Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2019/20

C. M. Bice, D.W. Schmarr, B. Zampatti and
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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* (TLM). 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 Environmental Water Management Plan.

The objective of this study in 2019/20 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 during winter–spring (targeted lamprey monitoring) and spring–summer (annual TLM monitoring) 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 2019/20, and assess spatio-temporal variation in assemblage structure over the period 2006–2019;
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 2019/20, and in relation to long-term data from 2006–2019;
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 2019/20, and in relation to long-term data from 2006–2019;
4. Utilise the data to inform 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 2019/20 was characterised by moderate freshwater discharge (685 GL; maximum discharge during sampling = ~24,900 ML.d^{-1}), and in association, salinity below the barrages was brackish (4–32 g.L^{-1}). The fish assemblage sampled was diverse (32 species) and dominated by the catadromous congolli (40.5% of total catch), marine estuarine-opportunist sandy sprat (*Hyperlophus vittatus*, ~21%), freshwater Australian smelt (*Retropinna semoni,* 16%) and the semi-catadromous common galaxias (~11%). The freshwater redfin perch (*Perca fluviatilis*, 3.5%) and bony herring (*Nematalosa erebi,* 1.7%) and solely estuarine lagoon goby (*Tasmanogobius lastii*, 2.7%) were also common. The 2019/20 fish assemblage was generally similar to those of previous years of low–moderate freshwater discharge (annual discharge 370–1647 GL), including 2013/14–2015/16 and 2017/18–2018/19, and characterised by low overall abundance, but high species richness, and moderate abundances of catadromous species.

In 2019/20, the abundances of the catadromous congolli and common galaxias were high relative to 2006–2011 but were similar to or slightly lower than abundances recorded annually since 2011/12. Nevertheless, >80% of all individuals sampled were newly recruited young-of-the-year (YOY). Peak periods of upstream migration for congolli were noted in December, and for common galaxias in October and December. This timing of migration is consistent with previous years of monitoring.

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.

Totals of 45 pouched lamprey (43 PIT tagged) and 16 short-headed lamprey (15 PIT tagged) were captured from fishways during sampling at the Murray Barrages in winter–spring 2019. The abundance of pouched lamprey was moderate to high relative to preceding years with targeted lamprey monitoring, whilst short-headed lamprey was sampled in greatest numbers since 2006. Both species were captured in greatest numbers from fishways on Goolwa and Mundoo barrages. Pouched lamprey were sampled predominantly in winter (July–August), whilst the short-headed lamprey were sampled from July–November, reinforcing the peak migration period for these species as winter and winter–spring, respectively.

Based on timing of upstream and downstream movements of diadromous species derived from fishway monitoring from 2006–2020, 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 2019/20, the fish assemblage generally trended towards low abundance, but moderate diversity 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). Anthropogenic modification of rivers, however, has diminished freshwater flows to estuaries and threatens the existence of estuarine habitats worldwide (Gillanders and Kingsford 2002, Flemer and Champ 2006). In addition, tidal barriers (e.g. barrages) that regulate flow may also 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. As such, these assemblages are often characterised by a spatio-temporally variable mix of freshwater, estuarine and marine fish species (Kupschus and Tremain 2001, Barletta *et al.* 2005). Additionally, estuaries 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), neccessitating regular dredging to maintain the openess of the Murray Mouth. 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 2006–2019, freshwater discharge to the Coorong was highly variable. Notably, over the period 2007–2010, a combination of reduced system-wide inflows and consumptive water use resulted in reduced flow to the Lower Lakes, cessation of freshwater flow to the Coorong estuary and disconnection of the Coorong from the Lower Lakes. The following nine-year period (2010–2019), was characterised by contrasting hydrology, which included flooding and large volumes of freshwater discharge in 2010/11, 2011/12, 2012/13 and 2016/17 (5177–12,498 GL.yr^{-1}), interspersed by years of low–moderate discharge (370–1647 GL.yr^{-1}). The absolute minimum annual target (650 GL) for barrage discharge volumes established under the Icon Site Environmental Water Management Plan was achieved in all years except 2015/16 and 2018/19. A further three-year target that stipulates a three-year rolling average (2000 GL.yr^{-1}) and annual discharge >650 GL was only achieved in years from 2012–2015.

From 2006–2019, variable hydrology, and accompanying connectivity and salinity regimes in the Coorong have been associated with variability in fish assemblage structure and species-specific abundance. During years of no freshwater discharge (2007–2010), the abundance of freshwater, diadromous and estuarine species decreased and marine species became more common (Zampatti *et al.* 2010). Specifically, catadromous congolli (*Pseudaphritis urvillii*) and common galaxias (*Galaxias maculatus*) exhibited significant declines in the abundance of young-of-the-year (YOY) migrants (Zampatti *et al.* 2011), whilst the anadromous short-headed lamprey (*Mordacia mordax*) and pouched lamprey (*Geotria australis*), present in 2006/07, were absent. In contrast, 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 and marine migrant (e.g. sandy sprat *Hyperlophus vittatus*) species (Bice *et al.* 2019). 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 species (e.g. sandy sprat). Throughout 2011–2019, the abundance of catadromous fishes has remained high, whilst pouched lamprey have been detected in seven years, and short-headed lamprey in two years.

The year 2019/20, represented the tenth consecutive year of freshwater discharge to the Coorong and connectivity between the Coorong and Lower Lakes, post the Millennium drought. 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 2019/2020, and assess spatio-temporal variation in fish assemblage structure in relation to 2006–2019;
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 2019/20, in relation to long-term data from 2006–2019;
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 2019/2020, and in relation to long-term data from 2006–2019;
4. Utilise the data to inform 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. 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).

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 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.

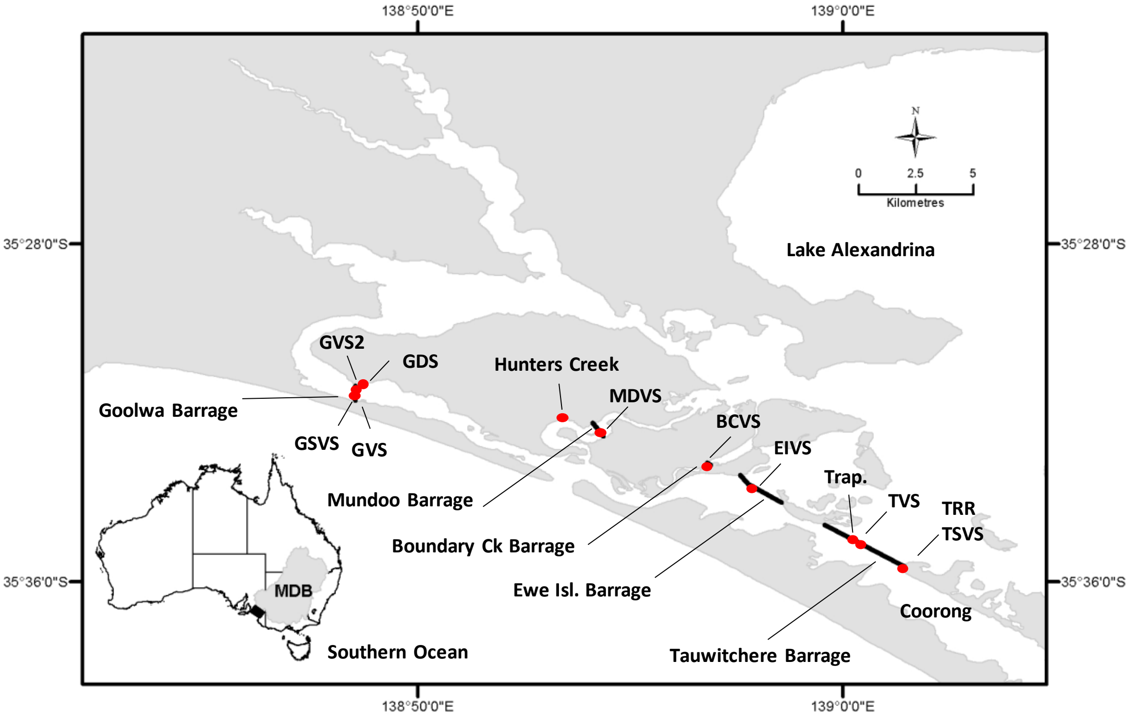

Figure 2-1. A map of the Coorong and Lake Alexandrina at the terminus of the River Murray, southern Australia showing the study area in the Coorong estuary, highlighting the Murray Barrages (bold lines). Barrages, fishways and fyke-net sampling sites (red dots); Goolwa vertical-slot (GVS), Goolwa vertical-slot 2 (GVS2), Goolwa small vertical-slot (GSVS), 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, EIVS and BCVS are sampled only during winter lamprey monitoring, while the Trapezoidal fishway and GSVS were not sampled in the current study.

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), 2018/19 (~370 GL) and 2019/20 (~685 GL), interspersed by high discharge in 2016/17 (~6536 GL) (Figure 2-2).

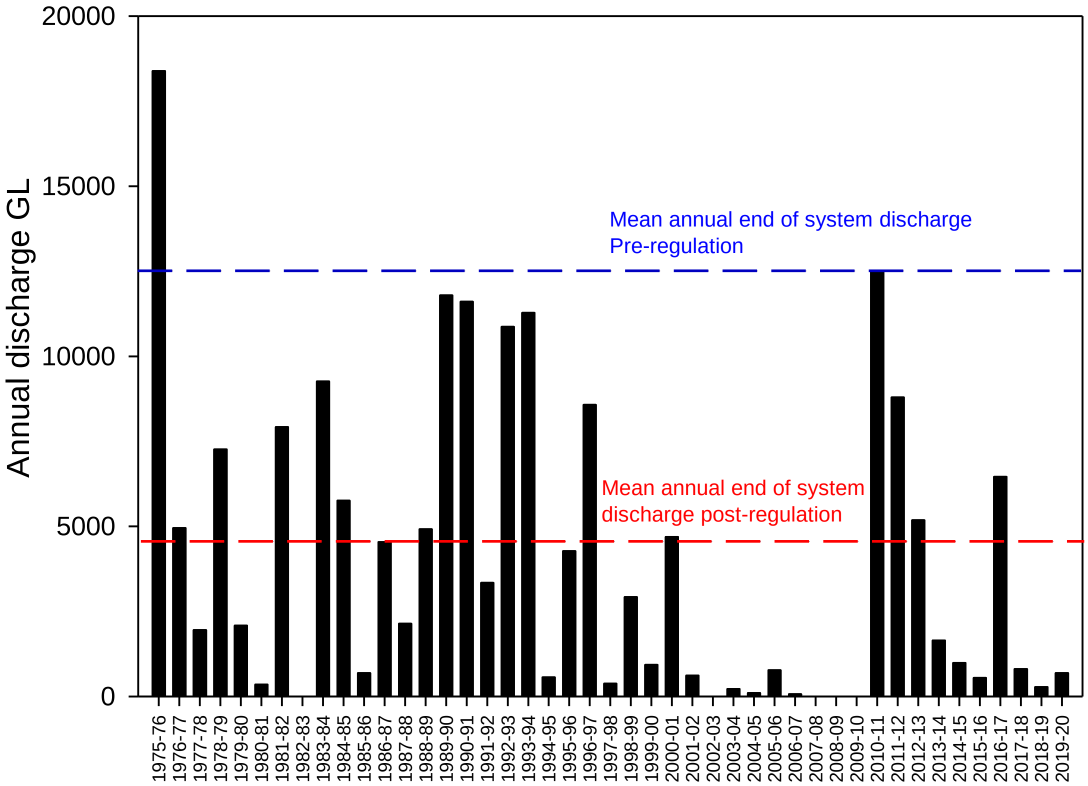

Figure 2-2. Annual freshwater discharge (GL) through the Murray Barrages into the Coorong estuary from 1975–June 2020. Dashed lines represent mean annual end of system discharge pre- (blue) and post-regulation (red).

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 2019/20, fish sampling occurred from July–January, for two distinct purposes: 1) assessment of abundance of upstream migrating anadromous lamprey (July–October); and 2) assessment of catadromous fish (congolli and common galaxias) migration and recruitment as per TLM targets (October–January; see section 2.4). Sampling in July–October involved trapping of seven vertical-slot fishways on Goolwa, Mundoo, Boundary creek, Ewe Island and Tauwitchere barrages (Figure 2-1 and Table 2-1). 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).

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. Fishway design and hydraulic details are presented as well as sampling dates. * denotes additional discharge from attraction gate at GSVS.

