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Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2014/15

C. M. Bice and B. P. Zampatti

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EXECUTIVE SUMMARY

Estuaries form a dynamic interface between freshwater and marine ecosystems, supporting high levels of biological productivity and diversity. Estuaries support diverse fish assemblages which are characterised by a spatio-temporally variable mix of freshwater, diadromous, estuarine and marine fishes, and provide critical spawning and recruitment habitats, and essential migratory pathways, for diadromous fish. Consequently, changes to flow regimes and physical barriers to movement represent two significant threats to estuarine dependent fishes.

The Lower Lakes and Coorong estuary lie at the terminus of Australia's longest river system, the Murray-Darling Basin (MDB), and the region is regarded as an 'Icon Site' under the Murray-Darling Basin Authority's (MDBA) *The Living Murray Program*. The MDB is highly regulated and on average only ~39% of the natural mean annual discharge now reaches the sea. The estuary is also separated from the Lower Lakes by a series of tidal barrages that form an abrupt physical and biological barrier between estuarine and freshwater environments. From 1997–2010, south-eastern Australia experienced severe drought and between 2006 and 2010, a combination of reduced system-wide inflows and over-allocation of water resulted in reduced flow to the Lower Lakes and the cessation of freshwater flow to the Coorong.

Decline in freshwater inflows, disconnection of freshwater and estuarine environments, and increasing salinity were accompanied by significant changes in fish assemblage structure at the Murray Barrages post–2007. Species diversity and abundance decreased, and fish assemblages became increasingly dominated by marine species in place of freshwater, diadromous and estuarine species. Furthermore, abundance and recruitment of catadromous congolli (*Pseudaphritis urvillii*) and common galaxias (*Galaxias maculatus*) were significantly reduced, and migration and spawning seasons contracted. In winter–spring 2010, extensive rainfall in the MDB, led to the reinstatement of connectivity and high volume (12,500 GL) freshwater discharge in 2010/11. Salinities downstream of the barrages decreased and fish assemblages differed significantly from 2007–early 2010, due to increased abundance of freshwater species and estuarine lagoon goby (*Tasmanogobius lasti*), and decreased abundances of marine and some estuarine species. Abundances of congolli and common galaxias increased significantly but anadromous lamprey were not sampled.

Moderate but declining freshwater flows occurred in 2011/12 (8795 GL), 2012/13 (5177 GL) and 2013/14 (1647 GL). The fish assemblages in 2011/12 and 2013/14 (no sampling was conducted in 2012/13) trended towards diverse but variable assemblages characteristic of dynamic

estuarine environments. Freshwater species remained present, but less abundant than in 2010/11, whilst the abundance of catadromous (congolli and common galaxias), and certain estuarine (e.g. lagoon goby) and marine migrant (sandy sprat *Hyperlophus vittatus*) species increased. Additionally, both short-headed lamprey (*Mordacia mordax*) and pouched lamprey (*Geotria australis*) were sampled in low numbers.

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. In the Coorong, such data can inform specific ecological targets within the Lower Lakes, Coorong and Murray Mouth Icon Site and aid development of the 'Lakes and Barrages Operating Strategy'. 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. By sampling fish attempting to move through the barrage fishways and residing at 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 2014/15, and assess spatio-temporal variation in assemblage structure in relation to 2006–2014;
2. Assess spatio-temporal variability in the recruitment and relative abundance of catadromous fish (i.e. congolli and common galaxias) attempting to migrate upstream at the Murray Barrages in 2014/15, and in relation to 2006–2014;
3. Utilise these data to inform Target F-1 of the Lower Lakes Coorong and Murray Mouth Icon Site Management Plan (Maunsell 2009) – *'maintain or improve recruitment success of diadromous fish in the Lower Lakes and Coorong'*; and
4. Inform operation of the barrages and development of the 'Lakes and Barrages Operating Strategy'.

The year 2014/15 represented the fifth consecutive year of freshwater discharge and high levels of hydrological connectivity between the Lower Lakes and Coorong. Annual discharge (~860 GL) was less than that from 2010–2014, and salinities increased, but remained within the 'brackish' range (7–32 $g.L^{-1}$) in the Coorong estuary. The fish assemblage sampled in 2014/15 was diverse (31 species) and similar to that of 2013/14. Sandy sprat remained the most abundant species, comprising 59% of the total catch numerically, although the majority of these individuals were sampled at sites adjacent to Goolwa and Tauwitchere barrages, rather than within vertical-slot fishways. The catadromous congolli was the second most abundant species overall (~25% of the total catch) and the most abundant species captured from vertical-slot fishway sites. The catadromous common galaxias, several freshwater species (e.g. Australian smelt, *Retropinna semoni*) and estuarine lagoon goby were also common.

The abundance of congolli and common galaxias continued on the positive trajectory observed from 2010–2014, and were sampled in the greatest numbers recorded over the nine-year study period. Over 90% of all individuals sampled were newly recruited young-of-the-year. Enhanced recruitment of catadromous species in 2014/15 was likely a result of a combination of two mechanisms: 1) high levels of hydrological connectivity between freshwater and marine environments throughout 2014/15 and subsequently, favourable conditions for migration, spawning and survival of larvae/juveniles under brackish salinities; and 2) enhanced spawning output as a result of high abundance of reproductively mature adults. Strong recruitment was observed in 2010/11 and 2011/12, and likely led to high abundance of reproductively mature individuals during the 2014 spawning season, contributing to enhanced spawning output. These results highlight the importance of providing freshwater discharge to the Coorong on an annual basis and the cumulative benefit of consecutive ‘favourable’ years on population dynamics.

Diadromous species exhibited seasonal peaks in migration, which were consistent with those from previous years and should be considered priority periods for barrage and fishway operation. Freshwater discharge and fishway operation should be facilitated at Tauwitchere and Goolwa Barrages annually from June–August to allow for downstream spawning migrations of congolli and common galaxias and upstream migrations of lamprey, and from October–January to allow for the upstream migrations of congolli and common galaxias. Diadromous species will typically migrate and accumulate where freshwater is being discharged; therefore, during times of water shortage and trade-offs between release locations, freshwater discharge should be limited (where possible) to barrages with effective fish passage. Following the construction and assessment of new fishways on the Murray Barrages (e.g. Boundary Creek, Mundoo Barrage and Ewe Island Barrage) an operations plan may be developed to prioritise opening/closure of fishways during times of water scarcity.

The results of this investigation suggest further changes to fish assemblages of the Coorong following prolonged freshwater inflow and hydrological connectivity. In general, the assemblage trended towards diverse but variable fish assemblages that characterise dynamic estuarine environments under freshwater influence. There is evidence to suggest the assemblage may follow a trajectory towards the assemblage of 2006/07 (a period of diminishing freshwater discharge) should freshwater discharge continue to decline from current levels. Notwithstanding, abundances of catadromous congolli and common galaxias peaked in 2014/15 following steady increases post the 2007–2010 no flow period and these data indicate that the target of '*maintain or improve recruitment success of diadromous fish in the Lower Lakes and Coorong'* was achieved. Importantly, continuous low-volume discharge throughout 2014/15 facilitated connectivity and the upstream migration of newly recruited individuals. 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 dynamism in estuarine fish communities.

1. INTRODUCTION

1.1. Background

Estuaries form a dynamic interface and important 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). Nevertheless, throughout the world, anthropogenic modification of rivers has diminished freshwater flows to estuaries and threatens the existence of estuarine habitats (Gillanders and Kingsford 2002, Flemer and Champ 2006). In addition, structures that regulate flow may alter the longitudinal connectivity between estuarine and freshwater environments (Lucas and Baras 2001).

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

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

From 1997–2010, south-eastern Australia experienced severe drought (the 'Millennium Drought') resulting in reduced inflows to the Murray-Darling Basin (MDB) (Van Dijk *et al.* 2013). Over a four year period (2006–10), a combination of reduced system-wide inflows and over-allocation of water resulted in reduced flow to the Lower Lakes (<600 $GL.y^{-1}$ in 2007 and 2008), causing a reduction in water level downstream of Lock 1 of >1.5 m and the cessation of freshwater flow to the Coorong estuary. Disconnection of the Coorong from the Lower Lakes resulted in increased salinities in the Coorong and a concomitant decrease in fish species diversity (Zampatti *et al.* 2010). When brackish conditions prevailed, fish assemblages were characterised by a diversity of freshwater, diadromous, estuarine and marine species. As salinities increased, however, the abundance of freshwater, diadromous and estuarine species decreased and marine species became more common (Zampatti *et al.* 2010). Furthermore, catadromous congolli (*Pseudaphritis urvillii*) and common galaxias (*Galaxias maculatus*) exhibited high inter-annual variations in recruitment, with significant declines in the abundance of young-of-the-year (YOY) migrants and contraction of migration and spawning periods (Zampatti *et al.* 2011a). Anadromous short-headed lamprey (*Mordacia mordax*) and pouched lamprey (*Geotria australis*), present in 2006/07, were absent through 2007–2010.

The following four year period (2010–2014), was characterised by contrasting hydrology; increased inflows in the MDB in 2010/11 resulted in the return of typical water levels to the Lower Lakes and subsequently, the delivery of large volumes (12,498 GL) of freshwater to the Coorong, with further moderate but declining volumes of freshwater in 2011/12 (8795 GL), 2012/13 (5177 GL) and 2013/14 (1647 GL). Increased discharge, relative to 2007–2010, was accompanied by significant changes in fish assemblage structure. The fish assemblage in 2010/11 was dominated by freshwater (e.g. Australian smelt *Retropinna semoni*) and small-bodied estuarine species (e.g. lagoon goby *Tasmanogobius lasti*), whilst marine species and some estuarine species decreased in abundance (Zampatti *et al.* 2012). Recruitment of catadromous congolli and common galaxias was enhanced, resulting in increased abundance relative to 2007–2010. Nonetheless, short-headed lamprey and pouched lamprey were not collected.

The fish assemblages in 2011/12 and 2013/14 (no sampling was conducted in 2012/13) trended towards diverse but variable assemblages characteristic of dynamic estuarine environments (Bice *et al.* 2012). Freshwater species remained present, but less abundant than in 2010/11, whilst the abundance of catadromous (congolli and common galaxias), and certain estuarine (e.g. lagoon goby) and marine migrant (sandy sprat *Hyperlophus vittatus*) species increased.

Additionally, both short-headed lamprey and pouched lamprey were sampled in low numbers in 2011/12.

The year 2014/15, represented the fifth consecutive year of freshwater discharge to the Coorong and connectivity between the Coorong and Lower Lakes, post the Millennium drought (Van Dijk *et al.* 2013). This provided the opportunity to assess the response of fish assemblage structure, movement and recruitment following a prolonged period of freshwater flow and connectivity (2010 onwards). Such data are important to gauge continued system recovery following drought and improve understanding of patterns in fish assemblage structure and movement under variable flow regimes. Ultimately, these data can be used to assess specific ecological targets in the Lower Lakes, Coorong and Murray Mouth Icon Site Condition Monitoring Plan (Maunsell 2009) and will aid future management of the system, including informing the development of a 'Lakes and Barrages Operating Strategy'.

1.2. Objectives

The objective of this study was to investigate the influence of freshwater inflows (supplemented by environmental water delivery) 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 2014/15, and assess spatio-temporal variation in assemblage structure in relation to 2006–2014;
2. Investigate spatio-temporal variability in the recruitment and relative abundance of catadromous fish (i.e. congolli and common galaxias) attempting to migrate upstream at the Murray Barrages in 2014/15, in relation to 2006–2014;
3. Utilise these data to inform Target F-1 of the Lower Lakes Coorong and Murray Mouth Icon Site Management Plan (Maunsell 2009) – *'maintain or improve recruitment success of diadromous fish in the Lower Lakes and Coorong'*; and
4. Inform operation of the barrages and development of the 'Lakes and Barrages Operating Strategy'.

2. METHODS

2.1. Study area and fishways

This study was conducted at the interface between the Coorong estuary and Lower Lakes of the River Murray, in southern Australia (Figure 2-1). The River Murray discharges into a shallow (mean depth 2.9 m) expansive lake system, comprised of Lakes Alexandrina and Albert before flowing into the Coorong and finally the Southern Ocean via the Murray Mouth. Under natural conditions, mean annual discharge was ~12,233 GL, but there was strong inter-annual variation (Puckridge *et al.* 1998). Under regulated conditions, an average of ~4,723 $GL.y^{-1}$ reaches the sea, although from 1997–2010 this was substantially less and zero for a period of over three years (March 2007 – September 2010) (Figure 2-2). Discharge increased abruptly in September 2010 and annual discharges in 2010/11, 2011/12 and 2012/13 were approximately 12,500, 8800 and 5200 GL, respectively (Figure 2-2). Annual discharge decreased in 2013/14 to ~1600 GL and further so in 2014/15 (~984 GL) (Figure 2-2).

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

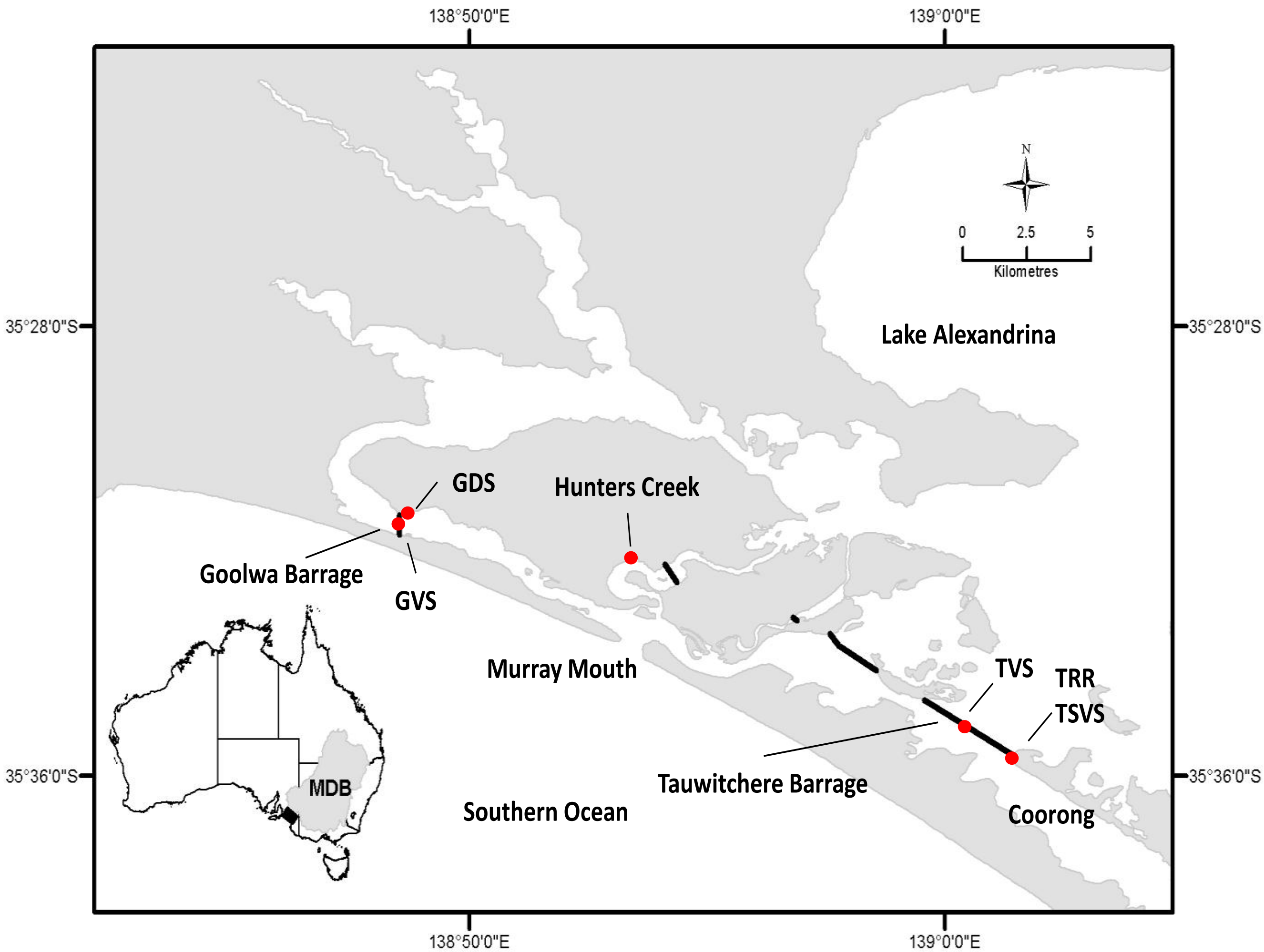

Figure 2-1. A map of the Coorong and Lake Alexandrina at the terminus of the River Murray, southern Australia showing the study area in the Coorong estuary, highlighting the Murray Mouth and Murray Barrages (bold lines). Goolwa and Tauwitchere barrages are identified, as are the fish sampling locations (red dots); Goolwa vertical-slot (GVS), adjacent Goolwa Barrage (GDS), Hunters Creek vertical slot (Hunters Creek), Tauwitchere large vertical-slot (TVS) and Tauwitchere small vertical-slot (TSVS) and rock ramp (TRR).

