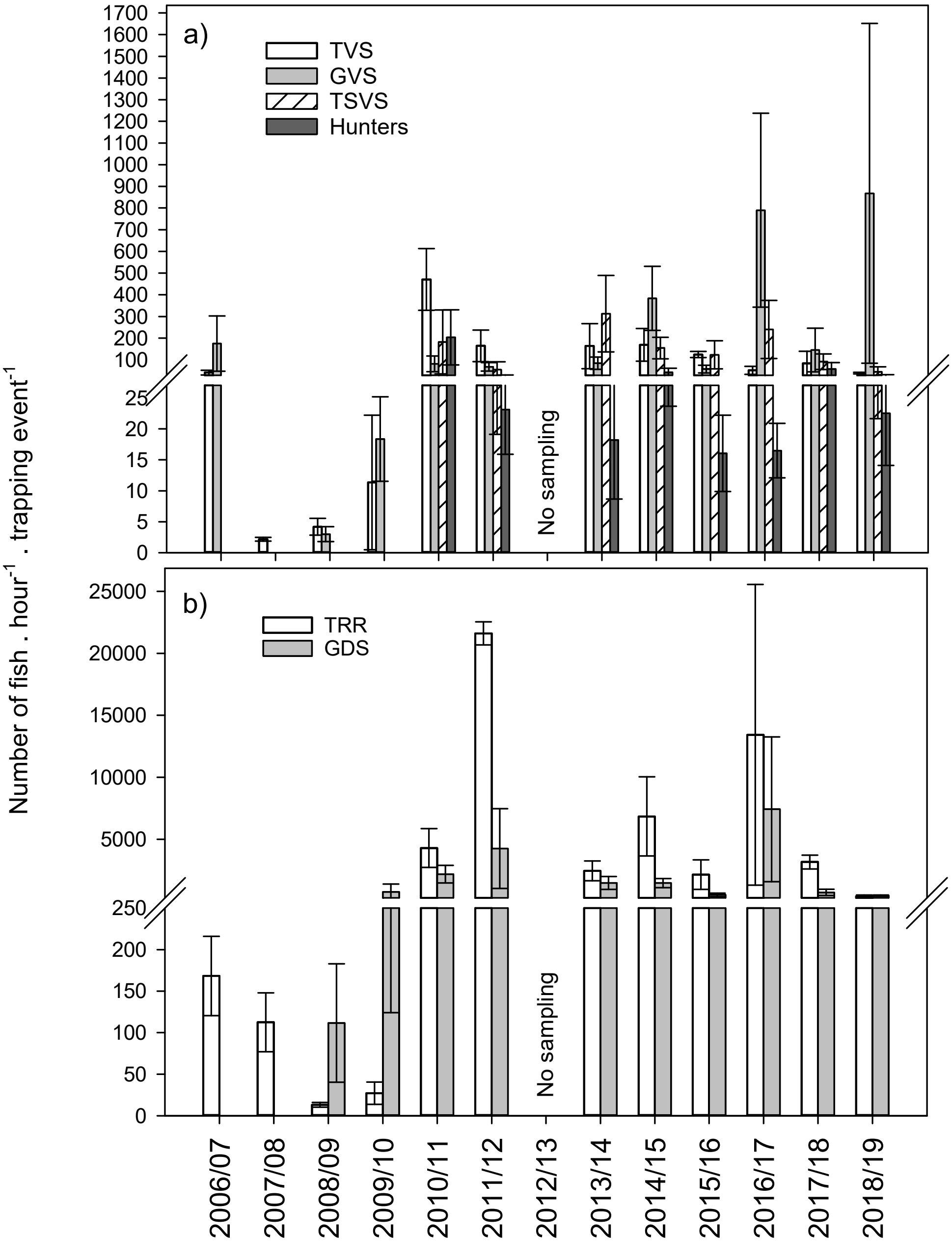

Figure 3-2. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of fish (all species combined) sampled at a) the Tauwitchere large vertical-slot (TVS), Goolwa vertical-slot (GVS), Tauwitchere small vertical-slot and Hunters Creek vertical-slot (Hunters), and b) the Tauwitchere rock ramp (TRR) and adjacent Goolwa Barrage (GDS), from 2006–2019. Goolwa vertical-slot was not sampled in 2007/08, whilst sampling at the Tauwitchere small vertical-slot and Hunters Creek vertical-slot (Hunters) commenced in 2010/11. Sampling at the site adjacent Goolwa Barrage commenced in 2008/09. No sampling was conducted at any site in 2012/13.

Species richness (all sites combined) has been relatively consistent among years, and generally ranged 28–32 species (Figure 3-3), with greatest species richness recorded in 2018/19 (*n* = 36). The number of species sampled from different estuarine use categories has varied substantially (Figure 3-3). The number of species from the freshwater category (freshwater ‘estuarine-opportunists’ and ‘stragglers’ combined) was lowest from 2007–2010 (*n* = 2–3), but greatest during times of high freshwater discharge and connectivity from 2010–2012 and 2016/17 (*n* = 10–11), but also in 2018/19 (*n* = 11). In contrast, the number of species of marine origin (marine ‘estuarine-opportunist’ and ‘stragglers’ combined) was greatest from 2008–2010 (*n* = 19–20) and lowest in 2016/17 (*n* = 7). The number of diadromous species was reduced during 2007–2010 and 2014/15 (*n* = 2), due to the absence of both lamprey species, whilst the number of estuarine species did not differ substantially over the entire study period (*n* = 7–8). High species richness in 2018/19 was primarily driven by the highest number of marine species (*n* = 14) since 2009/10.

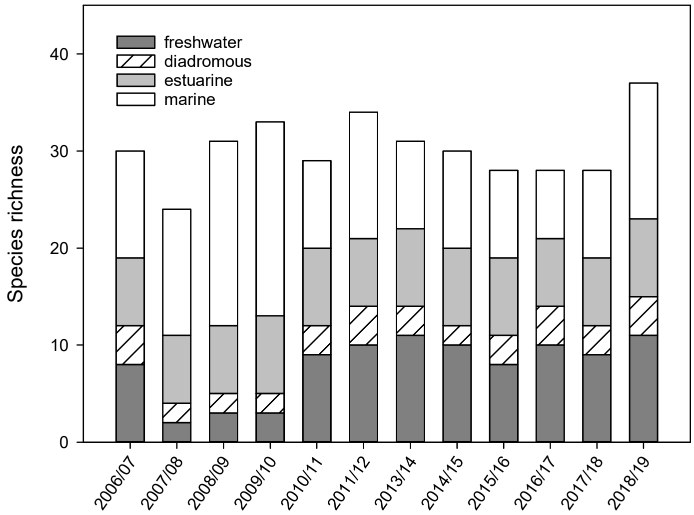

Figure 3-3. Species richness (all sites combined) from 2006–2019, including the contribution of species from different estuarine-use categories, i.e. freshwater (freshwater ‘estuarine-opportunists’ and ‘stragglers’ combined), diadromous (catadromous and anadromous combined), estuarine (solely estuarine and ‘estuarine and marine’ combined) and marine (marine ‘estuarine-opportunists’ and ‘stragglers’ combined). Guilds follow those proposed by Potter *et al.* (2015) and designated for species of the Coorong and Lower Lakes by Bice *et al.* (2018).

Assemblage structure

PERMANOVA detected significant differences in fish assemblages at the Tauwitchere rock ramp ($Pseudo\text{-}F_{11,\ 69} = 13.17$, $p < 0.001$), Tauwitchere large vertical-slot ($Pseudo\text{-}F_{11,\ 59} = 10.41$, $p < 0.001$), Tauwitchere small vertical-slot ($Pseudo\text{-}F_{7,\ 41} = 3.03$, $p < 0.001$), Goolwa vertical-slot ($Pseudo\text{-}F_{10,\ 59} = 4.82$, $p < 0.001$), adjacent Goolwa Barrage ($Pseudo\text{-}F_{9,\ 49} = 6.90$, $p < 0.001$) and Hunters Creek vertical-slot ($Pseudo\text{-}F_{7,\ 41} = 4.12$, $p < 0.001$). MDS trajectory plots illustrate changes in fish assemblages across time and grouping of years based on cluster analysis (Figure 3-4). These analyses indicate a general trend of variable assemblages during years of zero discharge from 2007/08 to 2009/10, with a substantial shift in trajectory in subsequent years. High flow years in 2010/11, 2011/12 and 2016/17 were generally grouped together, as were the low–moderate flow years from 2013–2016, and 2017–2019 (Table 3-2). In some instances (Figure 3-4a–c) there was a shift in assemblage structure in 2018/19 towards an assemblage similar to that in 2006/07.

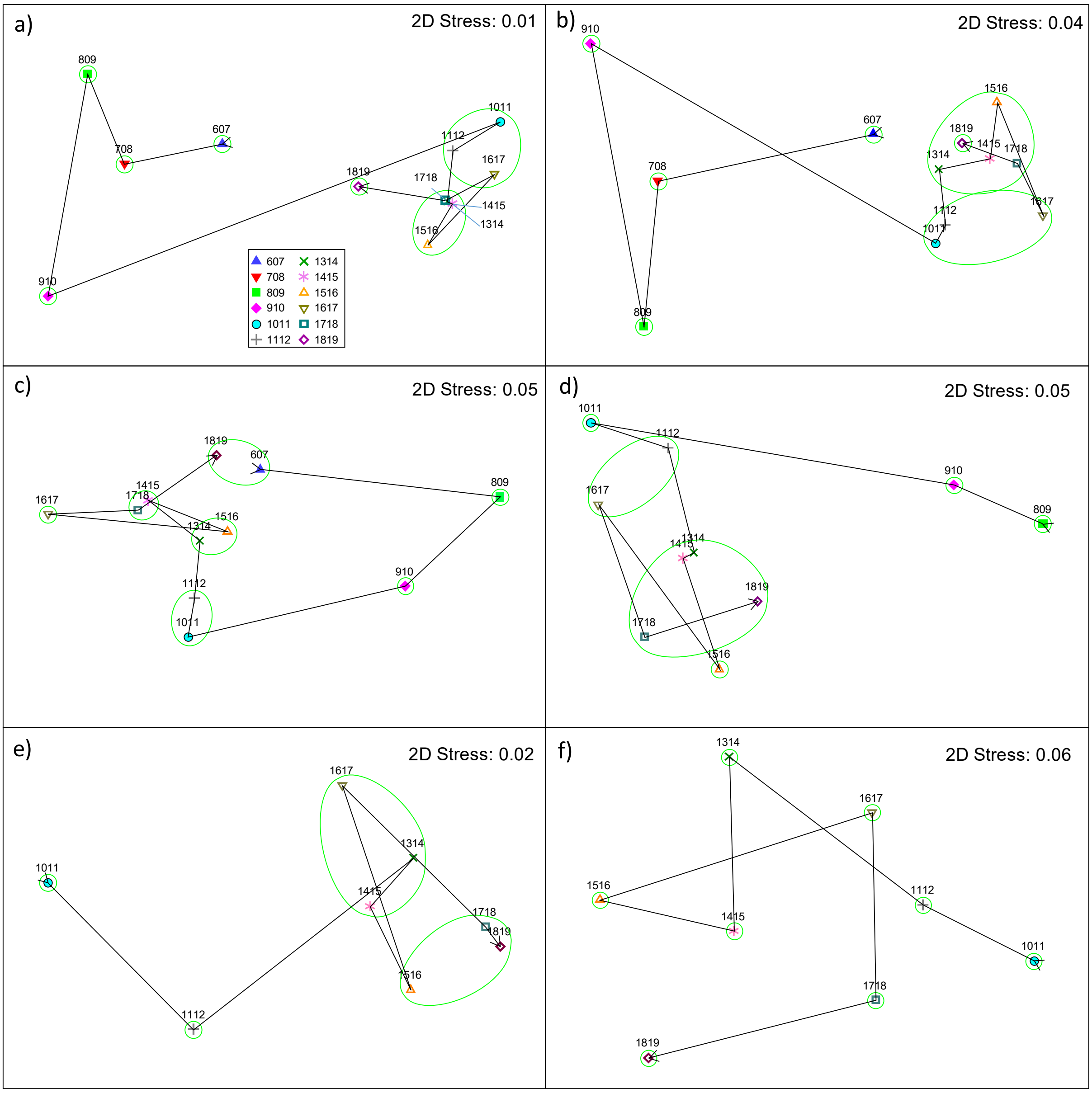

Figure 3-4. MDS ordination trajectory plots of fish assemblages sampled at a) Tauwitchere rock ramp, b) Tauwitchere large vertical-slot, c) Goolwa vertical-slot, d) adjacent Goolwa Barrage, e) Tauwitchere small vertical-slot and f) Hunters Creek vertical-slot, between 2006 and 2019. Groupings from Cluster analysis based on 70% similarity are indicated by green ellipses.