Name	Abbrev.	Barrage	Latitude	Longitude	Cell size L x W x D (m)	Slot width (m)	Max velocity ($m.s^{-1}$)	Max turbulence ($W.m^{-3}$)	Discharge ($ML.d^{-1}$)	Jul–Oct sampling	Oct–Jan sampling
Tauwitchere large vertical-slot	TVS	Tauwitchere	35°35’09.35’’S	139°00’30.58’’E	2.3 x 4.0 x 2.0 m	0.3	2.0	95	31	Y	Y
Tauwitchere small vertical-slot	TSVS	Tauwitchere	35°35’23.44’’S	139°00’56.23’’E	1.2 x 1.6 x 1.0	0.2	1.0	26	2.4	Y	Y
Tauwitchere rock ramp	TRR	Tauwitchere	35°35’23.60’’S	139°00’56.30’’E	-	-	-	-	-	N	Y
Tauwitchere trapezoidal	Trap.	Tauwitchere	35°35’08.74’’S	139°00’29.34’’E	1.0 x 3.46 x 1.5 m	0.1	-	-	-	N	N
Goolwa vertical-slot	GVS	Goolwa	35°31’34.44’’S	138°48’31.12’’E	2.6 x 3.6 x 3.6 m	0.2	1.7	26	40	Y	Y
Goolwa vertical-slot 2	GVS2	Goolwa	35°31’26.48’’S	138°48’32.89’’E	2.6 x 3.6 x 2.8 m	0.2	1.5	23	35	Y	N
Goolwa small vertical-slot	GSVS	Goolwa	35°31’37.65’’S	138°48’30.57’’E	1.24 x 0.93 x 2.0 m	0.11	1.0	20	10 (50)*	N	N
Adjacent Goolwa Barrage	GDS	Goolwa	35°31’24.16’’S	138°48’33.79’’E	-	-	-	-		N	Y
Hunters Creek vertical-slot	Hunters	Hunters Creek causeway	35°32’07.08’’S	138°53’07.48’’E	1.6 x 1.6 x 0.6 m	0.1	1.1	25	3	N	Y
Mundoo dual vertical-slot	MDVS	Mundoo	35°32’27.59’’S	138°54’16.97’’E	2.8 x 3.1 x 2.0 m	0.15	1.7	32	16	Y	N
Ewe Island dual vertical-slot	EIVS	Ewe Island	35°33’48.25’’S	138°57’51.63’’E	3.25 x 3.4 x 1.5 m	0.15	1.7	40	16	Y	N
Boundary Creek small vertical-slot	BCVS	Boundary Creek	35°33’13.05’’S	138°56’48.42’’E	1.1 x 1.1 x 0.4 m	0.1	0.92	20	2.2	Y	N

The entrances of the vertical-slot fishways were sampled using aluminium-framed cage traps, designed to fit into the first cell of each fishway (Table 2-1;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.

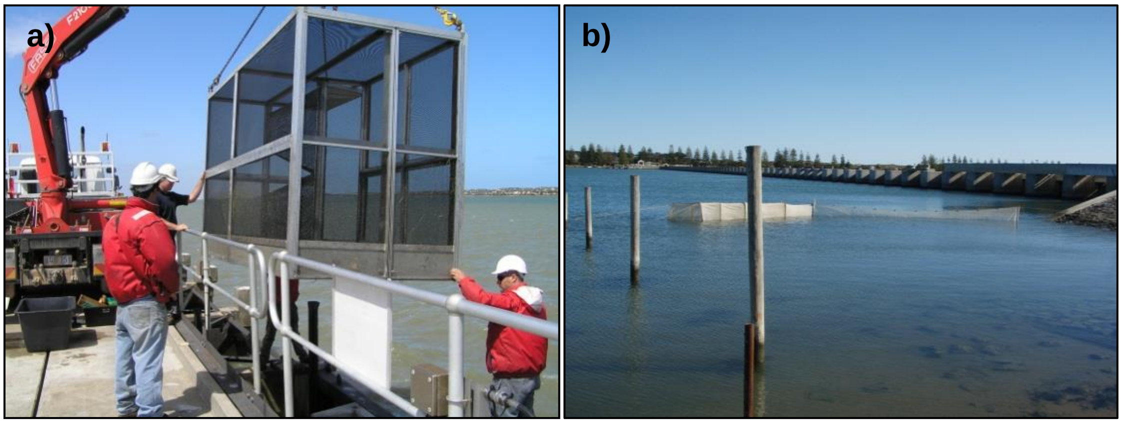

Figure 2-3 a) Cage trap used to sample the Tauwitchere and Goolwa vertical-slot fishways and b) large fyke net used to sample adjacent Goolwa Barrage. A net of the same dimensions was also used to sample adjacent to the Tauwitchere rock ramp.

Targeted sampling for lamprey was conducted periodically from 9 July–4 October 2019 (*n* = 11–20 sampling events per fishway) (Table 2-1). Cage traps at the large vertical-slot fishways were deployed and retrieved using a mobile crane (Figure 2-3a). All pouched lamprey and short-headed lamprey captured were enumerated and implanted with PIT (passive integrated transponder) tags before being released upstream (Bice *et al.* 2020). These tags enable monitoring of subsequent upstream movement through fishways on the main channel weirs of the River Murray.

Sampling in spring–summer occurred over four weeks approximately monthly from 21 October 2019–24 January 2020. 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. All fish were identified to species and counted before being released upstream. 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 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. 2006–2020). 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). 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 2019/20 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. ISA was then used to determine what species characterised assemblages at the different sampling locations in 2019/20.

Spatio-temporal variability in diadromous species abundance

Inter-annual variability in the total number (2006–2020) and standardised abundance from years of targeted winter monitoring (2015–2020; 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 2019/20 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 (DEWNR 2017) 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 ≥ 22.67 YOY.hr^{-1};
2. The annual abundance of upstream migrating YOY common galaxias is ≥ 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 $RI = (S_1(mean((r*A_{Nov}))+(r*A_{Dec})+(r*A_{Jan})) + S_2(mean((r*A_{Nov})+(r*A_{Dec})+(r*A_{Jan})).....S_n)$

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

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 vertical-slot 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 2015–2020. 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 2005–2020. 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 2017–2020); 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, resulting from unregulated flooding upstream, 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 of 49,955 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 = 10,823 ML.d^{-1}) and 2012/13 (range 220–69,000 ML.d^{-1}; mean = 12,617 ML.d^{-1}), although no sampling was conducted in 2012/13 (Figure 3-1a). Low–moderate volume flows occurred throughout 2013/14 with flow during the sampling season ranging 20–18,020 ML.d^{-1} and a mean discharge of 1617 ML.d^{-1}. Discharge continued to decrease through 2014/15 (range 8–2950 ML.d^{-1}; mean = 1547 ML.d^{-1}) and 2015/16 (range 1–1503 ML.d^{-1}; mean = 128 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 of 36,851 ML.d^{-1} over the sampling period. Flow had decreased during sampling in 2017/18, with a mean of 3340 ML.d^{-1} and range 0–12,498 ML.d^{-1}, decreased further in 2018/19, with a mean of 1013 ML.d^{-1} and range 0–1502 ML.d^{-1}, and increased slightly in 2019/20, with a mean of 1761 ML.d^{-1} and range 6–24,908 ML.d^{-1}.

During sampling in 2006/07, salinity below Tauwitchere and Goolwa Barrages fluctuated 20–34 g.L^{-1} (mean = 28.42 g.L^{-1}) and 11–29 g.L^{-1} (mean = 21.93 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 ranged 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 g.L^{-1}) and Tauwitchere (3.8 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 g.L^{-1}) and 3–26 g.L^{-1} (mean = 12.7 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 g.L^{-1}) at Goolwa and 5–22 g.L^{-1} (mean = 10.4 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 g.L^{-1}. Tauwitchere: range 15–32 g.L^{-1}; mean = 22.3 g.L^{-1}) and 2015/16 (Goolwa: range 21–31 g.L^{-1}; mean = 27 g.L^{-1}. Tauwitchere: range 19–34 g.L^{-1}; mean = 27.8 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 g.L^{-1}) and Tauwitchere (5 g.L^{-1}). In 2017/18, salinity was generally 'brackish' downstream of both Goolwa (range 4–24 g.L^{-1}; mean = 13 g.L^{-1}) and Tauwitchere Barrages (range 7–32 g.L^{-1}; mean = 16 g.L^{-1}). In 2018/19, salinity was again generally brackish downstream of Goolwa (range 7–31 g.L^{-1}; mean = 21 g.L^{-1}) and Tauwitchere Barrages (range 7–31 g.L^{-1}; mean = 18 g.L^{-1}). And, again in 2019/20, salinity was generally brackish downstream of Goolwa (range 4–32 g.L^{-1}; mean = 24.8 g.L^{-1}) and Tauwitchere Barrages (range 8–34 g.L^{-1}; mean = 25 g.L^{-1}).

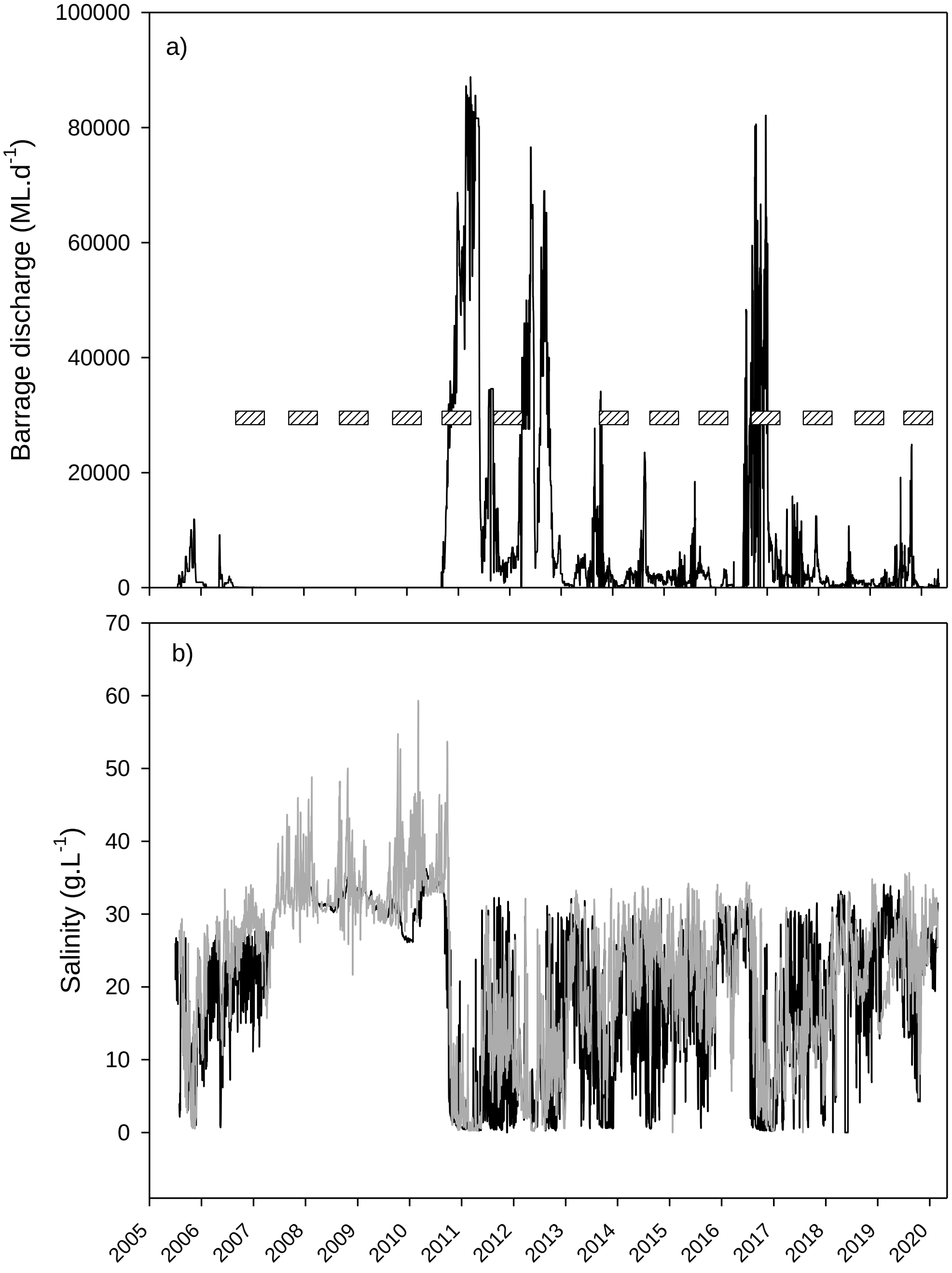

Figure 3-1. a) Mean daily flow (ML.d^{-1}) to the Coorong through the Murray Barrages (all barrages combined) from July 2005–May 2020 and b) Mean daily salinity (g.L^{-1}) of the Coorong below Tauwitchere (grey line) and Goolwa (black line) barrages from July 2005–February 2020. Sampling periods are 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 149,718 fish from 32 species were sampled in spring–summer 2019/20 (Table 3-1). The catch was dominated by the catadromous congolli (40.5%), marine estuarine-opportunist sandy sprat (21.2%), freshwater Australian smelt (*Retropinna semoni*, 16%) and the semi-catadromous common galaxias (10.8%). The freshwater redfin perch (*Perca fluviatilis*, 3.5%) and bony herring (*Nematalosa erebi,* 1.7%) and solely estuarine lagoon goby (*Tasmanogobius lastii*, 2.7%) were also abundant. The remaining 25 species collectively comprised <4% 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 2019/20. Species are categorised using estuarine use guilds from Potter et al. (2015) and designations presented by Bice *et al.* (2018).