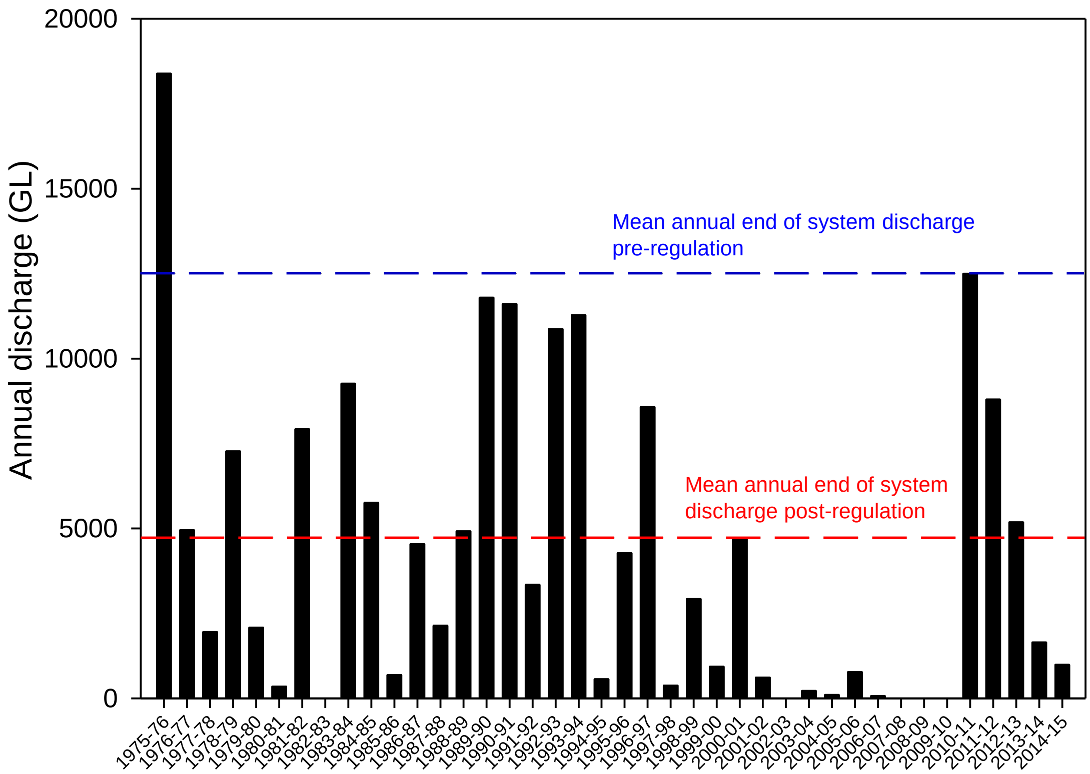

Figure 2-2. Annual freshwater discharge (GL) through the Murray barrages into the Coorong estuary from 1975–March 2015. Dashed lines represent mean annual end of system discharge pre- (blue) and post-regulation (red).

In the 1940s, five tidal barrages with a total length of 7.6 km were constructed to prevent saltwater intrusion into the Lower Lakes and maintain stable freshwater storage for consumptive use (Figure 2-1). The construction of the barrages dramatically reduced the extent of the Murray 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).

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

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

In 2004, three experimental fishways (2 x large vertical-slots and 1 x rock ramp) were constructed on the Murray Barrages (Barrett and Mallen-Cooper 2006) with the aim of facilitating fish movement between the Coorong and Lower Lakes. The two large vertical slot fishways (slope = 13.6%, slot width = 0.3 m), located on Goolwa and Tauwitchere Barrages, were designed to pass fish >150 mm total length (TL) and discharge approximately 30–40 ML day^{-1} (Mallen-Cooper 2001). Assessments of these fishways indicated they were effective in passing large-bodied species, but the passage of small-bodied species and small life stages (<100 mm TL) was largely obstructed (Stuart *et al.* 2005, Jennings *et al.* 2008b). The rock ramp fishway (slope = 1:27) 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.* 2008b).

In 2009, additional small vertical-slot fishways were constructed on Tauwitchere barrage and the Hunters Creek causeway. These new fishways were designed with internal hydraulics that were considered favourable for the upstream passage of small-bodied fish (i.e. low headloss, velocity and turbulence) and to operate with low discharge (<5 $ML.day^{-1}$). Both fishways effectively facilitate the passage of small-bodied fish (Zampatti *et al.* 2012).

2.2. Fish sampling

Samples of fish were collected from the entrances of all four vertical-slot fishways in 2014/15 (Figure 2-1 and Table 2-1). Samples of fish were also collected from 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 sites where fish were sampled at the Murray Barrages in 2014/15, including site name, abbreviated name used throughout and the barrage associated with site, as well as latitude and longitude.

Name	Abbreviation	Barrage	Latitude	Longitude
Tauwitchere large vertical-slot	TVS	Tauwitchere	35°35’09.35’’S	139°00’30.58’’E
Tauwitchere small vertical-slot	TSVS	Tauwitchere	35°35’23.44’’S	139°00’56.23’’E
Tauwitchere rock ramp	TRR	Tauwitchere	35°35’23.60’’S	139°00’56.30’’E
Goolwa vertical-slot	GVS	Goolwa	35°31’34.44’’S	138°48’31.12’’E
Adjacent Goolwa Barrage	GDS	Goolwa	35°31’24.16’’S	138°48’33.79’’E
Hunters Creek vertical-slot	Hunters	Hunters Creek causeway	35°32’07.08’’S	138°53’07.48’’E

The entrances of the vertical-slot fishways were sampled using aluminium-framed cage traps, designed to fit into the first cell of each fishway (Tauwitchere large vertical-slot: 2.3 m long x 4.0 m wide x ~2.0 m depth and 0.3 m slot widths; Tauwitchere small vertical-slot: 1.2 m long x 1.6 m wide x ~1.0 m depth and 0.2 m slot widths; Goolwa large vertical-slot: 2.6 m long x 3.6 m wide x ~3.6 m depth, 0.3 m slot widths (each baffle was modified in 2010 to three 200 mm wide x 500 mm deep orifices); Hunters Creek: 1.6 m long x 1.6 m wide x ~0.6 m depth and 0.1 m slot widths) (Figure 2-3a). Traps for the large vertical-slot fishways at Tauwitchere and Goolwa 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 at Tauwitchere and Hunters Creek were covered with 3 mm knotless mesh 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. At both locations, the net was set adjacent to the barrage to capture fish utilising this area.

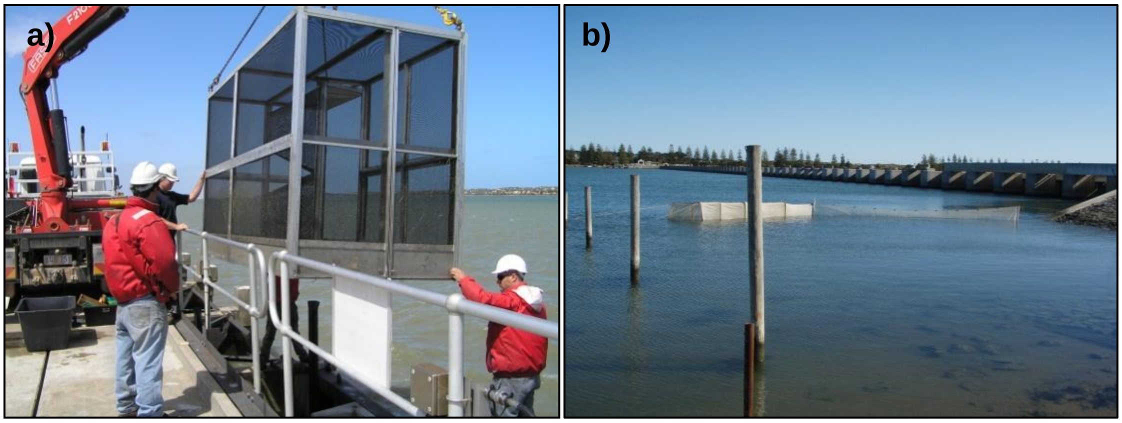

Figure 2-3 a) Cage trap used to sample the Tauwitchere and Goolwa vertical-slot fishways and b) large fyke net used to sample adjacent Goolwa barrage. A net of the same dimensions was also used to sample adjacent to the Tauwitchere rock ramp.

Four weeks of sampling were conducted monthly between 27 October 2014 and 30 January 2015. 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 3 times per sampling week, with the exception of the Tauwitchere large vertical-slot, which could not be sampled in January 2015 due to limited access on Tauwitchere barrage. 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. Each individual was then identified to species and counted. For catadromous congolli and common galaxias, during each trapping event a random sub-sample of up to 50 individuals were measured to the nearest mm (total length, TL) to represent the size structure of the population.

Estimated daily barrage discharge and salinity data were obtained from the Department of Environment, Water and Natural Resources (DEWNR).

2.3. Data analysis

Temporal variation in fish assemblages was investigated by assessing changes in total fish abundance (all species combined), species richness and diversity, and fish assemblage structure (i.e. species composition and individual species abundance). Differences in the relative abundance (fish.hour^{-1}.trap event^{-1}) of fish (all species combined) sampled between years at each site were analysed using uni-variate single-factor PERMANOVA (permutational ANOVA and MANOVA), in the software package PRIMER v. 6.1.12 and PERMANOVA+

(Anderson *et al.* 2008). These analyses were performed on fourth-root transformed relative abundance data. This routine tests the response of a variable (e.g. total fish abundance) to a single factor (e.g. year) in a traditional ANOVA (analysis of variance) experimental design using a resemblance measure (i.e. Euclidean distance) and permutation methods (Anderson *et al.* 2008). Unlike ANOVA, PERMANOVA does not assume samples come from normally distributed populations or that variances are equal. Changes in species richness and diversity were qualitatively assessed by comparing total species richness (number of species sampled across all sampling sites) and the contribution of species from different estuarine-use guilds (as defined by Elliott *et al.* 2007) between years. Data from the Tauwitchere small-vertical slot and Hunters Creek vertical-slot were excluded from these analyses as they have only been sampled since 2010.

The composition of fish assemblages sampled at each location was assessed between all sampling years (i.e. 2006–2015). Non-Metric Multi-Dimensional Scaling (MDS) 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 assemblages from different years in two dimensions. PERMANOVA, based on the same similarity matrices, was used to detect differences in assemblages between years. To allow for multiple comparisons between years at each site, a false discovery rate (FDR) procedure presented by Benjamini and Yekutieli (2001), hereafter the 'B–Y method' correction, was adopted ($\alpha = \sum_{i=1}^{n}(1/i)$; e.g. for $n_{comparisons}$ = 15, B-Y method α = 0.05/ (1/1 + 1/2 + 1/3…….+1/15) = 0.015) (Benjamini and Yekutieli 2001, Narum 2006). When significant differences occurred, a similarity of percentages (SIMPER) analysis was undertaken to identify species contributing to these differences. A 40% cumulative contribution cut-off was applied.

Indicator species analysis (ISA) (Dufrene and Legendre 1997) was used to calculate the indicator value (site fidelity and relative abundance) of species between years at each site using the package PCOrd v 5.12 (McCune and Mefford 2006). Non-abundant species may 'characterise' an assemblage without largely contributing to the difference between years detected with PERMANOVA. Such species may be important indicators of environmental change. 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 (α = 0.05).

Spatial variation in fish assemblages between sampling locations in 2014/15 was also investigated using MDS, PERMANOVA and ISA. Due to differences in sampling methods, spatial variation was assessed separately for the vertical-slot fishway sites and the two sites sampled with the large fyke net (i.e. the Tauwitchere rock ramp and adjacent Goolwa Barrage). MDS plots generated from Bray-Curtis similarity matrices were used to graphically represent assemblages from different locations in two dimensions and PERMANOVA was used to detect differences in assemblages between locations. To allow for multiple comparisons between sites within 2014/15, a B–Y method FDR correction for significance was adopted. ISA was then used to determine what species characterised assemblages at the different sampling locations in 2014/15.

Inter-annual (2006–2015) differences in the standardised abundance (fish.hour^{-1}.trap event^{-1}) of pouched lamprey and short-headed lamprey were qualitatively assessed. Inter-annual (2006–2015) differences in the standardised abundance of common galaxias and congolli (fish.hour^{-1}.trap event^{-1}) sampled at all six sites were analysed using uni-variate single-factor PERMANOVA (Anderson *et al.* 2008). Intra-annual (monthly) differences in the standardised abundance (fish.hour^{-1}.trap event^{-1}) of common galaxias and congolli sampled at all sites in 2014/15 were also analysed using uni-variate single-factor PERMANOVA (Anderson *et al.* 2008).

3. RESULTS

3.1. Hydrology

From mid-July 2005 to March 2006 and May to August 2006, low-volume freshwater flows of 1000–12,000 $ML.d^{-1}$ were consistently released into the Coorong through barrage ‘gates’ and fishways on Tauwitchere and Goolwa Barrages (Figure 3-1a). In September 2006, all barrage gates were shut and freshwater was released solely through the barrage fishways (Tauwitchere: 20-40 $ML.d^{-1}$, Goolwa: ~20 $ML.d^{-1}$) until March 2007, when all fishways were closed due to receding water levels in the Lower Lakes (Figure 3-1a). Persistent drought in the MDB resulted in no freshwater being released to the Coorong from March 2007–September 2010. Significant inflows to the Lower Lakes in late 2010 resulted in the release of large volumes of freshwater to the Coorong throughout the 2010/11 sampling season. Water was released through the barrage fishways and gates on Goolwa, Mundoo, Boundary Creek, Ewe Island and Tauwitchere Barrages, with cumulative flow across the barrages peaking at >80,000 $ML.d^{-1}$ and a mean daily discharge (±S.E.) of 49,955 ± 1396 $ML.d^{-1}$ over the 2010/11 sampling period (Figure 3-1a). Medium-volume freshwater flows continued throughout the 2011/12 sampling season (range 800–34,600 $ML.d^{-1}$; mean daily discharge = 10,823 ± 657 $ML.d^{-1}$) and 2012/13 (range 220–69,000 $ML.d^{-1}$; mean daily discharge = 12,617 ± 948 $ML.d^{-1}$), although no sampling was conducted in 2012/13 (Figure 3-1a). Low–medium volume flows occurred throughout 2013/14 with flow during the sampling season ranging 20–18,020 $ML.d^{-1}$ and a mean daily discharge of 1617 ± 217 $ML.d^{-1}$. Overall discharge decreased further in 2014/15 and ranged 8–2950 $ML.d^{-1}$ with a mean of 1547 ± 67 $ML.d^{-1}$ during sampling.

