

Inland Waters & Catchment Ecology

Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2021-22



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

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Report to the Department for Environment and Water



**Government
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Department of Primary
Industries and Regions



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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 (TLM) Initiative*. The region supports a diverse fish assemblage of ecological, cultural and commercial importance. An understanding of variability in estuarine fish populations and assemblage structure in relation to freshwater inflow and antecedent conditions is fundamental to the management of estuarine ecosystems. Data on diadromous fish migration and estuarine fish assemblage structure has been collected since 2006 to inform against specific ecological objectives and targets within the Lower Lakes, Coorong and Murray Mouth (LLCMM) Icon Site Environmental Water Management Plan (2014) and the Condition Monitoring Plan (Revised, 2017).

The objective of this study in 2021/22 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 fish 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 2021/22, and assess spatio-temporal variation in assemblage structure over the period 2006–2021;
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 2021/22, and in relation to long-term data from 2006–2021;
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 2021/22, and in relation to long-term data from 2006–2021;
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 2021/22 was characterised by high freshwater discharge (6180 GL; maximum discharge during sampling = $\sim 35,468 \text{ ML.d}^{-1}$), and in association, salinity below the barrages was typically $< 5 \text{ g.L}^{-1}$. The fish assemblage sampled in spring/summer was dominated by the freshwater Australian smelt (*Retropinna semoni*, 34%), redfin perch (*Perca fluviatilis*, 15%) and bony herring (*Nematalosa erebi*, 13%), and marine estuarine-opportunist sandy sprat (*Hyperlophus vittatus*, 17%). The 2021/22 fish assemblage was generally similar to those of previous years of high freshwater flow ($> 6000 \text{ GL}$), including 2010/11, 2011/12 and 2016/17, and characterised by moderate diversity, high freshwater species abundance, moderate abundance of catadromous species, and generally low abundance of marine species.

A total of 22 pouched lamprey (20 PIT tagged), but no short-headed lamprey, were captured from fishways during sampling at the Murray Barrages in winter–spring 2021. The abundance of pouched lamprey was moderate relative to previous years of targeted winter monitoring. Of the pouched lamprey PIT tagged, 15% ($n = 3$) were subsequently detected on River Murray fishway PIT reader systems from 1–15 September with estimated extents of migration ranging from 274–431 km (Lock 1–3).

In spring–summer 2021/22, the abundances of the catadromous congolli and common galaxias were high relative to 2006–2011, and low–moderate relative to the period 2011–2020. Nevertheless, $> 80\%$ of all individuals sampled were newly recruited young-of-the-year (YOY). Peak periods of upstream migration for YOY congolli were noted in December and January. This timing of migration is consistent with previous years of monitoring. For common galaxias peak abundances varied among sites and occurred from October–January.

Based on timing of upstream and downstream movements of diadromous species derived from fishway monitoring from 2006–2022, 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 2021/22, the fish assemblage generally trended towards moderate species diversity and numerical dominance by freshwater species that characterises estuaries subject to high freshwater flow. Abundances of catadromous congolli and common galaxias were low–moderate, but the annual recruitment target was met for both species. The migration target was not achieved for short-headed lamprey or pouched lamprey, although pouched lamprey was sampled in moderate abundance. 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 fishes, 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 and are characterised by a broad range of life history strategies (Whitfield 1999), and as such, fish 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 is located at the terminus of Australia's longest river system, the Murray–Darling, and the region is an icon site under *The Living Murray (TLM) Initiative*. 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), necessitating regular dredging of the Murray Mouth to maintain connectivity with the Southern Ocean. 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 2006–2021, 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 eleven-year period (2010–2021), was characterised by contrasting hydrology, which included flooding in the lower River Murray and large volumes of freshwater discharge to the Coorong 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 of 650 GL for barrage discharge volumes established under the LLCMM Icon Site Environmental Water Management Plan (2004) was achieved in all years except 2015/16 and 2018/19. A further three-year target that stipulates a three-year rolling average of 2000 GL.yr⁻¹ and annual discharge >650 GL was only achieved in years from 2012–2015.

From 2006–2021, 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 or limited freshwater discharge (2007–2010), the abundance of freshwater, diadromous and estuarine species decreased, and marine species became more common (Zampatti *et al.* 2010). Specifically, the 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-estuarine opportunist (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 particular estuarine (e.g. lagoon goby, *Tasmanogobius lasti*) and marine-estuarine opportunist species (e.g. sandy sprat). Throughout 2011–2021, the abundance of catadromous fishes has remained high. For anadromous species, pouched lamprey has been detected in eight years, and short-headed lamprey in three.

The year 2021/22, represented the twelfth consecutive year of consistent 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. Annual data are integral to the understanding of hydrologically mediated patterns in fish assemblage structure and

movement and can be used to assess specific ecological targets (DEWNR 2017). This data will also 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 2021/2022 and assess spatio-temporal variation in fish assemblage structure in relation to the period 2006–2021.
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 2021/22, in relation to long-term data from 2006–2021.
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 winter–spring 2021, and in relation to long-term data from 2006–2020.
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.

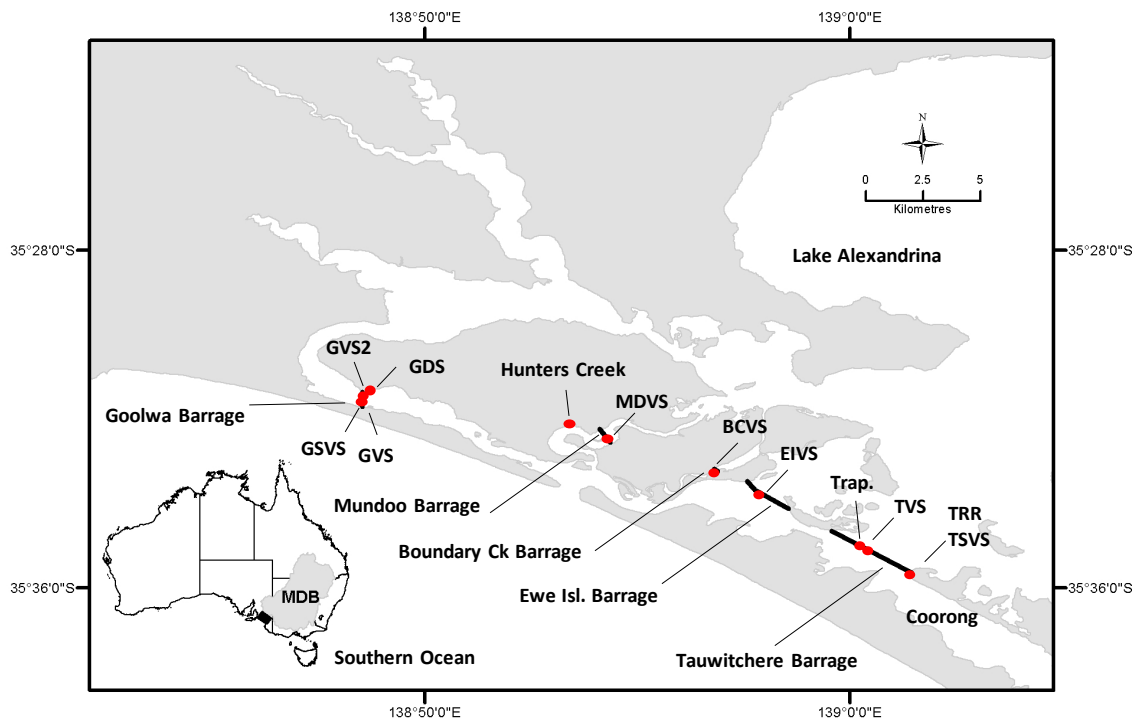


Figure 2-1. A map of a portion of the Coorong and Lake Alexandrina at the terminus of the River Murray, southern Australia showing the study area in the Coorong estuary, highlighting the Murray Barrages (bold lines). Barrages, fishways and fyke-net sampling sites (red dots); Goolwa vertical-slot (GVS), 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, GSVS, MDVS, EIVS, BCVS and Trap. fishway are sampled only during winter lamprey monitoring

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 (CSIRO 2008), 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 could be considered low–moderate in 2013/14 (~1600 GL), 2014/15 (~984 GL), 2015/16 (~562 GL), 2017/18 (~802 GL), 2018/19 (~370 GL), 2019/20 (~685 GL) and 2020/21 (~1260 GL), interspersed by high discharge in 2016/17 (~6536 GL) and 2021/22 (6180 GL) (Figure 2-2).

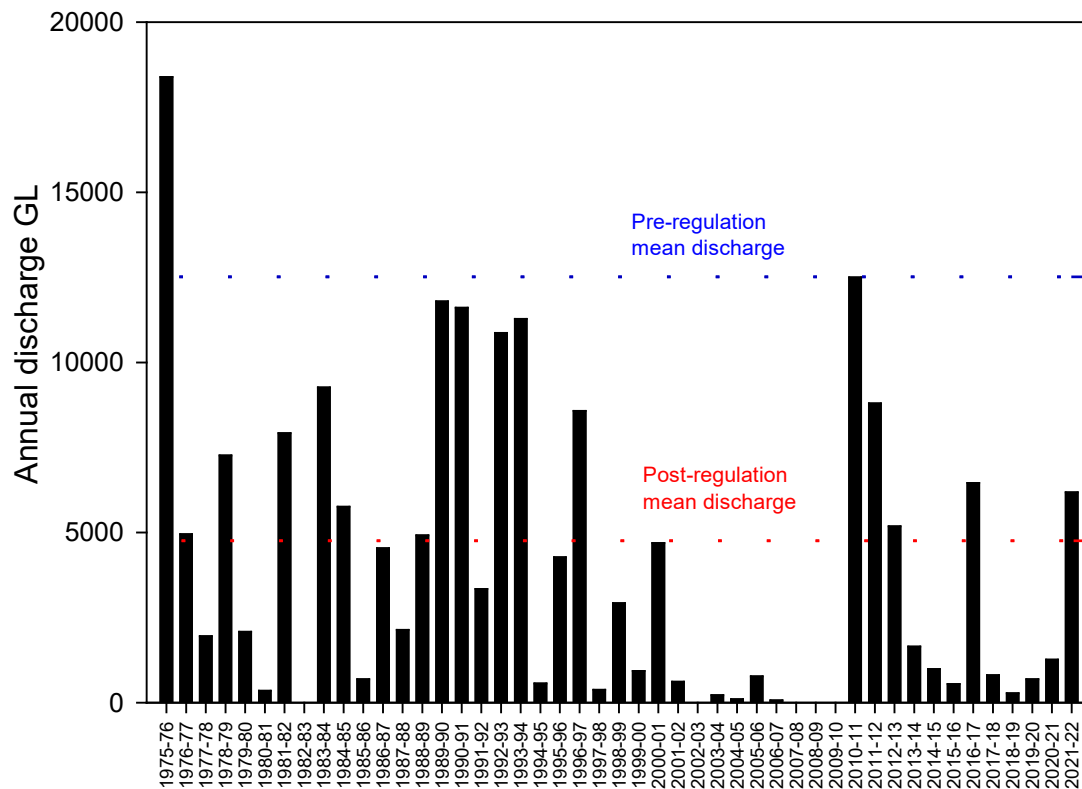


Figure 2-2. Annual freshwater discharge (GL) through the Murray Barrages into the Coorong estuary from June 1975–June 2022. Dashed lines represent mean annual end of system discharge pre- (blue) and post-regulation (red).

Following construction of the barrages, 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 ($>40 \text{ g.L}^{-1}$) conditions (Geddes 1987, Walker 2002). During times of low freshwater discharge, salinity ranges from marine ($30\text{--}35 \text{ g.L}^{-1}$) near the Murray Mouth to hypersaline ($>100 \text{ g.L}^{-1}$) 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. $5\text{--}30 \text{ g.L}^{-1}$) (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 $\sim 13.6\%$), 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 early life stages (<100 mm TL) of larger species, 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 have been shown to effectively facilitate the passage of small-bodied fish (Zampatti *et al.* 2012). A further seven fishways were constructed between 2014 and 2018 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 2021/22, fish sampling occurred from July–February, for two distinct purposes: 1) assessment of abundance of upstream migrating anadromous lamprey in winter–spring (August–September 2021); and 2) assessment of catadromous fish (congolli and common galaxias) migration and recruitment as per TLM targets in spring–summer (October 2021–February 2022; see section 2.4). Sampling in winter–spring involved trapping of seven fishways on Goolwa, Mundoo, Boundary Creek and Tauwitchere barrages (Figure 2-1 and Table 2-1). During spring–summer, samples of fish are typically collected from the entrances of four vertical-slot fishways on Tauwitchere (TVS and TSVS) and Goolwa Barrages (GVS), 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 incorporated into GSVS. BCVS also has an 'attraction gate'. But is integrated within the barrage. NOTE: discharge is indicative and may vary depending on headwater and tailwater levels.

| Name | Abbrev. | Barrage | 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) | Aug–Sep sampling | Oct–Feb sampling |
|---|---------|------------------------------|----------------------------|-------------------|---|---|------------------------------------|---------------------|---------------------|
| Tauwitchere large vertical- slot | TVS | Tauwitchere | 2.3 x 4.0 x 2.0 m | 0.3 | 2.0 | 95 | 31 | Y | Y |
| Tauwitchere small vertical- slot | TSVS | Tauwitchere | 1.2 x 1.6 x 1.0 | 0.2 | 1.0 | 26 | 2.4 | N | Y |
| Tauwitchere rock ramp | TRR | Tauwitchere | - | - | - | - | - | N | Y |
| Tauwitchere trapezoidal | Trap. | Tauwitchere | 1.0 x 3.46 x 1.5 m | 0.1 | - | - | 50 | Y | N |
| Goolwa vertical- slot | GVS | Goolwa | 2.6 x 3.6 x 3.6 m | 0.2 | 1.7 | 26 | 40 | Y | Y |
| Goolwa vertical- slot 2 | GVS2 | Goolwa | 2.6 x 3.6 x 2.8 m | 0.2 | 1.5 | 23 | 35 | Y | N |
| Goolwa small vertical-slot | GSVS | Goolwa | 1.24 x 0.93 x 2.0 m | 0.11 | 1.0 | 20 | 10 (50)* | Y | N |
| Adjacent Goolwa Barrage | GDS | Goolwa | - | - | - | - | - | N | Y |
| Hunters Creek vertical-slot | Hunters | Hunters Creek causeway | 1.6 x 1.6 x 0.6 m | 0.1 | 1.1 | 25 | 3 | N | Y |
| Mundoo dual vertical-slot | MDVS | Mundoo | 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 | 3.25 x 3.4 x 1.5 m | 0.15 | 1.7 | 40 | 16 | N | N |
| Boundary Creek small vertical- slot | BCVS | Boundary Creek | 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 aluminum-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.