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**
		Sampling events	9	11	4	12	4	10	
		No. of species	14	8	23	14	25	14	
Australian smelt	*Retropinna semoni*	Freshwater estuarine opportunist	1,815	16,422	1,249	2,052	2,416	5	23,959
Bony herring	*Nematalosa erebi*	Freshwater estuarine opportunist	28	2	2,472	8	95	18	2,623
Flat-headed gudgeon	*Philypnodon grandiceps*	Freshwater estuarine opportunist	418	8	35	438	193	45	1,137
Carp gudgeon	*Hypseleotris spp*	Freshwater straggler	1	-	-	-	-	-	1
Common carp	*Cyprinus carpio**	Freshwater straggler	1	-	1	-	8	-	10
Dwarf flat-headed gudgeon	*Philypnodon macrostomus*	Freshwater straggler	-	-	-	-	1	2	3
Eastern gambusia	*Gambusia holbrookii*	Freshwater straggler	-	-	-	-	-	2	2
Golden perch	*Macquaria ambigua*	Freshwater straggler	1	-	-	-	1	-	2
Goldfish	*Carassius auratus**	Freshwater straggler	1	-	1	-	-	-	2
Redfin perch	*Perca fluviatilis**	Freshwater straggler	1,843	16	393	74	2,944	1	5271
Short-headed lamprey	*Mordacia mordax*	Anadromous	-	-	-	2	1	-	3
Congolli	*Pseudaphritis urvillii*	Catadromous	1,780	5,617	13,632	18,508	18,876	2,332	60,745
Common galaxias	*Galaxias maculatus*	Semi-catadromous	3,119	9,181	1,623	1,432	484	388	16,227

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	-	-	-	-	2	-	2
Lagoon goby	*Tasmanogobius lasti*	Solely estuarine	1,498	2	2,491	34	26	2	4,053
River garfish	*Hyporhamphus regularis*	Solely estuarine	-	-	49	-	-	-	49
Small-mouthed hardyhead	*Atherinosoma microstoma*	Solely estuarine	15	-	197	-	1,069	338	1,619
Tamar River goby	*Afurcagobius tamarensis*	Solely estuarine	53	2	384	4	394	-	837
Blue-spot goby	*Pseudogobius olorum*	Solely estuarine	-	-	180	97	22	72	371
Bridled goby	*Arenogobius bifrenatus*	Estuarine & marine	-	-	232	20	619	-	871
Soldier fish	*Gymnapistes marmoratus*	Estuarine & marine	-	-	23	1	30	1	55
Flat-tailed mullet	*Liza argentea*	Marine estuarine-opportunist	-	-	1	-	1	-	2
Greenback flounder	*Rhombosolea tapirina*	Marine estuarine-opportunist	-	-	48	-	7	-	55
Long-snouted flounder	*Ammosetris rostratus*	Marine estuarine-opportunist	-	-	4	-	1	-	5

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
Mulloway	*Argyrosomus japonicus*	Marine estuarine-opportunist	-	-	3	-	-	-	3
Sandy sprat	*Hyperlophus vittatus*	Marine estuarine-opportunist	616	-	12,971	2,236	15,905	35	31,763
Smooth toadfish	*Tetractenos glaber*	Marine estuarine-opportunist	-	-	3	-	1	-	4
Yelloweye mullet	*Aldrichetta forsteri*	Marine estuarine-opportunist	-	-	15	-	-	1	16
Blue sprat	*Spratelloides robustus*	Marine straggler	-	-	-	1	24	-	25
Luderick	*Girella tricuspidata*	Marine straggler	-	-	-	-	1	-	1
Six-spined leatherjacket	*Meuschenia freycineti*	Marine straggler	-	-	1	-	-	-	1
Velvet leatherjacket	*Meuschenia scaber*	Marine straggler	-	-	-	-	1	-	1
		Total	11,189	31,250	36,008	24,907	43,122	3,242	149,718

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 2019/20 (Figure 3-2) at the Tauwitchere rock ramp ($Pseudo\text{-}F_{12, 73} = 9.52$, $p < 0.001$), Tauwitchere vertical-slot ($Pseudo\text{-}F_{12, 64} = 7.39$, $p < 0.001$), Goolwa vertical-slot ($Pseudo\text{-}F_{11, 63} = 2.48$, $p = 0.020$), but not at the Tauwitchere small vertical-slot ($Pseudo\text{-}F_{8, 45} = 0.55$, $p = 0.826$), adjacent Goolwa Barrage ($Pseudo\text{-}F_{10, 53} = 1.91$, $p = 0.070$) or Hunters Creek vertical-slot ($Pseudo\text{-}F_{8, 45} = 2.08$, $p = 0.056$). 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 2010–2020 (Figure 3-2). In 2019/20, however, total abundances were generally among the lowest recorded since 2010/11.

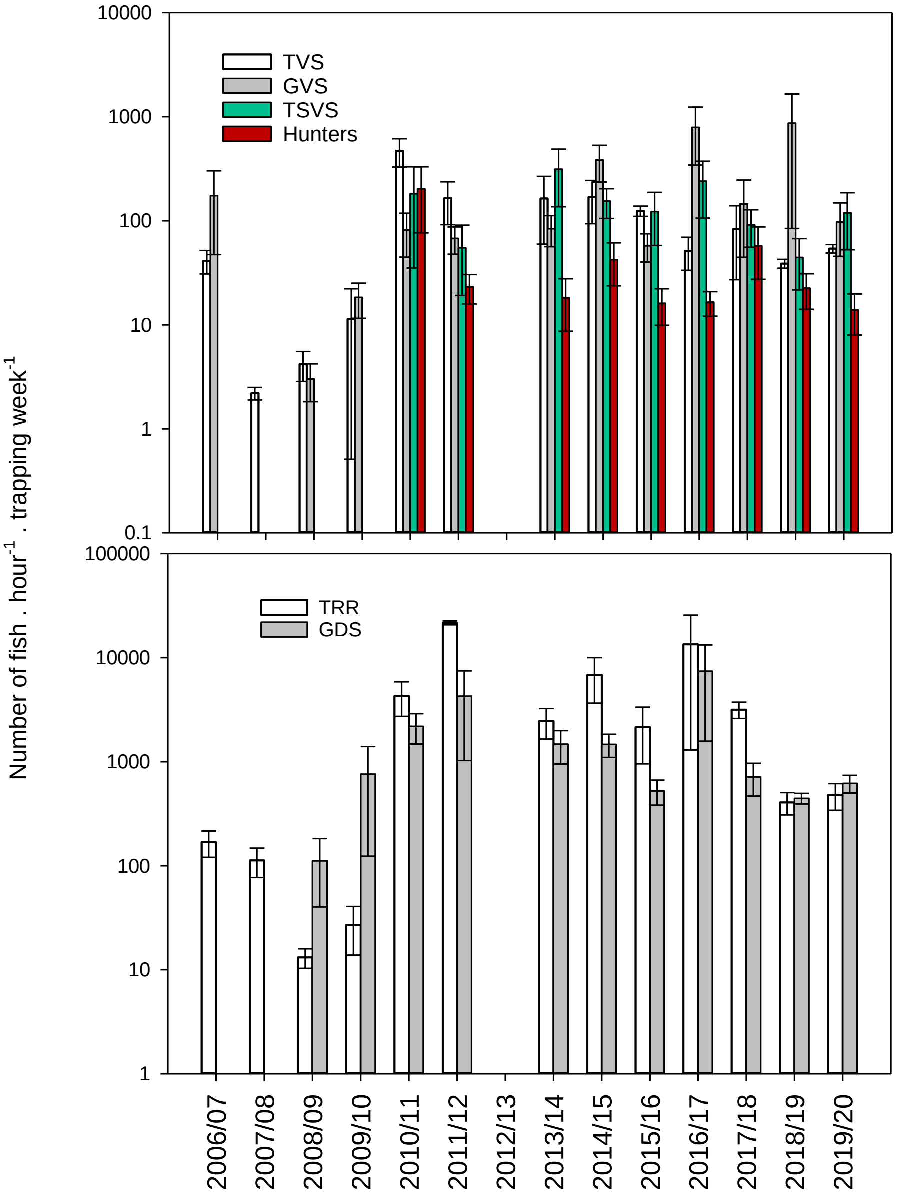

Figure 3-2. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of fish (all species combined) sampled at a) the Tauwitchere large vertical-slot (TVS), Goolwa vertical-slot (GVS), Tauwitchere small vertical-slot (TSVS) and Hunters Creek vertical-slot (Hunters), and b) the Tauwitchere rock ramp (TRR) and adjacent Goolwa Barrage (GDS), from 2006–2020. Goolwa vertical-slot was not sampled in 2007/08, whilst sampling at the Tauwitchere small vertical-slot and Hunters Creek vertical-slot 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 and 2019/20 (*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 2019/20 (*n* = 34) was primarily driven by high number of both marine (*n* = 11) and freshwater species (*n* = 11), relative to preceding years.

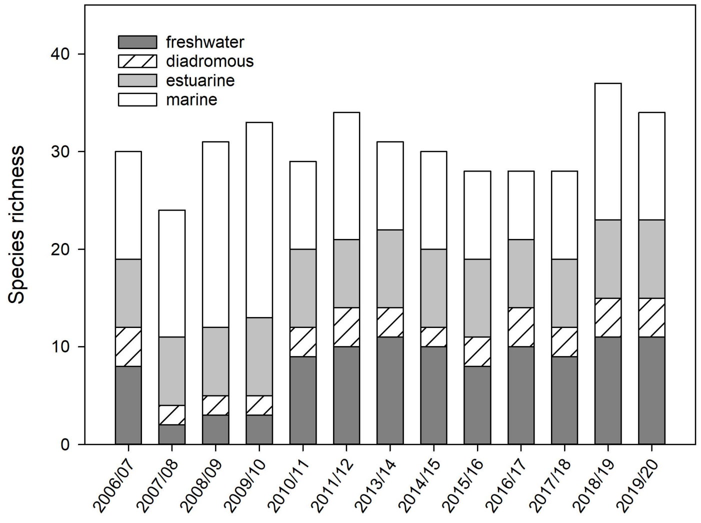

Figure 3-3. Species richness (all sites combined) from 2006–2020, including the contribution of species from different estuarine-use categories, i.e. freshwater (freshwater 'estuarine-opportunists' and 'stragglers' combined), diadromous (catadromous and anadromous combined), estuarine (solely estuarine 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 assemblage structure at the Tauwitchere rock ramp ($Pseudo\text{-}F_{12,\ 73}$ = 12.53, $p < 0.001$), Tauwitchere large vertical-slot ($Pseudo\text{-}F_{12,\ 63}$ = 10.07, $p < 0.001$), Tauwitchere small vertical-slot ($Pseudo\text{-}F_{8,\ 45}$ = 2.96, $p < 0.001$), Goolwa vertical-slot ($Pseudo\text{-}F_{11,\ 63}$ = 4.52, $p < 0.001$), adjacent Goolwa Barrage ($Pseudo\text{-}F_{10,\ 53}$ = 6.45, $p < 0.001$) and Hunters Creek vertical-slot ($Pseudo\text{-}F_{8,\ 45}$ = 3.83, $p < 0.001$). 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 2017–2020 (Table 3-2).