During sampling in 2006/07, salinity below Tauwitchere and Goolwa Barrages fluctuated 20–34 $g.L^{-1}$ (mean = 28.42 ± 0.18 $g.L^{-1}$) and 11–29 $g.L^{-1}$ (mean = 21.93 ± 0.29 $g.L^{-1}$), respectively (Figure 3-1b). Following the cessation of freshwater releases in March 2007, salinities at Tauwitchere increased and ranged 30–60 $g.L^{-1}$ until September 2010, with mean salinities during sampling ranging 34–36 $g.L^{-1}$. Salinities at Goolwa Barrage, between March 2007 and September 2010, also increased, ranging from 26–37 $g.L^{-1}$ with mean salinities during sampling ranging 26–34 $g.L^{-1}$. Following significant increases in freshwater releases to the Coorong in September 2010, salinities over the 2010/11 sampling period ranged 0.3–25 $g.L^{-1}$ at Goolwa Barrage and 0.2–27 $g.L^{-1}$ at Tauwitchere Barrage; however, mean salinities were significantly reduced at both Goolwa (1.95 ± 0.31 $g.L^{-1}$) and Tauwitchere (3.78 ± 0.33 $g.L^{-1}$) (Figure 3-1b). During 2011/12 sampling, salinity at Goolwa ranged 0.3–32 $g.L^{-1}$ (mean = 10.39 ± 0.77 $g.L^{-1}$)

and 3–26 $g.L^{-1}$ (mean = 12.69 ± 0.42 $g.L^{-1}$) at Tauwitchere (Figure 3-1b), but was more variable than 2010/11, appearing to follow a fortnightly lunar cycle, with higher tides resulting in seawater incursion and greater salinities. In 2012/13, salinity fluctuated over a similar range to 2011/12, but no sampling was conducted. During sampling in 2013/14, decreasing freshwater flows resulted in increased salinity relative to the three previous years; nevertheless, conditions remained ‘brackish’ with salinity ranging 0.5–30 $g.L^{-1}$ (mean = 13.53 ± 0.86 $g.L^{-1}$) at Goolwa and 4.74–21.66 $g.L^{-1}$ (mean = 10.39 ± 0.77 $g.L^{-1}$) at Tauwitchere. Further decrease in freshwater discharge in 2014/15 resulted in further increases in salinities, ranging 7–32 $g.L^{-1}$ (mean = 18.68 ± 0.60 $g.L^{-1}$) at Goolwa and 15–32 $g.L^{-1}$ (mean = 22.73 ± 0.39 $g.L^{-1}$) at Tauwitchere.

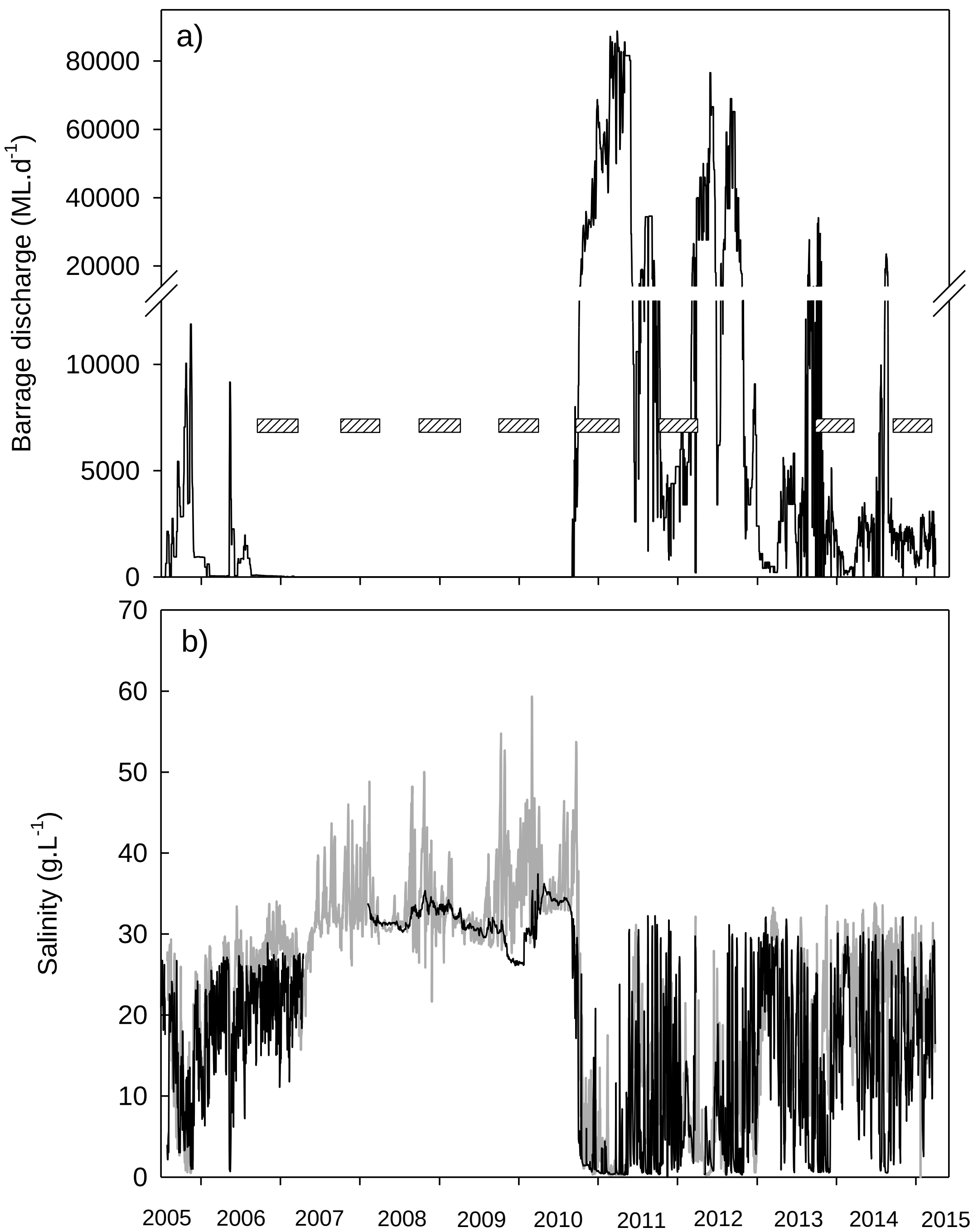

Figure 3-1. a) Mean daily flow (ML.d^{-1}) to the Coorong through the Murray Barrages (all barrages combined) from July 2005–March 2015 and b) Mean daily salinity (g.L^{-1}) of the Coorong below Tauwitchere (grey line) and Goolwa (black line) barrages from July 2005 – March 2015. Sampling periods are represented by hatched bars. Barrage discharge data was sourced from DEWNR, whilst salinity data was sourced from water quality monitoring stations immediately below Tauwitchere and Goolwa Barrages (DEWNR 2015).

3.2. Catch summary

A total of 843,324 fish from 31 species (21 families) were sampled in 2014/15 (Table 3-1). The marine migrant sandy sprat and catadromous congolli dominated, comprising ~59% and 25% of the total catch, respectively. The freshwater Australian smelt (5.3%), bony herring (*Nematalosa erebi*; 3%), catadromous common galaxias (3.6%) and estuarine lagoon goby (1.9%) were the next most abundant species, whilst the remaining 25 species collectively comprised <2% of the total catch.

Table 3-1. Summary of species and total number of fish sampled from the entrances of the Tauwitchere large vertical-slot, Tauwitchere small vertical-slot, Goolwa vertical-slot and Hunters Creek vertical-slot, and from the Tauwitchere rock-ramp and adjacent Goolwa Barrage in 2014/15. Species are categorised using estuarine use guilds from Elliott *et al.* (2007).

Common name	Scientific Name	Guild	Tauwitchere large vertical-slot	Tauwitchere small vertical-slot	Tauwitchere rock ramp	Goolwa vertical-slot	Adjacent Goolwa Barrage	Hunters Creek	Total
		Sampling events	9	12	4	12	4	12	
		No. of species	13	10	22	14	25	11	
Australian smelt	*Retropinna semoni*	Freshwater migrant	10317	18445	7697	7399	545	13	**44,416**
Bony herring	*Nematalosa erebi*	Freshwater migrant	653	99	16781	786	5433	1933	**25,685**
Flat-headed gudgeon	*Philypnodon grandiceps*	Freshwater migrant	1218	31	1308	384	1169	50	**4160**
Dwarf flat-headed gudgeon	*Philypnodon macrostomus*	Freshwater straggler	0	0	1	3	36	0	**40**
Carp gudgeon	*Hypseleotris* spp	Freshwater straggler	3	0	0	0	0	0	**3**
Golden perch	*Macquaria ambigua*	Freshwater migrant	0	0	0	1	0	0	**1**
Common carp	*Cyprinus carpio**	Freshwater migrant	29	0	4	0	0	1	**34**
Goldfish	*Carrasius auratus**	Freshwater straggler	0	0	1	0	0	0	**1**
Redfin perch	*Perca fluviatilis**	Freshwater straggler	36	446	4702	43	743	0	**5970**
Eastern gambusia	*Gambusia holbrooki**	Freshwater straggler	0	0	0	0	0	1	**1**
Common galaxias	*Galaxias maculatus*	Semi-catadromous	4712	6672	4899	13258	374	462	**30,367**
Congolli	*Pseudaphritis urvillii*	Semi-catadromous	5376	12786	81192	68726	34498	9706	**212,284**
Small-mouthed hardyhead	*Atherinosoma microstoma*	Estuarine	1	2	1631	1	44	54	**1733**

denotes introduced species

Table 3-1 continued.

Common name	Scientific Name	Guild	Tauwitchere large vertical-slot	Tauwitchere small vertical-slot	Tauwitchere downstream	Goolwa vertical-slot	Adjacent Goolwa Barrage	Hunters Creek	Total
Tamar River goby	*Afurcagobius tamarensis*	Estuarine	3	0	292	41	547	11	**894**
Blue-spot goby	*Pseudogobius olorum*	Estuarine	0	0	6	0	6	0	**12**
Lagoon goby	*Tasmanogobius lasti*	Estuarine	1187	28	13996	46	750	4	**16,011**
Bridled goby	*Arenogobius bifrenatus*	Estuarine	0	1	572	0	180	0	**753**
Greenback flounder	*Rhombosolea tapirina*	Estuarine	0	0	5	0	86	0	**91**
Long-snouted flounder	*Ammotretis rostratus*	Estuarine	0	0	3	0	1	0	**4**
River garfish	*Hyperhamphus regularis*	Estuarine	0	0	1	0	2	0	**3**
Black bream	*Acanthopagrus butcheri*	Estuarine	4	0	0	0	1	0	**6**
Yellow-eyed mullet	*Aldrichetta forsteri*	Marine migrant	0	0	0	5	35	0	**40**
Flat-tailed mullet	*Liza argentea*	Marine migrant	0	0	0	2	0	0	**2**
Mulloway	*Argyrosomus japonicus*	Marine migrant	0	0	12	0	16	0	**28**
Soldier fish	*Gymnapistes marmoratus*	Marine migrant	0	0	1	0	4	0	**5**
Smooth toadfish	*Tetractenos glaber*	Marine migrant	0	0	3	0	5	0	**8**
Sandy sprat	*Hyperlophus vittatus*	Marine migrant	10928	23	418512	14345	56956	1	**500,765**
Pug nose pipefish	*Pugnaso curtirostris*	Marine straggler	0	0	1	0	3	0	**4**
Bridled leatherjacket	*Acanthaluteres spilomelanurus*	Marine straggler	0	0	0	0	1	0	**1**
Six-spined leatherjacket	*Meuschenia freycineti*	Marine straggler	0	0	0	0	1	0	**1**
Ornate cowfish	*Aracana ornata*	Marine straggler	0	0	0	0	1	0	**1**
		Total	**34,467**	**38,533**	**551,620**	**105,040**	**101,437**	**12,236**	**843,324**

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 substantially from 2006/07 to 2014/15 (Figure 3-2), with significant differences between years detected at the Tauwitchere rock ramp (*Pseudo*-$F_{7, 53}$ = 4.874, p = 0.002), Tauwitchere vertical-slot (*Pseudo*-$F_{7, 45}$ = 10.471, p < 0.001) and Goolwa vertical-slot (*Pseudo*-$F_{6, 38}$ = 3.609, p = 0.011), but not adjacent Goolwa Barrage (*Pseudo*-$F_{5, 33}$ = 2.274, p = 0.086). The Tauwitchere small vertical-slot and Hunters Creek vertical-slot have only been sampled since 2010 and are included for completeness (Figure 3-2a). The mean number of fish varied significantly between years at the Hunters Creek vertical-slot (*Pseudo*-$F_{3, 25}$ = 2.988, p = 0.044), but not at the Tauwitchere small vertical-slot (*Pseudo*-$F_{3, 25}$ = 1.140, p = 0.357). Patterns of temporal variability in total fish abundance were similar at all locations, with substantial declines in total abundance during the period of no freshwater discharge and disconnection through 2007–2010 and dramatically increased abundance following the resumption of freshwater discharge and connectivity in 2010/11 and 2011/12 (Figure 3-2). Abundance remained high in 2014/15 and was comparable with the preceding three years, with the exception of peak abundance at the Tauwitchere vertical-slot in 2010/11 and at the rock ramp in 2011/12. In contrast, general fish abundance at the Goolwa vertical-slot over 2006–2015, peaked in 2014/15, and was >100 times greater than that recorded in 2008/09.

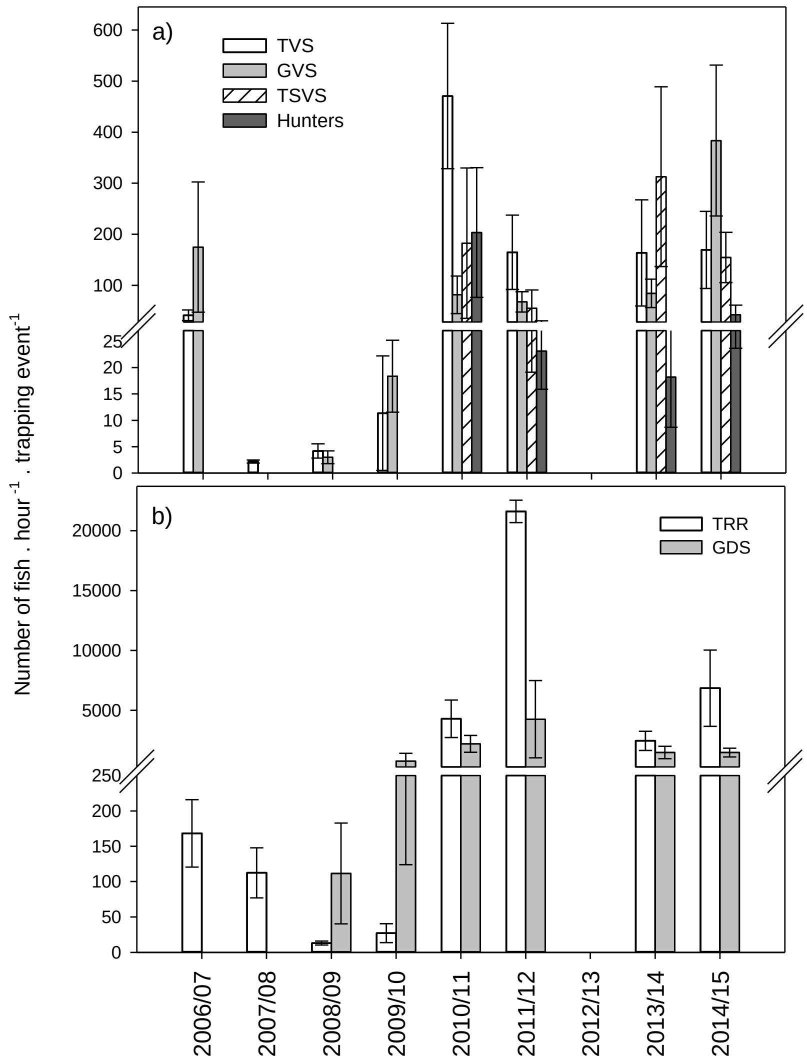

Figure 3-2. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of fish (all species combined) sampled at a) the Tauwitchere large vertical-slot (TVS), Goolwa vertical-slot (GVS), Tauwitchere small vertical-slot and Hunters Creek vertical-slot (Hunters), and b) the Tauwitchere rock ramp (TRR) and adjacent Goolwa Barrage (GDS), from 2006–2014. Goolwa vertical-slot was not sampled in 2007/08, whilst sampling at the Tauwitchere small vertical-slot and Hunters Creek vertical-slot (Hunters) commenced in 2010/11. Sampling at the site adjacent Goolwa Barrage commenced in 2008/09. No sampling was conducted at any site in 2012/13.