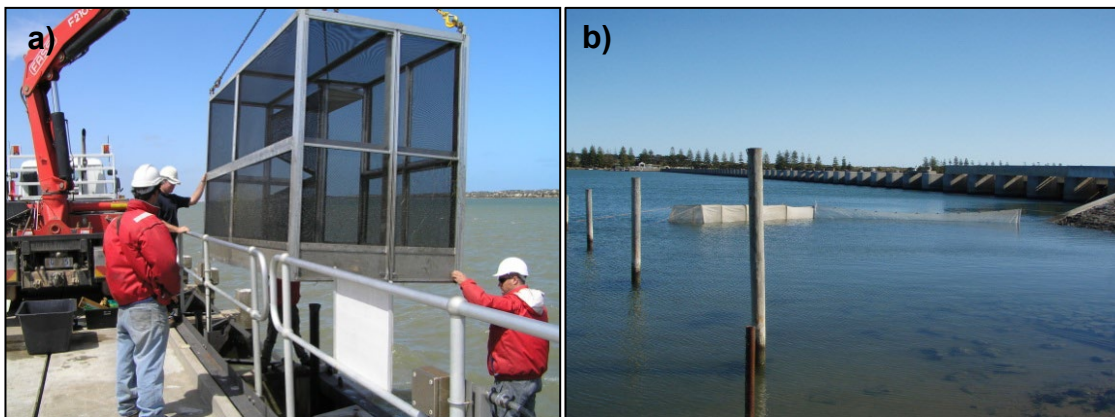


Figure 2-3 a) Cage trap used to sample the Tauwitchere and Goolwa vertical-slot fishways and b) large fyke net used to sample adjacent Goolwa Barrage. A net of the same dimensions was also used to sample adjacent to the Tauwitchere rock ramp.

Targeted sampling for lamprey was conducted periodically from 3 August–18 September 2021 ($n = 5\text{--}13$ sampling events per fishway) (Table 2-1). Cage traps at the large vertical-slot and trapezoidal fishways were deployed and retrieved using a mobile crane (Figure 2-3a). All pouched lamprey and short-headed lamprey captured were enumerated and the majority implanted with PIT (passive integrated transponder) and acoustic tags before being released upstream (Bice *et al.* 2020).

Sampling in spring–summer occurred from 19 October 2021–10 February 2022. Sampling typically occurs over four sampling weeks approximately monthly from October–January, but interruptions associated with COVID-19 meant January sampling at several sites (TVS and GVS)

was delayed till early February. 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. During each trapping event, for catadromous congolli and common galaxias, 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

All analyses described below are related to data collected during spring–summer sampling, with the exception of those related to anadromous lamprey, which are specifically targeted during winter–spring sampling.

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 total 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; note: lamprey species sampled in winter–spring sampling are included in this specific assessment).

The composition of fish assemblages sampled at each location was assessed between all sampling years (i.e. 2006–2022). 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 70% 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.* (2018a). 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 (<i>Sillaginodes punctatus</i>) |
| 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 (<i>Argyrosomus japonicus</i>) |
| Estuarine category | | |
| Solely estuarine | Species that complete their life cycles only in estuaries. | Small-mouthed hardyhead (<i>Atherinosoma microstoma</i>) |
| 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 (<i>Arenogobius bifrenatus</i>) |
| 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 (<i>Geotria australis</i>) |
| Catadromous | Most growth and adult residence occurs in the freshwater environments prior to migration into, spawning and larval/juvenile development in marine environments. | Congolli (<i>Pseudaphritis urvillii</i>) |
| Semi-catadromous | As per catadromous species, but spawning run extends as far as downstream estuarine areas rather than the ocean. | Common galaxias (<i>Galaxias maculatus</i>) |
| Freshwater category | | |
| Freshwater straggler | Truly freshwater species that spawn in freshwater environments and only sporadically enter estuaries, and in low numbers. | Golden perch (<i>Macquaria ambigua</i>) |
| 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 (<i>Nematalosa erebi</i>) |

Intra-annual spatial variability in fish assemblages

Spatial variation in fish assemblages between sampling locations in 2021/22 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's 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 2021/22.

Spatio-temporal variability in diadromous species abundance

Inter-annual variability in the total number (2006–2022) and standardised abundance (fish.hour⁻¹.trap event⁻¹) from years of targeted winter monitoring (2015–2022) of pouched lamprey and short-headed lamprey were qualitatively assessed. Inter-annual differences in the standardised abundance (fish.hour⁻¹.trap event⁻¹) of common galaxias and congolli 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 2021/22 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 (Revised, 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, which are also described in DEWNR (2017). These targets were developed from empirical data collected from 2006 to 2014 and relate specifically to the migration and recruitment of YOY 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 $\geq 60\%$ 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:

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

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:

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

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:

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

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

This provides a value of *MI* of ≤ 1.0 and an arbitrary tolerance of 0.4 is adopted, i.e. $MI \geq 0.6$ 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 2015–2021. 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 and salinity

Freshwater discharge to the Coorong and salinity were highly variable over the period 2005–2022. 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 2017–2021); and high discharge (5200–12,500 GL; 2010–2013, 2016/17 and 2021/22).

Persistent drought in the MDB resulted in no freshwater being released to the Coorong from March 2007 to September 2010 (Figure 3-1a). Significant inflows to the Lower Lakes in late 2010, saw the fishways and barrages reopened and the release of large volumes of freshwater to the Coorong throughout the 2010/11 sampling season (range 9,014–87,221 ML.d⁻¹; mean = 10,823 ML.d⁻¹) (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. In 2020/21 during the spring/summer sampling season, flow ranged 325–10,118 ML.d⁻¹, with a mean of 4021 ML.d⁻¹. In 2021/22, flow increased substantially and during the spring/summer sampling season ranged 8326–35,468 ML.d⁻¹, with a mean of 19,854 ML.d⁻¹.

Salinity downstream of the Murray Barrages fluctuated in association with freshwater discharge. During sampling in 2006/07, salinity below Tauwichee and Goolwa Barrages fluctuated from 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 Tauwichee increased and ranged from 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. Sampling seasons during high flow were characterised by reduced mean salinities in 2010/11 (Tauwichee = 3.8 g.L⁻¹, Goolwa = 2 g.L⁻¹),

2011/12 (Tauwitchere = 3.8 g.L⁻¹, Goolwa = 2 g.L⁻¹), 2016/17 (Tauwitchere = 12.7 g.L⁻¹, Goolwa = 10.4 g.L⁻¹) and 2021/22 (Tauwitchere = 3.1 g.L⁻¹, Goolwa = 2.4 g.L⁻¹) (Figure 3-1b). Remaining spring-summer sampling seasons from 2014–2021, have been characterised by brackish salinities downstream of both Tauwitchere and Goolwa, with seasonal averages that have ranged 13–28 g.L⁻¹ (Figure 3-1b).

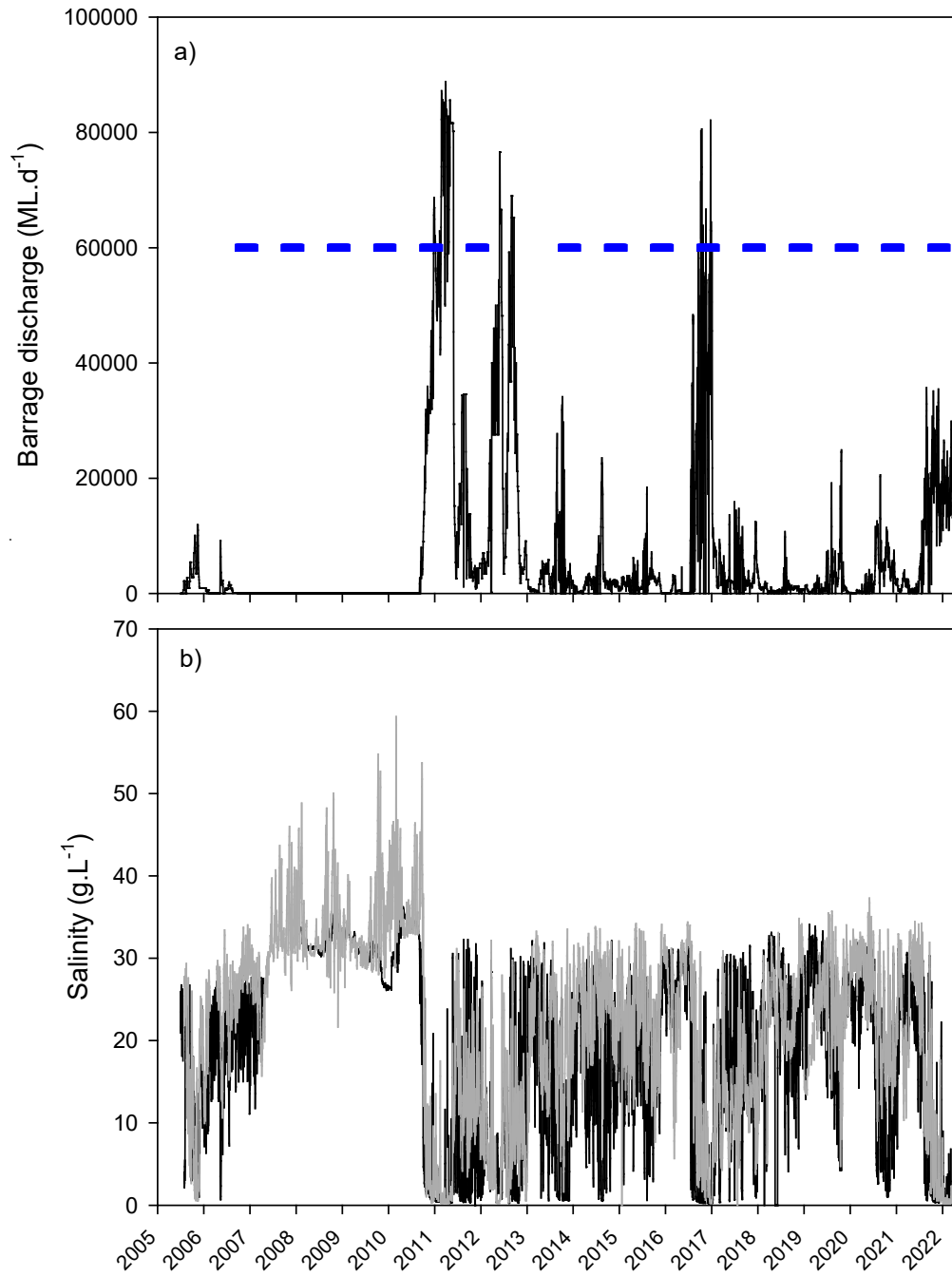


Figure 3-1. a) Mean daily flow (ML.d⁻¹) to the Coorong through the Murray Barrages (all barrages combined) from July 2005–March 2022 and b) Mean daily salinity (g.L⁻¹) of the Coorong below Tauwitchere (grey line) and Goolwa (black line) barrages from July 2005–June 2022. Sampling periods are represented by *blue horizontal bars* in plot 'a'.