Table 3-2. Groupings of sampling years at each site based on cluster analysis and arbitrary assemblage similarity of 75%.

	TRR	**TVS**	**GVS**	**GDS**	**TSVS**	**Hunters**
Group 1	06/07	06/07	06/07, 18/19	08/09	10/11	10/11
Group 2	07/08	07/08	08/09	09/10	11/12	11/12
Group 3	08/09	08/09	09/10	10/11	13/14, 14/15, 16/17	13/14
Group 4	09/10	09/10	10/11, 11/12	11/12, 16/17	15/16, 17/18, 18/19	14/15
Group 5	10/11, 11/12, 16/17	10/11, 11/12, 16/17	13/14, 15/16	13/14, 14/15, 17/18, 18/19	-	15/16
Group 6	13/14–15/16, 17/18	13/14–15/16, 17/18	14/15, 17/18	15/16	-	16/17
Group 7	18/19	18/19	16/17	-	-	17/18
Group 8						18/19

Tauwitchere sites

Cluster analysis of fish assemblages sampled at the Tauwitchere rock ramp and large vertical-slot both produced the identical seven groupings of sampling years (Table 3-2). These groupings could be described in terms of annual discharge: no flow (0 GL) = group 2 (2007/08), 3 (2008/09) and 4 (2009/10); low flow (63–370 GL) = group 1 (2006/07) and 7 (2018/19) (low flow); moderate flow (562–1600 GL) = group 6 (2013/14–2015/16, 2017/18); and high flow (6536–12,500 GL) = group 5 (2010/11, 2011/12, 2016/17). At the Tauwitchere small vertical-slot, assemblages produced four cluster groups: low flow (370–802 GL) = group 4; moderate–high flow (984–6536 GL) = group 3; and high flow (8800–12,500) = groups 1 (2010/11) and 2 (2011/12).

SIMPER indicated that fish assemblages sampled at the Tauwitchere rock ramp in 2018/19, differed from assemblages sampled in the no flow groups (years) due to greater abundance of the marine estuarine-opportunist sandy sprat, and freshwater bony herring and Australian smelt, and catadromous congolli in 2018/19. Alternatively, assemblages in 2018/19 differed from the moderate and high flow groupings, due to greater abundance of sandy sprat, and the freshwater Australian smelt and flat-headed gudgeon (*Philypnodon grandiceps*) in high flow years, and greater abundance of congolli in moderate flow years. At the Tauwitchere vertical-slot, assemblages in 2018/19 differed from 2006/07, and the no flow years, due to greater abundance of freshwater bony herring and Australian smelt, and catadromous congolli and common galaxias in 2018/19. Differences between 2018/19, and both moderate and high flow groupings, were driven by greater abundance of freshwater Australian smelt, flat-headed gudgeon and bony herring in moderate and high flow groupings. At the Tauwitchere small vertical-slot, differences between the low flow grouping that encompassed 2015/16, 2017/18 and 2018/19, and the preceding high and moderate flow groupings, was generally due to lower abundances of freshwater redfin perch, but greater abundances of the catadromous congolli and common galaxias during the recent low flow period.

At the Tauwitchere rock ramp, Indicator Species Analysis (ISA) suggested the fish assemblage in 2006/07 was characterised by the presence of the anadromous short-headed lamprey (Table 3-3). In contrast, the assemblages in the no flow year in 2007/08 was characterised by the marine estuarine-opportunist flat-tailed mullet (*Liza argentea*) and marine straggler blue sprat (*Spratelloides robustus*) (2007/08), and in 2009/10, the assemblage was characterised by the estuarine and marine estuary catfish (*Cnidglanis microcephalus*), five marine estuarine-opportunist species (i.e. Australian salmon (*Arripis truttaceus*), Australian herring (*Arripis georgianus*), prickly toadfish (*Contusus brevicaudus*), yellowfin whiting (*Sillago schomburgkii*) and Australian anchovy (*Engraulis australis*)) and four marine stragglers (i.e. King George whiting (*Sillaginodes punctatus*) big belly seahorse (*Hippocampus abdominalis*), silver spot (*Threpterius maculosus*) and Tucker's pipefish (*Mitotichthys tuckeri*)). The assemblage sampled in high flow years was characterised by six freshwater species (i.e. Australian smelt, flat-headed gudgeon, bony herring, common carp (*Cyprinus carpio*), golden perch (*Macquaria ambigua*) and redfin perch), together with two solely estuarine fishes (river garfish (*Hyporhamphus regularis*) and lagoon goby (*Tasmanogobius lastii*)), and one marine straggler (i.e. southern longfin goby (*Favonigobius lateralis*)). The assemblage from moderate flow years was characterised by the catadromous congolli and common galaxias, marine-estuarine opportunist sandy sprat, and estuarine Tamar River goby (*Afurcagobius tamarensis*). Finally, the 2018/19 low flow year was characterised by the estuarine and marine bridled goby (*Arenogobius bifrenatus*) and marine-estuarine opportunist mulloway (*Argyrosomus japonicas*).

At the Tauwitchere large vertical-slot, the assemblages sampled in 2006/07 were characterised by the anadromous short-headed lamprey, and the assemblages during 2007/08 by the estuarine blue-spot goby (*Pseudogobius olorum*) (Table 3-4). There were no significant indicators of the remaining no flow years, while assemblages during high flow years were characterised by four freshwater species (i.e. Australian smelt, bony herring, golden perch and common carp). Moderate flow years were characterised by the freshwater flat-headed gudgeon and catadromous congolli, while 2018/19 was characterised by the freshwater redfin perch and solely estuarine lagoon goby.

At the Tauwitchere small vertical-slot, the assemblages in 2010/11, were characterised by the freshwater flat-headed gudgeon, redfin perch, and carp gudgeon complex (*Hypseleotris* spp.) and the estuarine blue-spot goby and lagoon goby (Table 3-4). The assemblage in 2011/12 was characterised by the freshwater common carp and golden perch, and marine-estuarine opportunist sandy sprat. There were no indicators of moderate flow year assemblages (group 3), but the low flow group 4, was characterised by the semi-catadromous common galaxias.

Table 3-3. Indicator species analysis of fish assemblages in the Coorong at the Tauwitchere rock ramp based on groupings of sampling years from Cluster analysis (75% similarity). Cluster groupings are defined by annual flow: NF = no flow (0 GL), LF = low flow (63–370 GL), MF = moderate flow (562–1600 GL), HF = high flow (>6536 GL). Only significant indicators (i.e. $p < 0.05$) are presented. Species are categorised using estuarine use guilds proposed by Potter *et al.* (2015) and designated for species of the Coorong and Lower Lakes by Bice *et al.* (2018).

Species	**Guild**	**Year**	**Indicator Value**	***p* value**
Tauwitchere rockramp				
Short-headed lamprey	Anadromous	Group 1 (LF)	45.5	0.011
Blue sprat	Marine straggler	Group 2 (NF)	30.8	0.034
Flat-tailed mullet	Marine est-opportunist	Group 2 (NF)	31.1	0.048
Estuary catfish	Estuarine & marine	Group 4 (NF)	33.3	0.038
Australian salmon	Marine est-opportunist	Group 4 (NF)	36.1	0.021
Australian herring	Marine est-opportunist	Group 4 (NF)	59.7	0.001
Prickly toadfish	Marine est-opportunist	Group 4 (NF)	95.6	<0.001
Yellowfin whiting	Marine est-opportunist	Group 4 (NF)	46.1	0.010
Australian anchovy	Marine est-opportunist	Group 4 (NF)	35.9	0.029
King George whiting	Marine straggler	Group 4 (NF)	28.5	0.040
Tuckers pipefish	Marine straggler	Group 4 (NF)	33.3	0.041
Big belly seahorse	Marine straggler	Group 4 (NF)	33.3	0.047
Silver spot	Marine straggler	Group 4 (NF)	33.3	0.047
Australian smelt	Freshwater est-opportunist	Group 5 (HF)	45.2	0.030
Flat-headed gudgeon	Freshwater est-opportunist	Group 5 (HF)	48.8	<0.001
Bony herring	Freshwater est-opportunist	Group 5 (HF)	42.3	<0.001
Common carp	Freshwater straggler	Group 5 (HF)	59.5	<0.001
Golden perch	Freshwater straggler	Group 5 (HF)	62.0	0.001
Redfin perch	Freshwater straggler	Group 5 (HF)	40.0	0.046
River garfish	Solely estuarine	Group 5 (HF)	43.4	0.004
Lagoon goby	Solely estuarine	Group 5 (HF)	39.3	<0.001
Southern longfin goby	Marine straggler	Group 5 (HF)	42.9	0.008
Tamar River goby	Solely estuarine	Group 6 (MF)	23.2	0.009
Common galaxias	Semi-catadromous	Group 6 (MF)	38.3	<0.001
Congolli	Catadromous	Group 6 (MF)	32.8	0.002
Sandy sprat	Marine est-opportunist	Group 6 (MF)	30.6	0.027
Mulloway	Marine est-opportunist	Group 7 (LF)	43.7	0.006
Bridled goby	Estuarine & marine	Group 7 (LF)	24.7	0.006

Table 3-4. Indicator species analysis of fish assemblages in the Coorong at the Tauwitchere large vertical-slot and at the small vertical-slot, based on groupings of sampling years from Cluster analysis (75% similarity). Cluster groupings are defined by annual flow: NF = no flow (0 GL), LF = low flow (63–370 GL), MF = moderate flow (562–1600 GL), HF = high flow (>6536 GL). Only significant indicators (i.e. $p < 0.05$) are presented. Species are categorised using estuarine use guilds proposed by Potter *et al.* (2015) and designated for species of the Coorong and Lower Lakes by Bice *et al.* (In Press).