Species richness (all sites combined) varied little between years, except for 2007/08 when 24 species were sampled (Figure 3-3). Nevertheless, the Goolwa vertical-slot and the site adjacent Goolwa Barrage were not sampled in this year, likely resulting in reduced overall species richness. Species richness ranged 28–34 in all other years, with greatest species richness (*n* =

34) recorded in 2011/12. Nevertheless, the number of species sampled from different guilds of fish varied substantially (Figure 3-3). The number of species of freshwater origin (freshwater migrants and stragglers combined) was lowest from 2007–2010 (n = 2–3), but greatest during times of freshwater discharge and connectivity from 2010–2015 (n = 9–11). In contrast, the number of species of marine origin (marine migrants and stragglers combined) was greatest from 2007–2010 (n = 12–18) and lowest in 2006/07 and 2010–2015 (n = 7–11). The number of diadromous species was reduced during 2007–2011 and 2014/15 (n = 2), due to the absence of both lamprey species, whilst the number of estuarine species did not differ substantially over the entire study period (n = 8–10).

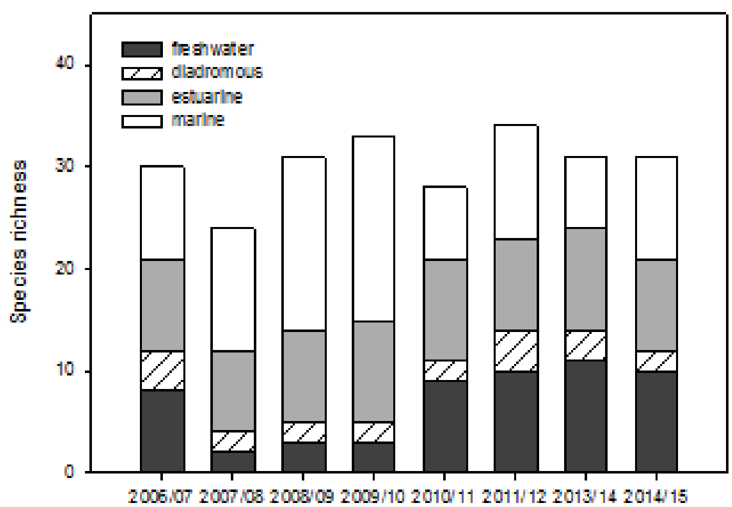

Figure 3-3. Species richness (all sites combined) from 2006–2014, including the contribution of species from different estuarine-use guilds, i.e. freshwater (freshwater migrants and stragglers combined), diadromous (catadromous and anadromous combined), estuarine and marine (marine migrants and stragglers combined). Guilds follow those proposed by Elliott *et al.* (2007).

Assemblage structure

MDS ordination plots show groupings of fish assemblages by year at each sampling location (Figure 3-4). These groupings are supported by PERMANOVA, which detected significant differences in fish assemblages at the Tauwitchere rock ramp ($Pseudo\text{-}F_{7,\ 53}$ = 17.078, $p < 0.001$), Tauwitchere large vertical-slot ($Pseudo\text{-}F_{7,\ 45}$ = 11.505, $p < 0.001$), Tauwitchere small vertical-slot ($Pseudo\text{-}F_{3,\ 25}$ = 3.606, $p < 0.001$), Goolwa vertical-slot ($Pseudo\text{-}F_{6,\ 44}$ = 6.293,

$p < 0.001$), adjacent Goolwa Barrage ($Pseudo\text{-}F_{5,\ 33} = 8.060$, $p < 0.001$) and Hunters Creek vertical-slot ($Pseudo\text{-}F_{3,\ 25} = 6.325$, $p < 0.001$).

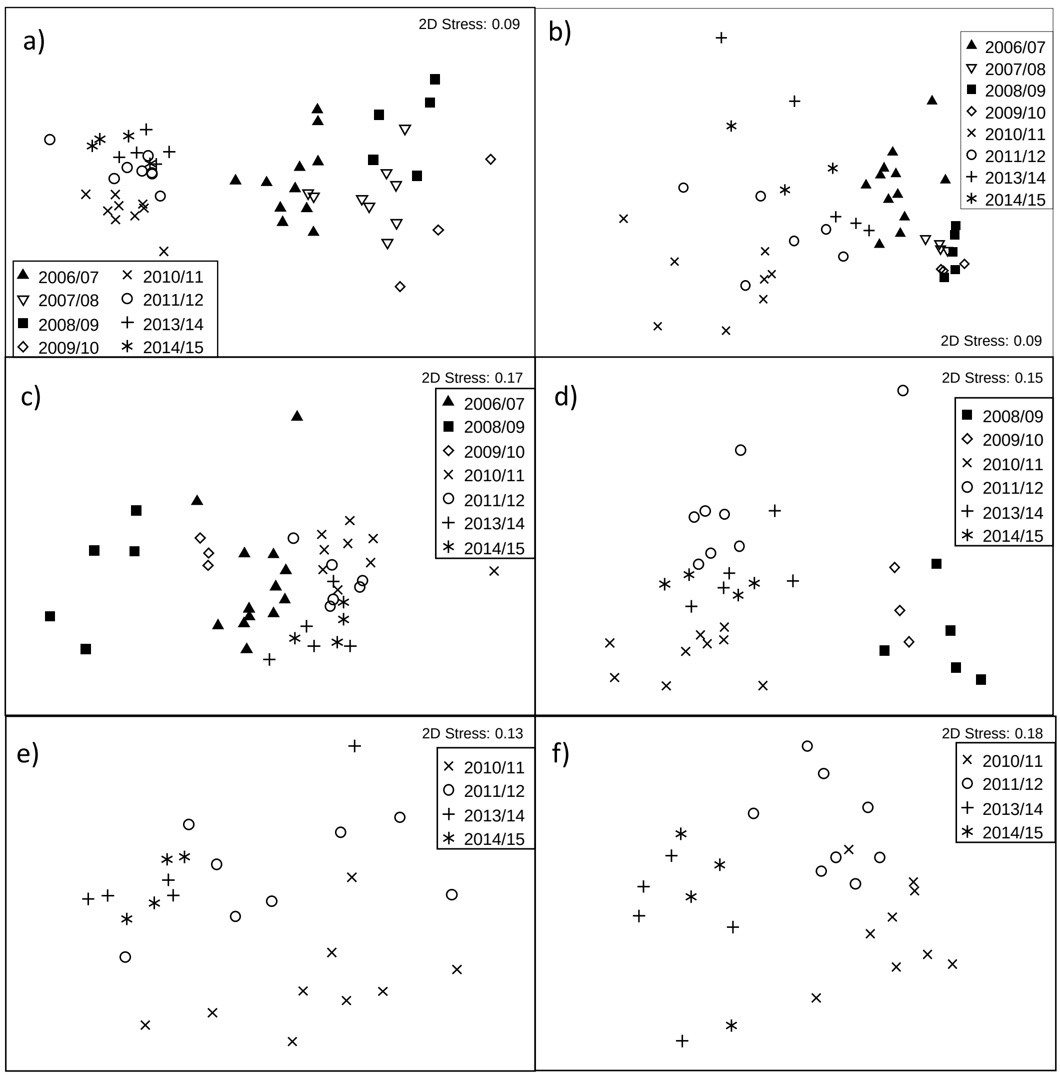

Figure 3-4. MDS ordination plots of fish assemblages sampled at a) Tauwitchere rock ramp, b) Tauwitchere large vertical-slot, c) Goolwa vertical-slot, d) adjacent Goolwa Barrage, e) Tauwitchere small vertical-slot and f) Hunters Creek vertical-slot, between 2006 and 2015.

Tauwitchere sites

Pair-wise comparisons revealed significant differences in fish assemblages at the Tauwitchere rock ramp between most years, except for 2008/09 and 2009/10, as well as 2009/10 and 2013–2015 (B-Y method corrected α = 0.012; Table 3-2). Fish assemblages sampled at the Tauwitchere vertical-slot in 2006/07 differed significantly from assemblages sampled in all subsequent years (B-Y method corrected α = 0.012; Table 3-3). No significant difference was detected between assemblages sampled in 2007/08, 2008/09, 2009/10 and 2014/15. Assemblages sampled in 2010/11 and 2011/12 were not significantly different but both years were significantly different from all previous years, and 2010/11 was also significantly different from all subsequent years. Similarly, the assemblage sampled in 2013/14 was not significantly different from that of 2011/12, but was significantly different from all other years. Assemblages sampled in 2013/14 and 2014/15 were not significantly different. Fish assemblages at the Tauwitchere small vertical-slot differed significantly between 2010/11 and all proceeding years, but assemblages sampled in 2011/12, 2013/14 and 2014/15 were not significantly different (B-Y method corrected α = 0.020; Table 3-3).

Table 3-2. PERMANOVA pair-wise comparisons of fish assemblages sampled from 2006–2015 at the Tauwitchere rock ramp (TRR). PERMANOVA was performed on Bray-Curtis similarity matrices. *denotes statistically significant *p* values; after B-Y method FDR correction α = 0.015. ns = non-significant.

Location	Pairwise comparison		*t*	*p* value
	Year	Year		
TRR	2006/07	2007/08	2.281	<0.001*
TRR	2006/07	2008/09	2.775	<0.002*
TRR	2006/07	2009/10	3.064	0.002*
TRR	2006/07	2010/11	5.202	<0.001*
TRR	2006/07	2011/12	4.980	<0.001*
TRR	2006/07	2013/14	3.892	0.002*
TRR	2006/07	2014/15	3.920	<0.001*
TRR	2007/08	2008/09	1.772	0.007*
TRR	2007/08	2009/10	2.144	0.005*
TRR	2007/08	2010/11	6.044	<0.001*
TRR	2007/08	2011/12	5.808	<0.001*
TRR	2007/08	2013/14	4.994	<0.001*
TRR	2007/08	2014/15	4.823	0.003*
TRR	2008/09	2009/10	2.086	0.014 ns
TRR	2008/09	2010/11	5.496	0.002*
TRR	2008/09	2011/12	5.461	0.002*
TRR	2008/09	2013/14	4.733	0.011*
TRR	2008/09	2014/15	4.484	0.010*
TRR	2009/10	2010/11	5.303	0.007*
TRR	2009/10	2011/12	5.277	0.005*
TRR	2009/10	2013/14	5.046	0.023 ns
TRR	2009/10	2014/15	4.595	0.030 ns
TRR	2010/11	2011/12	2.445	<0.001*
TRR	2010/11	2013/14	2.765	<0.001*
TRR	2010/11	2014/15	2.587	0.002*
TRR	2011/12	2013/14	1.763	0.002*
TRR	2011/12	2014/15	1.828	0.012*
TRR	2013/14	2014/15	1.457	0.047 ns

Table 3-3. PERMANOVA pair-wise comparisons between fish assemblages sampled from 2006–2015 at the Tauwitchere vertical-slot (TVS), and from 2010–2015 at the Tauwitchere small vertical-slot (TSVS). PERMANOVA was performed on Bray-Curtis similarity matrices. *denotes statistically significant *p* values; after B-Y method FDR correction α = 0.015 at TVS and α = 0.027 at TSVS. ns = non-significant.

Location	**Pairwise comparison**		***t***	***p* value**
	Year	**Year**		
TVS	2006/07	2007/08	2.784	0.002*
TVS	2006/07	2008/09	3.447	<0.001*
TVS	2006/07	2009/10	3.637	<0.001*
TVS	2006/07	2010/11	4.527	<0.001*
TVS	2006/07	2011/12	3.205	<0.001*
TVS	2006/07	2013/14	1.879	0.009*
TVS	2006/07	2014/15	2.212	0.007*
TVS	2007/08	2008/09	1.597	0.021 ns
TVS	2007/08	2009/10	2.622	0.028 ns
TVS	2007/08	2010/11	5.450	0.002*
TVS	2007/08	2011/12	4.676	0.004*
TVS	2007/08	2013/14	3.551	0.011*
TVS	2007/08	2014/15	4.406	0.026 ns
TVS	2008/09	2009/10	2.439	0.020 ns
TVS	2008/09	2010/11	4.963	<0.001*
TVS	2008/09	2011/12	4.290	0.004*
TVS	2008/09	2013/14	3.506	0.008*
TVS	2008/09	2014/15	3.609	0.013 ns
TVS	2009/10	2010/11	4.914	0.005*
TVS	2009/10	2011/12	4.232	0.014 ns
TVS	2009/10	2013/14	3.589	0.022 ns
TVS	2009/10	2014/15	3.723	0.109 ns
TVS	2010/11	2011/12	1.665	0.013 ns
TVS	2010/11	2013/14	2.319	0.003*
TVS	2010/11	2014/15	2.250	0.008*
TVS	2011/12	2013/14	1.399	0.075 ns
TVS	2011/12	2014/15	1.730	0.009*
TVS	2013/14	2014/15	0.739	0.762*
TSVS	2010/11	2011/12	1.793	0.010*
TSVS	2010/11	2013/14	2.310	0.009*
TSVS	2010/11	2014/15	2.496	0.004*
TSVS	2011/12	2013/14	1.476	0.080 ns
TSVS	2011/12	2014/15	1.765	0.023 ns
TSVS	2013/14	2014/15	0.765	0.731 ns

SIMPER indicated that differences in fish assemblages at the Tauwitchere rock ramp between 2006/07 and 2007/08, 2008/09 and 2009/10 were due to decreased abundance of the freshwater Australian smelt, estuarine small-mouthed hardyhead (*Atherinosoma microstoma*), lagoon goby, blue-spot goby (*Pseudogobius olorum*) and Tamar River goby (*Afurcagobius tamarensis*) and marine migrant sandy sprat, and increased abundance of the marine migrant yellow-eyed mullet (*Aldrichetta forsterii*), Australian salmon (*Arripis trutta*) and Australian herring (*Arripis georgianus*). Fish assemblages in 2010/11 were different from all other years due to greater abundances of freshwater species; namely Australian smelt, flat-headed gudgeon

(*Philypnodon grandiceps*), bony herring, redfin perch (*Perca fluviatilis*) and common carp (*Cyprinus carpio*). Whilst freshwater species were most abundant in 2010/11, they were also relatively abundant in 2011/12, 2013/14 and 2014/15 with high abundance of Australian smelt and bony herring, together with the estuarine lagoon goby and marine migrant sandy sprat, contributing to differences in assemblages in these years from preceding years (i.e. 2006–2010). Differences in assemblages between 2010/11, 2011/12, 2013/14 and 2014/15 were primarily due to greater abundances of freshwater Australian smelt, flat-headed gudgeon, redfin perch and common carp in 2010/11, greater abundances of the estuarine lagoon goby and marine migrant sandy sprat in 2011/12, and greater abundance of the catadromous congolli in 2014/15.

At the Tauwitchere vertical-slot, variation in assemblage structure between 2006/07 and the subsequent three years (2007/08, 2008/09 and 2009/10) was due to reduced abundance of the catadromous congolli and common galaxias, and freshwater flat-headed gudgeon. The years 2010/11 and 2011/12 were not significantly different, but differences between these years and preceding years was driven by increased abundance of the freshwater Australian smelt, bony herring and estuarine lagoon goby. The assemblage sampled in 2013/14 did not differ significantly from that of 2011/12 or 2014/15, but differed from the years 2006–2010 due to greater abundance of the catadromous congolli and common galaxias, freshwater Australian smelt and flat-headed gudgeon, estuarine lagoon goby, and marine migrant sandy sprat in 2013/14. Assemblage variation between 2014/15 and previous years was primarily driven by greater abundance of catadromous congolli in 2014/15.

The difference in fish assemblage structure between 2010/11 and the years 2011/12, 2013/14 and 2014/15 at the Tauwitchere small vertical-slot was primarily due to greater abundance of redfin perch in 2010/11 and greater abundances of the catadromous common galaxias and congolli, and freshwater Australian smelt in 2011/12, 2013/14, and 2014/15.