3.2. Catch summary

A total of 247,380 fish from 24 species were sampled in spring–summer 2021/22 (Table 3-1). The catch was dominated by several freshwater species, namely Australian smelt (*Retropinna semoni*, 34%), redfin perch (*Perca fluviatilis*, 15%), bony herring (*Nematalosa erebi*, 13%) and flat-headed gudgeon (*Philypnodon grandiceps*, 4%), the marine estuarine-opportunist sandy sprat (17%), catadromous congolli (8.5%) and common galaxias (2.5%), and estuarine lagoon goby (*Tasmanogobius lastii*, 5%). The remaining 16 species collectively comprised ~1% 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, Tauwitchere rock-ramp, Goolwa vertical-slot and Hunters Creek vertical-slot, and adjacent Goolwa Barrage in spring–summer 2021/22. Species are categorised using estuarine use guilds from Potter *et al.* (2015) and designations presented by Bice *et al.* (2018a). Note: total numbers of lamprey sampled during winter–spring are presented in a subsequent section.

| 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 | 10 | 12 | 4 | 10 | 4 | 12 | |
| | | No. of species | 10 | 7 | 20 | 10 | 20 | 14 | |
| Australian smelt | <i>Retropinna semoni</i> | Freshwater estuarine opportunist | 10,765 | 36,227 | 20,982 | 5250 | 11,838 | - | 85,062 |
| Bony herring | <i>Nematalosa erebi</i> | Freshwater estuarine opportunist | 282 | - | 14,823 | 942 | 14,721 | 790 | 31,558 |
| Flat-headed gudgeon | <i>Philypnodon grandiceps</i> | Freshwater estuarine opportunist | 354 | 30 | 5567 | 60 | 3527 | 227 | 9765 |
| Carp gudgeon | <i>Hypseleotris spp</i> | Freshwater straggler | - | 1 | 1 | - | - | 3 | 5 |
| Common carp | <i>Cyprinus carpio*</i> | Freshwater straggler | 1 | - | 4 | - | 1 | 2 | 8 |
| Dwarf flat-headed gudgeon | <i>Philypnodon macrostomus</i> | Freshwater straggler | - | - | - | - | 1 | - | 1 |
| Golden perch | <i>Macquaria ambigua</i> | Freshwater straggler | 17 | - | 253 | - | 1 | 5 | 276 |
| Goldfish | <i>Carassius auratus*</i> | Freshwater straggler | - | - | - | - | 1 | 4 | 5 |
| Redfin perch | <i>Perca fluviatilis*</i> | Freshwater straggler | 503 | 931 | 8916 | 209 | 25,614 | 680 | 36,853 |
| Congolli | <i>Pseudaphritis urvillii</i> | Catadromous | 210 | 1567 | 9240 | 2689 | 7057 | 718 | 21,481 |
| Common galaxias | <i>Galaxias maculatus</i> | Semi-catadromous | 269 | 761 | 1398 | 1669 | 424 | 1637 | 6158 |
| Lagoon goby | <i>Tasmanogobius lasti</i> | Solely estuarine | 78 | 6 | 12,027 | 1 | 160 | 5 | 12,277 |
| River garfish | <i>Hyporhamphus regularis</i> | Solely estuarine | - | - | 16 | - | - | - | 16 |

*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 |
|-------------------------|--------------------------------|------------------------------|---------------------------------|---------------------------------|-----------------------|----------------------|-------------------------|---------------|----------------|
| Small-mouthed hardyhead | <i>Atherinosoma microstoma</i> | Solely estuarine | - | - | 421 | 1 | 218 | 22 | 662 |
| Tamar River goby | <i>Afurcagobius tamarensis</i> | Solely estuarine | - | - | 114 | - | 417 | - | 531 |
| Blue-spot goby | <i>Pseudogobius olorum</i> | Solely estuarine | - | - | 105 | 1 | 193 | 30 | 329 |
| Bridled goby | <i>Arenogobius bifrenatus</i> | Estuarine & marine | - | - | 81 | - | 10 | 4 | 95 |
| Soldier fish | <i>Gymnapistes marmoratus</i> | Estuarine & marine | - | - | 1 | - | 2 | - | 3 |
| Australian anchovy | <i>Engraulis australis</i> | Marine estuarine-opportunist | - | - | 291 | - | - | - | 291 |
| Flat-tailed mullet | <i>Liza argentea</i> | Marine estuarine-opportunist | - | - | - | - | - | 15 | 15 |
| Greenback flounder | <i>Rhombosolea tapirina</i> | Marine estuarine-opportunist | - | - | 184 | - | 14 | - | 198 |
| Sandy sprat | <i>Hyperlophus vittatus</i> | Marine estuarine-opportunist | 3 | - | 2501 | 2 | 39,206 | - | 41,712 |
| Smooth toadfish | <i>Tetractenos glaber</i> | Marine estuarine-opportunist | - | - | - | - | 1 | - | 1 |
| Yelloweye mullet | <i>Aldrichetta forsteri</i> | Marine estuarine-opportunist | - | - | 18 | - | 38 | - | 56 |
| Total | | | 12,482 | 39,523 | 76,964 | 10,824 | 103,445 | 4142 | 247,380 |

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 2021/22 (Figure 3-2) at the Tauwitchere rock ramp (*Pseudo-F*_{14, 81} = 9.03, $p < 0.001$), Tauwitchere vertical-slot (*Pseudo-F*_{13, 67} = 5.93, $p < 0.001$) and Goolwa vertical-slot (*Pseudo-F*_{13, 71} = 2.48, $p = 0.009$), but not at the Tauwitchere small vertical-slot (*Pseudo-F*_{10, 53} = 0.48, $p = 0.88$), adjacent Goolwa Barrage (*Pseudo-F*_{12, 61} = 1.72, $p = 0.079$) or Hunters Creek vertical-slot (*Pseudo-F*_{10, 53} = 1.95, $p = 0.06$). 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 2010–2022 (Figure 3-2).

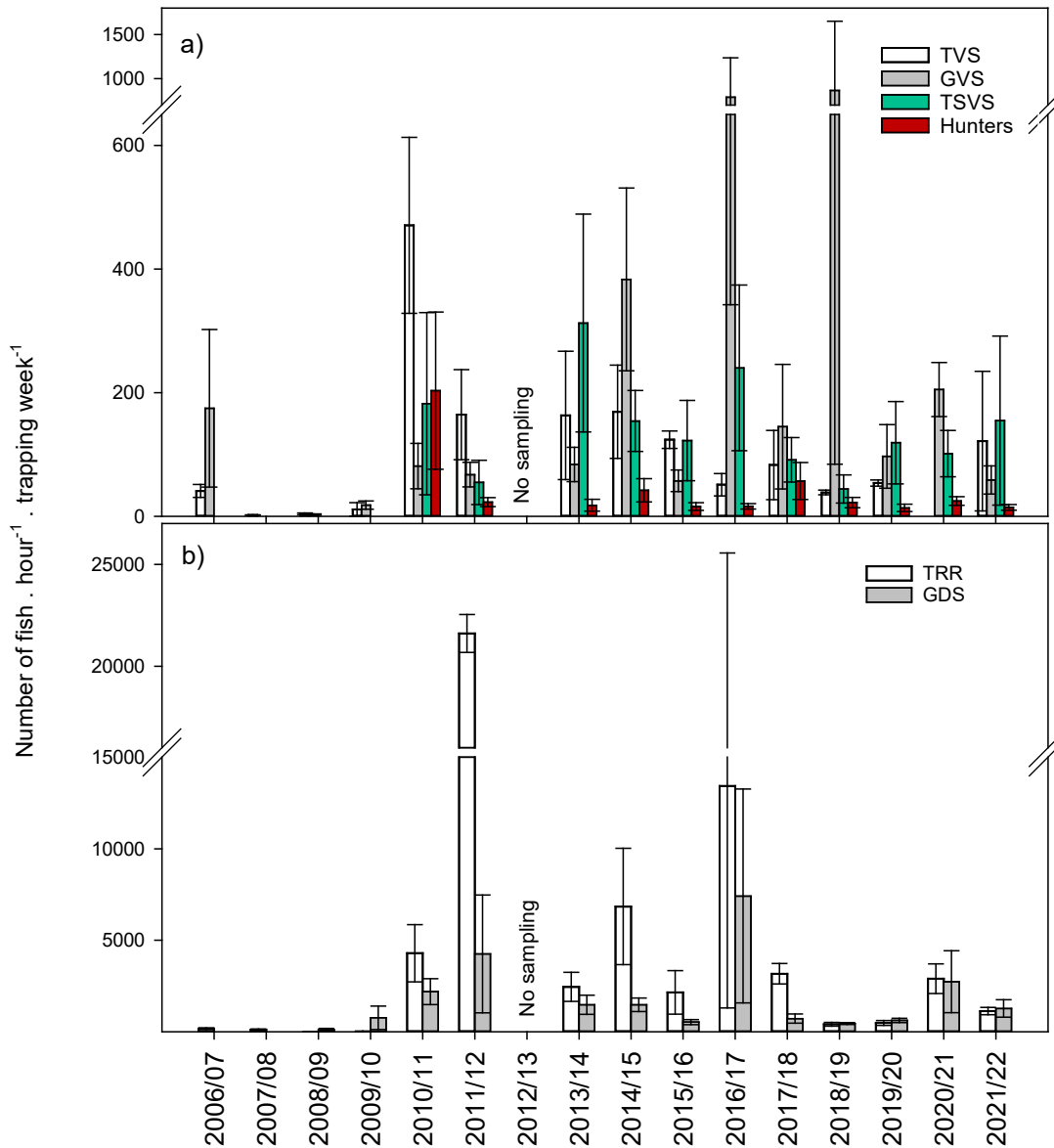


Figure 3-2. Relative abundance (number of fish·hour⁻¹·trap event⁻¹) of fish (all species combined) sampled at a) the Tauwicheere large vertical-slot (TVS), Goolwa vertical-slot (GVS), Tauwicheere small vertical-slot (TSVS) and Hunters Creek vertical-slot (Hunters), and b) the Tauwicheere rock ramp (TRR) and adjacent Goolwa Barrage (GDS), from 2006–2022. Goolwa vertical-slot was not sampled in 2007/08, whilst sampling at the Tauwicheere 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 and the Tauwicheere vertical-slot was not sampled in 2020/21.

Species richness (all sites, and winter and spring-summer sampling combined) has been relatively consistent among years, and typically ranged 28–32 species (Figure 3-3). Greatest species richness was recorded in 2018/19 ($n = 36$) and least in 2007/08 ($n = 24$) and 2021/22 ($n = 25$). 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 in 2010–2012, 2016/17 and 2021/22 ($n = 9$ –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 and 2021/22 ($n = 7$ –8). The number of diadromous species was reduced during 2007–2010 and in 2014/15 ($n = 2$), due to the absence of both lamprey species, whilst the number of estuarine species present was generally similar over the study period ($n = 7$ –8), with the exception of 2021/22 when just five species were sampled.

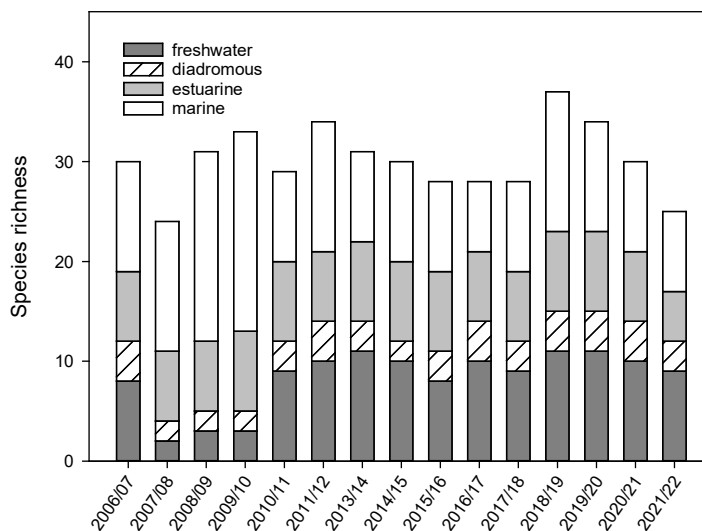


Figure 3-3. Species richness (all sites combined) from 2006–2022, including the contribution of species from different estuarine-use categories, i.e. freshwater (freshwater ‘estuarine-opportunists’ and ‘stragglers’ combined), diadromous (catadromous and anadromous combined), estuarine (solely estuarine 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.* (2018a).

Assemblage structure

PERMANOVA detected significant differences in fish assemblage structure among years at the Tauwitchere rock ramp ($Pseudo-F_{14, 81} = 12.21, p < 0.001$), Tauwitchere large vertical-slot ($Pseudo-F_{13, 67} = 9.99, p < 0.001$), Tauwitchere small vertical-slot ($Pseudo-F_{10, 53} = 2.77, p < 0.001$), Goolwa vertical-slot ($Pseudo-F_{13, 71} = 4.63, p < 0.001$), adjacent Goolwa Barrage ($Pseudo-F_{12, 61} = 6.00, p < 0.001$) and Hunters Creek vertical-slot ($Pseudo-F_{10, 53} = 3.69, p < 0.001$). 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, 2016/17 and 2021/22 were typically unique or grouped together, while low–moderate flow years from 2013–2016, and 2017–2021 were often grouped together (Table 3-2).