Species	**Guild**	**Year**	**Indicator Value**	***p* value**
Tauwitchere large vertical-slot				
Short-headed lamprey	Anadromous	Group 1 (LF)	33.3	0.042
Blue-spot goby	Solely estuarine	Group 2 (NF)	38.5	0.014
Australian smelt	Freshwater est-opportunist	Group 5 (HF)	48.6	<0.001
Bony herring	Freshwater est-opportunist	Group 5 (HF)	47.9	<0.001
Golden perch	Freshwater straggler	Group 5 (HF)	32.9	0.049
Common carp	Freshwater straggler	Group 5 (HF)	37.2	0.003
Flat-headed gudgeon	Freshwater est-opportunist	Group 6 (MF)	32.7	0.002
Congolli	Catadromous	Group 6 (MF)	32.4	<0.001
Redfin perch	Freshwater straggler	Group 7 (LF)	45.2	<0.001
Lagoon goby	Solely estuarine	Group 7 (LF)	30.5	0.011
Tauwitchere small vertical-slot				
Redfin perch	Freshwater straggler	Group 1 (HF)	99.2	0.001
Flat-headed gudgeon	Freshwater est-opportunist	Group 1 (HF)	93.4	<0.001
Carp gudgeon complex	Freshwater straggler	Group 1 (HF)	41.5	0.006
Lagoon goby	Solely estuarine	Group 1 (HF)	62.4	0.002
Blue-spot goby	Solely estuarine	Group 1 (HF)	44.4	0.002
Golden perch	Freshwater straggler	Group 2 (HF)	34.3	0.050
Common carp	Freshwater straggler	Group 2 (HF)	69.3	0.003
Sandy sprat	Marine est-opportunist	Group 2 (HF)	44.6	0.014
Common galaxias	Semi-catadromous	Group 4 (LF)	55.6	0.006

Goolwa sites

Cluster analysis of fish assemblages sampled at the Goolwa vertical-slot produced seven groupings of sampling years (Table 3-2). These groupings could be described in terms of annual discharge: no flow (0 GL) = group 2 (2008/09) and 3 (2009/10); low flow (63–370 GL) = group 1 (2006/07, 2018/19); moderate flow (562–1600 GL) = group 5 (2013/14, 2015/16) and 6 (2014/15, 2017/18); and high flow (6536–12,500 GL) = group 4 (2010/11, 2011/12) and 7 (2016/17). At the site adjacent Goolwa Barrage, six cluster groups were produced. These were: no flow (0 GL) = group 1 (2008/09) and 2 (2009/10); low–moderate flow (370–1600 GL) = group 5 (2013/14, 2014/15, 2017/18, 2018/19) and 6 (2015/16); and high flow (6536–12,500 GL) = group 3 (2010/11) and 4 (2011/12, 2016/17).

Based on SIMPER, the low flow grouping of fish assemblages from the Goolwa vertical-slot, which encompassed 2018/19, differed from no flow years due to greater abundances of freshwater Australian smelt, catadromous congolli and common galaxias, and estuarine-marine opportunist sandy sprat, in low flow years. Greater abundance of catadromous congolli and common galaxias, but lower abundance of freshwater Australian smelt, in low flow years, drove differences from high flow years. Alternatively, the groupings of low–moderate flow years (group 5 and 6) differed from the low flow grouping of 2006/07 and 2018/19, due to greater abundances of the catadromous congolli and common galaxias in the aforementioned groups.

In accordance, SIMPER of fish assemblage clusters sampled adjacent Goolwa Barrage suggested the low–moderate flow grouping (group 5) that encompassed 2018/19 differed from no flow years due to greater abundances of freshwater bony herring and Australian smelt, catadromous congolli and common galaxias, and estuarine-marine opportunist sandy sprat in low flow years. In addition, higher abundance of catadromous congolli and common galaxias, but lower abundance of freshwater bony herring and flat-headed gudgeon, drove differences with high flow years.

ISA of assemblage data from the Goolwa vertical-slot indicated the assemblage from low flow years encompassing 2006/07 and 2018/19 (group 1) was characterised by the anadromous short-headed lamprey and marine-estuarine opportunist mulloway (Table 3-5). No flow assemblages were characterised by the estuarine black bream and marine estuarine-opportunist flat-tailed mullet (group 2), the estuarine small-mouthed hardyhead (*Atherinosoma microstoma*) and Tamar River goby, estuarine and marine bridled goby, marine estuarine-opportunist Australian salmon and marine straggler zebra fish (*Girella zebra*) (group 3). Conversely, high flow assemblages were characterised by the freshwater golden perch, Australian smelt, redfin perch, and estuarine lagoon goby.

The assemblage sampled adjacent Goolwa Barrage during no flow years was characterised by the estuarine black bream and marine estuarine-opportunist yelloweye mullet (*Aldrichetta forsteri*) (2008/09), or the marine estuarine-opportunist smooth toadfish (*Tetractenos glaber*) and marine straggler zebra fish (2009/10) (Table 3-5). High flow years were characterised by a suite of freshwater species (i.e. flat-headed gudgeon, carp gudgeon, redfin perch, Australian smelt, golden perch), and the estuarine and marine bridled goby. The low flow grouping that encompassed sampling from 2018/19, was characterised by the catadromous congolli.

Table 3-5. Indicator species analysis of fish assemblages in the Coorong at the Goolwa vertical slot from and adjacent Goolwa Barrage based on groupings of sampling years from Cluster analysis (75% similarity). Cluster groupings are defined by annual flow: NF = no flow (0 GL), LF = low flow (63–1600 GL), HF = high flow (>5000 GL). Only significant indicators (i.e. $p < 0.05$) are presented. Species are categorised using estuarine use guilds proposed by Potter *et al.* (2015) and designated for species of the Coorong and Lower Lakes by Bice *et al.* (2018).

Species	**Guild**	**Year**	**Indicator Value**	***p* value**
Goolwa vertical-slot				
Short-headed lamprey	Anadromous	Group 1 (LF)	41.2	0.020
Mulloway	Marine est-opportunist	Group 1 (LF)	29.4	0.039
Black bream	Solely estuarine	Group 2 (NF)	45.9	0.008
Flat-tailed mullet	Marine est-opportunist	Group 2 (NF)	37.1	0.032
Small-mouthed hardyhead	Solely estuarine	Group 3 (NF)	50.0	<0.001
Bridled goby	Estuarine & marine	Group 3 (NF)	41.4	0.012
Tamar River goby	Solely estuarine	Group 3 (NF)	26.1	0.019
Australian salmon	Marine est-opportunist	Group 3 (NF)	40.3	0.031
Zebra fish	Marine straggler	Group 3 (NF)	61.4	0.004
Redfin perch	Freshwater straggler	Group 4 (HF)	27.3	0.009
Lagoon goby	Solely estuarine	Group 4 (HF)	38.8	0.013
Flat-headed gudgeon	Freshwater est-opportunist	Group 5 (LF)	23.9	0.023
Australian smelt	Freshwater est-opportunist	Group 7 (HF)	26.8	0.010
Golden perch	Freshwater straggler	Group 7 (HF)	52.7	0.002
Adjacent Goolwa Barrage				
Black bream	Solely estuarine	Group 1 (NF)	38.7	0.031
Yelloweye mullet	Marine est-opportunist	Group 1 (NF)	41.7	0.011
Smooth toadfish	Marine est-opportunist	Group 2 (NF)	52.3	0.002
Zebra fish	Marine straggler	Group 2 (NF)	33.3	0.050
Flat-headed gudgeon	Freshwater est-opportunist	Group 3 (HF)	41.9	<0.001
Carp gudgeon	Freshwater straggler	Group 3 (HF)	60.3	0.003
Redfin perch	Freshwater straggler	Group 3 (HF)	44.0	<0.001
Australian smelt	Freshwater est-opportunist	Group 3 (HF)	33.8	0.001
Bridled goby	Estuarine & marine	Group 3 (HF)	35.6	0.016
Golden perch	Freshwater straggler	Group 4 (HF)	41.3	0.022
Congolli	Catadromous	Group 5 (LF)	21.2	0.036
Blue-spot flathead	Marine est-opportunist	Group 6 (LF)	50.0	0.008
Common galaxias	Catadromous	Group 6 (LF)	44.7	<0.001
Small-mouthed hardyhead	Solely estuarine	Group 6 (LF)	31.8	0.039

Hunters Creek

Cluster analysis of fish assemblages sampled at the Hunters Creek vertical-slot grouped each sampling year separately (Table 3-2). SIMPER suggested these differences were generally due to fluctuating abundances of the freshwater redfin perch, common carp, flat-headed gudgeon and bony herring, and the catadromous congolli and common galaxias, among years. ISA determined that only assemblages sampled during high flow years had significant indicators. As such, the assemblage sampled in 2010/11 was characterised by the freshwater redfin perch, flat-headed gudgeon and common carp, the assemblage in 2011/12 by the freshwater golden perch and goldfish (*Carassius auratus*), and the assemblage sampled in 2016/17 was characterised by the freshwater carp gudgeon and dwarf flat-headed gudgeon, and marine estuarine-opportunist flat-tailed mullet (Table 3-6).

Table 3-6. Indicator species analysis of fish assemblages at the Hunters Creek vertical slot from 2010–2019. Only significant indicators (i.e. $p < 0.05$) are presented. Species are categorised using estuarine use guilds proposed by Potter *et al.* (2015) and designated for species of the Coorong and Lower Lakes by Bice *et al.* (2018).

Species	Guild	Year	Indicator Value	*p* value
Redfin perch	Freshwater straggler	Group 1 (HF)	42.7	0.005
Flat-headed gudgeon	Freshwater est-opportunist	Group 1 (HF)	25.4	0.003
Common carp	Freshwater est-opportunist	Group 1 (HF)	39.3	<0.001
Golden perch	Freshwater straggler	Group 2 (HF)	51.4	0.003
Goldfish	Freshwater straggler	Group 2 (HF)	33.7	0.033
Carp gudgeon	Freshwater straggler	Group 6 (HF)	39.3	0.004
Dwarf flat-headed gudgeon	Freshwater straggler	Group 6 (HF)	58.1	0.005
Flat-tailed mullet	Marine est-opportunist	Group 6 (HF)	54.6	0.006

3.4. Spatial variation in fish assemblages in 2018/19

MDS ordination of fish assemblage data from the vertical-slot fishways exhibited grouping of samples by sites (Figure 3-5a). The primary PERMANOVA detected significant differences in fish assemblages between capture locations ($Pseudo\text{-}F_{3,\ 15} = 1.85$, $p < 0.001$), and pair-wise comparisons suggested assemblages were significantly different among all comparisons (*p* <

0.05), with the exception of Hunters Creek, and the Tauwitchere small vertical-slot (t = 1.97, p = 0.058). MDS ordination of fish assemblage data from the Tauwitchere rock ramp and adjacent Goolwa Barrage (GDS) exhibited separation (Figure 3-5b) and PERMANOVA indicated assemblages sampled from these locations were significantly different ($Pseudo\text{-}F_{1,7}$ = 2.70, p = 0.030).

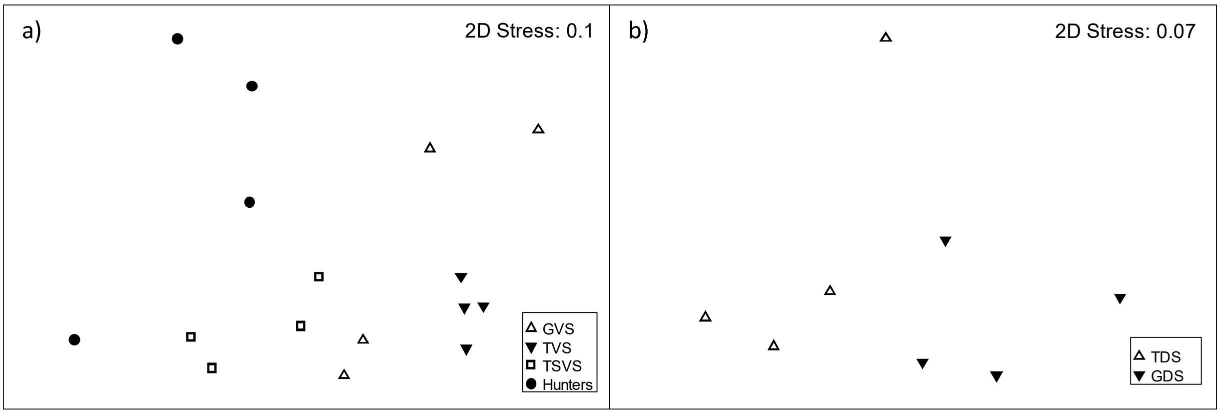

Figure 3-5. MDS ordination plot of fish assemblages sampled at the a) Tauwitchere large vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS), Goolwa vertical-slot (GVS), and Hunters Creek vertical-slot (Hunters), and b) Tauwitchere rock ramp and adjacent Goolwa Barrage (GDS) in 2018/19.