Whilst SIMPER reveals species that contribute substantially to differences in fish assemblages between years detected by PERMANOVA, the technique typically highlights the influence of highly abundant species. Whilst non-abundant species may not contribute greatly to the differences detected between assemblages, their presence or absence from given years may provide supportive information and indicate environmental change. Therefore ISA (Dufrene and Legendre 1997) was carried out to determine species that 'characterised' assemblages in different years at each site.

At the Tauwitchere rock ramp, the fish assemblage in 2006/07 was characterised by the presence of the anadromous short-headed lamprey (*Mordacia mordax*) and estuarine blue-spot goby (Table 3-4). In contrast, the assemblage in 2007/08 was characterised by the marine migrant flat-tailed mullet (*Liza argentea*) and marine straggler blue sprat (*Spratelloides robustus*), whilst in 2008/09 the assemblage was characterised by the estuarine black bream (*Acanthopagrus butcheri*). In 2009/10, the assemblage was characterised by three marine migrant species (i.e. mulloway (*Argyrosomus japonicus*), Australian salmon and Australian herring) and five marine stragglers (i.e. prickly toadfish (*Contusus brevicaudus*), yellowfin whiting (*Sillago schomburgkii*), big belly seahorse (*Hippocampus abdominalis*), silver spot (*Threpterius maculosus*) and Australian anchovy (*Engraulis australis*)). The assemblage sampled in 2010/11 was characterised by five freshwater species including carp gudgeon complex (*Hypseleotris* spp.), Australian smelt, flat-headed gudgeon, redfin perch and common carp and one marine migrant species (i.e. southern longfin goby (*Favonigobius lateralis*)). The assemblage in 2011/12 was characterised by the freshwater migrant golden perch (*Macquaria ambigua ambigua*), estuarine river garfish (*Hyperhamphus regularis*) and lagoon goby, and marine migrant sandy sprat, whilst the assemblage in 2013/14 was characterised by the estuarine Tamar River goby. The assemblage in 2014/15 was characterised by the catadromous congolli and common galaxias, and estuarine bridled goby (*Arenogobius bifrenatus*).

At the Tauwitchere large vertical-slot, assemblages in 2006/07 were also characterised by the anadromous short-headed lamprey (Table 3-4). The assemblage of 2007/08 was characterised by the estuarine blue-spot goby, whilst there were no significant indicators of the assemblage in 2008/09 and 2009/10. The assemblage in 2010/11 was characterised by freshwater species, namely bony herring, Australian smelt, redfin perch and common carp. The assemblage in 2011/12 was characterised by two further freshwater species, namely golden perch and goldfish (*Carrasiuss auratus*), whilst 2013/14 was characterised by the freshwater dwarf flat-headed gudgeon (*Philypnodon macrostomus*). The assemblage in 2014/15 was characterised by the catadromous congolli and common galaxias.

At the Tauwitchere small vertical-slot in 2010/11, assemblages were characterised by the freshwater flat-headed gudgeon and redfin perch and estuarine blue-spot goby. There were no significant indicators of the assemblage in 2011/12, but in 2013/14 the assemblage was characterised by freshwater common carp and in 2014/15, by the catadromous common galaxias.

Table 3-4. Indicator species analysis of fish assemblages in the Coorong at the Tauwitchere rock ramp, and large vertical-slot from 2006–2015, and at the small vertical-slot from 2010–2014. Only significant indicators (i.e. $p < 0.05$) are presented. Species are categorised using estuarine use guilds from Elliott *et al.* (2007).

Species	Guild	Year	Indicator Value	*p* value
Tauwitchere rockramp				
Short-headed lamprey	Anadromous	2006/07	45.5	0.009
Blue-spot goby	Estuarine	2006/07	21.1	0.035
Blue sprat	Marine straggler	2007/08	44.4	0.010
Flat-tailed mullet	Marine migrant	2007/08	31.1	0.033
Black bream	Estuarine	2008/09	32.9	0.043
Mulloway	Marine migrant	2009/10	47.0	0.003
Australian salmon	Marine migrant	2009/10	32.1	0.024
Australian herring	Marine migrant	2009/10	60.7	<0.001
Prickly toadfish	Marine straggler	2009/10	90.3	0.002
Yellowfin whiting	Marine straggler	2009/10	46.1	0.006
Big belly seahorse	Marine straggler	2009/10	33.3	0.049
Silver spot	Marine straggler	2009/10	33.3	0.049
Australian anchovy	Marine straggler	2009/10	36.8	0.019
Carp gudgeon complex	Freshwater straggler	2010/11	76.2	<0.001
Australian smelt	Freshwater migrant	2010/11	31.0	0.001
Flat-headed gudgeon	Freshwater migrant	2010/11	42.2	<0.001
Redfin perch	Freshwater straggler	2010/11	32.0	0.029
Common carp	Freshwater migrant	2010/11	61.6	<0.001
Southern longfin goby	Marine migrant	2010/11	82.9	<0.001
Golden perch	Freshwater migrant	2011/12	36.5	0.023
Lagoon goby	Estuarine	2011/12	27.5	0.014
River garfish	Estuarine	2011/12	62.6	0.018
Sandy sprat	Marine migrant	2011/12	28.9	0.028
Tamar River goby	Estuarine	2013/14	23.2	<0.001
Common galaxias	Semi-catadromous	2014/15	34.4	<0.001
Congolli	Semi-catadromous	2014/15	30.2	0.005
Bridled goby	Estuarine	2014/15	24.5	0.002
Tauwitchere large vertical-slot				
Short-headed lamprey	Anadromous	2006/07	33.3	0.050
Blue-spot goby	Estuarine	2007/08	36.4	0.002
Bony herring	Freshwater migrant	2010/11	32.7	0.027
Australian smelt	Freshwater migrant	2010/11	35.5	0.001
Redfin perch	Freshwater straggler	2010/11	39.1	0.013
Common carp	Freshwater migrant	2010/11	31.0	0.029
Golden perch	Freshwater migrant	2011/12	40.5	0.016
Goldfish	Freshwater straggler	2011/12	35.9	0.048
Dwarf flat-headed gudgeon	Freshwater straggler	2013/14	40.0	0.030
Common galaxias	Semi-catadromous	2014/15	29.0	<0.001
Congolli	Semi-catadromous	2014/15	29.2	<0.001
Tauwitchere small vertical-slot				
Redfin perch	Freshwater straggler	2010/11	59.1	0.009
Flat-headed gudgeon	Freshwater migrant	2010/11	45.6	0.002
Blue-spot goby	Estuarine	2010/11	44.4	0.031
Common carp	Freshwater migrant	2013/14	44.4	0.044
Common galaxias	Semi-catadromous	2014/15	37.7	0.035

Goolwa sites

Pair-wise comparisons revealed that fish assemblages sampled at the Goolwa vertical-slot in 2014/15 were not significantly different from those in 2006/07, 2009/10, 2011/12 or 2013/14, but differed significantly from all other years (B-Y method corrected α = 0.014; Table 3-5). Assemblages sampled in 2008/09 and 2009/10 were not significantly different. Fish assemblages sampled in 2010/11 and 2011/12 were also not significantly different from one another but both years were typically significantly different from all other years. Fish assemblages adjacent Goolwa Barrage did not differ significantly between 2008/09 and 2009/10 (B-Y method corrected α = 0.015; Table 3-5), whilst the years 2009/10 and 2013–15 were also not significantly different, but all other comparisons were statistically significant.

Patterns of temporal variation in fish assemblages at the Goolwa vertical-slot were similar to the Tauwitchere large vertical-slot. The difference in the assemblages between 2006/07 and 2008/09 was driven by decreases in the abundance of catadromous congolli and common galaxias, freshwater Australian smelt and marine migrant sandy sprat. Differences in assemblages between 2010/11 and 2011/12, and preceding years was due to increases in the abundance of freshwater species, namely Australian smelt, bony herring and redfin perch, a decrease in the abundance of the marine migrant flat-tailed mullet and slightly diminished abundance of catadromous congolli and common galaxias relative to 2006/07. Differences in assemblages between both 2013/14 and 2014/15 and preceding years, was primarily due to elevated abundance of the catadromous congolli and common galaxias in both 2013/14 and 2014/15.

Table 3-5. PERMANOVA pair-wise comparisons between fish assemblages sampled from 2006–2015 at the Goolwa vertical-slot (GVS) and from 2008–2015 adjacent Goolwa Barrage (GDS). PERMANOVA was performed on Bray-Curtis similarity matrices. . *denotes statistically significant *p* values; after B-Y method FDR correction α = 0.015 at the vertical-slot and α = 0.017 adjacent Goolwa Barrage. Ns = non-significant.

Location	**Pairwise comparison**		***t***	***p* value**
	Year	**Year**		
GVS	2006/07	2008/09	2.805	<0.001*
GVS	2006/07	2009/10	1.72	0.017 ns
GVS	2006/07	2010/11	2.977	<0.001*
GVS	2006/07	2011/12	2.020	<0.001*
GVS	2006/07	2013/14	1.644	0.009*
GVS	2006/07	2014/15	1.681	0.018 ns
GVS	2008/09	2009/10	1.865	0.030 ns
GVS	2008/09	2010/11	3.974	<0.001*
GVS	2008/09	2011/12	3.745	0.002*
GVS	2008/09	2013/14	3.142	0.005*
GVS	2008/09	2014/15	3.450	0.004*
GVS	2009/10	2010/11	2.640	0.006*
GVS	2009/10	2011/12	3.044	0.013*
GVS	2009/10	2013/14	2.580	0.018 ns
GVS	2009/10	2014/15	3.197	0.027 ns
GVS	2010/11	2011/12	1.456	0.059 ns
GVS	2010/11	2013/14	2.089	0.001*
GVS	2010/11	2014/15	2.065	<0.001*
GVS	2011/12	2013/14	1.615	0.008*
GVS	2011/12	2014/15	1.643	0.029 ns
GVS	2013/14	2014/15	1.017	0.465 ns
GDS	2008/09	2009/10	1.295	0.126 ns
GDS	2008/09	2010/11	4.222	<0.001*
GDS	2008/09	2011/12	3.370	<0.001*
GDS	2008/09	2013/14	3.358	0.007*
GDS	2008/09	2014/15	4.018	0.010*
GDS	2009/10	2010/11	3.334	0.005*
GDS	2009/10	2011/12	2.519	0.006*
GDS	2009/10	2013/14	2.614	0.019 ns
GDS	2009/10	2014/15	3.475	0.029 ns
GDS	2010/11	2011/12	2.731	<0.001*
GDS	2010/11	2013/14	2.390	<0.001*
GDS	2010/11	2014/15	2.367	0.004*
GDS	2011/12	2013/14	1.859	0.005*
GDS	2011/12	2014/15	2.093	0.006*
GDS	2013/14	2014/15	1.066	0.344 ns

At the site adjacent Goolwa Barrage, differences in assemblages between 2008/09 and 2009/10, and both 2010/11 and 2011/12 were driven by increased abundances of four freshwater species (flat-headed gudgeon, bony herring, Australian smelt and redfin perch), estuarine lagoon goby and the marine migrant sandy sprat, as well as a reduction in the marine migrant yellow-eyed mullet in 2010/11 and 2011/12. Differences between 2008/09 and the years 2013–15 were also driven by increases in the abundance of catadromous congolli and common galaxias in 2013–15. Assemblages sampled in 2010/11, 2011/12 and 2013–15 differed primarily due to greater abundances of freshwater species (flat-headed gudgeon and redfin perch) and estuarine small-mouthed hardyhead and bridled goby in 2010/11, greater abundance of sandy sprat and Australian salmon in 2011/12, and greater abundance of the catadromous congolli in 2013/14 and 2014/15.

ISA of assemblage data from the Goolwa vertical-slot indicated that assemblages in 2006/07 were characterised by the anadromous short-headed lamprey (Table 3-6). The assemblage in 2008/09 was characterised by the estuarine black bream and marine migrant flat-tailed mullet, whilst the assemblage in 2009/10 was characterised by estuarine small-mouthed hardyhead and bridled goby, marine migrant soldier fish (*Gymnapistes marmoratus*) and marine straggler zebra fish (*Girella zebra*). The assemblage in 2010/11 was characterised by the estuarine lagoon goby and freshwater redfin perch, and the 2011/12 assemblage by the freshwater goldfish. There were no significant indicators of the assemblage in 2013/14, but the assemblage in 2014/15 was characterised by the catadromous congolli and common galaxias.

The assemblage sampled adjacent Goolwa Barrage in 2008/09 was characterised by the estuarine black bream and marine migrant yellow-eyed mullet, whilst the assemblage in 2009/10 was characterised by the marine migrant smooth toadfish (*Tetractenos glaber*) (Table 3-6). The assemblage sampled in 2010/11 was characterised by five freshwater species, namely bony herring, carp gudgeon, Australian smelt, flat-headed gudgeon, and redfin perch and the estuarine bridled goby. The assemblage sampled in 2011/12 was characterised by the freshwater golden perch and marine migrant Australian salmon. The assemblage sampled in 2013/14 was characterised by the catadromous common galaxias, and in 2014/15 by freshwater dwarf flat-headed gudgeon and catadromous congolli.

Table 3-6. Indicator species analysis of fish assemblages in the Coorong at the Goolwa vertical slot from 2006–2015 and adjacent Goolwa Barrage from 2008–2015. Only significant indicators (i.e. $p < 0.05$) are presented. Species are categorised using estuarine use guilds from Elliott *et al.* (2007).

Species	Guild	Year	Indicator Value	*p* value
Goolwa vertical-slot				
Short-headed lamprey	Anadromous	2006/07	46.2	0.008
Black bream	Estuarine	2008/09	44.4	0.010
Flat-tailed mullet	Marine migrant	2008/09	35.7	0.026
Bridled goby	Estuarine	2009/10	35.9	0.023
Small-mouthed hardyhead	Estuarine	2009/10	43.7	<0.001
Soldier fish	Marine migrant	2009/10	35.3	0.046
Zebra fish	Marine straggler	2009/10	58.3	0.004
Redfin perch	Freshwater straggler	2010/11	27.9	0.013
Lagoon goby	Estuarine	2010/11	33.6	0.041
Goldfish	Freshwater straggler	2011/12	46.2	0.006
Common galaxias	Semi-catadromous	2013/14	24.6	0.035
Congolli	Semi-catadromous	2013/14	31.6	0.016
Adjacent Goolwa Barrage				
Black bream	Estuarine	2008/09	36.2	0.034
Yellow-eyed mullet	Marine migrant	2008/09	40.9	0.016
Smooth toadfish	Marine migrant	2009/10	56.6	0.018
Bony herring	Freshwater migrant	2010/11	30.6	0.027
Flat-headed gudgeon	Freshwater migrant	2010/11	42.9	<0.001
Carp gudgeon	Freshwater straggler	2010/11	61.3	0.003
Redfin perch	Freshwater straggler	2010/11	43.3	0.002
Australian smelt	Freshwater migrant	2010/11	34.4	0.004
Bridled goby	Estuarine	2010/11	39.9	0.003
Golden perch	Freshwater migrant	2011/12	54.2	<0.001
Australian salmon	Marine migrant	2011/12	51.3	0.002
Common galaxias	Semi-catadromous	2013/14	37.9	0.009
Dwarf flat-headed gudgeon	Freshwater straggler	2014/15	72.1	<0.001
Congolli	Semi-catadromous	2014/15	38.4	0.002

Hunters Creek

Pair-wise comparisons revealed that fish assemblages sampled at the Hunters Creek vertical-slot differed significantly between all years, with the exception of 2013/14 and 2014/15 (B-Y method corrected $\alpha = 0.020$) (Table 3-7). SIMPER indicated the assemblage in 2010/11 differed from proceeding years due to greater relative abundances of the freshwater redfin perch, flat-headed gudgeon, bony herring and common carp in 2010/11. Variation in assemblages between 2011/12 and the years 2013–15 was primarily driven by greater relative abundances of the freshwater redfin perch and common carp in 2011/12 and greater abundances of the catadromous congolli in 2013–15, which also drove differences with 2010/11. Furthermore, ISA determined that the assemblage sampled in 2010/11 was characterised by the freshwater carp gudgeon, flat-headed gudgeon, redfin perch and common carp, whilst the assemblage in

2011/12 was characterised by the freshwater golden perch (Table 3-8). There were no significant indicators of the assemblage in either 2013/14 or 2014/15.