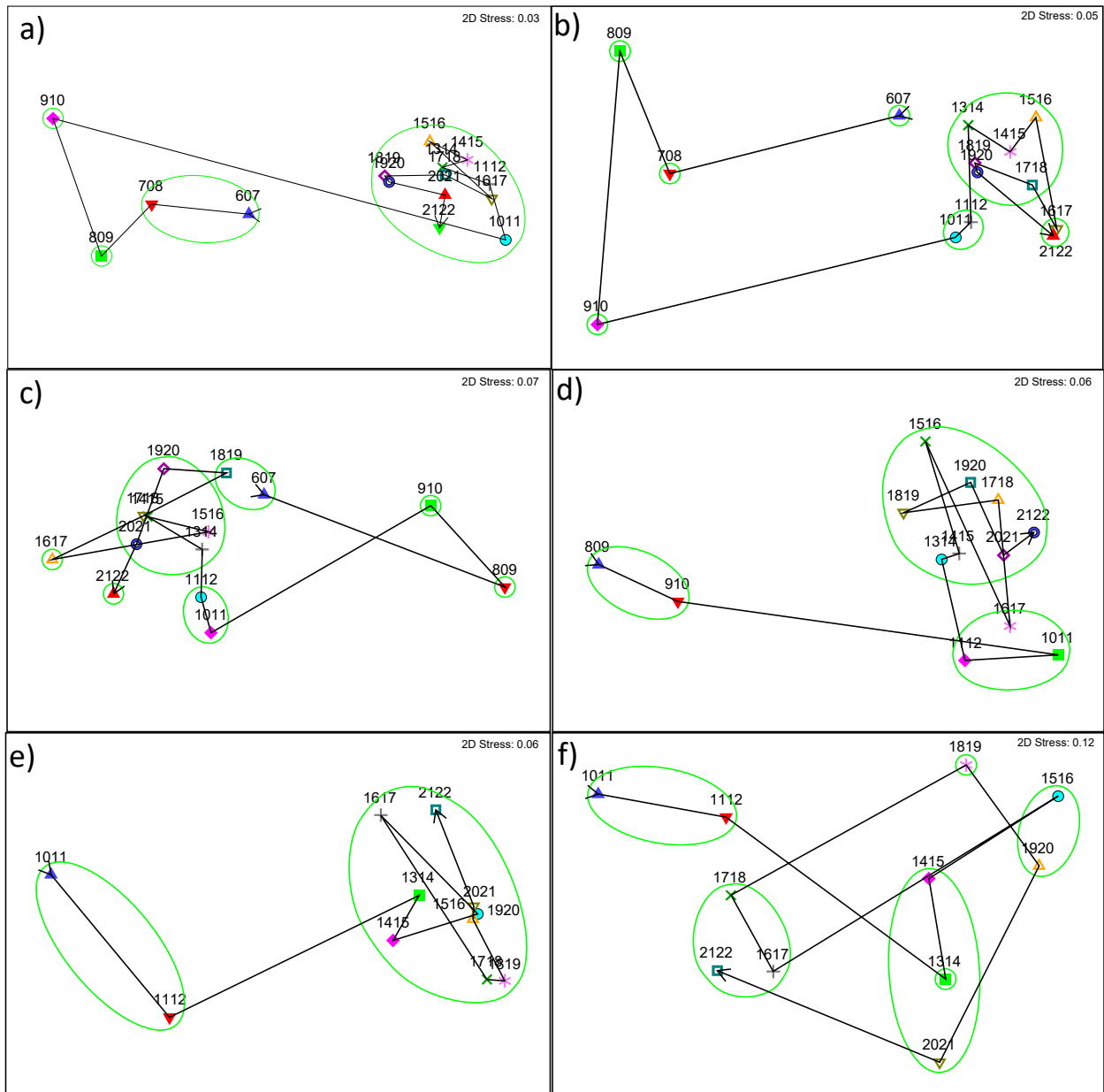


Figure 3-4. MDS ordination trajectory plots of fish assemblages sampled at a) Tauwitchere rock ramp, b) Tauwitchere large vertical-slot, c) Goolwa vertical-slot, d) adjacent Goolwa Barrage, e) Tauwitchere small vertical-slot and f) Hunters Creek vertical-slot, between 2006 and 2022. Groupings from Cluster analysis based on 70% similarity are indicated by green ellipses.

Table 3-2. Groupings of sampling years at each site based on cluster analysis and arbitrary assemblage similarity of 70%. Tauwitchere rock ramp = TRR, Tauwitchere large vertical-slot = TVS, Goolwa vertical-slot = GVS, adjacent Goolwa Barrage = GDS, Tauwitchere small vertical-slot = TSVS and Hunters Creek vertical-slot = Hunters.

| | TRR | TVS | GVS | GDS | TSVS | Hunters |
|---------|--------------|-----------------------------|--|-----------------------------|---|--|
| Group 1 | 06/07, 07/08 | 06/07 | 06/07, 18/19 | 08/09, 09/10 | 10/11, 11/12 | 10/11, 11/12 |
| Group 2 | 08/09 | 07/08 | 08/09 | 10/11, 11/12, 16/17 | 13/14–15/16, 17/18, 19/20, 20/21, 21/22 | 13/14–15/16, 17/18, 19/20, 20/21 |
| Group 3 | 09/10 | 08/09 | 09/10 | 13/14–15/16, 17/18–21/22 | 16/17 | 16/17, 21/22 |
| Group 4 | 10/11–21/22 | 09/10 | 10/11, 11/12 | | 18/19 | 18/19 |
| Group 5 | | 10/11, 11/12 | 13/14–15/16, 17/18, 19/20, 20/21 | | - | |
| Group 6 | | 13/14–15/16, 17/18–19/20 | 16/17 | | - | |
| Group 7 | | 16/17, 21/22 | 21/22 | - | - | |

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–low flow (0 or 63 GL) = group 1 (2006/07, 2007/08); no flow (0 GL) = group 2 (2008/09) and 3 (2009/10); and low–high flow (370–12,498 GL) = group 4 (2010/11–2021/22). At the Tauwitchere large vertical-slot, assemblages produced seven cluster groups: low flow (63 GL) = group 1 (2006/07); no flow (0 GL) = groups 2 (2007/08), 3 (2008/09) and 4 (2009/10); high flow (6180–12,498 GL) = groups 5 (2010/11, 2011/12) and 7 (2016/17 and 2021/22); and low–moderate flow (370–1647 GL) = group 6 (2013/14–2015/16, 2017/18–2019/20). At the Tauwitchere small vertical-slot, assemblages produced four cluster groups: high flow (6456–12,498 GL) = group 1 (2010/11, 2011/12) and group 3 (2016/17); moderate–high flow (542–6180 GL) = group 2 (2013/14–2015/16, 2017/18, 2019/20–2021/22); and low flow (370 GL) = group 4 (2018/19).

At the Tauwitchere rock ramp, Indicator Species Analysis (ISA) suggested the fish assemblage in 2006/07 and 2007/08 was characterised by the estuarine blue-spot goby (*Pseudogobius olorum*) (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 following species; the marine-estuarine opportunists mulloway

(*Argyrosomus japonicas*), prickly toadfish (*Contusus brevicaudus*), yellowfin whiting (*Sillago schomburgkii*), Australian anchovy (*Engraulis australis*), Australian salmon (*Arripis truttaceus*) and Australian herring (*Arripis georgianus*); the marine stragglers big-bellied seahorse (*Hippocampus abdominalis*), silver spot (*Threpterus maculosus*) and Tuckers pipefish (*Mitotichthys tuckeri*); and the estuarine and marine estuary catfish (*Cnidoglanis macrocephalus*). The assemblage sampled in moderate-high flow years was characterised by five freshwater species (i.e. Australian smelt, flat-headed gudgeon, bony herring, common carp (*Cyprinus carpio*) and redfin perch), together with two catadromous (congolli and common galaxias) and four estuarine fishes (river garfish (*Hyporhamphus regularis*), lagoon goby, Tamar River goby (*Afurcagobius tamarensis*) and bridled goby (*Arenogobius bifrenatus*)), and the marine estuarine-opportunist sandy sprat.

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). The 2008/09 no flow year was characterised by soldierfish (*Gymnapistes marmoratus*) and 2009/10 by the estuarine black bream. Assemblages during high flow years of 2010–12 (group 5) 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), while there were no significant indicators of the high flow grouping of 2016/17 and 2021/22 (group 7). Moderate flow years (group 6) were characterised by the freshwater flat-headed gudgeon and carp gudgeon complex (*Hypseleotris* spp.), and catadromous congolli and common galaxias.

At the Tauwitchere small vertical-slot, the assemblages in high flow years 2010–2012, were characterised by the freshwater common carp and the marine estuarine-opportunist sandy sprat (Table 3-4). There were no significant indicators of any other cluster groups.

Table 3-3. Indicator species analysis of fish assemblages in the Coorong at the Tauwitechere rock ramp based on groupings of sampling years from Cluster analysis (70% similarity). Cluster groupings are defined by annual flow: NF/LF = no to low flow (0–63 GL), NF = no flow (0 GL), LF/HF = low to high flow (370–12,498 GL). Only significant indicators (i.e. $p < 0.05$) are presented.

| Species | Guild | Year | Indicator Value | p value |
|------------------------------|----------------------------|-----------------|-----------------|-----------|
| Tauwitechere rockramp | | | | |
| Bluespot goby | Solely estuarine | Group 1 (NF/LF) | 39.5 | 0.006 |
| Black bream | Solely estuarine | Group 2 (NF) | 34.2 | 0.031 |
| Mulloway | Marine est-opportunist | Group 3 (NF) | 72.7 | <0.001 |
| Prickly toadfish | Marine est-opportunist | Group 3 (NF) | 98.2 | <0.001 |
| Yellowfin whiting | Marine est-opportunist | Group 3 (NF) | 50.8 | 0.012 |
| Australian anchovy | Marine est-opportunist | Group 3 (NF) | 49.4 | 0.021 |
| Australian salmon | Marine est-opportunist | Group 3 (NF) | 54.8 | 0.013 |
| Australian herring | Marine est-opportunist | Group 3 (NF) | 70.3 | <0.001 |
| Big-bellied seahorse | Marine straggler | Group 3 (NF) | 33.3 | 0.037 |
| Silver spot | Marine straggler | Group 3 (NF) | 33.3 | 0.037 |
| Tuckers pipefish | Marine straggler | Group 3 (NF) | 33.3 | 0.038 |
| Estuary catfish | Estuarine & marine | Group 3 (NF) | 33.3 | 0.036 |
| Common carp | Freshwater straggler | Group 4 (LF/HF) | 63.1 | 0.006 |
| Bony bream | Freshwater est-opportunist | Group 4 (LF/HF) | 97.6 | <0.001 |
| Redfin perch | Freshwater straggler | Group 4 (LF/HF) | 89.8 | <0.001 |
| Flathead gudgeon | Freshwater est-opportunist | Group 4 (LF/HF) | 87.9 | <0.001 |
| Australian smelt | Freshwater est-opportunist | Group 4 (LF/HF) | 86.0 | <0.001 |
| Common galaxias | Semi-catadromous | Group 4 (LF/HF) | 76.4 | <0.001 |
| Congolli | Catadromous | Group 4 (LF/HF) | 58.5 | <0.001 |
| Lagoon goby | Solely estuarine | Group 4 (LF/HF) | 80.4 | <0.001 |
| River Garfish | Solely estuarine | Group 4 (LF/HF) | 70.4 | <0.001 |
| Tamar River goby | Solely estuarine | Group 4 (LF/HF) | 39.4 | 0.003 |
| Bridled goby | Estuarine & marine | Group 4 (LF/HF) | 37.9 | 0.023 |
| Sandy sprat | Marine est-opportunist | Group 4 (LF/HF) | 65.3 | <0.001 |

Table 3-4. Indicator species analysis of fish assemblages in the Coorong at the Tauwitechere large vertical-slot and at the small vertical-slot, based on groupings of sampling years from Cluster analysis (70% similarity). Cluster groupings are defined by annual flow: NF = no flow (0 GL), LF = low flow (63 GL), HF = high flow (>6180 GL), LF/MF = low to moderate flow (370–1647 GL). Only significant indicators (i.e. $p < 0.05$) are presented.

| Species | Guild | Year | Indicator Value | p value |
|---|----------------------------|-----------------|-----------------|---------|
| Tauwitechere large vertical-slot | | | | |
| Short-headed lamprey | Anadromous | Group 1 (LF) | 33.3 | 0.029 |
| Bluespot goby | Solely estuarine | Group 2 (NF) | 41 | 0.009 |
| Soliderfish | Estuarine & marine | Group 3 (NF) | 30.6 | 0.036 |
| Black bream | Solely estuarine | Group 4 (NF) | 38.4 | 0.014 |
| Common carp | Freshwater straggler | Group 5 (HF) | 54 | <0.001 |
| Australian smelt | Freshwater est-opportunist | Group 5 (HF) | 44.8 | <0.001 |
| Lagoon goby | Solely estuarine | Group 5 (HF) | 37.5 | <0.001 |
| Bony bream | Freshwater est-opportunist | Group 5 (HF) | 45.5 | <0.001 |
| Redfin perch | Freshwater straggler | Group 5 (HF) | 37.5 | 0.002 |
| Golden perch | Freshwater straggler | Group 5 (HF) | 31.4 | 0.045 |
| Common galaxias | Semi-catadromous | Group 6 (LF/MF) | 32.7 | <0.001 |
| Congolli | Catadromous | Group 6 (LF/MF) | 32.7 | <0.001 |
| Flathead gudgeon | Freshwater est-opportunist | Group 6 (LF/MF) | 34.1 | 0.002 |
| Carp gudgeon | Freshwater straggler | Group 6 (LF/MF) | 34.5 | 0.028 |
| Tauwitechere small vertical-slot | | | | |
| Common carp | Freshwater straggler | Group 1 (HF) | 75.2 | 0.002 |
| Sandy sprat | Marine est-opportunist | Group 1 (HF) | 36.5 | 0.038 |

Goolwa sites

Cluster analysis of fish assemblages sampled at the Goolwa vertical-slot produced six groupings of sampling years (Table 3-2). These groupings could be described in terms of annual discharge: low flow (63–370 GL) = group 1 (2006/07 and 2018/19); no flow (0 GL) = group 2 (2008/09) and group 3 (2009/10); high flow (6180–12,500 GL) = group 4 (2010/11 and 2011/12), group 6 (2016/17) and group 7 (2021/22); and moderate flow (562–1647 GL) = group 5 (2013/14–2015/16, 2017/18, 2019/20, 2020/21). 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 (6456–12,500 GL) = group 2 (2010/11–2011/12, 2016/17); and low–high flow (370–6180 GL) = group 3 (2013/14–2015/16, 2017/18–21/22).