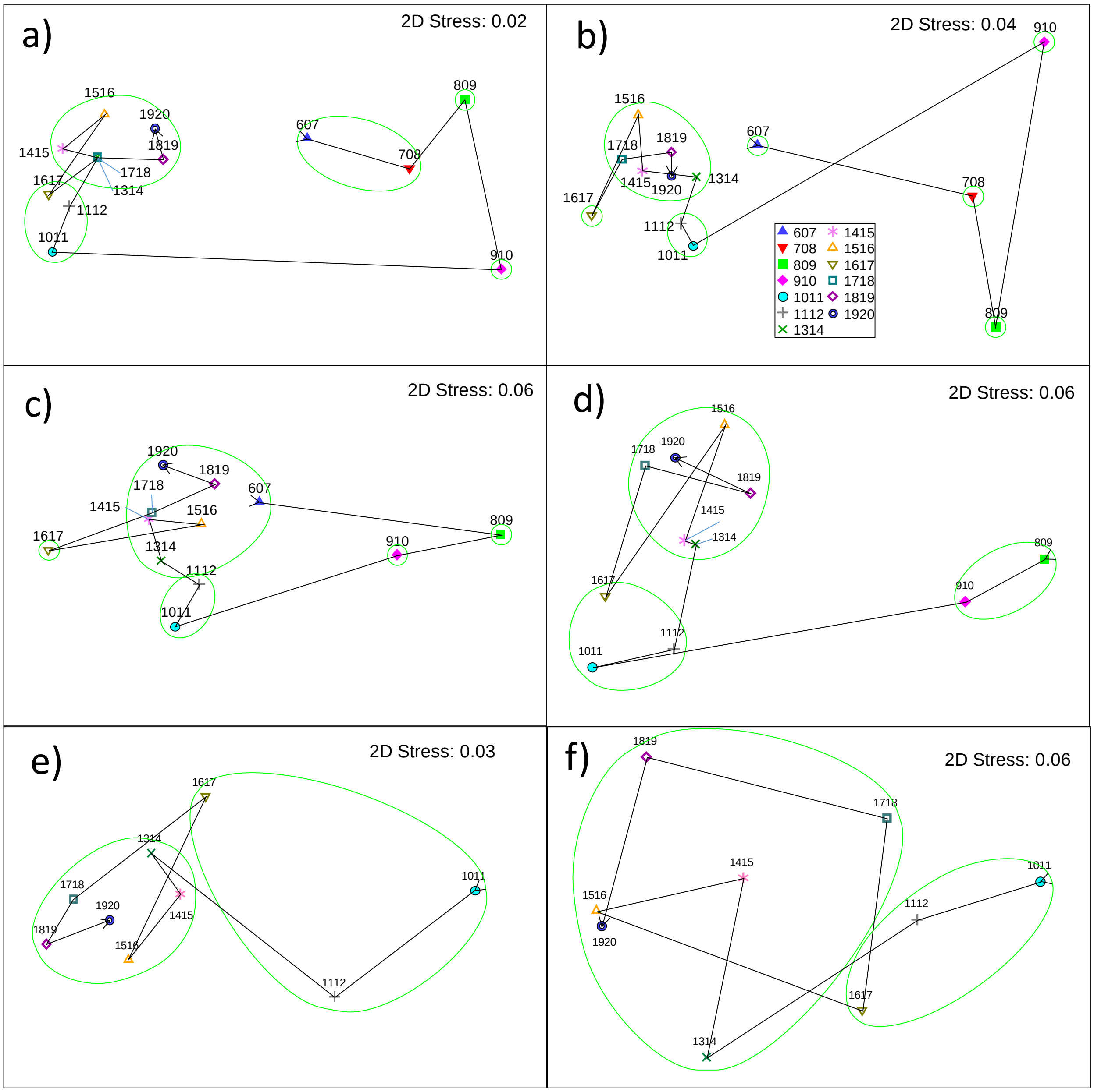

Figure 3-4. MDS ordination trajectory plots of fish assemblages sampled at a) Tauwitchere rock ramp, b) Tauwitchere large vertical-slot, c) Goolwa vertical-slot, d) adjacent Goolwa Barrage, e) Tauwitchere small vertical-slot and f) Hunters Creek vertical-slot, between 2006 and 2020. Groupings from Cluster analysis based on 75% 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, 07/08	06/07	06/07, 13/14–15/16, 17/18–19/20	08/09, 09/10	10/11, 11/12, 16/17	10/11, 11/12, 16/17
Group 2	08/09	07/08	08/09	10/11, 11/12, 16/17	13/14–15/16, 17/18–19/20	13/14–15/16, 17/18–19/20
Group 3	09/10	08/09	09/10	13/14–15/16, 17/18–19/20		
Group 4	10/11, 11/12, 16/17	09/10	10/11, 11/12			
Group 5	13/14–15/16, 17/18–19/20	10/11, 11/12	16/17		-	
Group 6		13/14–15/16, 17/18–19/20			-	
Group 7		16/17		-	-	

Tauwitchere sites

Cluster analysis of fish assemblages sampled at the Tauwitchere rock ramp (Table 3-2) could be described in terms of annual discharge: no flow or low flow (0 or 63–274 GL) = group 1 (2006/07, 2007/08); no flow (0 GL) = group 2 (2008/09) and 3 (2009/10); high flow (6456–12,498 GL) = group 4 (2010/11, 2011/12, 2016/17) and moderate flow (370–1647 GL) = group 5 (2013/14–2015/16, 2017/18–2019/20). At the Tauwitchere large vertical-slot, assemblages produced six cluster groups: low flow (63–274 GL) = group 1 (2006/07); no flow (0 GL) = groups 2 (2007/08), 3 (2008/09) and 4 (2009/10); high flow (6456–12,498 GL) = groups 5 (2010/11, 2011/12) and 7 (2016/17); and moderate flow (370–1647 GL) = group 6 (2013/14–2015/16, 2017/18–2019/20). At the Tauwitchere small vertical-slot, assemblages produced two cluster groups: high flow (6456–12,498 GL) = group 1 (2010/11, 2011/12, 2016/17); and moderate flow (370–1647 GL) = group 2 (2013/14–2015/16, 2017/18–2019/20).

At the Tauwitchere rock ramp, Indicator Species Analysis (ISA) suggested the fish assemblage in 2006/07 and 2007/08 was characterised by the presence of the marine estuarine-opportunist flat-tailed mullet (*Liza argentea*), the estuarine blue-spot goby (*Pseudogobius olorum*) and the anadromous short-headed lamprey (Table 3-3). The assemblages in the no flow year in 2008/09 were characterised by the estuarine black bream (*Acanthopagrus butcheri*), and in 2009/10, the assemblage was characterised by the marine-estuarine opportunists mulloway (*Argyrosomus japonicas*), prickly toadfish (*Contusus brevicaudus*), Australian herring (*Arripis georgianus*), yellowfin whiting (*Sillago schomburgkii*), Australian anchovy (*Engraulis australis*), Australian salmon (*Arripis truttaceus*), and the marine stragglers big-bellied seahorse (*Hippocampus abdominalis*), silver spot (*Threpterius maculosus*) and Tuckers pipefish (*Mitotichthys tuckeri*), and the estuarine and marine estuary catfish (*Cnidoglanis macrocephalus*). The assemblage sampled in high flow years was characterised by six freshwater species (i.e. Australian smelt, flat-headed gudgeon (*Philypnodon grandiceps*), 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*)), one marine straggler (southern longfin goby (*Favonigobius lateralis*), and marine estuarine-opportunist sandy sprat (*Hyperlophus vittatus*)). The assemblages from moderate flow years were characterised by the catadromous congolli and common galaxias, estuarine Tamar River goby (*Afurcagobius tamarensis*) and the estuarine and marine bridled goby (*Arenogobius bifrenatus*).

At the Tauwitchere large vertical-slot, the assemblages sampled in 2006/07 were characterised by the anadromous short-headed lamprey, and during 2007/08 by the estuarine blue-spot goby (Table 3-4). There was no significant indicator of the 2008/09 no flow year, but the 2009/10 no flow year was characterized by the estuarine black bream. Assemblages during high flow years were characterised by five freshwater species (i.e. Australian smelt, bony herring, golden perch, redfin perch and common carp) and one estuarine species (lagoon goby). Moderate flow years were characterised by the freshwater flat-headed gudgeon and carp gudgeon complex (*Hypseleotris* spp.), and catadromous congolli.

At the Tauwitchere small vertical-slot, the assemblages in high flow years 2010–2012, were characterised by the freshwater flat-headed gudgeon, golden perch, common carp, goldfish, redfin perch, and carp gudgeon complex and the estuarine blue-spot goby and lagoon goby (Table 3-4). The assemblages in moderate and low flow years were characterised by the semi-catadromous common galaxias and catadromous congolli.

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 (63–274 GL), MF = moderate flow (370–1647 GL), HF = high flow (>6536 GL). Only significant indicators (i.e. $p < 0.05$) are presented.

Species	**Guild**	**Year**	**Indicator Value**	***p* value**
Tauwitchere rockramp				
Flat-tail mullet	Marine est-opportunist	Group 1 (NF)	37.9	0.032
Bluespot goby	Solely estuarine	Group 1 (NF)	29.6	0.034
Short-headed lamprey	Anadromous	Group 1 (NF)	25	0.041
Black bream	Solely estuarine	Group 2 (NF)	32.7	0.033
Mulloway	Marine est-opportunist	Group 3 (NF)	61.2	<0.001
Prickly toadfish	Marine est-opportunist	Group 3 (NF)	95.6	<0.001
Australian herring	Marine est-opportunist	Group 3 (NF)	69.5	0.001
Yellowfin Whiting	Marine est-opportunist	Group 3 (NF)	50.8	0.006
Australian anchovy	Marine est-opportunist	Group 3 (NF)	51	0.007
Australian salmon	Marine est-opportunist	Group 3 (NF)	48.2	0.012
Big-bellied seahorse	Marine straggler	Group 3 (NF)	33.3	0.037
Silver spot	Marine straggler	Group 3 (NF)	33.3	0.037
Estuary cobbler	Estuarine & marine	Group 3 (NF)	33.3	0.041
Tuckers pipefish	Marine straggler	Group 3 (NF)	33.3	0.042
Carp	Freshwater straggler	Group 4 (HF)	74.4	<0.001
Bony bream	Freshwater est-opportunist	Group 4 (HF)	56.7	<0.001
Redfin perch	Freshwater straggler	Group 4 (HF)	59.5	<0.001
Flathead gudgeon	Freshwater est-opportunist	Group 4 (HF)	63.8	<0.001
Australian smelt	Freshwater est-opportunist	Group 4 (HF)	61.8	<0.001
Lagoon goby	Solely estuarine	Group 4 (HF)	54	<0.001
Golden perch	Freshwater straggler	Group 4 (HF)	64.7	0.001
Sandy sprat	Marine est-opportunist	Group 4 (HF)	42.2	0.007
River Garfish	Solely estuarine	Group 4 (HF)	50.1	0.008
Longfin goby	Marine straggler	Group 4 (HF)	42.9	0.023
Common galaxias	Semi-catadromous	Group 5 (MF)	56.6	<0.001
Congolli	Catadromous	Group 5 (MF)	46.5	<0.001
Bridled goby	Estuarine & marine	Group 5 (MF)	35.4	<0.001
Tamar River goby	Solely estuarine	Group 5 (MF)	29.9	0.0192

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 (63–274 GL), MF = moderate flow (542–1647 GL), HF = high flow (>6536 GL). Only significant indicators (i.e. $p < 0.05$) are presented.

Species	Guild	Year	Indicator Value	*p* value
Tauwitchere large vertical-slot				
Short-headed lamprey	Anadromous	Group 1 (LF)	33.3	0.029
Bluespot goby	Solely estuarine	Group 2 (NF)	41	0.010
Black bream	Solely estuarine	Group 4 (NF)	38.4	0.022
Carp	Freshwater straggler	Group 5 (HF)	50.3	<0.001
Australian smelt	Freshwater est-opportunist	Group 5 (HF)	44.2	<0.001
Lagoon goby	Solely estuarine	Group 5 (HF)	39.7	<0.001
Bony bream	Freshwater est-opportunist	Group 5 (HF)	44.3	<0.001
Redfin perch	Freshwater straggler	Group 5 (HF)	39.4	0.004
Golden perch	Freshwater straggler	Group 5 (HF)	33.2	0.042
Common galaxias	Semi-catadromous	Group 6 (MF)	32.8	<0.001
Congolli	Catadromous	Group 6 (MF)	32.3	<0.001
Flathead gudgeon	Freshwater est-opportunist	Group 6 (MF)	32.5	0.002
Carp gudgeon	Freshwater straggler	Group 6 (MF)	34.5	0.038
Tauwitchere small vertical-slot				
Carp	Freshwater straggler	Group 1 (HF)	73.9	<0.001
Lagoon goby	Solely estuarine	Group 1 (HF)	55.2	<0.001
Golden perch	Freshwater straggler	Group 1 (HF)	35.5	0.002
Goldfish	Freshwater straggler	Group 1 (HF)	28.6	0.004
Redfin perch	Freshwater straggler	Group 1 (HF)	64.5	0.006
Flathead gudgeon	Freshwater est-opportunist	Group 1 (HF)	60.5	0.012
Carp gudgeon	Freshwater straggler	Group 1 (HF)	28.1	0.029
Blue-spotted flathead	Marine est-opportunist	Group 1 (HF)	19	0.037
Carp gudgeon	Freshwater straggler	Group 1 (HF)	21.2	0.045
Common galaxias	Semi-catadromous	Group 2 (MF)	68.7	<0.001
Congolli	Catadromous	Group 2 (MF)	67.8	<0.001

Goolwa sites

Cluster analysis of fish assemblages sampled at the Goolwa vertical-slot produced five groupings of sampling years (Table 3-2). These groupings could be described in terms of annual discharge: low flow and moderate flow (63–1647 GL) = group 1 (2006/07, 2013/14–2015/16, 2017/18–2019/20); no flow (0 GL) = group 2 (2008/09) and 3 (2009/10); and high flow (6456–12,498 GL) = group 4 (2010/11, 2011/12) and 5 (2016/17). At the site adjacent Goolwa Barrage, three cluster groups were produced. These were: no flow (0 GL) = group 1 (2008/09, 2009/10); high flow (6456–12,498 GL) = group 2 (2010/11–2011/12, 2016/17); low–moderate flow (274–1647 GL) = group 3 (2013/14–2015/16, 2017/18–2019/20).