Table 3-7. PERMANOVA pairwise comparisons between fish assemblages sampled from 2010–2015 at the Hunters Creek vertical-slot fishway. PERMANOVA was performed on Bray-Curtis similarity matrices. After B-Y method FDR correction α = 0.020.

Location	Pairwise comparison		*t*	*p* value
	Year	Year		
Hunters	2010/11	2011/12	2.209	0.002
Hunters	2010/11	2013/14	3.049	<0.001*
Hunters	2010/11	2014/15	2.713	<0.001*
Hunters	2011/12	2013/14	2.637	<0.001*
Hunters	2011/12	2014/15	2.580	<0.001*
Hunters	2013/14	2014/15	1.238	0.207 ns

Table 3-8. Indicator species analysis of fish assemblages at the Hunters Creek vertical slot from 2010–2015. Only significant indicators (i.e. $p < 0.05$) are presented. Species are categorised using estuarine use guilds from Elliott *et al.* (2007).

Species	Guild	Year	Indicator Value	*p* value
Carp gudgeon	Freshwater straggler	2010/11	48.7	0.023
Redfin perch	Freshwater straggler	2010/11	58.9	0.003
Flat-headed gudgeon	Freshwater migrant	2010/11	45.1	<0.001
Common carp	Freshwater migrant	2010/11	49.6	0.001
Golden perch	Freshwater migrant	2011/12	64.0	0.003

3.4. Spatial variation in fish assemblages in 2014/15

MDS ordination of fish assemblage data from the vertical-slot fishways exhibited interspersion of samples from several sites and a grouping of samples from Hunters Creek (Figure 3-5a), supported by PERMANOVA, which detected significant differences in fish assemblages between capture locations ($Pseudo\text{-}F_{3,\ 14} = 4.298$, $p < 0.001$). Pair-wise comparisons, when adopting a correction of significance to account for multiple comparisons (i.e. B-Y corrected α = 0.02), suggest there was no significant differences between any fishway (Table 3-9). Nonetheless, if in this case we adopt a significance level of α = 0.05, pairwise comparisons suggest that assemblages at Hunters Creek are significantly differently from all other fishways, whilst all other comparisons remain non-significant. MDS ordination of fish assemblage data from the Tauwitchere rock ramp and adjacent Goolwa Barrage (GDS) exhibited grouping by site

(Figure 3-5b) and PERMANOVA suggested assemblages sampled from these locations were also significantly different (*Pseudo-*$F_{1,7}$ = 2.937, p = 0.036).

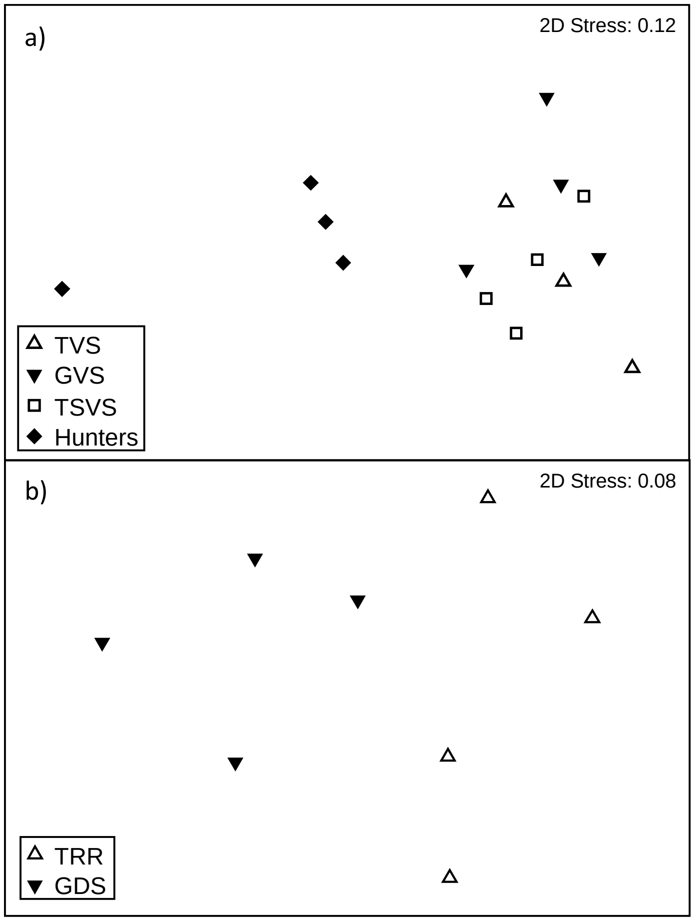

Figure 3-5. MDS ordination plot of fish assemblages sampled at the a) Tauwitchere large vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS), Goolwa vertical-slot (GVS), and Hunters Creek vertical-slot (Hunters), and b) Tauwitchere rock ramp and adjacent Goolwa Barrage (GDS) in 2014/15.

Table 3-9. PERMANOVA pair-wise comparisons of fish assemblages from the Tauwitchere large vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS), Goolwa vertical-slot (GVS) and Hunters Creek vertical-slot (Hunters) in 2014/15. PERMANOVA was performed on bray-curtis similarity matrices. B-Y method corrected α = 0.02.

Pairwise comparison		*t*	*p* value
Location	**Location**		
TVS	GVS	1.060	0.444 ns
TVS	TSVS	1.581	0.070 ns
TVS	Hunters	2.274	0.023 ns*
GVS	Hunters	2.327	0.026 ns*
GVS	TSVS	1.749	0.056 ns
Hunters	TSVS	2.704	0.031 ns*

Indicator species analysis was used to determine species that characterised assemblages at the different vertical-slot fishways in 2014/15. Of 30 species sampled, four were significant indicators of the fish assemblage at a particular location (Table 3-10). The freshwater flat-headed gudgeon, and estuarine lagoon goby and black bream, characterised the assemblage at the Tauwitchere large vertical-slot, whilst the estuarine small-mouthed hardyhead characterised the assemblage at the Hunters Creek vertical-slot. Of the two sites sampled with large fyke nets in 2014/15, the assemblage at the Tauwitchere rock ramp was characterised by the freshwater flat-headed gudgeon, and estuarine black bream and lagoon goby, whilst the assemblage at Goolwa was characterised by the freshwater dwarf flat-headed gudgeon.

Table 3-10. Indicator species analysis of fish assemblages in the Coorong at the Tauwitchere vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS), Goolwa vertical-slot (GVS) and Hunters Creek vertical-slot, and at the Tauwitchere rock ramp (TRR) and adjacent Goolwa Barrage (GDS) in 2014/15.

Species		**Location**	**Indicator Value**	***p* value**
Vertical-slot fishways				
Flat-headed gudgeon	Freshwater migrant	TVS	38.3	0.022
Black bream	Estuarine	TVS	66.7	0.027
Lagoon goby	Estuarine	TVS	54.5	0.002
Small-mouthed hardyhead	Estuarine	Hunters	64.3	0.009
Fyke net sites				
Australian smelt	Freshwater migrant	TRR	62.6	0.028
Lagoon goby	Estuarine	TRR	66.7	0.028
Dwarf flat-headed gudgeon	Freshwater straggler	GDS	87.0	0.028

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

Inter-annual variation in abundance

Lamprey

No short-headed lamprey or pouched lamprey were captured during sampling in spring/summer 2014/15. Pouched lamprey was sampled in low numbers in September 2006, from the Tauwitchere rock ramp, but was sampled in greater abundance, across four locations in July and September 2011, before again being sampled in low numbers from the Goolwa vertical-slot during specific winter monitoring in July 2013. Short-headed lamprey was sampled in moderate abundance across three locations from September to November 2006 and in low abundance adjacent Goolwa Barrage in November 2011, but were absent from sampling in 2013/14 and 2014/15 (Figure 3-6b).

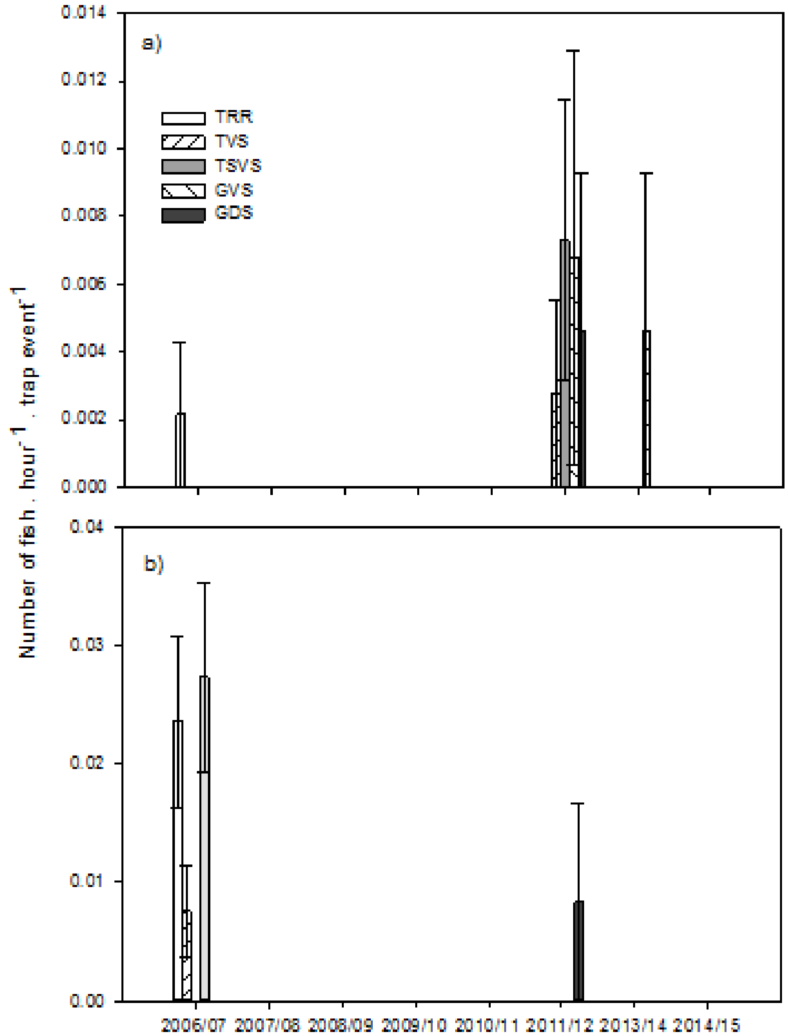

Figure 3-6. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of a) pouched lamprey and b) short-headed lamprey at the Tauwitchere rock ramp (TRR), Tauwitchere large vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS), Goolwa vertical-slot (GVS) and adjacent Goolwa Barrage (GDS) from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

Congolli and common galaxias

The abundance of the catadromous congolli and common galaxias differed significantly between years at all sampling locations (Table 3-11), with the exception of common galaxias at Hunters Creek (Table 3-11). The abundances of congolli recorded in 2014/15 were the highest recorded since the inception of the current project (2006/07) (Figure 3-7a). Patterns of variability in abundance were generally 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.

Table 3-11. 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 2006–2015 at the Tauwitchere rock ramp (TRR), Tauwitchere vertical-slot (TVS), Goolwa vertical-slot (GVS), adjacent Goolwa Barrage (GDS), Tauwitchere small-vertical-slot and Hunters Creek vertical-slot. PERMANOVA was performed on Euclidean Distance similarity matrices. α = 0.05.

		Congolli		**Common galaxias**	
Site	**df**	***Pseudo-F***	***P* value**	***Pseudo-F***	***P* value**
TRR	7, 94	31.79	<0.001*	31.15	<0.001*
TVS	7, 115	20.88	<0.001*	47.44	<0.001*
GVS	6, 119	25.69	<0.001*	5.68	<0.001*
GDS	5, 42	23.08	<0.001*	18.34	<0.001*
TSVS	3, 65	11.45	<0.001*	18.14	<0.001*
Hunters	3, 65	7.56	<0.001*	0.58	0.652 ns

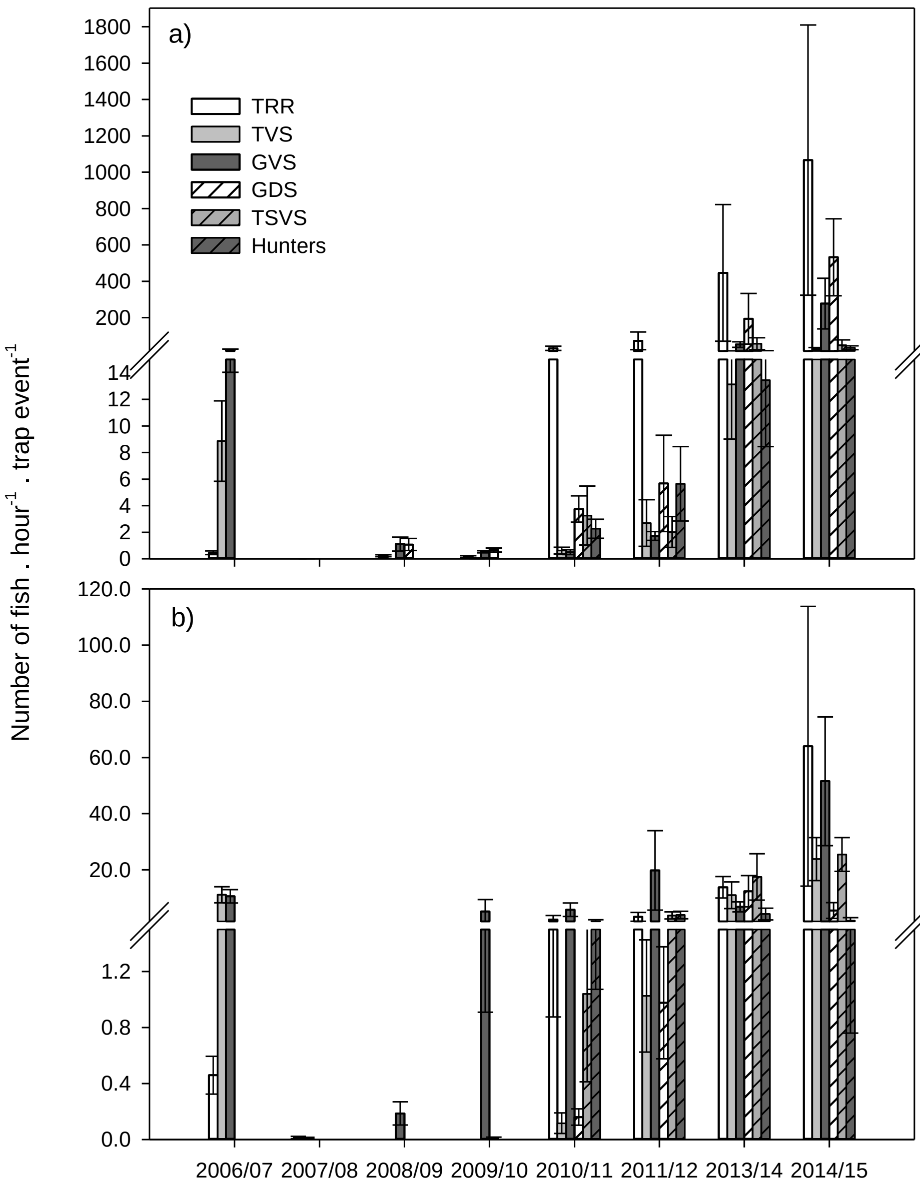

Figure 3-7. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of a) congolli and b) common galaxias at the Tauwitchere rock ramp (TRR), Tauwitchere vertical-slot (TVS), Goolwa vertical-slot (GVS), adjacent Goolwa Barrage (GDS), Tauwitchere small vertical-slot (TSVS) and Hunters Creek vertical-slot (Hunters) from 2006–2014. Goolwa vertical-slot was not sampled in 2007/08 and adjacent Goolwa Barrage was not sampled in 2006/07 and 2007/08. The Tauwitchere small vertical-slot and Hunters Creek vertical-slot were sampled from 2010/11 onwards. All sites were not sampled in 2012/13.