Indicator species analysis was used to determine species that characterised assemblages at the different sites in 2018/19. Among the vertical-slot fishways, the marine estuarine-opportunist sandy sprat and yelloweye mullet, and catadromous congolli characterised the assemblages at Goolwa large vertical-slot, the freshwater carp gudgeon, redfin perch, flat-headed gudgeon and estuarine lagoon goby characterised the assemblage at the Tauwitchere large vertical-slot, and the estuarine smallmouth hardyhead characterised the Hunters Creek vertical-slot (Table 3-7). Between the Tauwitchere rock ramp and site adjacent Goolwa Barrage, assemblages at the former were characterised by the marine-estuarine opportunist mulloway and estuarine lagoon goby, whilst the estuarine Tamar River goby characterised the latter.

Table 3-7. Indicator species analysis of fish assemblages in the Coorong at vertical-slot fishway (i.e. the Tauwitchere vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS), Goolwa vertical-slot (GVS) and Hunters Creek vertical-slot) and sites sampled with fyke nets (i.e. Tauwitchere rock ramp (TRR), and adjacent Goolwa Barrage (GDS)) in 2018/19.

Species		**Location**	**Indicator Value**	***p* value**
Vertical-slot sites				
Congolli	Freshwater straggler	GVS	33.1	0.033
Sandy sprat	Marine est-opportunist	GVS	71.7	0.030
Yelloweye mullet	Marine est-opportunist	GVS	75.0	0.030
Carp gudgeon	Freshwater straggler	TVS	59.2	0.025
Redfin perch	Freshwater straggler	TVS	51.1	0.015
Flat-headed gudgeon	Freshwater est-opportunist	TVS	49.5	0.014
Lagoon goby	Soley estuarine	TVS	81.9	0.002
Smallmouth hardyhead	Soley estuarine	Hunters	69.6	0.019
Fyke net sites				
Mulloway	Marine est-opportunist	TRR	77.7	0.029
Lagoon goby	Soley estuarine	TRR	74.6	0.029
Tamar River goby	Soley estuarine	GDS	62.2	0.029

3.5. Spatio-temporal variation in the abundance and recruitment of diadromous species

Inter-annual variation in abundance

Lamprey

A total of 6 pouched lamprey were sampled from the Goolwa vertical-slot (*n* = 4), Mundoo dual vertical-slot (*n* = 1) and Tauwitchere large vertical-slot (*n* = 1) fishways during winter monitoring in 2018. This followed the sampling of variable numbers of pouched lamprey in winter 2017 (*n* = 53), 2016 (*n* = 7), 2015 (*n* = 56), 2013 (*n* = 2) and 2011 (*n* = 10). In addition, in October 2018, a single short-headed lamprey was sampled from the Goolwa vertical-slot fishway. Short-headed lamprey was sampled in moderate abundance across three locations from September to November 2006, but was absent from 2007–2011, before being sampled in low abundance adjacent Goolwa Barrage in November 2011. The species was then absent from 2012–2018 (Figure 3-6b).

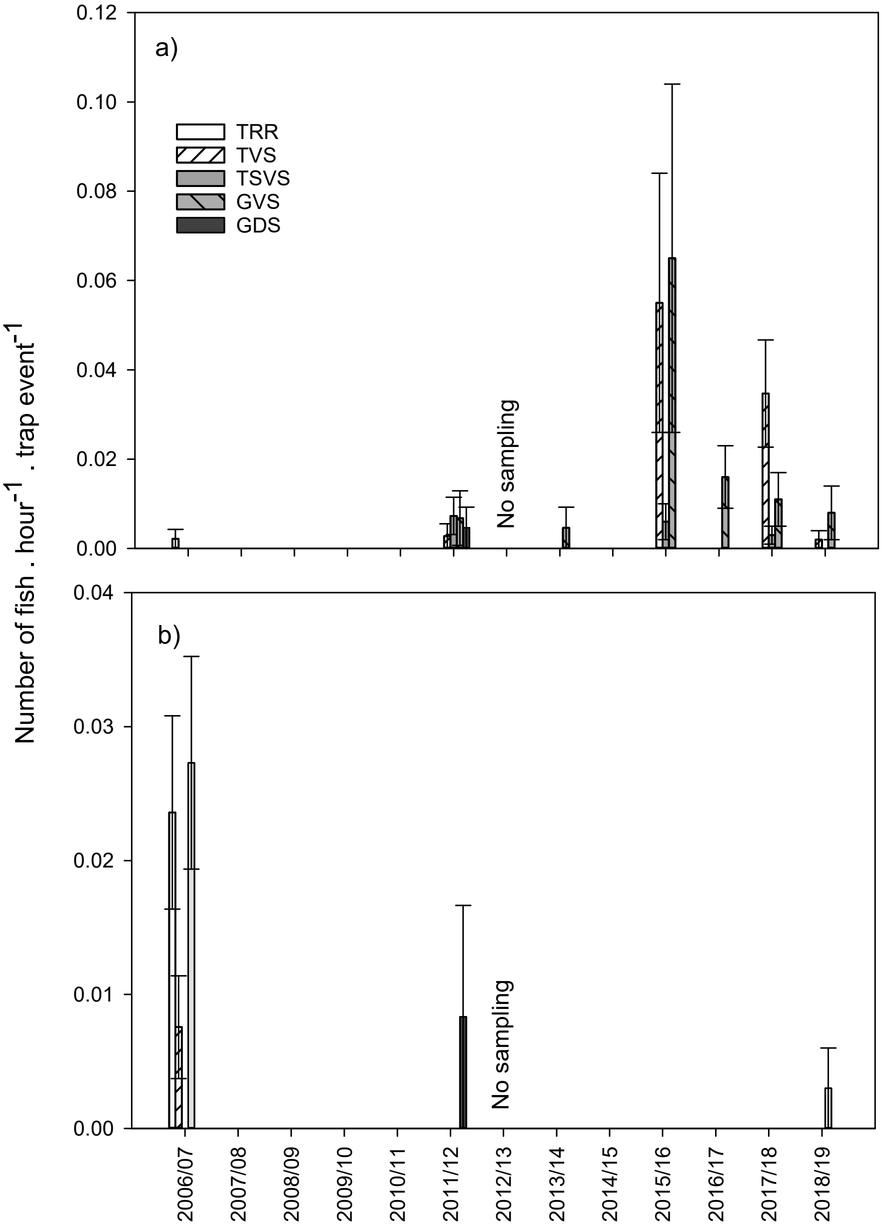

Figure 3-6. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of a) pouched lamprey and b) short-headed lamprey at the Tauwitchere rock ramp (TRR), Tauwitchere large vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS), Goolwa vertical-slot (GVS) and adjacent Goolwa Barrage (GDS) from 2006–2019. No sampling was undertaken in 2012/13, whilst Goolwa vertical-slot was not sampled in 2007/08 and the site adjacent Goolwa Barrage was not sampled in 2006/07 and 2007/08. The Tauwitchere small vertical-slot was only sampled in 2010/11, 2011/12 and 2013/14. Data from 2011/12, 2013/14, 2015/16, 2016/17, 2017/18 and 2018/19 includes supplementary sampling in winter.

Congolli and common galaxias

The abundance of the catadromous congolli and common galaxias differed significantly between years at all sampling locations (Table 3-8). Overall, patterns of variability in abundance of congolli were consistent across sites with decreased abundances over the period 2007–2010, relative to 2006/07, and a trend of gradually increasing abundance from 2010/11 through to 2014/15. Since this time, abundances of congolli have been relatively high, but variable; nevertheless abundances recorded in 2018/19, whilst greater than recorded from 2006–2010, were among the lowest recorded since 2011/12 (Figure 3-7a).

Table 3-8. Summary of results of uni-variate single factor PERMANOVA to determine differences in the relative abundance (number of fish.hour^{-1}.trap event^{-1}) of congolli and common galaxias sampled from 2006–2019 at the Tauwitchere rock ramp (TRR), Tauwitchere vertical-slot (TVS), Goolwa vertical-slot (GVS), adjacent Goolwa Barrage (GDS), Tauwitchere small-vertical-slot and Hunters Creek vertical-slot. PERMANOVA was performed on Euclidean Distance similarity matrices. α = 0.05.

		Congolli		**Common galaxias**	
Site	**df**	***Pseudo-F***	***P* value**	***Pseudo-F***	***P* value**
TRR	11, 110	27.47	<0.001*	27.42	<0.001*
TVS	11, 149	16.84	<0.001*	43.79	<0.001*
GVS	10, 164	13.20	<0.001*	4.93	<0.001*
GDS	9, 58	12.09	<0.001*	11.93	<0.001*
TSVS	7, 112	7.58	<0.001*	11.51	<0.001*
Hunters	7, 110	4.77	0.003*	2.07	0.050*

As with congolli, common galaxias was typically sampled in low abundances through the period 2007–2010, with the exception of the Goolwa vertical-slot where this species was sampled in relatively high abundance in 2009/10 (Figure 3-7b). Following the reconnection of the Lower Lakes and Coorong in 2010/11 abundance generally increased relative to preceding years, with further increases occurring annually until abundance peaked in 2014/15. Abundance in 2018/19, remained high relative to the period 2006–2011, but abundances at several sites (TRR, GDS, Hunters) were among the lowest recorded over the period 2013–2019 (Figure 3-7b).