ISA of assemblage data from the Goolwa vertical-slot indicated the assemblage from low flow years was characterised by the marine-estuarine opportunist mulloway (Table 3-5). No flow assemblages were characterised by the estuarine black bream and marine estuarine-opportunist flat-tailed mullet (group 2), the estuarine small-mouthed hardyhead (*Atherinosoma microstoma*)

and Tamar River goby, estuarine and marine bridled goby, marine estuarine-opportunist Australian salmon, and marine straggler zebra fish (*Girella zebra*) and blue sprat (*Spratelloides robustus*) (group 3). Conversely, high flow assemblages were characterised by the freshwater redfin perch and estuarine lagoon goby (group 4), the freshwater golden perch and Australian smelt, and the catadromous congolli (group 6). There were no significant indicators of low–moderate flow years (group 5).

The assemblage sampled adjacent Goolwa Barrage during no flow years was characterised by the estuarine black bream and several marine estuarine-opportunists, namely: yelloweye mullet (*Aldrichetta forsteri*); Australian herring; Australian salmon; smooth toadfish (*Tetractenos glaber*); flat-tailed mullet (*Liza argentea*); and long-snouted flounder (*Ammotretis rostratus*) (Table 3-5). High flow years were characterised by a suite of freshwater species (i.e. golden perch, carp gudgeon, goldfish, common carp, redfin perch, bony herring, flat-headed gudgeon and Australian smelt), and the estuarine lagoon goby. The moderate to high flow grouping that encompassed sampling from 2013/14–2015/16 and 2017/18–2021/22, was characterised by the catadromous congolli, the semi-catadromous common galaxias, and the estuarine bluespot goby.

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 (70% 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 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.* (2018a).

| Species | Guild | Year | Indicator Value | p value |
|--------------------------------|----------------------------|--------------|-----------------|-----------|
| Goolwa vertical-slot | | | | |
| Mulloway | Marine est-opportunist | Group 1 (LF) | 29.4 | 0.045 |
| Black bream | Solely estuarine | Group 2 (NF) | 45.9 | 0.012 |
| Flat-tail mullet | Marine est-opportunist | Group 2 (NF) | 39.1 | 0.026 |
| Small-mouthed hardyhead | Solely estuarine | Group 3 (NF) | 50.7 | <0.001 |
| Tamar River goby | Solely estuarine | Group 3 (NF) | 30.1 | 0.010 |
| Bridled goby | Estuarine & marine | Group 3 (NF) | 42.2 | 0.016 |
| Australian salmon | Marine est-opportunist | Group 3 (NF) | 40.3 | 0.027 |
| Zebra fish | Marine straggler | Group 3 (NF) | 61.4 | 0.003 |
| Blue sprat | Marine straggler | Group 3 (NF) | 30.9 | 0.034 |
| Redfin perch | Freshwater straggler | Group 4 (HF) | 27.6 | 0.002 |
| Lagoon goby | Solely estuarine | Group 4 (HF) | 48.5 | 0.001 |
| Australian smelt | Freshwater est-opportunist | Group 6 (HF) | 25.2 | 0.016 |
| Congolli | Catadromous | Group 6 (HF) | 27.1 | 0.025 |
| Golden perch | Freshwater straggler | Group 6 (HF) | 58.1 | 0.001 |
| Adjacent Goolwa Barrage | | | | |
| Black bream | Solely estuarine | Group 1 (NF) | 73.7 | <0.001 |
| Yellow-eyed mullet | Marine est-opportunist | Group 1 (NF) | 75.2 | <0.001 |
| Australian herring | Marine est-opportunist | Group 1 (NF) | 57.4 | <0.001 |
| Australian salmon | Marine est-opportunist | Group 1 (NF) | 54.6 | <0.001 |
| Smooth toadfish | Marine est-opportunist | Group 1 (NF) | 51.5 | 0.002 |
| Flat-tail mullet | Marine est-opportunist | Group 1 (NF) | 38.1 | 0.004 |
| Longsnout flounder | Marine est-opportunist | Group 1 (NF) | 43 | 0.008 |
| Golden perch | Freshwater straggler | Group 2 (HF) | 69.1 | <0.001 |
| Carp gudgeon | Freshwater straggler | Group 2 (HF) | 41.1 | 0.003 |
| Goldfish | Freshwater straggler | Group 2 (HF) | 36 | 0.007 |
| Common carp | Freshwater straggler | Group 2 (HF) | 48.1 | 0.007 |
| Redfin perch | Freshwater straggler | Group 2 (HF) | 50.4 | 0.004 |
| Bony bream | Freshwater est-opportunist | Group 2 (HF) | 60.3 | <0.001 |
| Flathead gudgeon | Freshwater est-opportunist | Group 2 (HF) | 59.4 | <0.001 |
| Australian smelt | Freshwater est-opportunist | Group 2 (HF) | 47.3 | 0.003 |
| Lagoon goby | Solely estuarine | Group 2 (HF) | 46.1 | 0.027 |
| Common galaxias | Semi-catadromous | Group 3 (MF) | 62.8 | <0.001 |
| Congolli | Catadromous | Group 3 (MF) | 59.3 | <0.001 |
| Bluespot goby | Solely estuarine | Group 3 (MF) | 47 | 0.004 |

Hunters Creek

Cluster analysis of fish assemblages sampled at the Hunters Creek vertical-slot produced four cluster groups: high flow (6456–12,498 GL) = group 1 (2010/11, 2011/12) and group 3 (2016/17, 2021/22); moderate flow (562–1647 GL) = group 2 (2013/14–2015/16, 2017/18, 2019/20, 2020/21); and low flow (370 GL) = group 4 (2018/19) (Table 3-2). ISA determined the assemblages from the high flow group 1 were characterised by the freshwater common carp, redfin perch, goldfish and flat-headed gudgeon, and high flow group 3 by the freshwater carp gudgeon complex and dwarf flat-headed gudgeon, the semi-catadromous common galaxias and marine estuarine-opportunist flat-tailed mullet (Table 3-6). The low flow year of 2018/19 was characterised by small-mouthed hardyhead, while there were no significant indicators of group 2.

Table 3-6. Indicator species analysis of fish assemblages at the Hunters Creek vertical slot from 2010–2022. 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.* (2018a).

| Species | Guild | Year | Indicator Value | p value |
|------------------------|----------------------------|--------------|-----------------|-----------|
| Common carp | Freshwater straggler | Group 1 (HF) | 75.2 | <0.001 |
| Redfin perch | Freshwater straggler | Group 1 (HF) | 58.7 | 0.003 |
| Flathead gudgeon | Freshwater est-opportunist | Group 1 (HF) | 37.3 | 0.019 |
| Goldfish | Freshwater straggler | Group 1 (HF) | 45.1 | 0.013 |
| Carp gudgeon | Freshwater straggler | Group 3 (HF) | 39.9 | 0.026 |
| Common galaxias | Semi-catadromous | Group 3 (HF) | 32.4 | 0.016 |
| Dwarf flathead gudgeon | Freshwater est-opportunist | Group 3 (HF) | 30.6 | 0.049 |
| Flat-tail mullet | Marine est-opportunist | Group 3 (HF) | 50.7 | 0.009 |
| Small-mouth Hardyhead | Solely estuarine | Group 4 (LF) | 41.6 | 0.039 |

3.4. Spatial variation in fish assemblages in 2021/22

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 ($Pseudo-F_{3, 15} = 3.41$, $p = 0.002$), and pair-wise comparisons suggested assemblages were significantly different between Hunters Creek and all other fishways, but all other comparisons were non-significant ($p > 0.05$ for all comparisons). MDS

ordination of fish assemblage data from the Tauwitechere rock ramp and adjacent Goolwa Barrage (GDS) also exhibited separation (Figure 3-5b) and PERMANOVA indicated assemblages were significantly different ($Pseudo-F_{1,7} = 2.71$, $p = 0.029$).

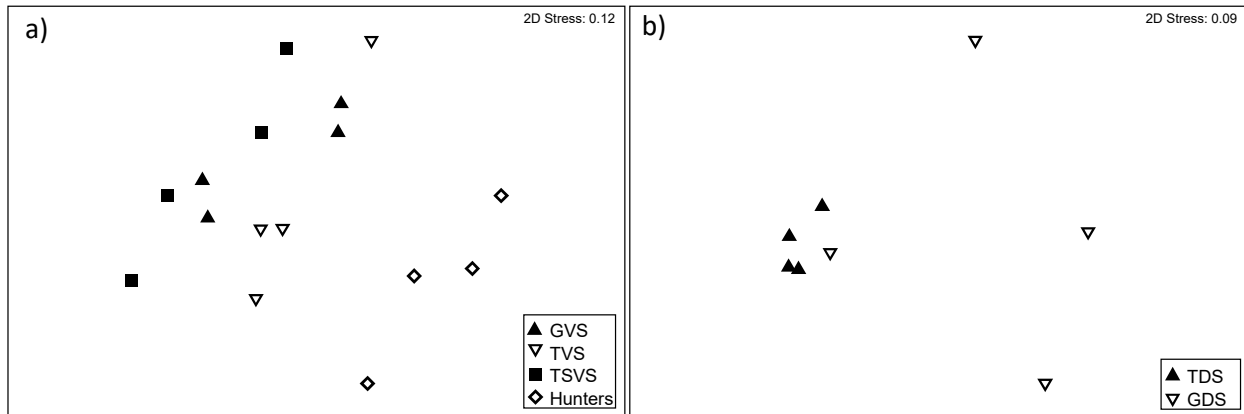


Figure 3-5. MDS ordination plot of fish assemblages sampled at the a) Tauwitechere small vertical-slot (TSVS), Goolwa vertical-slot (GVS), Hunters Creek vertical-slot (Hunters) and Mundoo dual vertical-slot (Mundoo), and b) Tauwitechere rock ramp and adjacent Goolwa Barrage (GDS) in 2021/22.

Indicator species analysis was used to determine species that characterised assemblages at the different sites in 2020/21. Among the vertical-slot fishways, the estuarine lagoon goby characterised the assemblages at Tauwitechere large vertical-slot fishway and the estuarine bluespot goby characterised assemblages at the Hunters Creek fishway (Table 3-7). Assemblages at the Tauwitechere rock ramp were characterised by the estuarine river garfish and lagoon goby, and there were no significant indicator species at the site adjacent Goolwa Barrage.

Table 3-7. Indicator species analysis of fish assemblages in the Coorong at vertical-slot fishways (i.e. the Tauwitechere vertical-slot (TVS), Tauwitechere small vertical-slot (TSVS), Goolwa vertical-slot (GVS) and Hunters Creek vertical-slot) in 2021/22.

| Species | | Location | Indicator Value | <i>p</i> value |
|----------------------------|------------------|----------|-----------------|----------------|
| Vertical-slot sites | | | | |
| Lagoon goby | Solely estuarine | TVS | 57.6 | 0.002 |
| Bluespot goby | Solely estuarine | Hunters | 62.1 | 0.027 |
| Fyke-net sites | | | | |
| River garfish | Solely estuarine | TRR | 100.0 | 0.028 |
| Lagoon goby | Solely estuarine | TRR | 71.9 | 0.031 |

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

Inter-annual variation in abundance

Lamprey

In 2021/22, a total of 22 pouched lamprey (495–613 mm TL) were captured from fishways at the Murray Barrages. No short-headed lamprey were sampled. Generally, abundances of pouched lamprey could be considered moderate relative to previous years of targeted winter monitoring (Table 3-8; Figure 3-6) with greatest numbers sampled from large vertical-slot fishways on Goolwa Barrage ($n = 20$) and lower numbers sampled from the Tauwitchere large vertical-slot. Of the 22 pouched lamprey sampled, 20 were implanted with PIT and acoustic tags. Subsequently, three individuals were detected by PIT readers on one or more main channel weir fishway on the River Murray between Lock and Weir 1 and 3. One individual was detected on the fishways at Locks 1, 2 and 3, while the remaining two lamprey were only detected passing the fishway on Lock 1. As such, the greatest distance travelled was ≥ 431 km from the Murray Mouth by the individual detected at Lock 3 (Overland Corner). Pouched lamprey were detected migrating through River Murray fishways from 1–15 September 2021.