A similar pattern was evident for common galaxias in 2014/15, which was sampled in greatest abundances, relative to all previous years, at the Tauwitchere rock ramp, Tauwitchere large vertical-slot, Tauwitchere small vertical-slot and Goolwa vertical-slot (Figure 3-7b). Abundances adjacent Goolwa barrage and at Hunters Creek were similar to those recorded in 2013/14. As with congolli, common galaxias was typically sampled in low abundances through the period 2007–2010, with the exception of the Goolwa vertical-slot where this species was sampled in relatively high abundance in 2009/10. Following the reconnection of the Lower Lakes and Coorong in 2010/11 there were generally increases in the abundances of this species relative to the preceding years, with further increases occurring annually until peak abundance in 2014/15.

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

The abundance of upstream migrating congolli was significantly different between months at the Goolwa vertical-slot ($Pseudo\text{-}F_{3,\ 11}$ = 8.04, p = 0.006), Tauwitchere small vertical-slot ($Pseudo\text{-}F_{3,\ 11}$ = 7.39, p < 0.001) and Hunters Creek vertical-slot ($Pseudo\text{-}F_{3,\ 11}$ = 39.76, p = 0.002), but not at the Tauwitchere large vertical-slot ($Pseudo\text{-}F_{2,\ 8}$ = 7.35, p = 0.158). Statistical tests of significance could not be carried out on data from the Tauwitchere rock ramp or adjacent Goolwa Barrage, as these sites were only sampled once each week; nevertheless, abundance varied substantially between months. Intra-annual variation in abundance was similar between sites, with congolli sampled in greatest abundance in November at the Goolwa vertical-slot, adjacent Goolwa barrage, Tauwitchere small vertical-slot and Hunters Creek vertical-slot, and in December at the Tauwitchere rock ramp. Abundance was also high at most sites in October, while lowest abundances were recorded at all sites in January.

Peak abundance of congolli in 2014/15 was detected at the Tauwitchere rock ramp in December (~3000 fish.hr^{-1}), whilst at the Goolwa vertical-slot in November an average of 764 ± 486 fish.hr^{-1} were detected migrating upstream through the fishway during the sampling event.

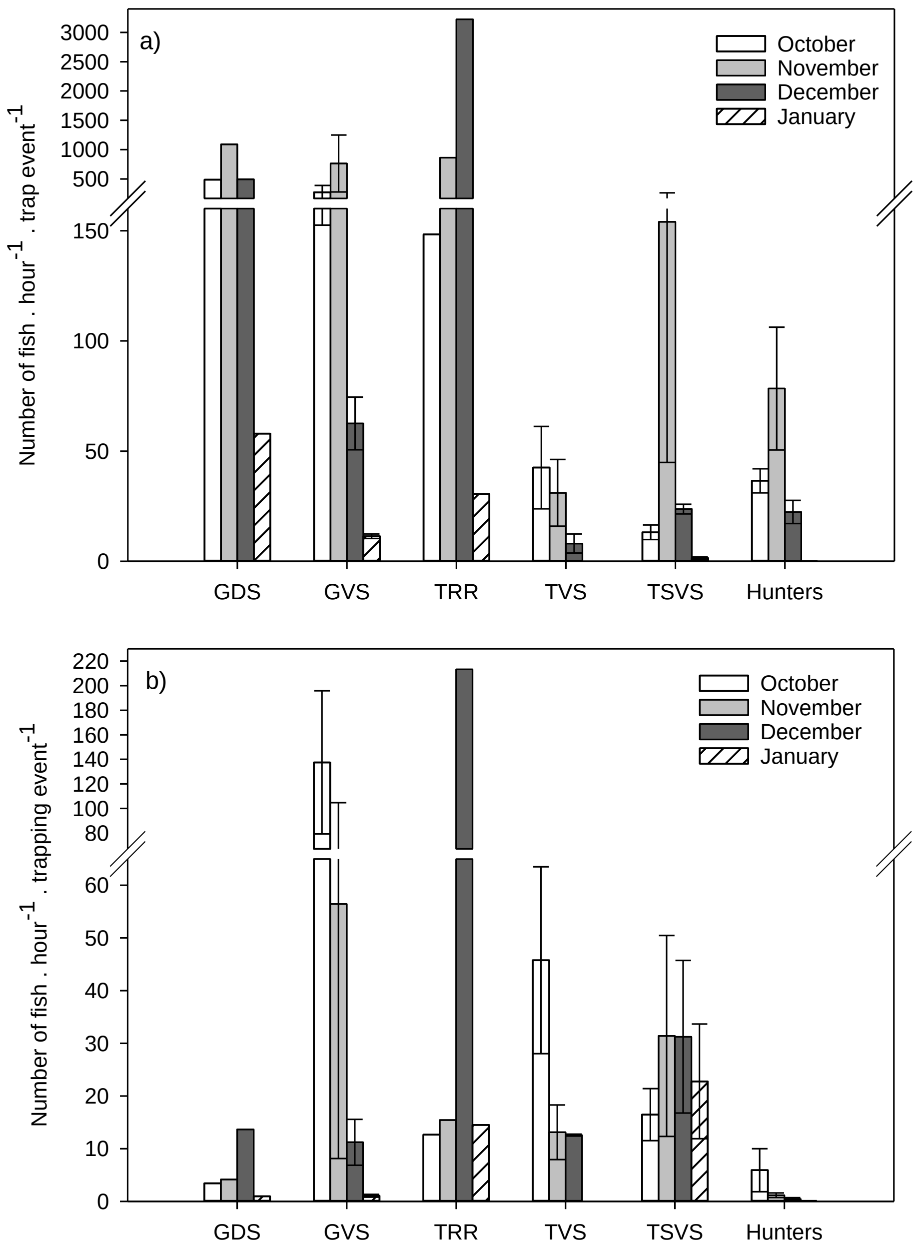

Figure 3-8. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of a) congolli and b) common galaxias at adjacent Goolwa Barrage (GDS), Goolwa vertical-slot (GVS), Tauwitchere rock ramp (TRR), Tauwitchere vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS) and Hunters Creek vertical-slot (Hunters) from October 2014–January 2015.

The abundance of upstream migrating common galaxias was significantly different between months at the Goolwa vertical-slot (*Pseudo-*$F_{3, 11}$ = 5.05, p = 0.024) and Hunters Creek vertical-slot (*Pseudo*-$F_{3, 11}$ = 5.48, *p* = 0.007), but not at the Tauwitchere large vertical-slot (*Pseudo*-$F_{2, 8}$ = 2.58, *p* = 0.207) or Tauwitchere small vertical-slot (*Pseudo*-$F_{3, 11}$ = 0.11, *p* = 0.951). Statistical tests of significance could not be carried out on data from the Tauwitchere rock ramp or adjacent Goolwa Barrage, as these sites were only sampled once each week; nevertheless, abundance varied between months and peaked at both locations in December (Figure 3-8b). In contrast, abundance peaked at the Goolwa vertical-slot, Tauwitchere large vertical-slot and Hunters Creek vertical-slot in October.

Below Tauwitchere Barrage (Tauwitchere rock ramp, large vertical-slot and small vertical-slot data combined) in October 2014, congolli ranged 22–122 mm TL, but the sampled population was dominated (~96%) by fish ranging 22–54 mm TL (Figure 3-9a). Whilst fish were not aged in 2014/15, fish of this size have previously been determined to represent a 0+ cohort (Bice *et al.* 2012). This cohort increased in length throughout the sampling period (November 2014: 28–58 mm TL, December 2014: 33–61 mm TL and January 2015: 38–63 mm TL) and represented ≥95% of the sampled population during each month.

A similar pattern was evident below Goolwa Barrage (vertical-slot and adjacent Goolwa Barrage data combined) with the sampled population of fish ranging 18–168 mm TL and dominated by a YOY cohort (18–52 mm TL; ~93% of population) in October 2014 (Figure 3-9b). Growth of this cohort was evident through the following months, progressing to 25–54, 27–60 and 33–60 mm TL in November 2014, December 2014 and January 2015, respectively. This cohort remained dominant throughout sampling, comprising ≥90% of the population in all months.

Length-frequency distributions at Hunters Creek were dissimilar to both Tauwitchere and Goolwa, with only one individual >100 mm TL sampled for the entire sampling season (Figure 3-9c). As such, the 0+ cohort dominated. Growth of the cohort was evident with individuals ranging 26–51, 30–59, 34–57 and 37–66 mm TL during sequential sampling events and represented 97–100% of the sampled population at all times. This is not unexpected given all fish sampled at this site were sampled within the entrance of the fishway and are undertaking obligate upstream juvenile migrations. In contrast, length-frequencies from Goolwa and Tauwitchere include data from sites sampled adjacent these barrages (i.e. the Tauwitchere rock ramp and site adjacent Goolwa Barrage), where adult male fish (100–150 mm) commonly reside.

Common galaxias ranged 32–103 mm TL at Tauwitchere in October 2014, but a 0+ cohort (32–52 mm TL) comprised ~92% of the sampled population (Figure 3-10a). As for congolli, whilst common galaxias were not aged in 2014/15, fish of this size have been determined to represent a 0+ cohort in previous years (see Bice *et al.* 2012). The size of the 0+ cohort lengthened and broadened through the sampling season and represented >90% of the sampled population in each sampling month.

At Goolwa in October 2014, the 0+ cohort of common galaxias ranged 31–58 mm TL and comprised ~97% of the sampled population (Figure 3-10b). Larger individuals progressively comprised greater proportions of the population in subsequent months indicating growth of the 0+ cohort, whilst small individuals <35 mm remained present suggesting a persistent influx of young fish. The 0+ cohort remained dominant throughout sampling comprising ~95% of the sampled population in November 2014 and December 2014, before declining to ~65% in January 2015.

The length-frequency distributions for common galaxias at Hunters Creek in 2014/15 were similar to Tauwitchere and Goolwa, in that the 0+ cohort (<60 mm TL) typically comprised ≥90% of the sampled population in all months (Figure 3-10c). Length-frequency distributions were, however, more constrained at Hunters Creek than at both Tauwitchere and Goolwa.

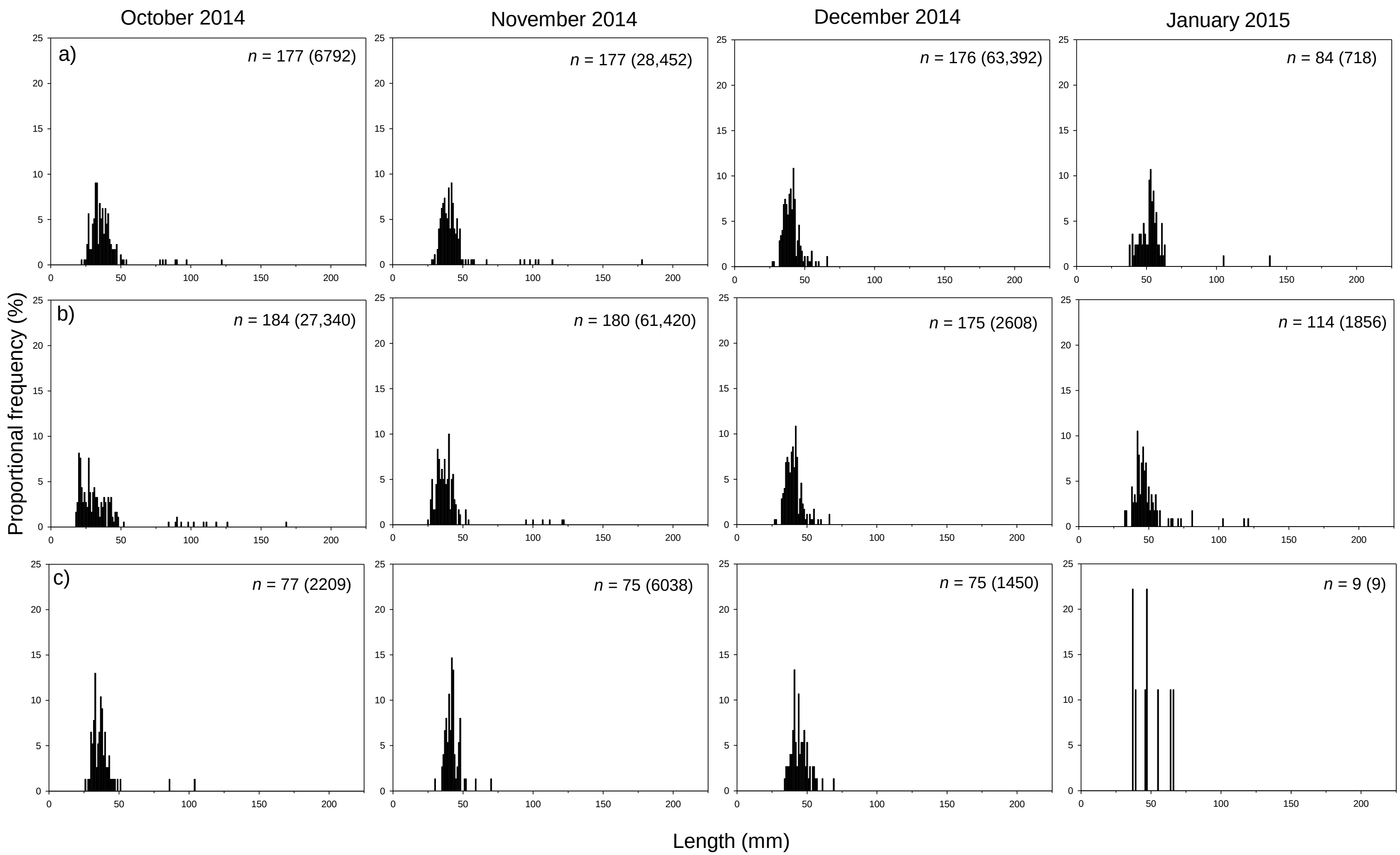

Figure 3-9. Monthly length-frequency distributions (total length, mm) of congolli sampled below a) Tauwitchere Barrage (rock ramp, large vertical-slot and small vertical-slot combined) b) Goolwa Barrage (vertical-slot and adjacent Goolwa Barrage combined) and c) at the entrance of the Hunters Creek vertical-slot from October 2014–January 2015. *n* is the number of fish measured and the total number of fish collected in each month at each site is presented in brackets.