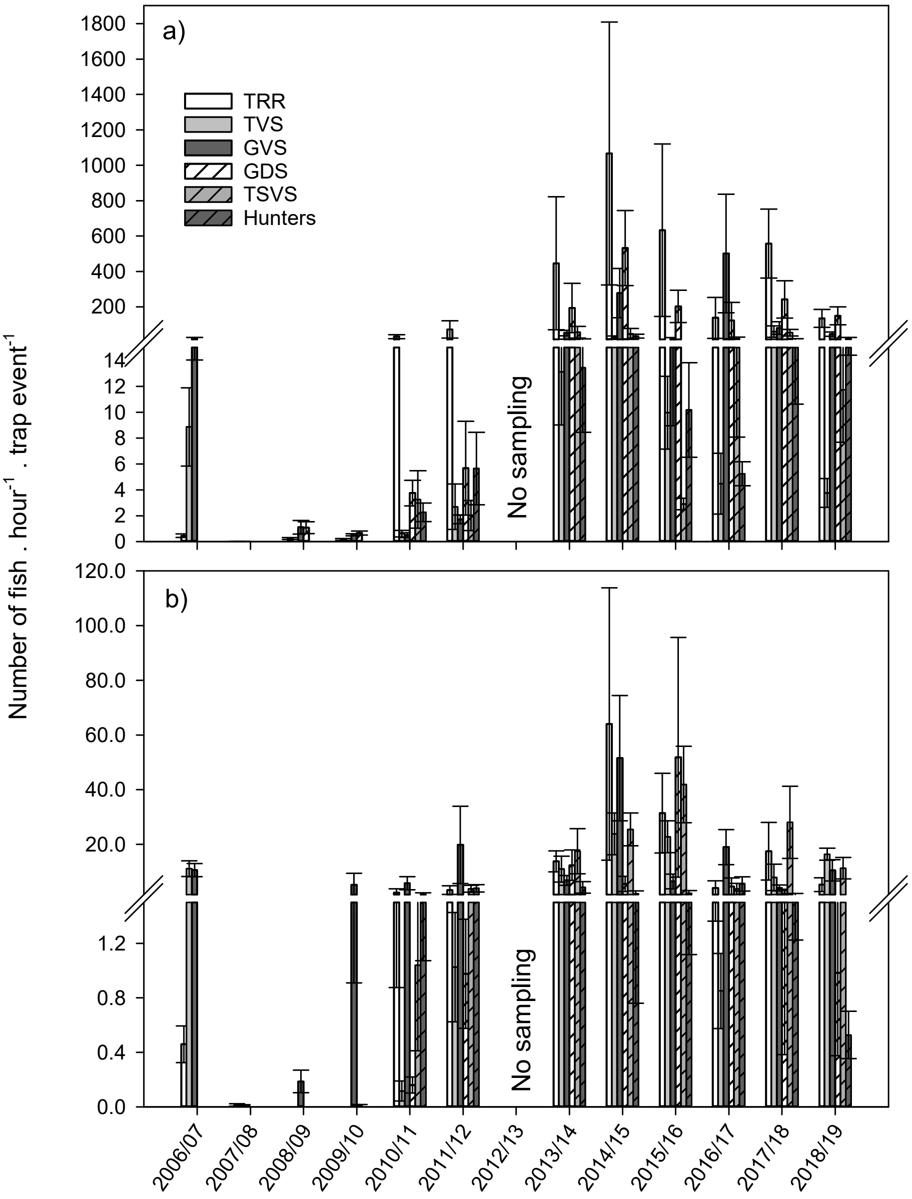

Figure 3-7. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of a) congolli and b) common galaxias at the Tauwitchere rock ramp (TRR), Tauwitchere vertical-slot (TVS), Goolwa vertical-slot (GVS), adjacent Goolwa Barrage (GDS), Tauwitchere small vertical-slot (TSVS) and Hunters Creek vertical-slot (Hunters) from 2006–2019. Goolwa vertical-slot was not sampled in 2007/08 and adjacent Goolwa Barrage was not sampled in 2006/07 and 2007/08. The Tauwitchere small vertical-slot and Hunters Creek vertical-slot were sampled from 2010/11 onwards. All sites were not sampled in 2012/13.

Intra-annual variation in abundance and recruitment of congolli and common galaxias

The abundance of upstream migrating congolli varied substantially between months. Across all sites, abundance was typically greatest in December, with the exception of *adjacent Goolwa Barrage*, where abundance peaked in January (Figure 3-8a). In 2018/19, peak daily abundance of congolli was detected at the Goolwa vertical-slot on 13 December when 172 fish.hr^{-1} were detected migrating upstream.

The abundance of upstream migrating common galaxias also varied substantially between months, but patterns of variability differed among sites (Figure 3-8b). Abundance peaked in October at Hunters Creek, November at the Goolwa vertical-slot, December at sites on Tauwitchere Barrage, and in January adjacent Goolwa Barrage. In 2018/19, peak daily abundance of common galaxias was detected at the Tauwitchere small vertical-slot on 12 December when 45 fish.hr^{-1} were detected migrating upstream.

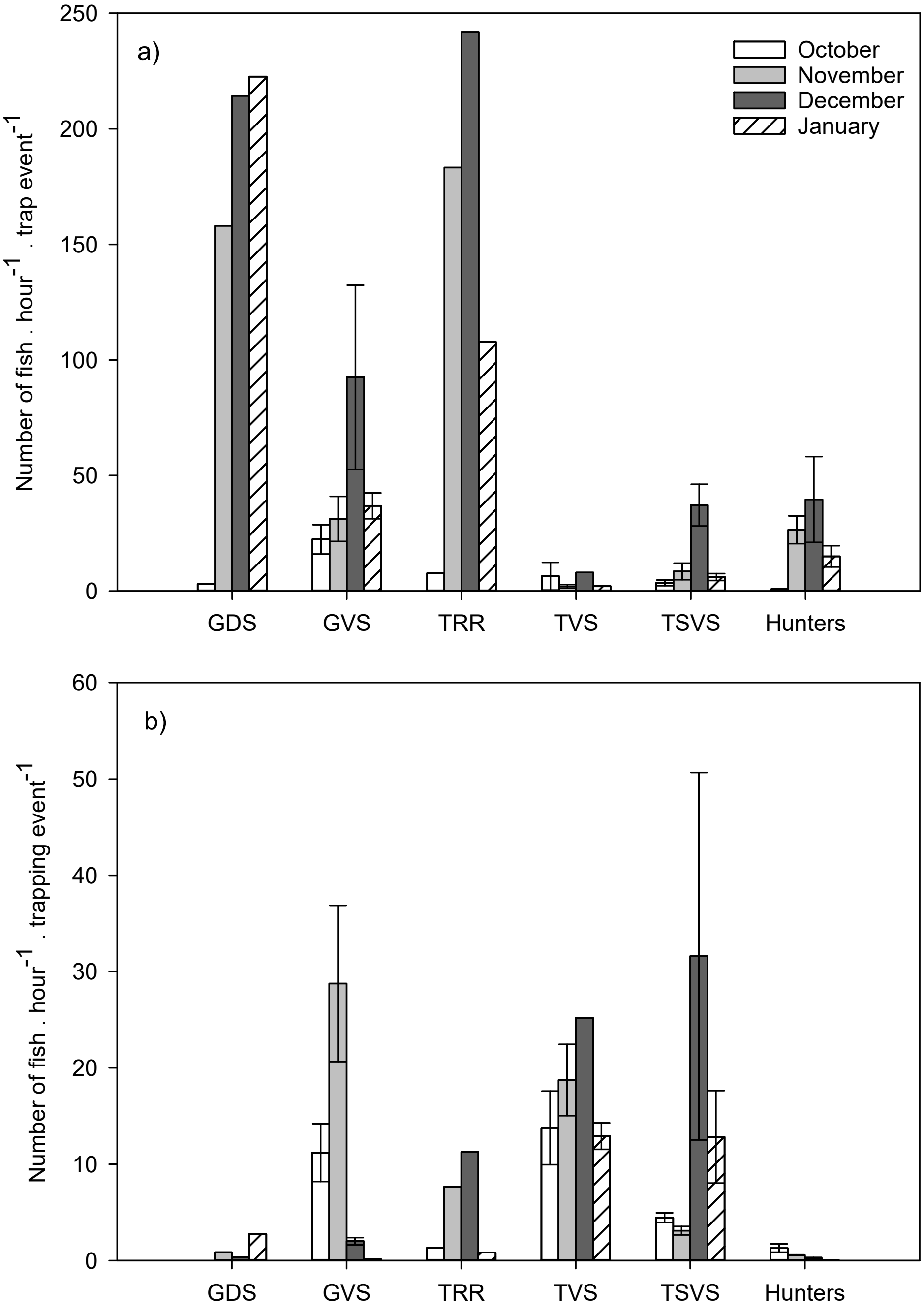

Figure 3-8. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of a) congolli and b) common galaxias at adjacent Goolwa Barrage (GDS), Goolwa vertical-slot (GVS), Tauwitchere rock ramp (TRR), Tauwitchere vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS) and Hunters Creek vertical-slot (Hunters) from October 2018–January 2019.

Below Tauwitchere Barrage (Tauwitchere rock ramp, large vertical-slot and small vertical-slot data combined) in October 2018, congolli were sampled across a broad length distribution ranging 24–148 mm TL (Figure 3-9a). A YOY cohort ranging 24–32 mm TL was present and represented 19% of the sampled population. Whilst fish were not aged in 2018/19, fish of this size have previously been determined to represent a 0+ cohort (Bice *et al.* 2012). The mode and range of length distributions for the YOY cohort increased throughout the sampling period (November 2018: 24–49 mm TL, December 2018: 30–57 mm TL and January 2019: 35–60 mm TL), and increased in prominence, comprising 82–95% of the sampled population during each month.

A similar pattern was evident below Goolwa Barrage (vertical-slot and adjacent Goolwa Barrage data combined) with the sampled population of fish ranging 23–122 mm TL (Figure 3-9b), with a prominent YOY cohort (26–48 mm TL; 64% of population) in October 2018 (Figure 3-9b). Growth of this cohort was evident through the following months, progressing to 23–47, 24–55 and 32–59 mm TL in November 2018, December 2018 and January 2019, respectively. This cohort increased in dominance, comprising >95% of the population in November–January.

Length-frequency distributions at Hunters Creek were similar to both Tauwitchere and Goolwa (Figure 3-9c). Sampled fish ranged 26–138, 34–122, 36–114 and 33–117 mm TL during sequential sampling events and the YOY cohort (<60 mm TL) represented >95% of the sampled population during all months, with the exception of October (63%).

Common galaxias ranged 35–103 mm TL at Tauwitchere in October 2018, but individuals 35–50 mm TL comprised 81% of the sampled population (Figure 3-10a). As for congolli, whilst common galaxias were not aged in 2018/19, fish of this size have been determined to represent a YOY cohort in previous years (see Bice *et al.* 2012). The 0+ cohort represented >96% of the sampled population in November–January.

At Goolwa in October 2018, the YOY cohort of common galaxias ranged 29–50 mm TL and comprised 100% of the sampled population (Figure 3-10b). The mode of this cohort gradually increased across sampling months and it comprised >87% of the sampled population in all months.

The length-frequency distributions for common galaxias at Hunters Creek in October and November 2018 were different to Tauwitchere and Goolwa, ranging 48–120 and 46–108 mm TL, respectively, and dominated by fish >60 mm TL (Figure 3-10c). A 0+ cohort (<60 mm TL) was apparent in December comprising 94% of the sampled population, while only two fish were sampled in January 2019 (60–62 mm TL), both of which were likely 0+ (Figure 3-10c).