ISA of assemblage data from the Goolwa vertical-slot indicated the assemblage from low–moderate flow years encompassing 2006/07, 2013/14–2015/16 and 2017/18–2019/20 (group 1) was not characterised by any particular species (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, the catadromous congolli 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-opportunists Australian herring, Australian salmon and 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, carp and goldfish), and the estuarine lagoon goby. The moderate flow grouping that encompassed sampling from 2013/14–2015/16 and 2017/18–2019/20, was characterised by the catadromous congolli, the semi-catadromous common galaxias, the freshwater dwarf flathead gudgeon, the estuarine Bluespot goby and the marine estuarine opportunist soldierfish.

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), MF = low-moderate flow (63–1647 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				
Black bream	Solely estuarine	Group 2 (NF)	49	0.017
Flat-tail mullet	Marine est-opportunist	Group 2 (NF)	44.2	0.042
Small-mouthed hardyhead	Solely estuarine	Group 3 (NF)	58.5	0.001
Zebra fish	Marine straggler	Group 3 (NF)	61.4	0.007
Australian salmon	Marine est-opportunist	Group 3 (NF)	45.7	0.034
Tamar River goby	Solely estuarine	Group 3 (NF)	34.6	0.036
Bridled goby	Estuarine & marine	Group 3 (NF)	44.5	0.041
Redfin perch	Freshwater straggler	Group 4 (HF)	42	<0.001
Lagoon goby	Solely estuarine	Group 4 (HF)	61.5	<0.001
Australian smelt	Freshwater est-opportunist	Group 5 (HF)	39	0.003
Congolli	Catadromous	Group 5 (HF)	39.9	0.007
Golden perch	Freshwater straggler	Group 5 (HF)	61.2	0.009
Common galaxias	Semi-catadromous	Group 5 (HF)	32	0.028
Adjacent Goolwa Barrage				
Black bream	Solely estuarine	Group 1 (NF)	72.5	<0.001
Yellow-eyed mullet	Marine est-opportunist	Group 1 (NF)	76.7	<0.001
Australian herring	Marine est-opportunist	Group 1 (NF)	59.8	<0.001
Australian salmon	Marine est-opportunist	Group 1 (NF)	54.4	0.002
Smooth toadfish	Marine est-opportunist	Group 1 (NF)	50	0.003
Australian anchovy	Marine est-opportunist	Group 1 (NF)	32.7	0.004
Flat-tail mullet	Marine est-opportunist	Group 1 (NF)	37.5	0.006
Longsnout flounder	Marine est-opportunist	Group 1 (NF)	40.6	0.019
Golden perch	Freshwater straggler	Group 2 (HF)	69.2	<0.001
Bony bream	Freshwater est-opportunist	Group 2 (HF)	64.2	<0.001
Flathead gudgeon	Freshwater est-opportunist	Group 2 (HF)	61.7	<0.001
Redfin perch	Freshwater straggler	Group 2 (HF)	56.1	<0.001
Australian smelt	Freshwater est-opportunist	Group 2 (HF)	48.5	0.002
Carp gudgeon	Freshwater straggler	Group 2 (HF)	40.5	0.004
Goldfish	Freshwater straggler	Group 2 (HF)	38.1	0.005
Carp	Freshwater straggler	Group 2 (HF)	47	0.009
Lagoon goby	Solely estuarine	Group 2 (HF)	47.2	0.027
Common galaxias	Semi-catadromous	Group 3 (MF)	62.7	<0.001
Congolli	Catadromous	Group 3 (MF)	60	<0.001
Dwarf flathead gudgeon	Freshwater straggler	Group 3 (MF)	35.3	0.029
Bluespot goby	Solely estuarine	Group 3 (MF)	42.2	0.032
Soldierfish	Marine est-opportunist	Group 3 (MF)	35.9	0.046

Hunters Creek

Cluster analysis of fish assemblages sampled at the Hunters Creek vertical-slot produced two cluster groups: high flow (6456–12,498 GL) = group 1 (2010/11, 2011/12, 2016/17); and moderate flow (370–1647 GL) = group 2 (2013/14–2015/16, 2017/18–2019/20) (Table 3-2). ISA determined the assemblages from the high flow grouping were characterised by the freshwater common carp, redfin perch, flat-headed gudgeon, goldfish (*Carassius auratus*), carp gudgeon complex, golden perch and bony herring, and the assemblages from moderate flow years were characterised by the catadromous congolli (Table 3-6).

Table 3-6. Indicator species analysis of fish assemblages at the Hunters Creek vertical slot from 2010–2020. 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**
Carp	Freshwater straggler	Group 1 (HF)	85.4	<0.001
Redfin perch	Freshwater straggler	Group 1 (HF)	76.2	<0.001
Flathead gudgeon	Freshwater est-opportunist	Group 1 (HF)	65.7	<0.001
Goldfish	Freshwater straggler	Group 1 (HF)	50.9	<0.001
Carp gudgeon	Freshwater straggler	Group 1 (HF)	37.5	0.002
Golden perch	Freshwater straggler	Group 1 (HF)	30.9	0.006
Bony bream	Freshwater est-opportunist	Group 1 (HF)	58.3	0.014
Congolli	Catadromous	Group 2 (MF)	59.7	0.003

3.4. Spatial variation in fish assemblages in 2019/20

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 ($Pseudo\text{-}F_{3,\ 15} = 3.02$, $p = 0.003$), and pair-wise comparisons suggested assemblages were significantly different between Tauwitchere large vertical-slot and Hunters Creek, and Tauwitchere small vertical-slot fishways ($p < 0.05$ for all comparisons). MDS ordination of fish assemblage data from the Tauwitchere rock ramp and adjacent Goolwa Barrage (GDS) exhibited some separation (Figure 3-5b), but PERMANOVA indicated assemblages sampled from these locations were not significantly different (*Pseudo*-$F_{1,7}$ = 1.67, *p* = 0.177).

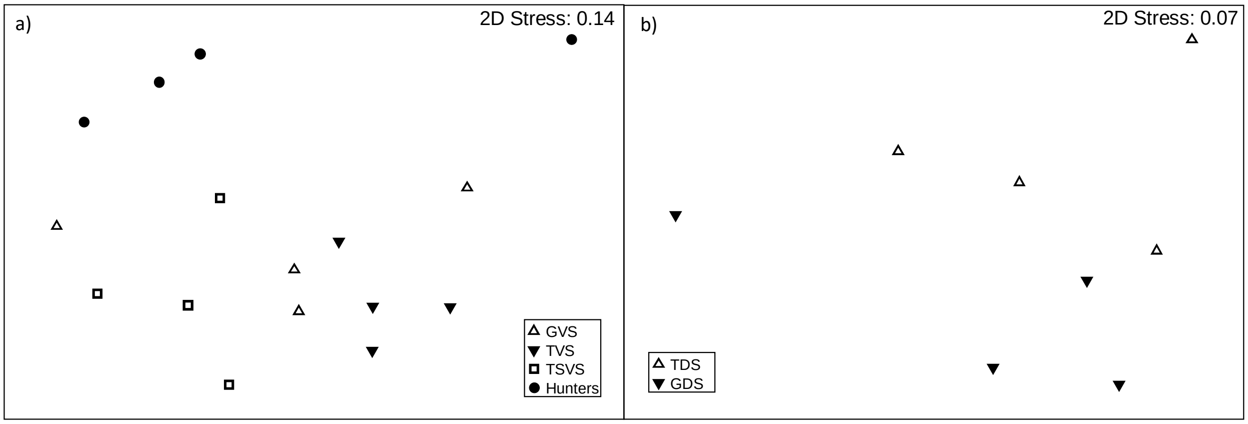

Figure 3-5. MDS ordination plot of fish assemblages sampled at the a) Tauwitchere large vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS), Goolwa vertical-slot (GVS), and Hunters Creek vertical-slot (Hunters), and b) Tauwitchere rock ramp and adjacent Goolwa Barrage (GDS) in 2019/20.

Indicator species analysis was used to determine species that characterised assemblages at the different sites in 2019/20. Among the vertical-slot fishways, the estuarine Tamar River goby and lagoon goby characterised the assemblages at Tauwitchere large vertical-slot fishway, while the semi-catadromous common galaxias characterised the Tauwitchere small vertical-slot fishway (Table 3-7). The Tauwitchere rock ramp and site adjacent Goolwa Barrage did not have significant indicator species.

Table 3-7. Indicator species analysis of fish assemblages in the Coorong at vertical-slot fishways (i.e. the Tauwitchere vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS), Goolwa vertical-slot (GVS) and Hunters Creek vertical-slot) in 2019/20.

Species		**Location**	**Indicator Value**	***p* value**
Vertical-slot sites				
Tamar River goby	Solely estuarine	TVS	74.3	0.0048
Lagoon goby	Solely estuarine	TVS	69.4	0.0048
Common galaxias	Semi-catadromous	TSVS	34.3	0.013

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

Inter-annual variation in abundance

Lamprey

In 2019/20 a total of 45 pouched lamprey and 16 short-headed lamprey were captured from fishways at the Murray Barrages. This was among the highest number of pouched lamprey sampled since monitoring began in 2006/07, and the greatest number of short-headed lamprey since the inaugural year of monitoring (Table 3-8)

The greatest numbers and abundance of pouched lamprey (PL, *n* = 32) and short-headed lamprey (SHL, *n* = 12) were sampled from fishways on Goolwa Barrage, with lower numbers from Mundoo (PL *n* = 9 and SHL *n* = 1), Tauwitchere (PL *n* = 1 and SHL *n* = 1) and Boundary Creek (PL *n* = 1 and SHL *n* = 0), whilst neither species was detected at Ewe Island (Table 3-8; Figure 3-6). Generally, abundances of pouched lamprey and short-headed lamprey were among the highest recorded since consistent targeted winter–spring monitoring began in 2015 (Figure 3-6). Of the lamprey sampled, 41 pouched lamprey (mean TL ± SE = 554 ± 5 mm) and 14 short-headed lamprey (mean TL ± SE = 429 ± 6 mm) were implanted with PIT tags. Of these, 44% of pouched lamprey and 7% of short-headed lamprey were subsequently detected on one or more fishway PIT readers along the River Murray. Estimated extent of migration ranged from 274–726 km (Lock 1–8) for pouched lamprey, and 825 km (Lock 10) for the single short-headed lamprey detected.

Table 3-8. Total numbers of pouched lamprey and short-headed lamprey sampled from the Murray Barrages annually from 2006–2020. In years when targeted winter and spring-summer sampling has occurred (2011/12, 2013/14 and 2015–2020), numbers are pooled.