Table 3-8. Total numbers of pouched lamprey and short-headed lamprey sampled from the Murray Barrages annually from 2006–2021. In years when targeted winter and spring-summer sampling has occurred (2011/12, 2013/14 and 2015–2021), 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 | 20/21 | 20/22 |
|-----------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Pouched lamprey | 1 | - | - | - | - | 10 | 2 | - | 56 | 7 | 53 | 6 | 45 | 102 | 22 |
| Short-headed lamprey | 40 | - | - | - | - | 1 | - | - | - | - | - | 1 | 16 | 4 | - |

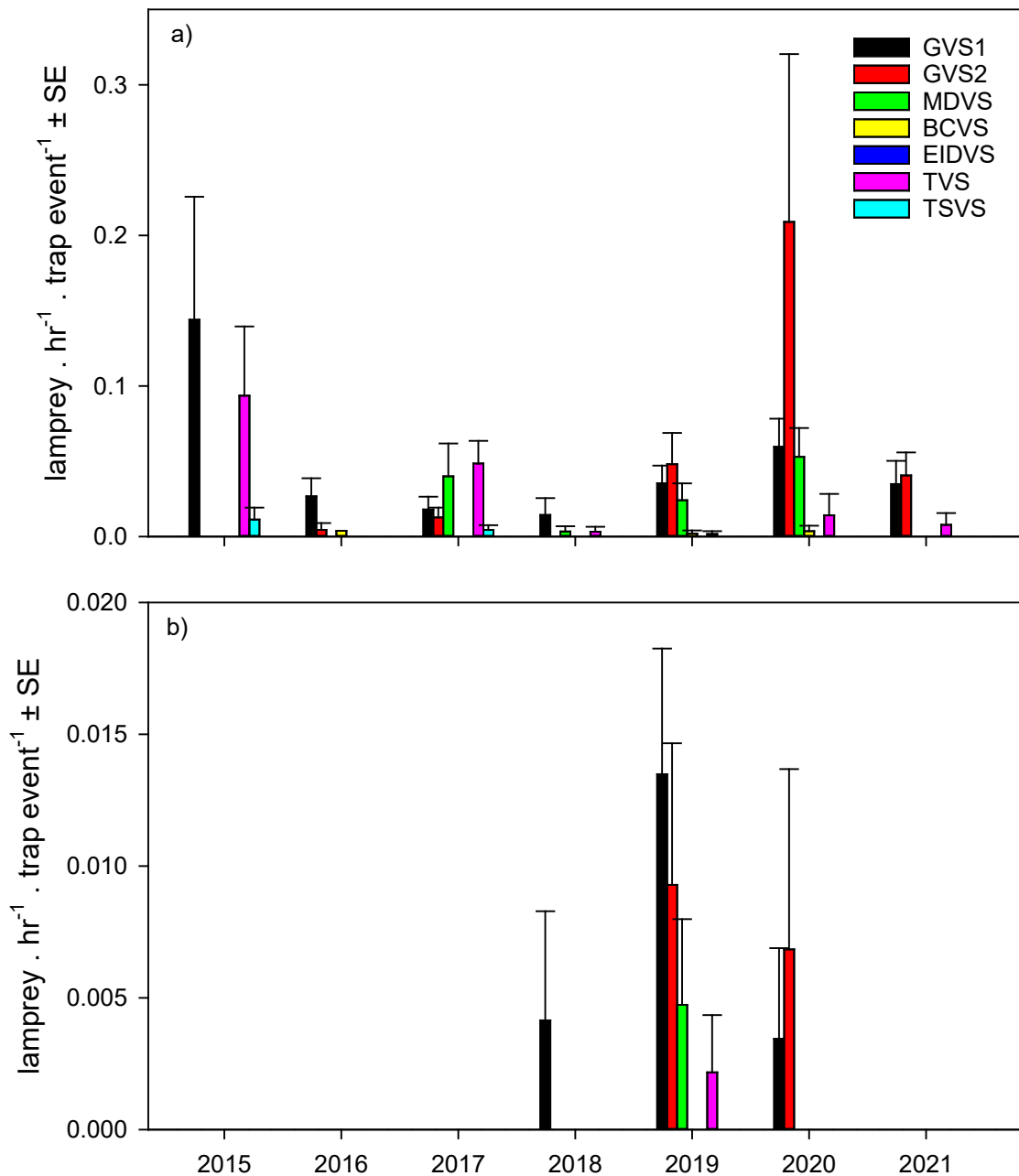


Figure 3-6. Relative abundance (number of fish.hour⁻¹.trap event⁻¹) of a) pouched lamprey and b) short-headed lamprey at the Goolwa vertical-slot (GVS1), Goolwa vertical-slot 2 (GVS2), Mundoo dual vertical-slot (MDVS), Boundary Creek vertical-slot (BCVS), Ewe Island dual vertical-slot (EIDVS), Tauwitchere vertical-slot (TVS) and Tauwitchere small vertical-slot (TSVS) during targeted sampling in winter–spring from 2015–2021. 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 among years at all sampling locations (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 2021/22 were greater than recorded from 2006–2012 but were lower than 2013–2020 at certain sites (e.g. TVS and Hunters; 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 2006–2022 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. $\alpha = 0.05$.

| Site | df | Congolli | | Common galaxias | |
|---------|---------|----------|---------|-----------------|---------|
| | | Pseudo-F | P value | Pseudo-F | P value |
| TRR | 14, 122 | 22.88 | <0.001* | 27.64 | <0.001* |
| TVS | 13, 168 | 15.52 | <0.001* | 43.17 | <0.001* |
| GVS | 13, 197 | 11.33 | <0.001* | 4.91 | <0.001* |
| GDS | 12, 70 | 9.41 | <0.001* | 9.71 | <0.001* |
| TSVS | 10, 146 | 5.73 | <0.001* | 10.50 | <0.001* |
| Hunters | 10, 143 | 4.20 | <0.001* | 2.88 | 0.003* |

Similarly, common galaxias was 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 2021/22, remained high relative to the period 2006–2011, but had declined relative to 2020/21 at several sites (Figure 3-7b).

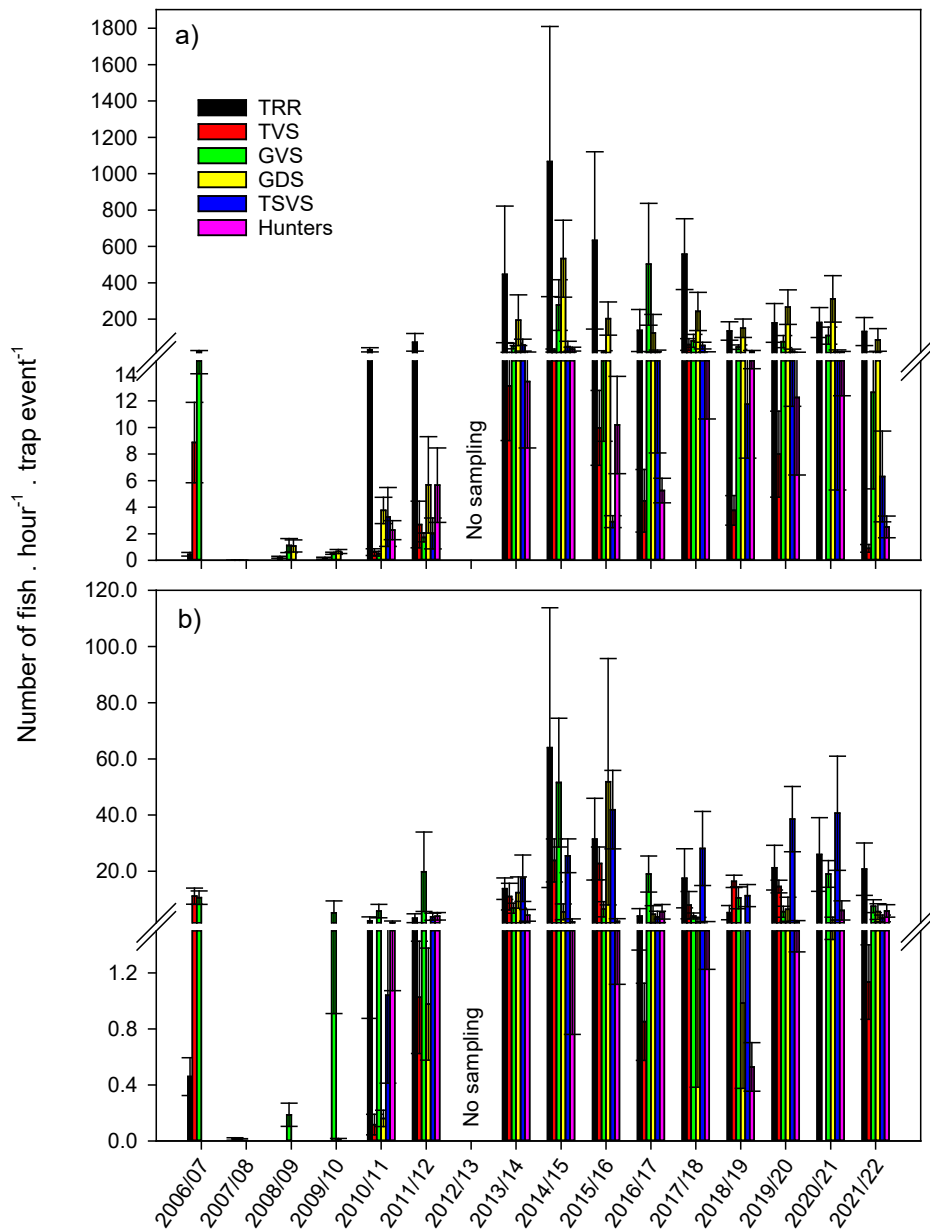


Figure 3-7. Relative abundance (number of fish.hour⁻¹.trap event⁻¹) of a) congolli and b) common galaxias at the Tauwichtere rock ramp (TRR), Tauwichtere vertical-slot (TVS), Goolwa vertical-slot (GVS), adjacent Goolwa Barrage (GDS), Tauwichtere small vertical-slot (TSVS) and Hunters Creek vertical-slot (Hunters) from 2006–2022. Goolwa vertical-slot was not sampled in 2007/08 and adjacent Goolwa Barrage was not sampled in 2006/07 and 2007/08. The Tauwichtere small vertical-slot and Hunters Creek vertical-slot were sampled from 2010/11 onwards. The Tauwichtere large vertical-slot was not sampled in 2020/21.

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

The abundance of upstream migrating congolli varied substantially between months and was typically greatest in December (Figure 3-8a). Overall, abundance was greatest at the Tauwitchere rock ramp and adjacent Goolwa Barrage (GDS). Among vertical-slot fishway sites, abundance was greatest at the Goolwa large vertical-slot (GVS) where daily abundance peaked on 16 December when 73 fish.hr⁻¹ were detected migrating upstream.

The abundance of upstream migrating common galaxias also varied substantially between months, with peak abundances occurring in December (Figure 3-8b). Abundances were greatest at the Tauwitchere rock ramp (TRR) and Goolwa large vertical-slot (GVS). Among vertical-slot fishway sites, peak daily abundance of common galaxias was detected at the Goolwa vertical-slot on 20 October when 21 fish.hr⁻¹ were detected migrating upstream.

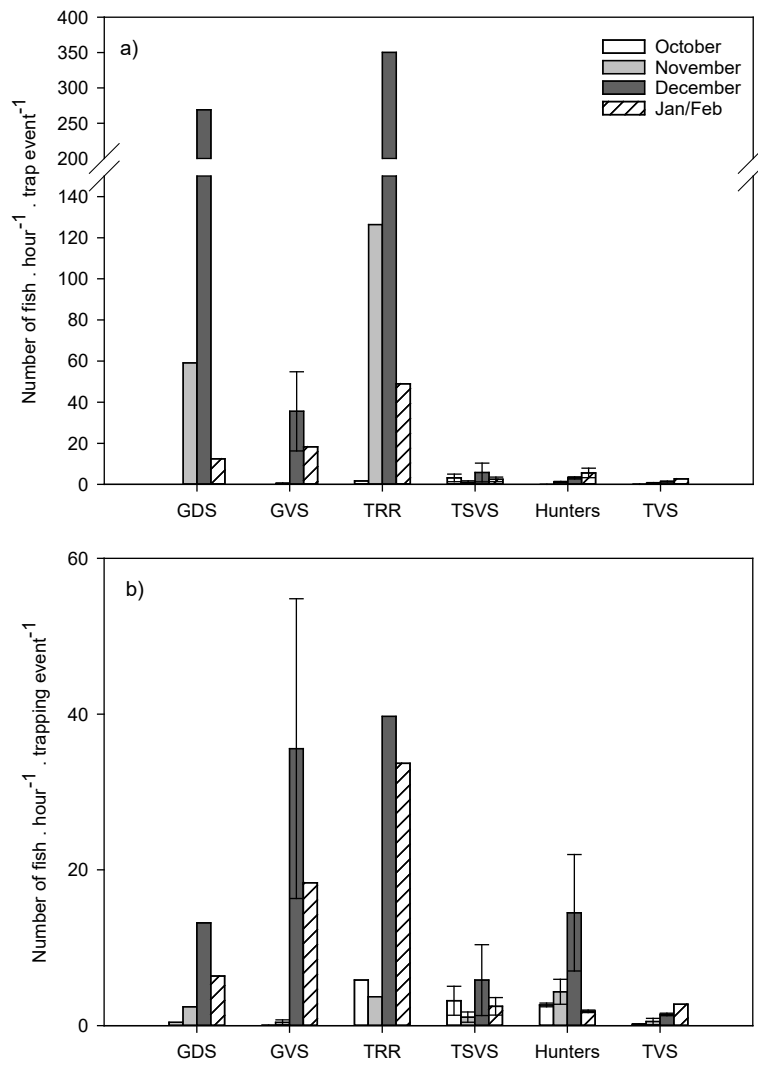


Figure 3-8. Relative abundance (number of fish.hour⁻¹.trap event⁻¹) of a) congolli and b) common galaxias at adjacent Goolwa Barrage (GDS), Goolwa vertical-slot (GVS), Tauwitchere rock ramp (TRR), Tauwitchere vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS) and Hunters Creek vertical-slot (Hunters) from October 2021–January/February 2022.