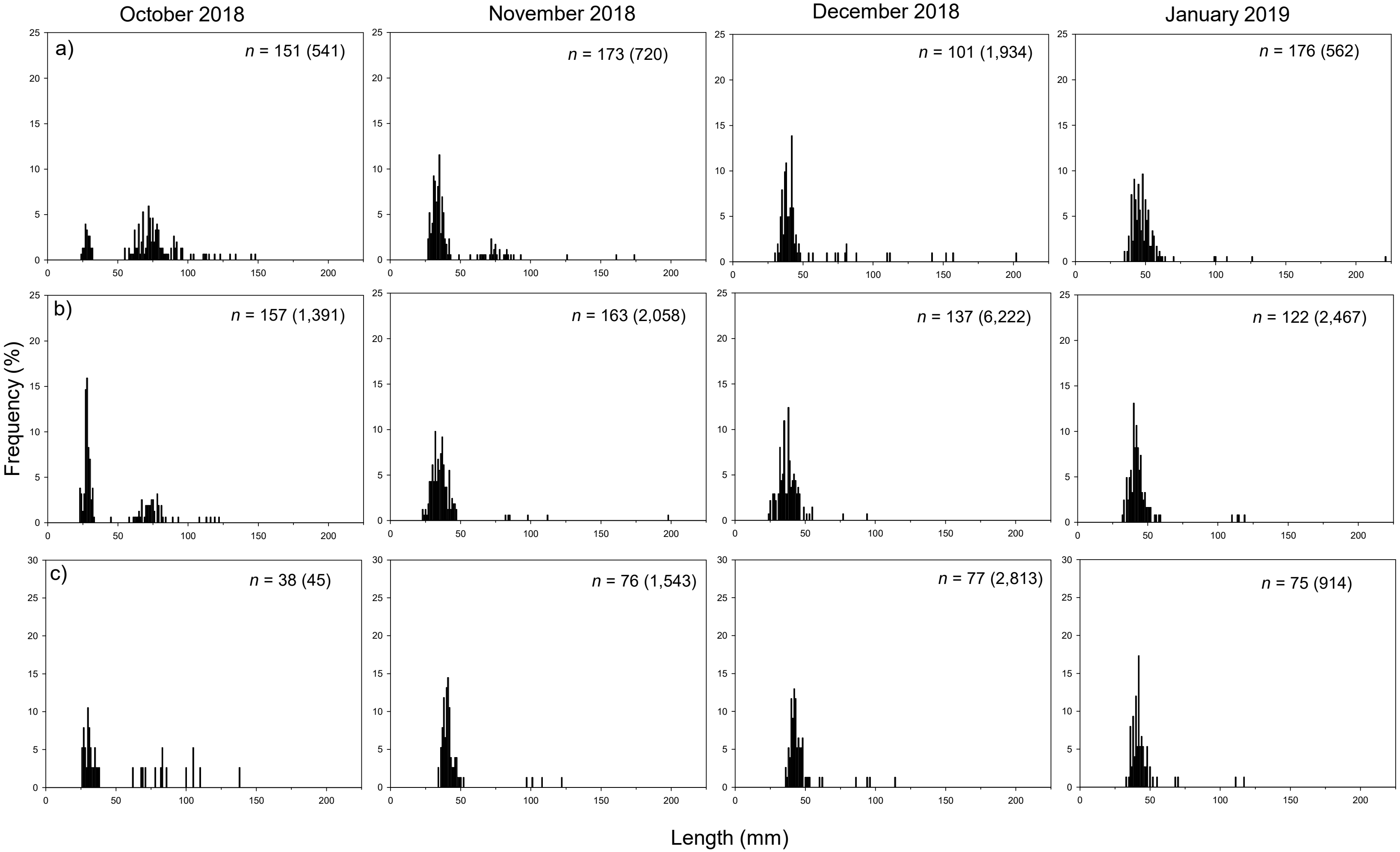

Figure 3-9. Monthly length-frequency distributions (total length, mm) of congolli sampled below a) Tauwitchere Barrage (rock ramp, large vertical-slot and small vertical-slot combined) b) Goolwa Barrage (vertical-slot and adjacent Goolwa Barrage combined) and c) at the entrance of the Hunters Creek vertical-slot from October 2018–January 2019. *n* is the number of fish measured and the total number of fish collected in each month at each site is presented in brackets.

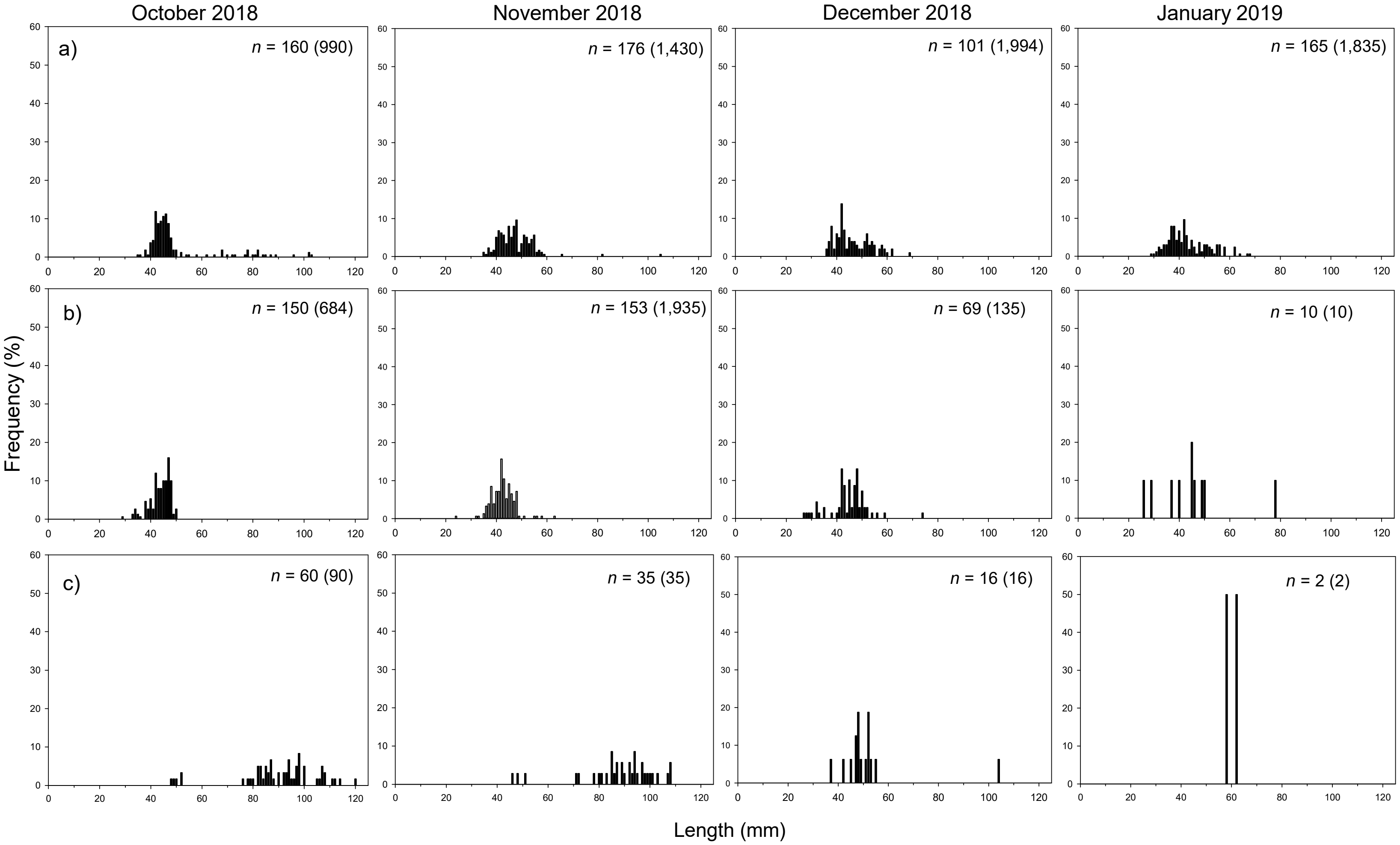

Figure 3-10. Monthly length-frequency distributions (total length, mm) of common galaxias sampled below a) Tauwitchere Barrage (rock ramp, large vertical-slot and small vertical-slot combined) b) Goolwa Barrage (vertical-slot and adjacent Goolwa Barrage combined) and c) at the entrance of the Hunters Creek vertical-slot from October 2018–January 2019. *n* is the number of fish measured and the total number of fish collected in each month at each site is presented in brackets.

3.6. Assessment of TLM condition monitoring targets

Target 1 and 2: Catadromous fish migration and recruitment

Comparison of the annual recruitment index (*RI*) against the predetermined reference value suggests that Target 1 was met for congolli in 2018/19 (Figure 3-11a). The target was also met in 2013/14, 2014/15, 2015/16, 2016/17 and 2017/18, but not met in 2006/07, 2007/08, 2008/09, 2009/10 and 2010/11. A similar pattern of variability in abundance of upstream migrating juveniles was evident for common galaxias; Target 2 was met in all years (including 2018/19) with the exception of 2007/08, 2008/09, 2010/11 and 2016/17 (Figure 3-11b).

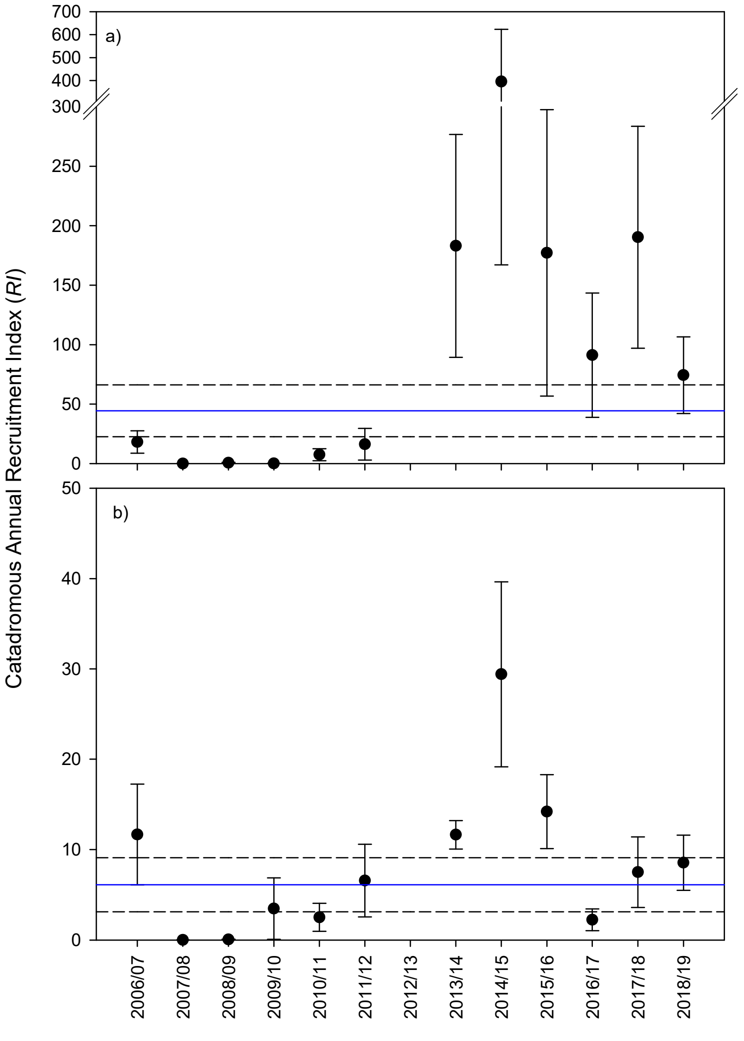

Figure 3-11. Catadromous annual recruitment index (*RI,* number of upstream migrating YOY.hour^{-1} ± half confidence interval for a) congolli and b) common galaxias from 2006/07 to 2018/19 (no sampling was conducted in 2012/13). The reference value is indicated by the blue line and half confidence intervals indicated by dashed lines.

Target 3: Anadromous migration

The migration index (*MI*) for short-headed lamprey was not met 2018/19, despite being sampled for the first time since 2011 (Figure 3-12). This target has only been achieved in 2006/07. The migration index (*MI*) for pouched lamprey was not met in 2018/19, although the species was sampled at 40% of fishway sites (Figure 3-12). Pouched lamprey was only sampled from one site in 2006/07, resulting in low *MI* and failure to meet the target, and similar to short-headed lamprey, this was followed by absence from monitoring and failure to meet the target from 2007 to 2011. Individuals were subsequently sampled at 80% of fishway sites in 2011/12 and the target was met for this species. Individuals were sampled from one fishway site in 2013/14 and were absent in 2014/15, resulting in failure to meet the target in both years. In 2015/16, pouched lamprey were detected at all fishway sites, resulting in the target being met. In 2016/17 and 2017/18, the species was sampled from 50 and >60% of fishway sites. Notably, *MI* is typically highest during years with specific winter monitoring.