	06/07	**07/08**	**08/09**	**09/10**	**10/11**	**11/12**	**13/14**	**14/15**	**15/16**	**16/17**	**17/18**	**18/19**	**19/20**
Pouched lamprey	1	-	-	-	-	10	2	-	56	7	53	6	45
Short-headed lamprey	40	-	-	-	-	1	-	-	-	-	-	1	16

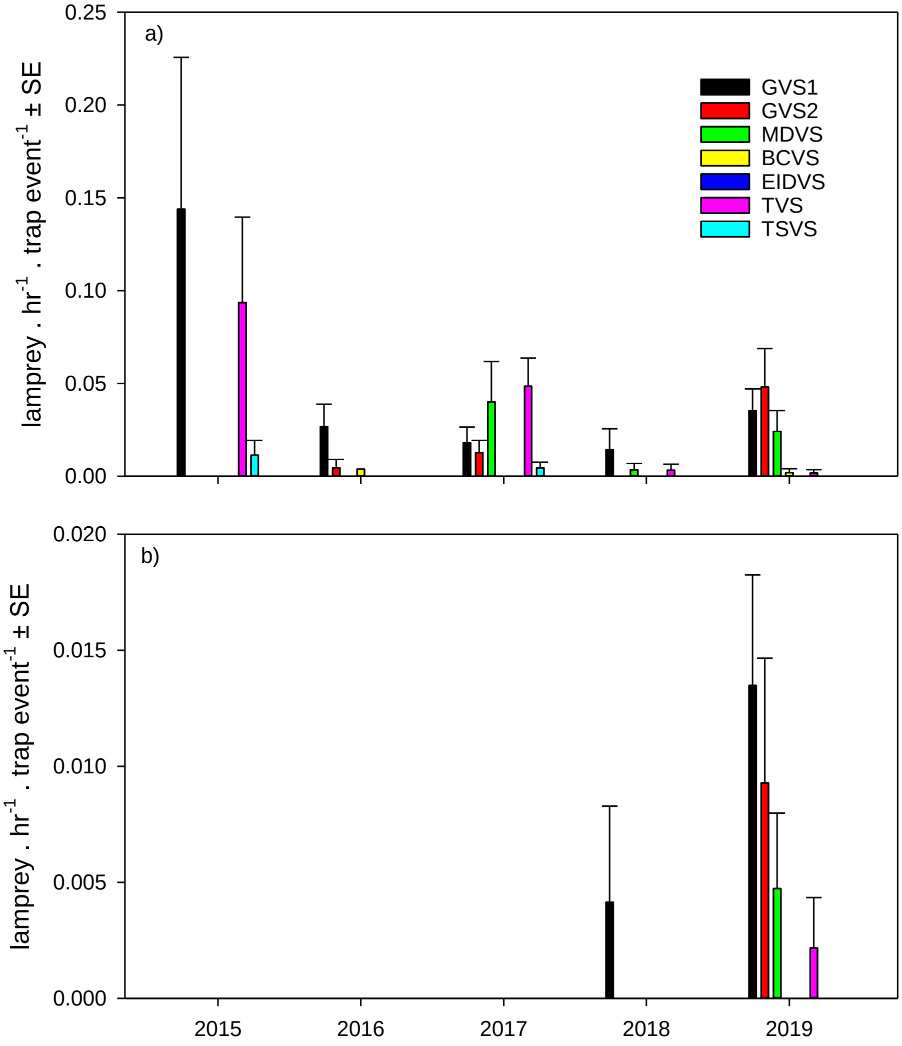

Figure 3-6. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of a) pouched lamprey and b) short-headed lamprey at the Goolwa vertical-slot (GVS1), Goolwa vertical-slot 2 (GVS2), Mundoo dual vertical-slot (MDVS), Boundary Creek vertical-slot (BCVS), Ewe Island dual vertical-slot (EIDVS), Tauwitchere vertical-slot (TVS) and Tauwitchere small vertical-slot (TSVS) during targeted sampling in winter–spring from 2015–2020. Note sampling at GVS2, BCVS and EIVS began in 2016, and at MDVS in 2017.

Congolli and common galaxias

The abundance of the catadromous congolli and semi-catadromous common galaxias differed significantly between years at all sampling locations except common galaxias at Hunters Creek (Table 3-9). 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; abundances recorded in 2019/20 were greater than recorded from 2006–2010, but were generally lower than 2014–2018 (Figure 3-7a).

Table 3-9. 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 (TSVS) 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	12, 114	25.67	<0.001*	28.75	<0.001*
TVS	12, 158	16.16	<0.001*	43.58	<0.001*
GVS	11, 176	12.30	<0.001*	4.66	<0.001*
GDS	10, 62	11.22	<0.001*	10.80	<0.001*
TSVS	8, 123	6.63	<0.001*	11.68	<0.001*
Hunters	8, 120	4.18	<0.001*	1.94	0.056

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 2019/20, remained high relative to the period 2006–2011, with abundances among the highest recorded since 2015/16 (Figure 3-7b).

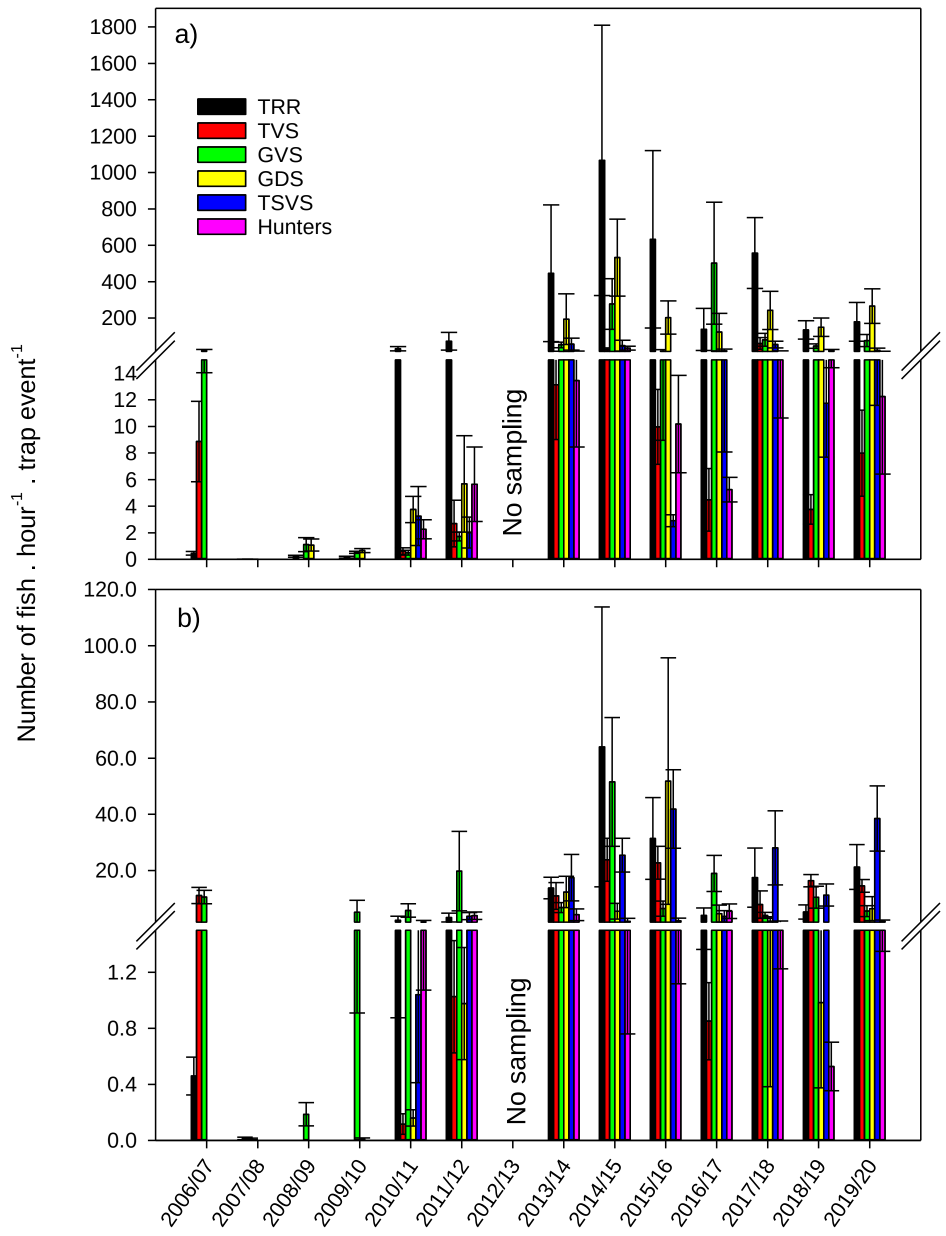

Figure 3-7. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of a) congolli and b) common galaxias at the Tauwitchere rock ramp (TRR), Tauwitchere vertical-slot (TVS), Goolwa vertical-slot (GVS), adjacent Goolwa Barrage (GDS), Tauwitchere small vertical-slot (TSVS) and Hunters Creek vertical-slot (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.

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 (Figure 3-8a). At vertical-slot fishway sites in 2019/20, peak daily abundance of congolli was detected at the Goolwa vertical-slot on 1 December when 220 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, December at the Goolwa vertical-slot, October or December at sites on Tauwitchere Barrage, and in December adjacent Goolwa Barrage. In 2019/20, peak daily abundance of common galaxias was detected at the Tauwitchere small vertical-slot on 23 October when 113 fish.hr^{-1} were detected migrating upstream.

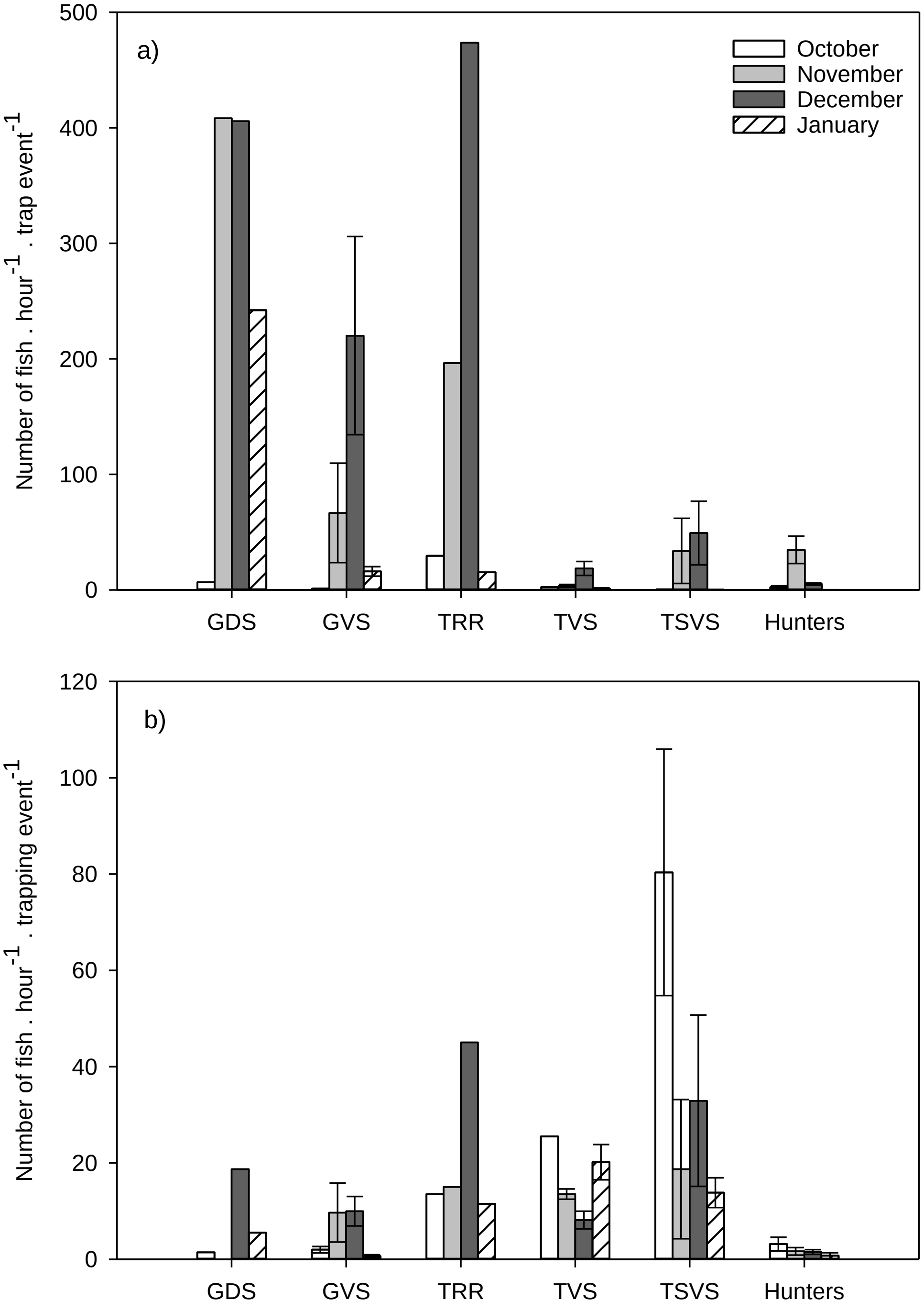

Figure 3-8. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of a) congolli and b) common galaxias at adjacent Goolwa Barrage (GDS), Goolwa vertical-slot (GVS), Tauwitchere rock ramp (TRR), Tauwitchere vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS) and Hunters Creek vertical-slot (Hunters) from October 2019–January 2020.