Below Tauwitchere Barrage (Tauwitchere rock ramp and small vertical-slot data combined) in October 2021, congolli were sampled across a broad length distribution ranging 36–199 mm TL (Figure 3-9a). A YOY cohort ranging 36–46 mm TL was present and represented 8% of the sampled population. Whilst fish were not aged in 2021/22, 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 2021: 30–57 mm TL,

December 2021: 35–76 mm TL and January/February 2022: 32–78 mm TL), and increased in prominence, comprising >85% 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) in October 2021, with the sampled population of fish ranging 30–151 mm TL and a YOY cohort present (30–40 mm TL; 36% of population) (Figure 3-9a). Growth of this cohort was evident through the following months, progressing to 27–54, 34–62 and 39–72 mm TL in November 2021, December 2021 and January/February 2022, respectively. This cohort increased in dominance, comprising >95% 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 35–39, 32–97, 32–113 and 40–71 mm TL during sequential sampling events and the YOY cohort (<70 mm TL) represented >95% of the sampled population during all months.

Common galaxias ranged 35–107 mm TL at Tauwitchere in October 2021, but individuals 35–55 mm TL comprised 47% of the sampled population (Figure 3-10a). Common galaxias were not aged in 2021/22, 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 >80% of the sampled population in November–January (Figure 3-10b-d).

At Goolwa in October 2021, common galaxias ranged 38–98 mm TL (Figure 3-10a). A YOY cohort was present with a mode ~42 mm TL, but was not distinct from larger, presumably older fish. The YOY cohort was more distinct in subsequent months and comprised >75% of the sampled population in all months (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 40–126, 38–106, 42–118 and 30–96 mm TL during sequential sampling events and individuals <60 mm TL comprised 55–85% of the sampled population in all months.

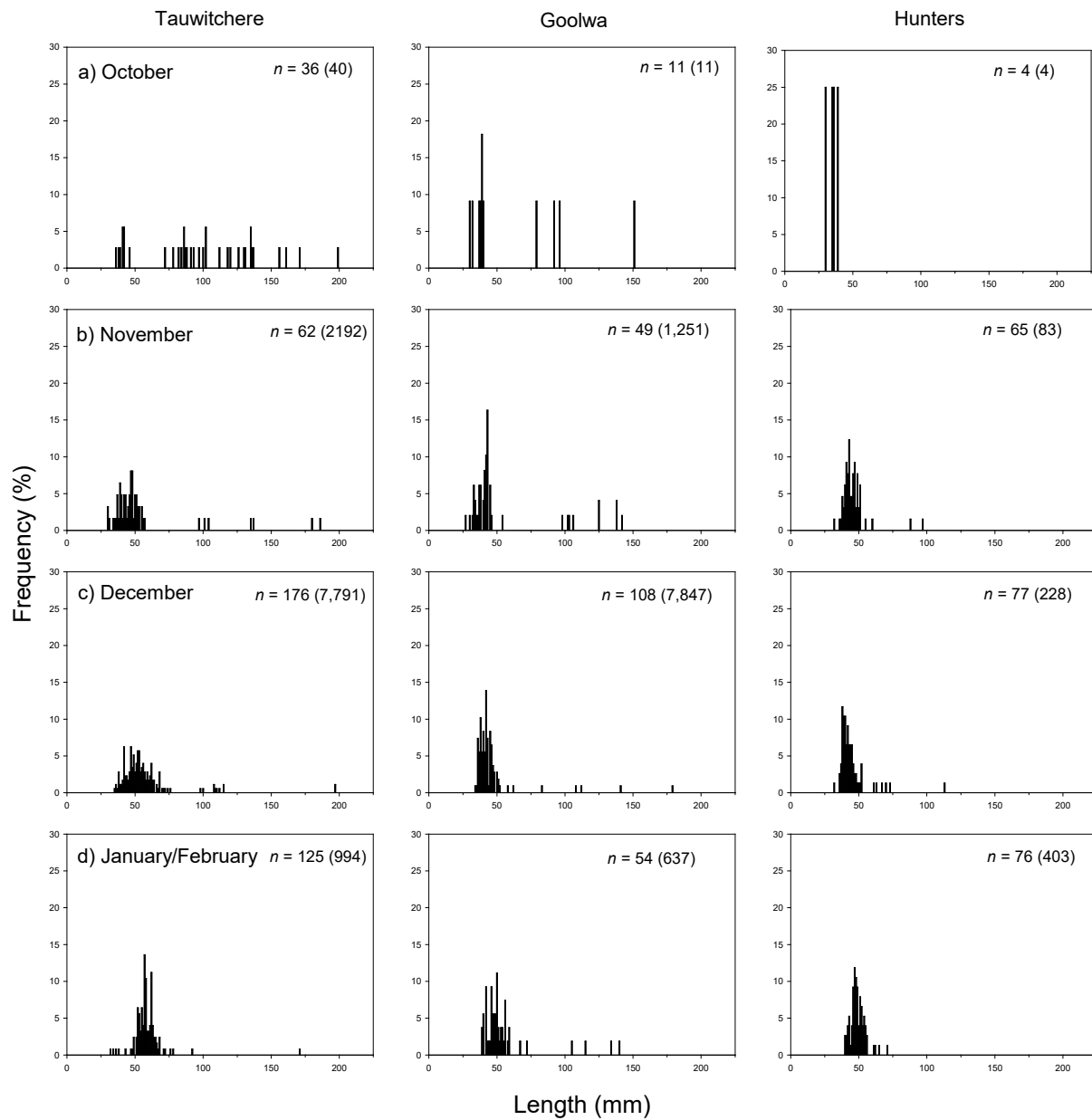


Figure 3-9. Monthly length-frequency distributions (total length, mm) of congolli sampled below Tauwitschere Barrage (rock ramp and small vertical-slot combined; left column), Goolwa Barrage (vertical-slot and adjacent Goolwa Barrage combined; middle column) and at the entrance of the Hunters Creek vertical-slot (right column) in a) October 2021, b) November 2021, c) December 2021 and d) January/February 2022. *n* is the number of fish measured and the total number of fish collected in each month at each site is presented in brackets.

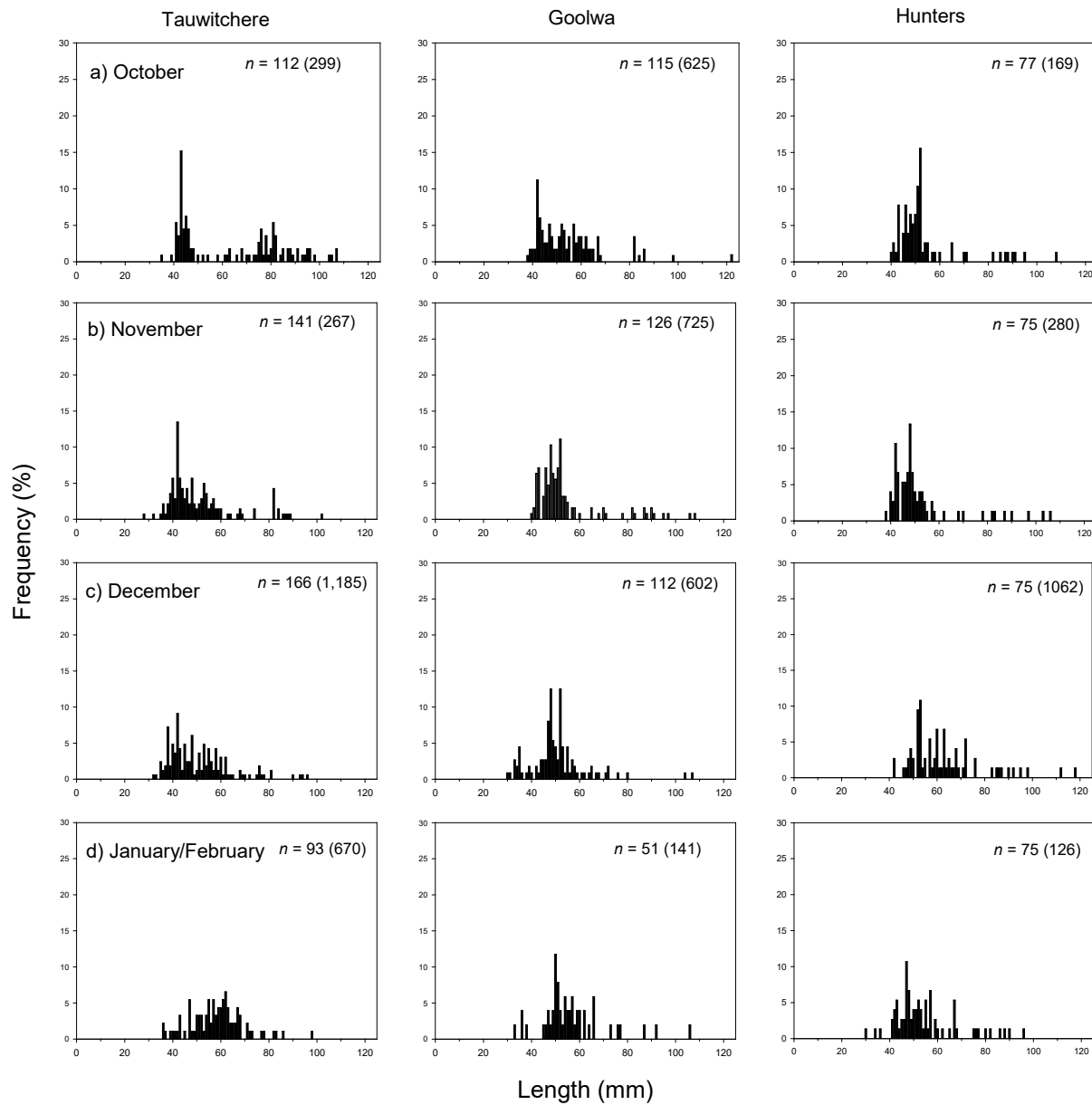


Figure 3-10. Monthly length-frequency distributions (total length, mm) of common galaxias sampled below Tauwitchenere Barrage (rock ramp and small vertical-slot combined; left column), Goolwa Barrage (vertical-slot and adjacent Goolwa Barrage combined; middle column) and at the entrance of the Hunters Creek vertical-slot (right column) in a) October 2021, b) November 2021, c) December 2021 and d) January/February 2022. *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 2021/22 (Figure 3-11a). Nonetheless, the reference value was the lowest recorded since 2011/12. The target has been met in all years since 2013/14, but was not met from 2006/07–2011/12. A similar pattern of variability in abundance of upstream migrating juveniles was evident for common galaxias; Target 2 was met in all years (including 2020/21) with the exception of 2007/08–2010/11, 2016/17 and 2021/22 (Figure 3-11b).

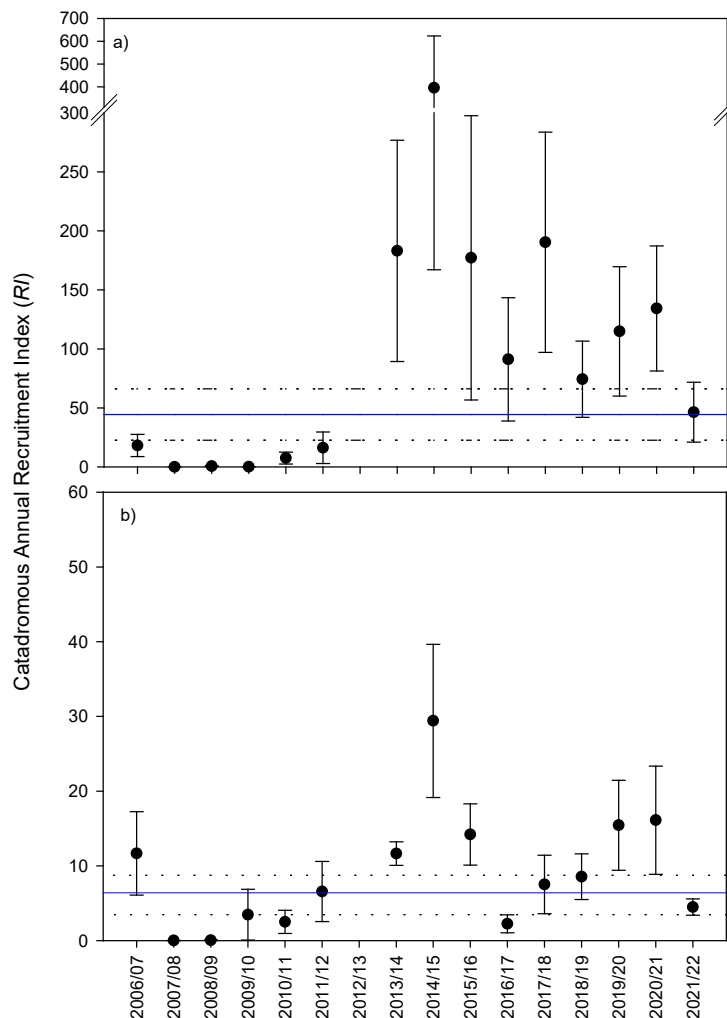


Figure 3-11. Catadromous annual recruitment index (RI , number of upstream migrating YOY.hour⁻¹ \pm half confidence interval for a) congolli and b) common galaxias from 2006/07 to 2021/22 (no sampling was conducted in 2012/13). The reference value is indicated by the blue line and half confidence intervals indicated by dashed lines.