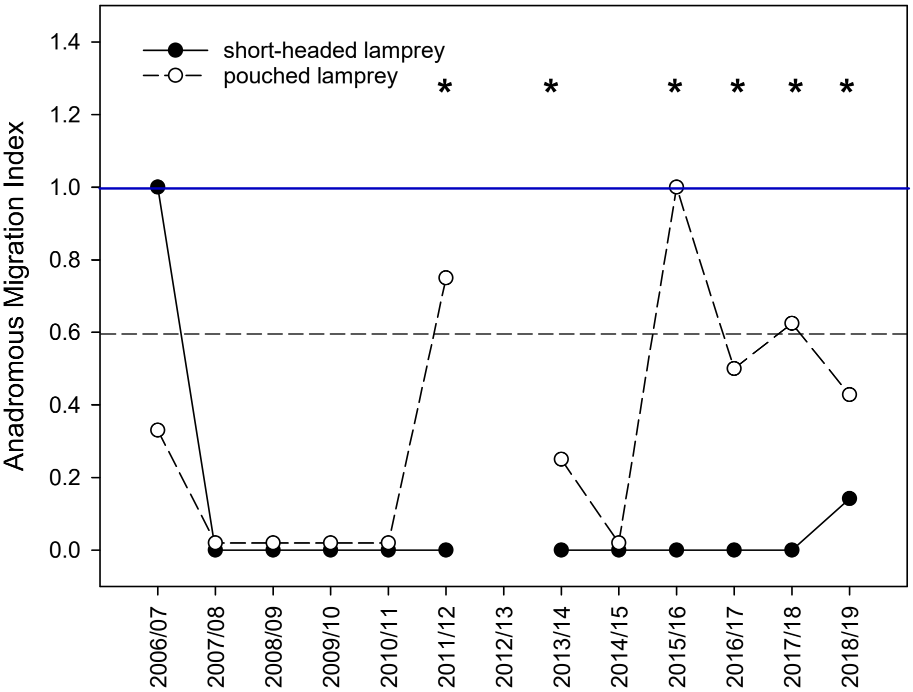

Figure 3-12. Anadromous migration index (*MI*) for short-headed lamprey (*open circles*) and pouched lamprey (*closed circles*) from 2006/07 to 2018/19 (no sampling was conducted in 2012/13). The blue line represents the reference value and dashed line indicates a 40% tolerance and level deemed to indicate target was met. * indicate years in which specific sampling for lamprey occurred during winter.

4. DISCUSSION

4.1. Fish assemblages

Inter-annual variation

2018/19 represented a year of low discharge (mean daily discharge 1013 ML.d^{-1}), but the ninth consecutive year of continuous freshwater discharge to the Coorong post the end of the Millennium Drought (September 2010). These conditions promoted connectivity between the Lower Lakes and Coorong, and a persistent salinity gradient from brackish to marine in the Coorong estuary. In 2018/19, 36 fish species, representing 25 families, were sampled at six sites immediately downstream of the Murray Barrages and the assemblage consisted of a diverse range of life history categories including freshwater, diadromous, estuarine and marine species. The structure of fish assemblages was characteristic of a dynamic estuary under the influence of low freshwater discharge, with similarity to other years of low (2006/07) and moderate discharge (e.g. 2015/16 and 2017/18). Young-of-the-year (YOY) of catadromous species were abundant, but generally less so than the period 2013–2018.

Among sites, there was a consistent pattern of temporal variability in fish assemblages across years from 2006/07 to 2018/19, characterised by four primary groupings of sampling years based on hydrology/freshwater discharge. These are: 1) depauperate assemblages during the extended period (2007–2010) of no freshwater discharge to the Coorong when marine species and some medium to large-bodied estuarine species were dominant, and diadromous and freshwater species were absent or in low abundance (Zampatti *et al.* 2011a); 2) assemblages associated with years of low discharge (e.g. 2006/07, 2018/19), characterised by low overall abundance, but high diversity, with moderate abundances of catadromous species; 3) assemblages associated with years of high discharge (2010/11, 2011/12 and 2016/17), characterised by high overall abundance, and high species-specific abundance for freshwater species, as well as the marine-estuarine opportunist sandy sprat; and 4) assemblages associated with years of intermediate discharge (2006/07, 2013–2016, 2017/18), characterised by total fish abundances intermediate between the two previous groupings, including moderate abundances of freshwater species, and the marine-estuarine opportunist sandy sprat, but typically high abundance of catadromous species.

Inter-annual variability in overall fish abundance is largely influenced by fluctuations in the abundance of the marine estuarine-opportunist sandy sprat. This species is a small-bodied (typically <100 mm TL), pelagic, schooling clupeid, which is common in coastal bays and estuaries across southern Australia (Gaughan *et al.* 1996, Gomon *et al.* 2008). Whilst considered a marine estuarine-opportunist species, it exhibits a positive association with freshwater inflows to the Coorong, being caught in greatest abundance during years of high freshwater flow (2010/11, 2011/12 and 2016/17). In 2011/12 and 2016/17, the mean abundance of sandy sprat at the Tauwitchere rock ramp was 19,989 and 11,215 fish.hr^{-1}, respectively, whilst in years of intermediate discharge, abundance ranged 176–1831 fish.hr^{-1}. In both high and intermediate flow years, the species typically comprises >50% of the total catch numerically (as high as 88% in 2011/12).

From 2006 to 2010, during years of low or no discharge, sandy sprat abundance at the Tauwitchere rock ramp ranged just 0.5–22 fish.hr^{-1}, and in 2018/19, was ~116 fish.hr^{-1}. Sandy sprat is zooplanktivorous and a recent study, utilising gut content and stable isotope analyses, indicated both the direct predation of freshwater zooplankton transported to the Coorong in freshwater discharge, and assimilation of organic matter of freshwater origin (Bice *et al.* 2016). Bice *et al.* (2016) proposed this trophic subsidy as a potential mechanism driving the abundance–discharge association for the species. Sandy sprat is fundamental to trophic dynamics in the Coorong (Giatas and Ye 2016), particularly the Murray estuary and upper North Lagoon, where, contrary to the South Lagoon, it supplants smallmouth hardyhead as the most abundant small-bodied fish (Ye *et al.* 2012). Increases in the abundance of sandy sprat are likely to have flow on effects to higher trophic organisms, including juvenile mulloway (Giatas and Ye 2015).

The influence of salinity on spatio-temporal variation in estuarine fish assemblage structure has been documented widely (Lonergan and Bunn 1999, Barletta *et al.* 2005, Baptista *et al.* 2010). Indeed the results of this study, from 2006–2019, confirm the importance of spatio-temporal variation in salinity in influencing fish assemblage patterns in the Coorong. At a range of spatial and temporal scales, low salinities promoted by high freshwater flows (e.g. 2010/11) often result in low species diversity and high abundances of freshwater and estuarine dependent species (Lamberth *et al.* 2008). Brackish salinities, such as those present in the Murray estuary in 2006/07, and 2011–2019 result in high species diversity, with a range of freshwater, diadromous, estuarine and marine migrant and straggler species present (Baptista *et al.* 2010). In contrast high salinities (e.g. marine and greater), such as those resulting from diminished freshwater inflows to the Coorong estuary from 2007–2010, result in decreased species diversity and an assemblage characterised by the loss of freshwater species and increases in marine species (Martinho *et al.* 2007).

Intra-annual spatial variation

In 2018/19, fish assemblages varied among vertical-slot fishways and reflected differences in abundances among Goolwa and Tauwitchere barrages, and differences in species-specific use of large and small vertical-slot fishways (Bice *et al.* 2017). Similar patterns were evident for the sites adjacent the barrages. Sites at Goolwa were characterised by the marine-estuarine sandy sprat and yelloweye mullet, estuarine Tamar River goby, and catadromous congolli. Alternatively, the freshwater redfin perch, carp gudgeon and flat-headed gudgeon, along with the estuarine lagoon goby, and marine-estuarine opportunist mulloway, characterised the assemblage at Tauwitchere. These spatial patterns are commonly observed across years with freshwater species typically more common at Tauwitchere. Sandy sprat, have also previously been shown to be most abundant at Goolwa during periods of low flow (e.g. 2006/07) (Zampatti *et al.* 2010); this contrasts spatial patterns during intermediate and high flows, when this species is most abundant at Tauwitchere (Bice *et al.* 2016), and may indicate a shift in the spatial distribution of sandy sprat within the Coorong with declining discharge in 2018/19.

Whilst not compared statistically, the fish assemblages sampled at the vertical-slot fishways and sites adjacent the barrages (i.e. Tauwitchere rock ramp and adjacent Goolwa Barrage) vary substantially. This variation reflects potential behavioural differences between species and the specificity of sampling locations at these sites. Sampling in the entrance of vertical-slot fishways typically collects fish in the process of undertaking ‘active’ migrations between the Coorong and Lower Lakes, whilst sampling at sites adjacent to the barrages captures accumulations of such species but also, large numbers of species from estuarine and marine life history categories residing adjacent the barrages. As such, species richness and overall abundance are typically greatest at the sites adjacent the barrages. Indeed, species richness varied from six species at the Tauwitchere small vertical-slot to 25 species adjacent the Tauwitchere rock ramp and Goolwa Barrage.

4.2. Abundance, recruitment and assessment of ecological targets for diadromous fish

Catadromous species

Total numbers and relative abundances of congolli in 2018/19, were high relative to the period 2006–2011, but were the lowest recorded since 2011/12 (Zampatti *et al.* 2010, 2011, Bice *et al.* 2012, Bice and Zampatti 2014). Nonetheless, congolli was the second most abundant species sampled in 2018/19, and when excluding the highly abundant sandy sprat, represented >50% of all remaining fish sampled. Similar patterns were evident for common galaxias in 2018/19, which could be considered abundant relative to 2006–2011, but abundance had declined relative to 2012–2018. Whilst no ageing of fish was conducted in 2018/19, length-at-age data from previous years (Zampatti *et al.* 2010, 2011, Bice *et al.* 2012), indicate that typically >80% of all individuals sampled for both species, in each month, were newly recruited YOY. Given moderate abundances of newly recruited YOY congolli and common galaxias, the annual recruitment index in 2018/19 was moderate in comparison to preceding years, but the condition monitoring target was achieved.

Annual recruitment of catadromous fishes appears influenced by two primary factors: 1) the abundance of reproductively mature adults (i.e. potential spawning biomass); and 2) hydrological connectivity between freshwater, estuarine and marine environments during the preceding winter/early spring, and subsequently, capacity for adult migration, spawning and survival of larvae/juveniles under brackish salinities (Whitfield 1994, Gillanders and Kingsford 2002). Recruitment and subsequent YOY abundance steadily increased from 2010/11 to 2014/15, following reinstatement of freshwater discharge and high levels of connectivity (Figure 4-1). The lack of connectivity and reduced recruitment of congolli and common galaxias from 2007–2010 may have resulted in a depleted population of reproductively mature adults. As such, while recruitment was enhanced following the resumption of freshwater flow in 2010/11, the number of juveniles produced may have been limited by the adult spawning biomass. Congolli typically mature at 3–4 years of age (Hortle 1978) and thus, the adult spawning population post–2014 was likely abundant and comprised of fish that recruited and migrated into freshwater habitats from 2010/11 to 2014/15. Fluctuations in abundance of YOY post-2014, however, likely reflect variability in connectivity during the winter downstream migration period. Indeed, since 2014, a metric of connectivity we term ‘percentage of connected days’, (the percentage of days over June–August when at least one barrage bay is open) fluctuates in unison with YOY abundance

(Figure 4-1). As such, providing connectivity through open barrage gates during winter is likely an important driver of subsequent recruitment.