Below Tauwitchere Barrage (Tauwitchere rock ramp, large vertical-slot and small vertical-slot data combined) in October 2019, congolli were sampled across a broad length distribution ranging 31–173 mm TL (Figure 3-9a). A YOY cohort ranging 31–43 mm TL was present and represented 17% of the sampled population. Whilst fish were not aged in 2019/20, 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 2019: 32–56 mm TL, December 2019: 37–64 mm TL and January 2020: 42–72 mm TL), and increased in prominence, comprising 72–98% of the sampled population during each month (Figure 3-9a-d).

A similar pattern was evident below Goolwa Barrage (vertical-slot and adjacent Goolwa Barrage data combined) with the sampled population of fish ranging 26–129 mm TL (Figure 3-9a-d), with a prominent YOY cohort (26–45 mm TL; 29% of population) in October 2019. Growth of this cohort was evident through the following months, progressing to 28–52, 33–60 and 39–63 mm TL in November 2019, December 2019 and January 2020, respectively. This cohort increased in dominance, comprising 88–98% of the sampled population during each month.

Length-frequency distributions at Hunters Creek were similar to both Tauwitchere and Goolwa (Figure 3-9a-d). Sampled fish ranged 31–125, 38–56, 35–125 and 40–77 mm TL during sequential sampling events and the YOY cohort (<60 mm TL) represented >90% of the sampled population during all months, with the exception of October (83%).

Common galaxias ranged 36–104 mm TL at Tauwitchere in October 2019, but individuals 36–61 mm TL comprised 95% of the sampled population (Figure 3-10a). Similar to congolli, common galaxias were not aged in 2019/20, yet fish of this size have been determined to represent a YOY cohort in previous years (see Bice *et al.* 2012). The 0+ cohort represented >95% of the sampled population in November–January (Figure 3-10b-d).

At Goolwa in October 2019, the YOY cohort of common galaxias ranged 35–58 mm TL and comprised 87% of the sampled population (Figure 3-10a). The mode of this cohort gradually increased across sampling months and it comprised 100% of the sampled population in November and December, and 80% in January 2020 (Figure 3-10b-d).

The length-frequency distributions for common galaxias at Hunters Creek were similar to both Tauwitchere and Goolwa (Figure 3-10a-d). Sampled fish ranged 40–121, 37–116, 37–96 and 42–68 mm TL during sequential sampling events. In October 2019, individuals 40–55 mm TL comprised 73% of the sampled population. This cohort increased in dominance, comprising 89, 98 and 100% of the sampled population in each successive month.

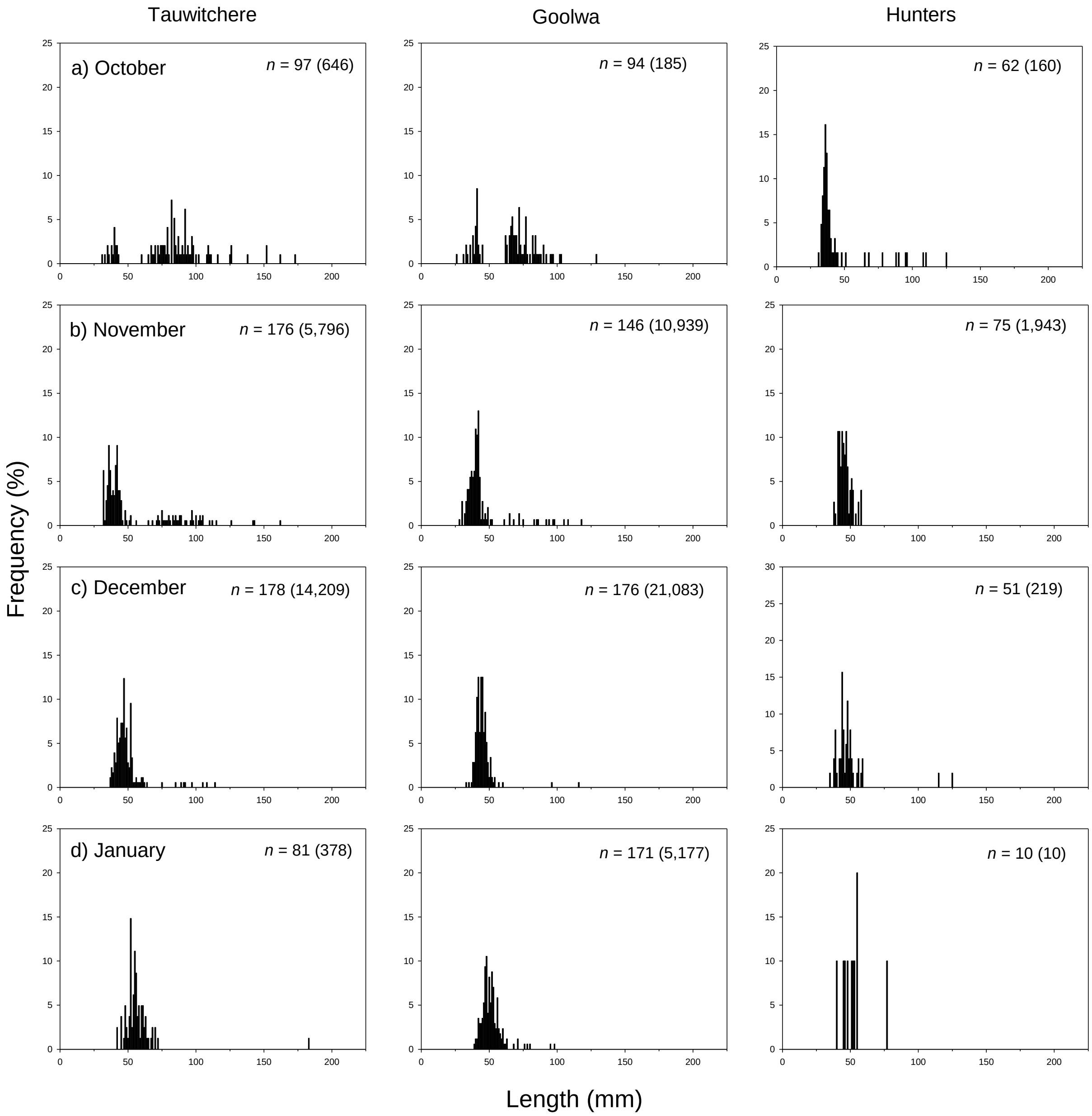

Figure 3-9. Monthly length-frequency distributions (total length, mm) of congolli sampled below Tauwitchere Barrage (rock ramp, large vertical-slot and small vertical-slot combined; left column), Goolwa Barrage (vertical-slot and adjacent Goolwa Barrage combined; middle column) and at the entrance of the Hunters Creek vertical-slot (right column) in a) October 2019, b) November 2019, c) December 2019 and d) January 2020. *n* is the number of fish measured and the total number of fish collected in each month at each site is presented in brackets.

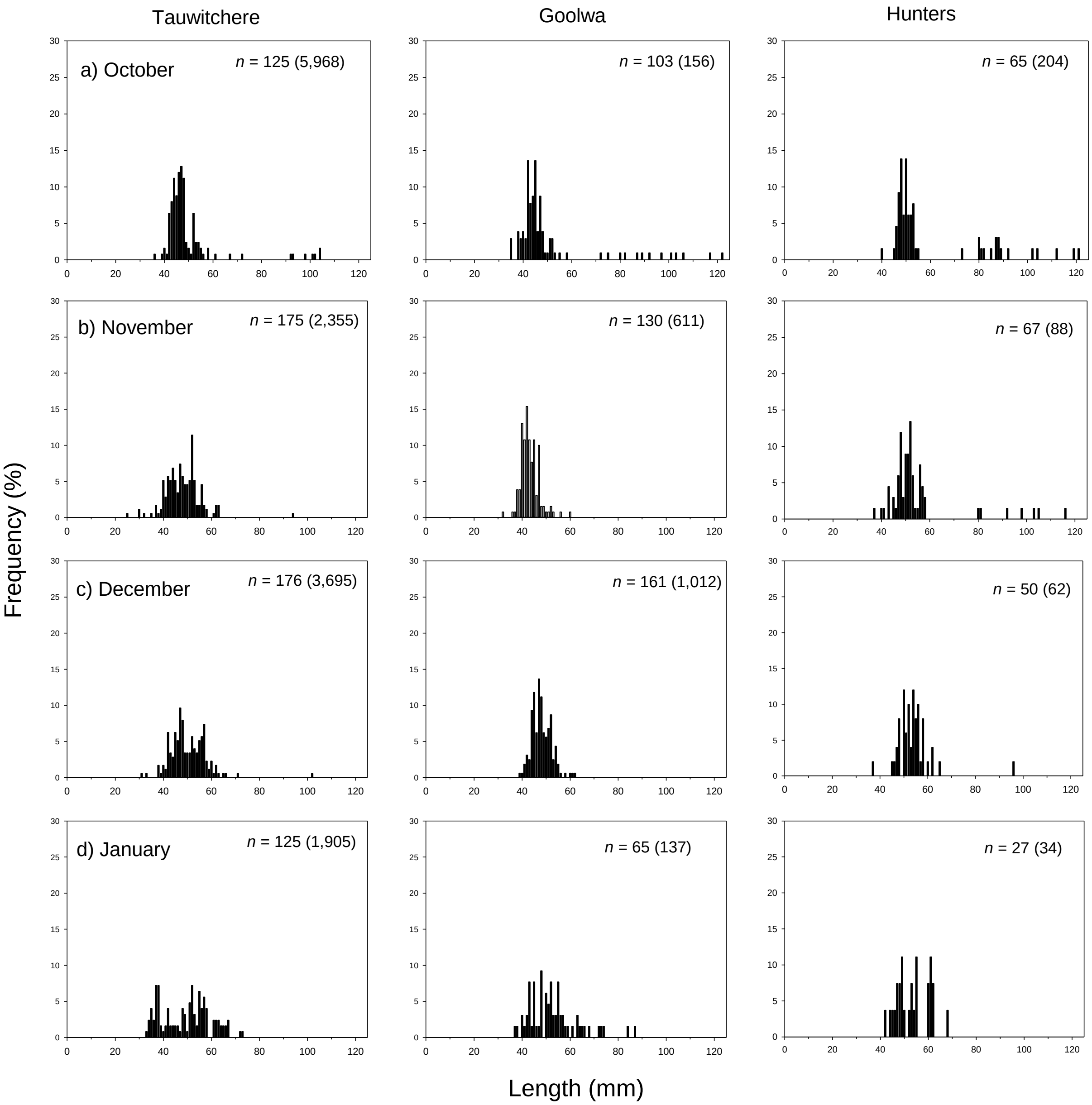

Figure 3-10. Monthly length-frequency distributions (total length, mm) of common galaxias sampled below Tauwitchere Barrage (rock ramp, large vertical-slot and small vertical-slot combined; left column), Goolwa Barrage (vertical-slot and adjacent Goolwa Barrage combined; middle column) and at the entrance of the Hunters Creek vertical-slot (right column) in a) October 2019, b) November 2019, c) December 2019 and d) January 2020. *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 2019/20 (Figure 3-11a). The target has been met in all years since 2013/14, but was 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 2019/20) with the exception of 2007/08, 2008/09, 2010/11 and 2016/17 (Figure 3-11b).