Target 3: Anadromous migration

In 2021/22, no short-headed lamprey were sampled and therefore the migration index (*MI*) reference and target were not achieved (Figure 3-12). The species only achieved the reference in 2006/07 and was absent from sampling from 2007–2018.

For pouched lamprey, the *MI* was also not met in 2021/22, as the species was sampled from just three of the seven fishways (43%) sampled during winter (Figure 3-12). Nonetheless, the 2021/22 index was only slightly below the 60% reference tolerance to indicate achievement of target. 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. Since 2015/16, the migration target for pouched lamprey has been met in all years, with the exception of 2016/17, 2018/19 and 2021/22 when *MI* was slightly below the target.

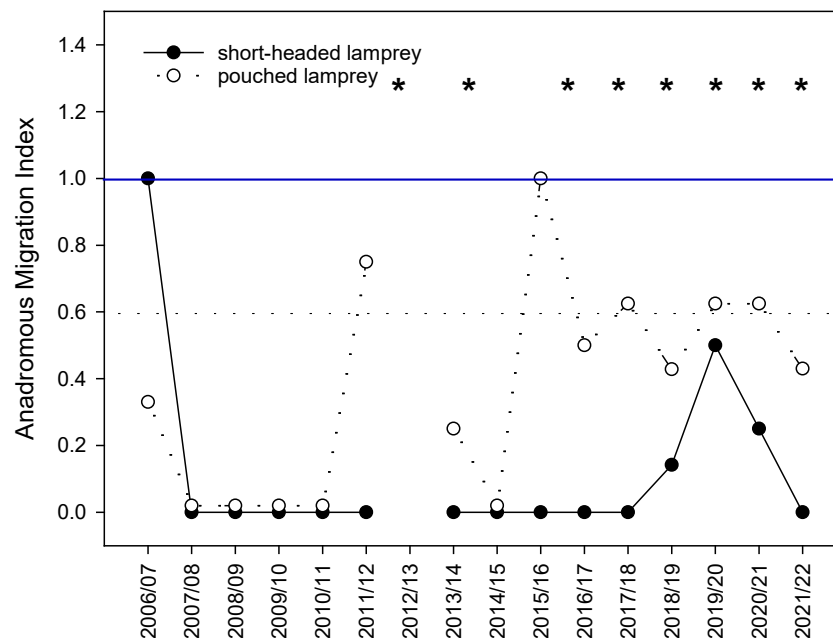


Figure 3-12. Anadromous migration index (*MI*) for short-headed lamprey (*open circles*) and pouched lamprey (*closed circles*) from 2006/07 to 2021/22 (no sampling was conducted in 2012/13). The blue line represents the reference value and dashed black line indicates a 40% tolerance and level deemed 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 2021/22 represented a year of relatively high discharge (~6180 GL; maximum discharge during sampling = ~35,468 ML.d⁻¹), and the twelfth consecutive year of continuous freshwater discharge to the Coorong post the end of the Millennium Drought (September 2010), when freshwater flow ceased for a period of approximately three years. These conditions promoted connectivity between the Lower Lakes and Coorong, and freshwater to brackish salinities in the Coorong estuary in the vicinity of the Murray Barrages. During spring–summer 2021/22, 24 fish species, representing 16 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 high freshwater discharge, with similarity to other years of high discharge (e.g. 2010/11 and 2016/17), with freshwater species being numerically dominant.

Among sites, there was a consistent pattern of temporal variability in fish assemblages across years from 2006/07 to 2021/22, 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.* 2011); 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, 2016/17 and 2021/22), 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, 2019–2021), 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, Rogers and Ward 2007). Whilst considered a marine estuarine-opportunist species, it exhibits a positive association with freshwater inflows to the Coorong, being caught in greatest abundance during certain 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 176–2536 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 from just 0.5–22 fish.hr⁻¹. Sandy sprat is zooplanktivorous and a 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 small-mouthed hardyhead as the most abundant small-bodied fish (Ye *et al.* 2012). Variability in the abundance of sandy sprat may 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 2006–2022, 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. 2021/22) 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 2021/22, fish assemblages sampled at vertical-slot fishways were generally similar, with the exception of the Hunters Creek fishway. Differences among assemblages from the Hunters Creek fishway and other sites have been detected in previous years (e.g. 2014/15, 2015/16, 2017/18, 2020/21) (Bice and Zampatti 2015, Bice *et al.* 2016, 2019, 2021) and are likely due to differences in habitat upstream and downstream of the fishways. Both upstream and downstream of the Hunters Creek causeway, aquatic habitat is characterised by small, sheltered streams and wetlands, in contrast to the other fishways, which are situated on the barrages and characterised by open water habitats both upstream and downstream. During moderate and high discharge, salinities downstream of the Hunters Creek causeway are lower and less variable than at other sites. As such, several pelagic freshwater species (e.g. Australian smelt) and marine species (e.g. sandy sprat) are typically uncommon at Hunters Creek, whilst the assemblage is often dominated by YOY catadromous species (congolli and common galaxias). Furthermore, overall fish abundance is typically lower at Hunters Creek than the other sites, which likely reflects the narrow nature of this creek, lower relative discharge and subsequently, lower attraction of fish.

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 seven species at the Tauwitchere small vertical-slot to 20 at both the Tauwitchere rock ramp and site adjacent Goolwa Barrage.

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

Catadromous species

Total numbers and relative abundances of congolli in 2021/22 were high relative to the period 2006–2011, but generally lower than the period 2013–2021. Nonetheless, the species still comprised >8% of the total fish sampled. Similar patterns were evident for common galaxias in 2021/22, which was sampled in high abundance relative to 2006–2011, but had declined relative to 2020/21. Whilst no ageing of fish was conducted in 2021/22, length-at-age data from previous years (Zampatti *et al.* 2010, 2011, Bice *et al.* 2012) indicate that the majority of individuals sampled for both species, in most months, were newly recruited YOY. Given moderate abundance of newly recruited YOY congolli, the annual recruitment index exceeded the reference and the condition monitoring target was achieved in 2021/22. For common galaxias, the recruitment index was below the reference, but above the half confidence tolerance level, and as such, the condition monitoring target was also considered achieved in 2021/22. The temporal period used to calculate the annual recruitment index (October–December) may have resulted in a low index value to 2021/22. This is typically the period of peak abundance for common galaxias, yet in 2021/22, abundance was greater in January/February than October. In future years, we propose to expand the period of index calculation to October–January to cater for inter-annual variability in timing of migration.

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 downstream 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 from 2014–2021 appeared to reflect variability in connectivity during the winter downstream migration period. Indeed, 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) fluctuated in unison with YOY abundance (Figure 4-1). As such, providing connectivity through open barrage gates during winter appears an important driver of subsequent recruitment. Nonetheless, abundance in 2021/22 was contrary to this pattern. Low abundance, despite high levels of connectivity the preceding winter, may be related to low adult abundance (i.e. spawning biomass). While adult abundance is not presented here, recruitment three-years prior was also relatively low; these individuals would have comprised the bulk of mature fish during the winter 2021 spawning season.

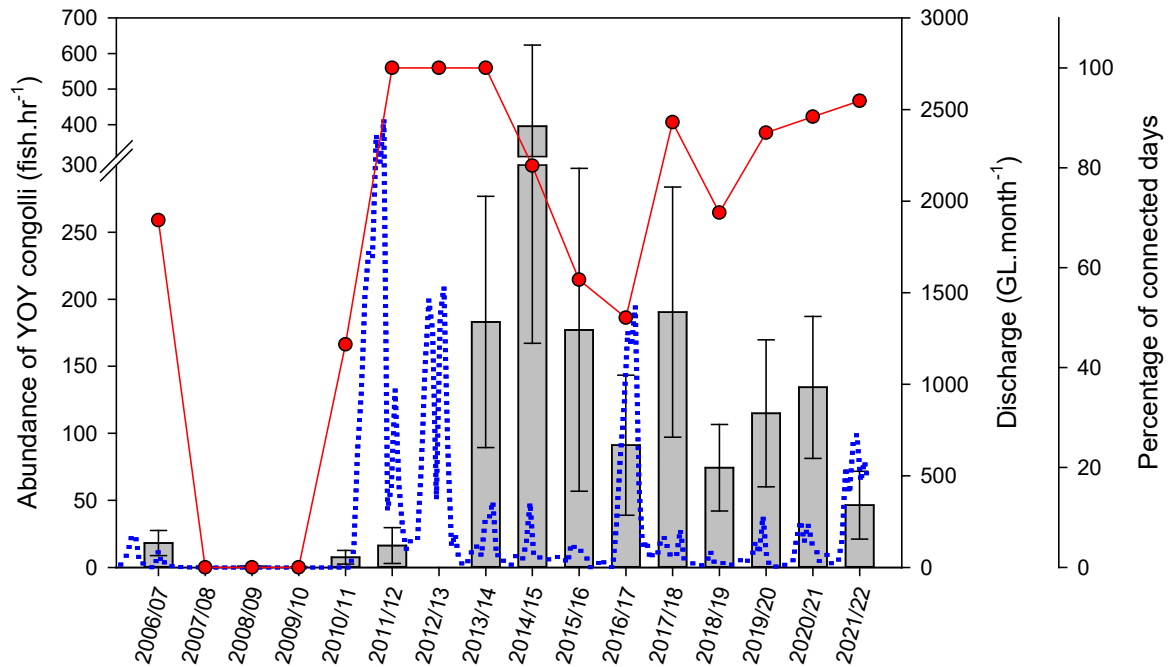


Figure 4-1. The abundance of YOY congolli sampled across the Murray Barrages (grey bars) from 2006–2021 (fish.hr⁻¹), with discharge (GL.month⁻¹, blue dotted line) and percentage of connected days (red line) overlaid.

Anadromous species

In 2021/22, a total of 22 pouched lamprey and no short-headed lamprey were sampled at the barrages. The annual migration index and LLCMM Icon Site ecological target was not achieved

for short-headed lamprey or pouched lamprey, although for pouched lamprey, the migration index was only marginally below the reference tolerance level. Nonetheless, several external factors may have influenced this result. Firstly, commencement of sampling was slightly delayed (August rather than July) and therefore part of the peak pouched lamprey migration season was missed, whilst relatively high barrage discharge (i.e. $>20,000 \text{ ML}\cdot\text{day}^{-1}$) during much of the monitoring period likely reduced sampling efficiency. Of the 20 pouched lamprey implanted with PIT tags, three (15%) passed through fishways on the River Murray. Two individuals were detected passing the Lock 1 fishway (274 km from the Murray Mouth), while another individual was last detected passing the Lock 3 fishway (431 km from the Murray Mouth).

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 and 2020/21 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 2006–2022 and related projects (Jennings *et al.* 2008, 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, when possible, should be prioritised for freshwater releases and fishway operation.

Newly recruited YOY congolli and common galaxias migrate upstream to freshwater habitats 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 generally occur over a protracted period from September–March.

Adult congolli and common galaxias must also migrate downstream from freshwater to marine and estuarine environments, respectively, 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.

In contrast to congolli and common galaxias, anadromous species (pouched and short headed lamprey) migrate from marine to freshwater habitats to spawn. 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 Tauwichee 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 (2014–2018) 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 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 spawning 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 Tauwichee, 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 Tauwichee and Goolwa) to facilitate downstream migrations of catadromous species and provide attraction flow for upstream migrations of anadromous species. Barrage gates are likely to facilitate greater levels of downstream fish 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 Tauwichee 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. 2021/22 represented a period of high freshwater discharge that followed low–moderate annual discharge in 2017–2021. In 2021/22, freshwater discharge was largely provided by unregulated flows, and to a lesser degree, supported by allocations of water for the environment. Freshwater to brackish salinities prevailed in the Coorong estuary and fish assemblages were typical of a dynamic temperate estuary under the influence of high freshwater flow.

Abundances of catadromous congolli and common galaxias were high relative to the period 2006–2011 and low–moderate relative to the period 2011–2020. The majority of individuals sampled in 2021/22 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 2021/22. The objective (b) – *‘promote the successful spawning migration of anadromous fish species in the Lower Lakes and Coorong’*, was not achieved for pouched lamprey or short-headed lamprey, but pouched lamprey were detected in moderate abundance.

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, and will aid the management of water for the environment, and fishway and barrage operation.

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