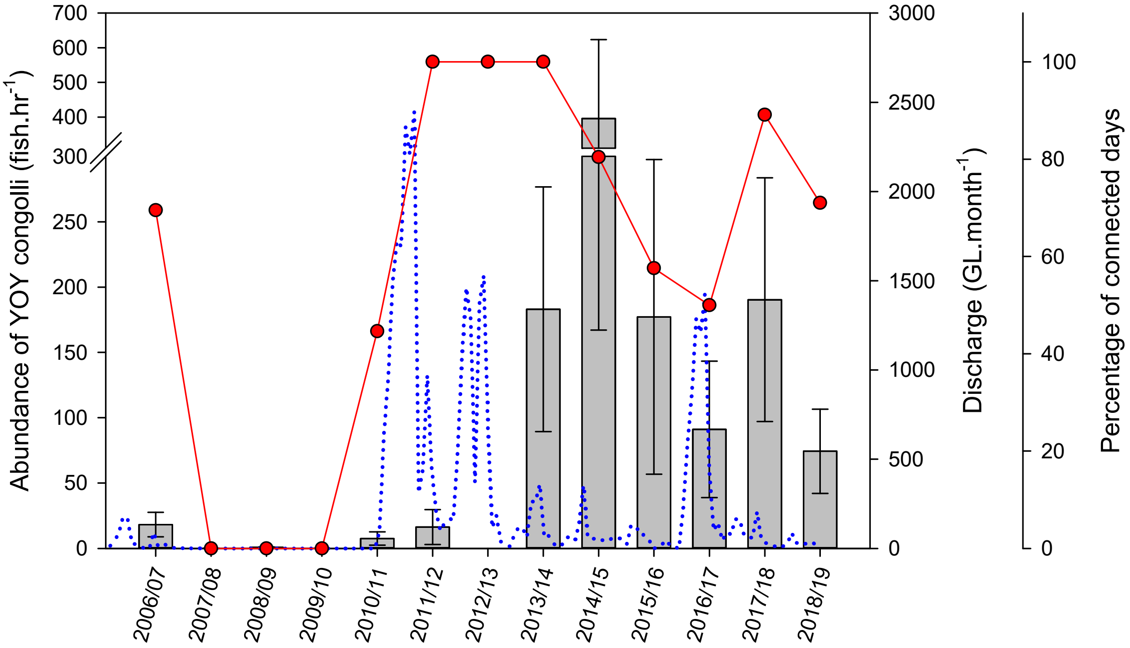

Figure 4-1. The abundance of YOY congolli sampled across the Murray Barrages from 2006–2019, with discharge (GL.month^{-1}, *blue dotted line*) and percentage of connected days (*red line*) overlaid.

Anadromous species

In 2018/19, a total of 6 pouched lamprey and a single short-headed lamprey were sampled during monitoring, and the annual migration index and Icon Site ecological target was not achieved for either species. Nevertheless, pouched lamprey were sampled from 50% of fishway sites, just below the 60% required to meet the target, while the capture of a single short-headed lamprey represented the first detection of this species at the Murray Barrages since 2011.

Whilst the migration of pouched lamprey and short-headed lamprey at the Murray Barrages, and more broadly in the MDB, remains poorly understood, a model for the movement of these species is emerging. Capture of pouched lamprey in all years in which specific winter monitoring (June–September) has been undertaken, as well as knowledge of migration from other river systems (McDowall 1996), suggests winter is the key upstream migration period for this species.

Alternatively, peak upstream migration of short-headed lamprey at the Murray Barrages likely occurs slightly later, in late winter–spring, which is consistent with peak migration in other systems in southeastern Australia (McDowall 1996). This period is typically not sampled during specific winter monitoring or annual spring/summer sampling, which generally commences from mid/late-October. Assessment of the status of lamprey species is reliant on sampling during specific periods. As such, we propose that in years when monitoring is conducted from June to August, a reliable assessment of pouched lamprey status may be achieved. Nonetheless, rigorous assessment of the status of short-headed lamprey likely requires sampling from August to November.

4.3. Implications for management and operation of the barrages and fishways

Data collected from this project from 2006–2019 (Bice *et al.* 2007, 2012, 2016, 2017b, 2019, Jennings *et al.* 2008a, Zampatti *et al.* 2010, 2011, 2012, Bice and Zampatti 2014, 2015) and related projects (Jennings *et al.* 2008b, Bice *et al.* 2016, 2017a, 2018b) provide fundamental knowledge to inform the operation of the Murray Barrages and associated fishways to aid in the conservation and restoration of native fish populations in the MDB. Indeed, specific periods of peak migration can be identified for different life stages of diadromous species, which are obliged to move between freshwater and marine/estuarine environments to complete their lifecycle. These periods should be prioritised for freshwater releases and fishway operation.

Newly recruited YOY congolli and common galaxias migrate upstream during spring/summer, but there are often subtle differences in the timing of peak migration. Peak migration of congolli typically occurs in December–January, whilst peak migration of common galaxias may occur from October–December (Bice *et al.* 2007, 2012, Zampatti *et al.* 2012, Bice and Zampatti 2015), and as such, the period October–January represents a critical period for fishway operation. Whilst both of these species typically migrate upstream in greatest numbers during specific months, migrations can generally occur over a protracted period from September–March.

Adult congolli and common galaxias must also migrate downstream to spawn. The key downstream migration period for adult congolli occurs from June–August (Bice *et al.* 2018b). The downstream migration of adult common galaxias has not been directly observed in the Lower Lakes and Coorong, but the presence of reproductively active fish (i.e. ‘running ripe’) near the barrages in winter (SARDI unpublished data) suggests peak downstream migration also occurs at this time, but likely extends into spring. Additionally, analyses of the otolith microstructure of newly recruited upstream migrants suggests peak spawning activity of congolli in July–August and common galaxias in August–September (Bice *et al.* 2012). The provision of open 'barrage gates', in addition to open fishways, is likely critical over this period; indeed, the abundance of upstream migrant YOY appears correlated with connectivity and opportunities for downstream spawning migrations the previous winter. Vertical-slot fishways, like those present at the Murray Barrages, are designed to facilitate upstream migrations and thus, are generally poor at facilitating downstream migrations (Clay 1995, Larinier and Marmulla 2004). Rates of downstream migration are likely to be far greater through open barrage gates.

Peak upstream migration of pouched lamprey also appears to occur during winter, with peak migration of short-headed lamprey likely extending into spring. However, this species is rare and there is limited empirical data on timing of migration. Furthermore, timing of downstream migration of newly metamorphosed juveniles in the region is unknown, but in other regions also occurs in winter (McDowall 1996).

Periods of peak migration for diadromous species indicate important seasons and months for barrage and fishway operation, but prioritising locations (i.e. specific barrages) for freshwater releases, in relation to fish migration, is more difficult. Whilst there were specific differences in the abundance of upstream migrating congolli and common galaxias between sites, overall, abundances downstream of Goolwa and Tauwitchere Barrages were not substantially different. YOY catadromous fish are likely to respond to salinity and olfactory cues from freshwater discharge during their upstream migration, and moderate–high abundances at Goolwa and Tauwitchere potentially reflect consistent freshwater discharge, and thus, attraction at both of these locations during the study period. In support of this hypothesis, in 2009/10, upstream migrating common galaxias were moderately abundant at the Goolwa vertical-slot, but absent from sites at Tauwitchere Barrage (Zampatti *et al.* 2011). No freshwater was discharged from Tauwitchere in 2009/10, but small volumes were released at Goolwa during navigation lock operation, which occurred in association with the Goolwa Channel Water Level Management Plan (Bice and Zampatti 2011). This suggests that these species migrate and accumulate where freshwater is being discharged and thus, the actual release location (i.e. barrage) may not be of major importance, but rather releases should be prioritised to barrages where effective fish passage is facilitated.

New fishways were recently constructed on Goolwa, Mundoo, Boundary Creek, Ewe Island and Tauwitchere barrages. The majority of these fishways have been assessed for biological effectiveness and all are successfully passing YOY common galaxias and congolli, among other species (Bice *et al.* 2017). Nonetheless, an important aspect of fishway effectiveness is attraction efficiency, or the ability of fish to locate the entrance of the fishway. The way in which flow is discharged from a regulating structure fundamentally influences attraction efficiency. Whilst data is scarce with regard to the delivery of freshwater from tidal barriers in a manner that maximises attraction, we suggest that releases should be prioritised to gates immediately adjacent to and preferably on only one side of the fishways. Upon completion of all assessments of fishway effectiveness (two remain) and determination of differences in species utilisation between fishways, an operations plan could be developed to inform the order of closing/opening fishways and adjacent gates during times of water scarcity, to maximise fish passage benefits.

Operating the barrages and their respective fishways in a manner that enhances fish migration is fundamental to the sustainability of fish populations, particularly diadromous species, in the MDB. Suggestions for future barrage and fishway operation, considering fish migration, are summarised below:

1) Freshwater discharge and operation of all fishways on the Murray Barrages should occur, at a minimum, 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 YOY congolli and common galaxias (and other species) from October to January.
2) Where possible, attraction flow should be provided from barrage gates immediately adjacent to each fishway. If discharge is being decreased at Tauwitchere, gates adjacent the small vertical-slot fishway should be the last to 'shut-down' as this fishway is the most effective at passing small-bodied fishes.
3) In addition to the operation of fishways from June to August, gates should be opened on the barrages (with priority given to Tauwitchere and Goolwa) to facilitate downstream migrations of catadromous species and provide attraction flow for upstream migrations of anadromous species. Barrage gates are likely to far better facilitate downstream movement than fishways.
4) During periods of low flow and drought, fishways should remain open for at least two months following the complete closure of barrage gates to facilitate the return migrations of freshwater fishes. Catches of freshwater species (e.g. Australian smelt, bony herring and flat-headed gudgeon) are commonly high following decreased barrage discharge and increasing salinity within the Coorong.

5) Following the assessment of the remaining new fishways on the Murray Barrages, the knowledge generated under the current project, and related studies, should be incorporated into the Barrage Operating Strategy.

5. CONCLUSION

Freshwater flows and connectivity between freshwater and marine environments play a crucial role in structuring estuarine fish assemblages and facilitating the recruitment of catadromous congolli and common galaxias, among other species, in the Coorong estuary. During 2006–2010, the cessation of freshwater discharge to the Coorong estuary led to increases in salinity, a loss of fish species diversity and reduced abundances, particularly in the case of diadromous species. 2018/19 represented a year of low freshwater discharge that followed high and moderate discharge in 2016/17 and 2017/18, respectively. Importantly in 2018/19, the majority of freshwater discharge, and continuous fishway operation, were supported by environmental water allocations. Brackish salinities prevailed in the Coorong estuary and fish assemblages were typical of a spatio-temporally dynamic temperate estuary under the influence of freshwater flow, albeit declining in magnitude.

Abundances of catadromous congolli and common galaxias were high relative to the period 2006–2011, but appeared to be declining from the period 2013–2018. Nonetheless, the majority of individuals sampled represented newly recruited YOY, and the species-specific recruitment target was met for congolli and common galaxias. As such, the results of the current study suggest the ecological objective (F-1) – '*Promote the successful migration and recruitment of diadromous fish species in the Lower Lakes and Coorong'* (Robinson 2014), and more specifically (a) – '*promote the successful migration and recruitment of catadromous fish species in the Lower Lakes and Coorong',* was achieved in 2018/19. The objective (b) – '*promote the successful spawning migration of anadromous fish species in the Lower Lakes and Coorong',* was not achieved for pouched lamprey or short-headed lamprey, although both species were detected in 2018/19.

The current project has contributed to a greater understanding of the dynamics of fish assemblages in the Coorong in association with variable freshwater discharge. Such data will form a basis for determining the status and trajectories of fish assemblages and populations in the Coorong estuary into the future.

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