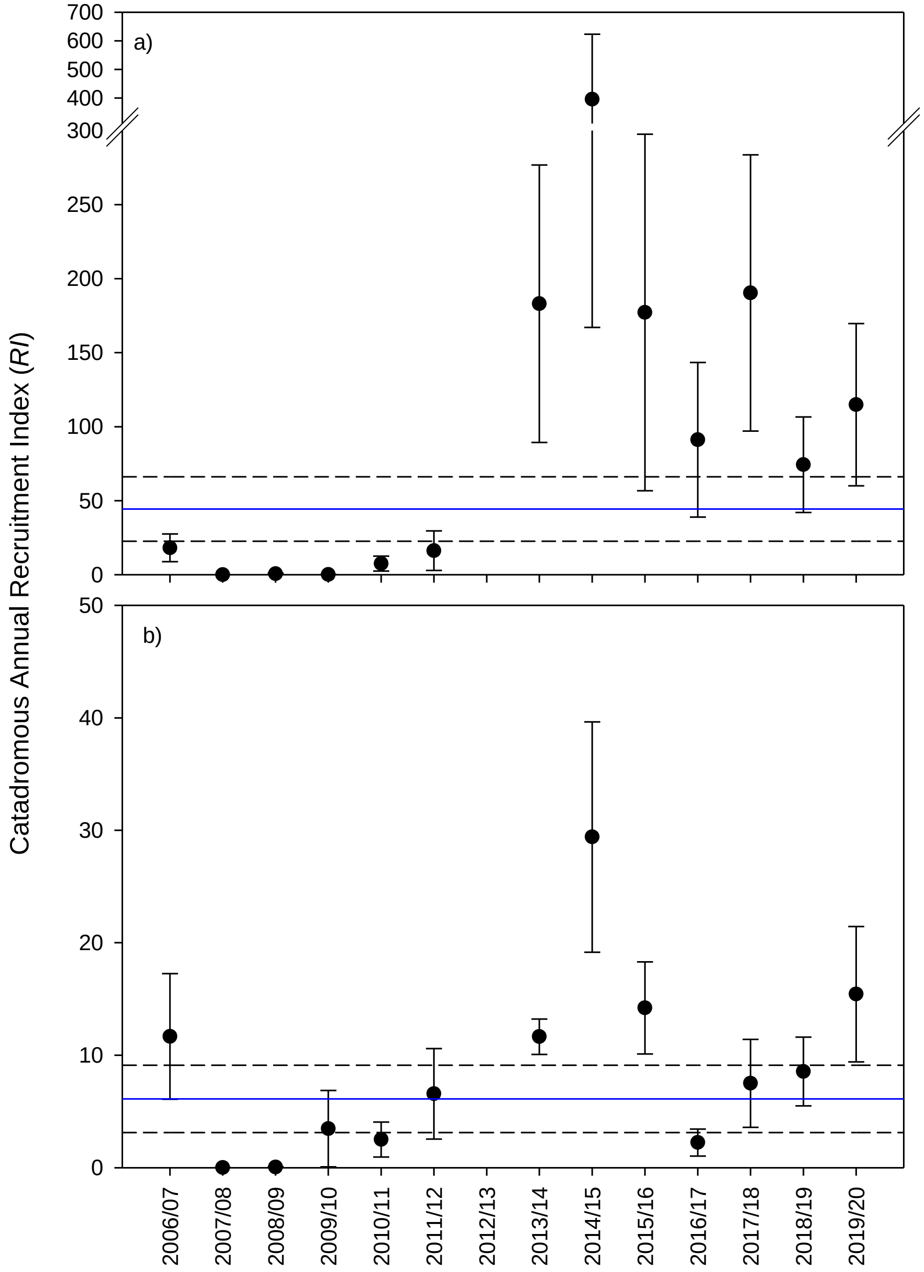

Figure 3-11. Catadromous annual recruitment index (*RI,* number of upstream migrating YOY.hour^{-1} ± half confidence interval for a) congolli and b) common galaxias from 2006/07 to 2019/20 (no sampling was conducted in 2012/13). The reference value is indicated by the blue line and half confidence intervals indicated by dashed lines.

Target 3: Anadromous migration

In 2019/20, the migration index (*MI*) for short-headed lamprey was slightly below the reference value, despite being sampled from ~50% of vertical-slot fishways and in greatest numbers since 2006/07 (Figure 3-12). The species only achieved the reference in 2006/07 and was absent from sampling from 2007–2018.

For pouched lamprey, the migration index was met in 2019/20, with the species sampled from >60% 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 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.

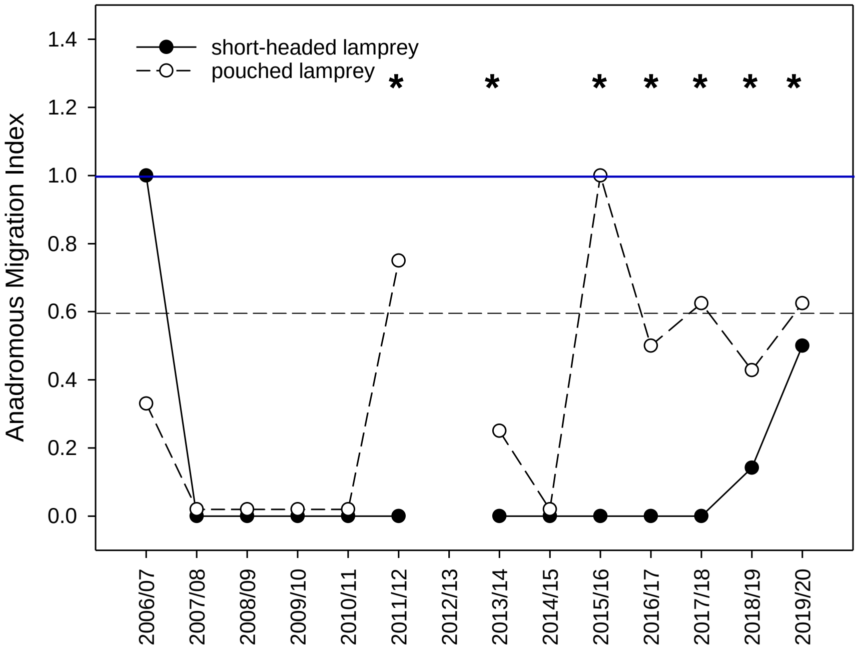

Figure 3-12. Anadromous migration index (*MI*) for short-headed lamprey (*open circles*) and pouched lamprey (*closed circles*) from 2006/07 to 2019/20 (no sampling was conducted in 2012/13). The blue line represents the reference value and dashed line indicates a 40% tolerance and level deemed to indicate target was met. * indicate years in which specific sampling for lamprey occurred during winter.

4. DISCUSSION

4.1. Fish assemblages

Inter-annual variation

The year of 2019/20 represented a year of low–moderate discharge (685 GL; maximum discharge during sampling = ~24,900 ML.d^{-1}), and the tenth 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. During spring–summer 2019/20, 32 fish species, representing 21 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 moderate freshwater discharge, with similarity to other years of moderate discharge (e.g. 2013–2016 and 2017/18). Young-of-the-year (YOY) of catadromous species were generally abundant.

Among sites, there was a consistent pattern of temporal variability in fish assemblages across years from 2006/07 to 2019/20, 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 moderate discharge (2013–2016, 2017/18, 2019/20), 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 moderate discharge, abundance ranged 176–1831 fish.hr^{-1}. In both high and moderate 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 2019/20, was ~29.5 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 2006–2020, 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 2011–2020 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 2019/20, fish assemblages varied among certain vertical-slot fishways and reflected differences in species-specific use of large and small vertical-slot fishways (Bice *et al.* 2017). The semi-catadromous common galaxias is commonly sampled in high abundance at the Tauwitchere small vertical-slot fishway, particularly during years of low–moderate discharge when attraction to this fishway is maximised. This is encouraging as this fishway was specifically designed to pass small-bodied fishes, including upstream migrating juvenile common galaxias.

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 specific 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 eight species at the Tauwitchere small vertical-slot to 23 and 25 species adjacent the Tauwitchere rock ramp and Goolwa Barrage respectively.

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

Catadromous species

Total numbers and relative abundances of congolli in 2019/20 were high relative to the period 2006–2011, but were low in comparison to most years since 2011/12 (Zampatti *et al.* 2010, 2011, Bice *et al.* 2012, Bice and Zampatti 2014). Nonetheless, congolli was the most abundant species sampled in 2019/20 representing over 40% of the total fish sampled. Similar patterns were evident for common galaxias in 2019/20, which could be considered abundant relative to 2006–2011. Whilst no ageing of fish was conducted in 2019/20, length-at-age data from previous years (Zampatti *et al.* 2010, 2011, Bice *et al.* 2012) indicate that >80% of all individuals sampled for both species, in each month, were newly recruited YOY. Given high abundances of newly recruited YOY congolli and common galaxias, the annual recruitment index and condition monitoring target were achieved in 2019/20.

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.

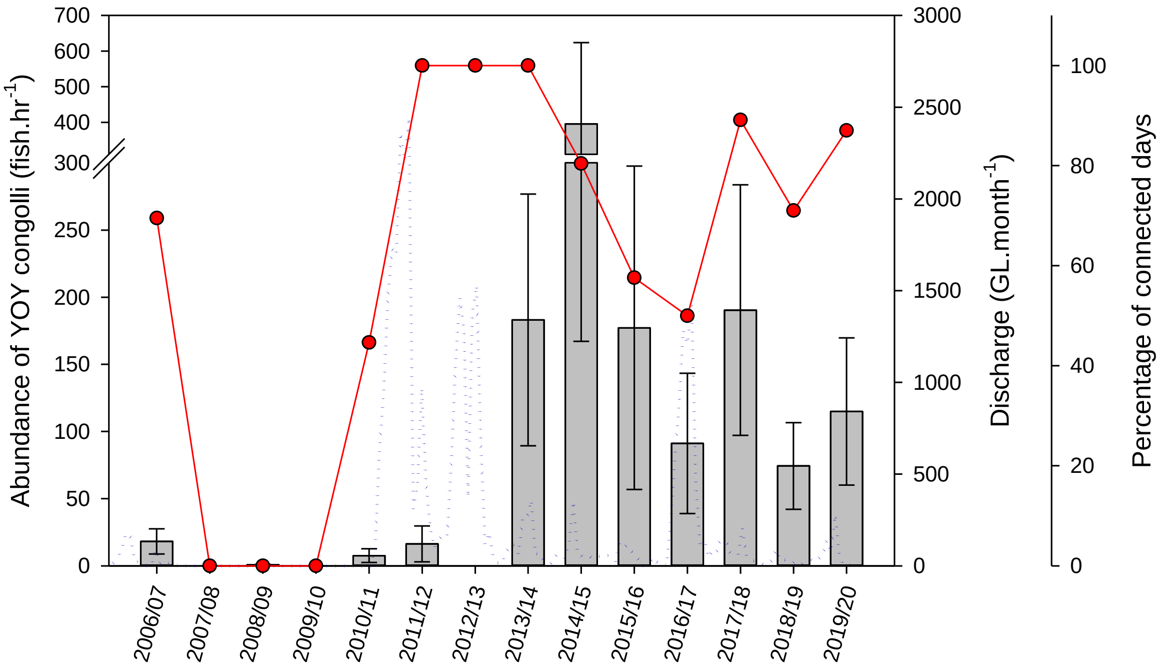

Figure 4-1. The abundance of YOY congolli sampled across the Murray Barrages from 2006–2020 (fish.hr^{-1}), with discharge (GL.month^{-1}, *blue dotted line*) and percentage of connected days (*red line*) overlaid.

Anadromous species

In 2019/20, a total of 45 pouched lamprey and 16 short-headed lamprey were sampled at the barrages. The annual migration index and Icon Site ecological target was met for pouched lamprey, but not met for short-headed lamprey. Nevertheless, short-headed lamprey were sampled from 50% of fishway sites, just below the 60% required to meet the target, and the species was sampled in greatest numbers at the Murray Barrages since the first survey in 2006/07. In addition, an individual short-headed lamprey was for the first time tracked passing through fishways on the River Murray main channel weirs; based on PIT tag detections, this individual passed through multiple fishways before being last detected at Lock 10, 825 km upstream of the Murray Mouth (Bice *et al.* 2020). For pouched lamprey, 44% of PIT tagged individuals were subsequently detected on fishway PIT reader systems and estimated extent of migration ranged from 274–726 km (Lock 1–8) (Bice *et al.* 2020).

Increasing data on the migration of pouched lamprey and short-headed lamprey at the Murray Barrages, and more broadly in the MDB, is improving the conceptual models for the movement of these species. 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), indicates winter is the key upstream migration period for this species. For short-headed lamprey, data from 2019/20 confirms previous assertions that peak upstream migration at the Murray Barrages likely occurs slightly later, in late winter–spring (Bice *et al.* 2019). 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 and 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 2006–2020 (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 extending into spring. 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, and research, 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 from June to September; 2) allow for upstream migrations of pouched lamprey from June to August; 3) allow for upstream migrations of short-headed lamprey from August to November; and 4) 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 September, 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) Further investigations of fish passage at the Murray Barrages should include assessment of passage efficiency at remaining fishways during spring/summer (i.e. Goolwa small vertical-slot and Tauwitchere trapezoidal) and assessment of passage through barrage gates.
6) Following completion of the above monitoring and research, the knowledge generated should be incorporated with that of related studies 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 semi-catadromous 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. 2019/20 represented a year of moderate freshwater discharge that followed moderate and low discharge in 2017/18 and 2018/19, respectively. Importantly, in 2019/20, all freshwater discharge, and continuous fishway operation, were supported by allocations of water for the environment. 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. The majority of individuals sampled in 2019/20 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 2019/20. The objective (b) – '*promote the successful spawning migration of anadromous fish species in the Lower Lakes and Coorong',* was achieved for pouched lamprey, but not short-headed lamprey, although the species was detected in considerable numbers in 2019/20.

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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