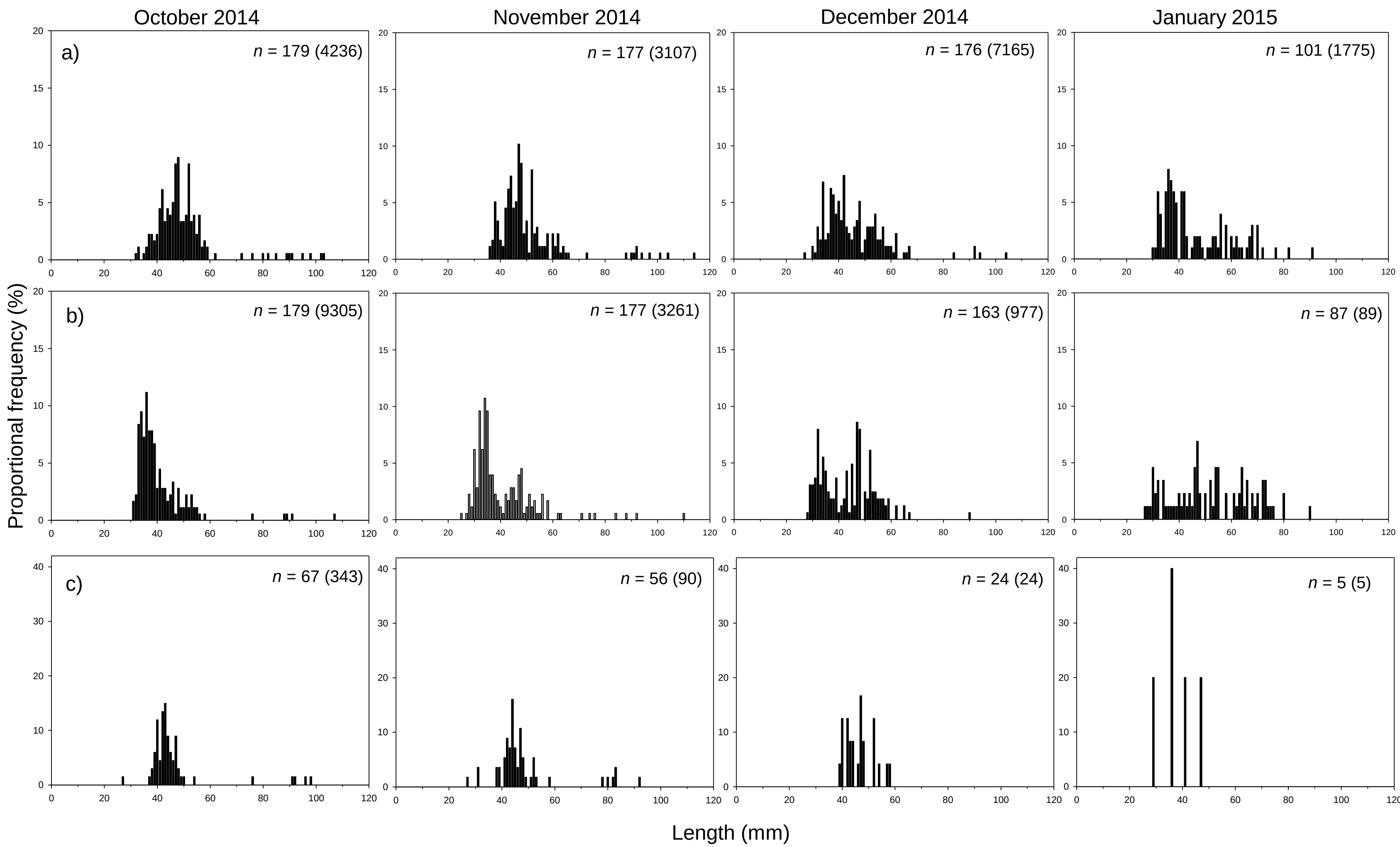

Figure 3-10. Monthly length-frequency distributions (total length, mm) of common galaxias sampled below a) Tauwitchere Barrage (rock ramp, large vertical-slot and small vertical-slot combined) b) Goolwa Barrage (vertical-slot and adjacent Goolwa Barrage combined) and c) at the entrance of the Hunters Creek vertical-slot from October 2014–February 2015. *n* is the number of fish measured and the total number of fish collected in each month at each site is presented in brackets.

4. DISCUSSION

4.1. Fish assemblages

Inter-annual variation

From 2007–2010, drought and over-allocation of water resources resulted in cessation of freshwater discharge to the Coorong, disconnection of the Lower Lakes and Coorong, and elevated salinities in the Coorong, to the detriment of a range of native flora and fauna (Kingsford *et al.* 2011). Nonetheless, 2014/15 represented the fifth consecutive year of continuous freshwater discharge to the Coorong post the end of the Millennium Drought (late 2010), promoting connectivity between the Coorong and Lower Lakes and persistence of an estuarine salinity gradient (predominantly 'brackish') in the Coorong estuary. In 2014/15, however, discharge decreased relative to the four preceding years, with associated increases in salinity, but the structure of fish assemblages remained characteristic of a dynamic estuary under freshwater influence. Patterns of change in the abundance of certain species (e.g. catadromous species) reflected the cumulative effect of multiple and consecutive years of freshwater discharge, highlighting the importance of providing freshwater flow to the Coorong on an annual basis.

In 2014/15, 31 fish species, representing 21 families, were sampled at six sites immediately downstream of the Murray Barrages in the Coorong estuary. The fish assemblage consisted of a diverse range of life history strategies including freshwater, diadromous, estuarine and marine species, with each represented by one or more species that was abundant (i.e. >10,000 individuals). This contrasts the depauperate fish assemblage during the extended period (2007–2010) of no freshwater discharge to the Coorong when species of marine origin and some medium to large-bodied estuarine resident species were dominant, whilst diadromous and freshwater species were absent or in low abundance (Zampatti *et al.* 2011a). It also contrasts the fish assemblage in 2010/11, which was diverse but dominated by a group of common freshwater species (i.e. Australian smelt, redfin perch, bony herring and flat-headed gudgeon) which numerically comprised >65% of the total catch (Zampatti *et al.* 2012). The assemblage in 2014/15 was statistically similar to that in 2013/14 (Bice and Zampatti 2014); nonetheless, the number of species of marine origin increased from 8 to 10, including 3 marine stragglers not typically sampled (i.e. bridled leatherjacket, six-spined leatherjacket and ornate cowfish), potentially indicating greater marine influence with decreased freshwater discharge in 2014/15. Indeed, with the exception of high abundances of catadromous species, the assemblage of 2014/15 appeared increasingly similar to that of 2006/07 (a year of low discharge, 63 GL, and preceded by a year of low discharge in 2005/06, 770 GL), suggesting a potential trajectory towards an assemblage associated with 'drying' conditions.

Similar to all years from 2010 to 2014, the marine migrant sandy sprat was the dominant species sampled, numerically comprising ~59% of the overall catch. Sandy sprat is a small-bodied (typically <100 mm TL), pelagic, schooling clupeid, which is common in coastal bays and estuaries across southern Australia (Gaughan *et al.* 1996, Gomon *et al.* 2008). Whilst considered a marine migrant species, the results of this study suggest an association with freshwater inflows to the Coorong, with the species caught in greatest abundance during years of freshwater flow (i.e. 2006/07 and 2010–15) and lowest during years of low or zero freshwater inflow (2007–2010) (Zampatti *et al.* 2011a, 2012, Bice *et al.* 2012, Bice and Zampatti 2014). Sandy sprat is zooplanktivorous and is likely benefited during times of high freshwater flow due to influxes of freshwater zooplankton into the Coorong and increased estuarine productivity as a result of elevated phytoplankton and nutrient loads (Aldridge and Brookes 2011, Shiel and Aldridge 2011). In turn, recent research has highlighted the importance of sandy sprat in the diets of piscivorous fishes in the Coorong (e.g. juvenile mulloway) (Giatas and Ye 2015), particularly in the Murray estuary (between Pelican Point and Goolwa Barrage) where, contrary to the North and South Lagoons, it supplants small-mouthed hardyhead as the most abundant small-bodied fish (Ye *et al.* 2012). The association between the abundance of sandy sprat within the Coorong and freshwater discharge, particularly in regards to trophic subsidy, is currently the focus of a specific research project (SARDI unpublished data).

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 2006–2015, 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 caused by high freshwater flows (e.g. 2010/11) often result in low species diversity and high abundances of a few freshwater and estuarine dependent species (Lamberth *et al.* 2008). Brackish salinities, such as those present in the Murray estuary in 2006/07, 2011/12, 2013/14 and 2014/15 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 caused by 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 2014/15, fish assemblages sampled at vertical-slot fishways were generally similar, with the exception of the Hunters Creek vertical-slot, which differed from all other fishways. This pattern of intra-annual spatial variability between fishways is consistent with that observed in 2013/14 (Bice and Zampatti 2014). Hunters Creek is a small stream (~5 m wide) and, during times of freshwater discharge, the area downstream of the fishway is generally characterised by freshwater salinities. In contrast, the other sites are situated on the barrages, highly exposed and influenced by water level and salinity fluctuations characteristic of the broader Coorong. Subsequently, in comparison to other sites, the assemblage at the Hunters Creek vertical-slot is typically comprised of fewer species and dominated by freshwater and diadromous species.

Of the vertical-slot fishways, the greatest number of fish were sampled at the Goolwa vertical-slot (*n* = 105,040), followed by the Tauwitchere small vertical-slot (*n* = 38,533) and then the Tauwitchere large vertical-slot (*n* = 34,467). This pattern was also specifically evident for congolli. The Goolwa vertical-slot and Tauwitchere small vertical-slot are both more effective than the Tauwitchere large vertical-slot at passing small-bodied fishes (Zampatti *et al.* 2012), particularly juveniles of catadromous species. This suggests that during times of water scarcity, the operation of these fishways could be prioritised over the Tauwitchere large vertical-slot.

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) appear to vary substantially. This variation reflects potential behavioural differences in fish and the specificity of sampling locations at these sites. Sampling in the entrance of vertical-slot fishways typically collects fish in the process of undertaking ‘driven’ 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 estuarine and marine species residing adjacent the barrages. As such, species richness and overall abundance are typically greatest at the sites adjacent the barrages (Zampatti *et al.* 2011a, 2012, Bice *et al.* 2012). Indeed, species richness and overall fish abundance varied from 10 species at the Tauwitchere small vertical-slot and 12,236 individuals (~1.5% of all fish sampled in 2014/15) at the entrance of the Hunters Creek vertical-slot to 25 species adjacent Goolwa Barrage and a total of 551,620 individuals (~65% of all fish sampled in 2014/15) at the Tauwitchere rock ramp.

4.2. Abundance and recruitment of diadromous fish

No short-headed lamprey or pouched lamprey were sampled in spring/summer 2014/15. Failure to detect lamprey in spring/summer is not unexpected given peak upstream migration is likely to occur in winter (McDowall 1996). This highlights the need for specific sampling during winter to assess the status of lamprey by targeting the peak upstream migration period and promotes the importance of freshwater flow and connectivity during winter.

Total numbers and relative abundances of congolli in 2014/15, were the greatest recorded since the inception of this monitoring program in 2006/07 (Zampatti *et al.* 2010, 2011a, Bice *et al.* 2012, Bice and Zampatti 2014). Indeed, congolli was the second most abundant species sampled in 2014/15 (i.e. ~25% of the total catch) after sandy sprat, whilst the total number sampled (*n* = 212,284) was double the previous highest total number from 2013/14 (*n* = 104,462). Common galaxias was also sampled in the greatest abundances, relative to all previous sampling years, with total number also doubling (*n* = 30,367) that of 2013/14 (*n* = 15,679). Whilst no ageing of fish was conducted in 2014/15, length-at-age data from previous years (Zampatti *et al.* 2010, 2011a, Bice *et al.* 2012), indicate that typically >90% of all individuals sampled for both species, in each month, were newly recruited YOY.

Successful recruitment of catadromous species in 2014/15 was likely a result of a combination of two mechanisms: 1) high levels of hydrological connectivity between freshwater and marine environments throughout 2014/15 and subsequently, favourable conditions for migration, spawning and survival of larvae/juveniles under brackish salinities (Whitfield 1994, Gillanders and Kingsford 2002); and 2) enhanced spawning output as a result of high abundance of reproductively mature adults. Recruitment and subsequent YOY abundance has steadily increased since 2010/11 following reinstatement of freshwater discharge and high levels of connectivity, despite discharge steadily decreasing from 2011/12 to 2014/15. A trend of increasing abundance of YOY likely reflects cumulative benefits of multiple consecutive years of enhanced connectivity. 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 in winter 2014 was likely abundant and comprised, in large part, of fish that were recruited in 2010/11 and 2011/12. Whilst there are no projects specifically investigating congolli populations in the freshwater Lower Lakes, there are data to suggest that reproductively mature fish were abundant in 2014 (Wedderburn pers comm.; SARDI unpublished data). These results highlight the importance of providing freshwater discharge to the Coorong on an annual basis and the influence of consecutive 'favourable' years on population dynamics of diadromous fishes.

Substantial variability in the abundance of congolli was observed between months in 2014/15 at several sites, with timing of peak abundance differing between sites. Peak abundance at sites at Goolwa and Hunters Creek were observed in October and November 2014, in contrast to November and December 2014 at sites at Tauwitchere. Abundance in January 2015 was consistently reduced relative to previous months at all sites. This contrasts with data from 2013/14, when abundance peaked at all sites in December 2013 and abundance in January 2014 was comparable to that of November 2013, and greater than that of October 2013 (Bice and Zampatti 2014). This suggests that upstream migration may have occurred earlier in 2014/15, relative to 2013/14.

Intra-annual variability in the abundance of common galaxias was greater than that for congolli. Of particular note, abundance at the large vertical-slot fishways at both Goolwa and Tauwitchere peaked in October, but abundance at the Tauwitchere rock-ramp and adjacent Goolwa Barrage peaked in December. The mechanism behind this pattern is unclear, but a similar pattern in variability in peak abundance was observed in 2013/14.

Differences in patterns of intra-annual variability in the abundance of catadromous species between years and thus, potential differences in timing of migration, have implications for the sampling designs required to address targets for the site under *The Living Murray Program.* Indeed, recent refinement of targets related to catadromous species has focused upon data from sampling during October–December and November–January for common galaxias and congolli, respectively. Apparently 'earlier' migration of congolli in 2014/15 suggests the abundance of YOY during October should also be considered in future assessment of targets.

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

Data collected from this project from 2006–2015 (Bice *et al.* 2007, 2012, Jennings *et al.* 2008a, Zampatti *et al.* 2010, 2011a, 2012, Bice and Zampatti 2014) and related projects (Jennings *et al.* 2008b, Zampatti *et al.* 2011b), 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 require movement between freshwater and marine/estuarine environments to complete their lifecycle. These periods should be prioritised for freshwater releases and fishway operation.

Newly recruited YOY congolli and common galaxias migrate upstream during spring/summer, but there are often subtle differences in the timing of peak migration. Peak migration of congolli in 2014/15 occurred at all sites during November and December, with moderate abundance in October. During previous years of freshwater flow and connectivity (i.e. 2006/07 and 2010–2014) peak abundances have been observed in November and December (Bice *et al.* 2007, 2012, Zampatti *et al.* 2012). In contrast, peak abundance of upstream migrating common galaxias differed between sites, occurring from October–December depending on location. In previous years of freshwater flow and connectivity, peak migration was observed in October and November. Whilst both of these species migrate upstream in greatest numbers during specific months, migrations occur over a protracted period from September–March (Bice *et al.* 2007).

Adults of both congolli and common galaxias must also migrate downstream to spawn. The key downstream migration period for adult congolli occurs from June–August (Zampatti *et al.* 2011b). 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 in winter. 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). Importantly, the provision of open ‘barrage gates’, rather than just open fishways, is likely important over this period. Vertical-slot fishways, like those present at the Murray Barrages, are designed to facilitate upstream migrations and thus, are generally poor at facilitating downstream migrations (Clay 1995, Larinier and Marmulla 2004). Rates of downstream migration are likely to be far greater through open barrage gates.

Peak upstream migration of short-headed and pouched lamprey also appears to occur during winter, but may extend into spring (Bice *et al.* 2012). Nevertheless, as these species are rare, the data collected on timing of migration in the current project are not as comprehensive as that for congolli and common galaxias, and should be viewed with some caution. Furthermore, timing of downstream migration of newly metamorphosed juveniles in the region is unknown, but in other regions also occurs in winter (McDowall 1996).

Periods of peak migration for diadromous species indicate important seasons and months for barrage and fishway operation, but prioritising locations (i.e. specific barrages) for freshwater releases, in relation to fish migration, is more difficult. Whilst there were specific differences in the abundance of upstream migrating congolli and common galaxias between sites, overall, abundances downstream of Goolwa and Tauwitchere Barrages were not substantially different. YOY catadromous fish are likely to respond to salinity and olfactory cues from freshwater discharge during their upstream migration, and moderate–high abundances at Goolwa and Tauwitchere potentially reflect consistent freshwater discharge, and thus attraction, at both of these locations during the study period.

In support of this hypothesis, in 2009/10, upstream migrating common galaxias were moderately abundant at the Goolwa vertical-slot, but absent from sites at Tauwitchere Barrage (Zampatti *et al.* 2011a). No freshwater was discharged from Tauwitchere in 2009/10 but small volumes were released at Goolwa during navigation lock operation, which occurred during 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.

Currently, the Goolwa vertical-slot fishway and Tauwitchere small vertical-slot fishway facilitate the upstream passage of YOY common galaxias and congolli (Zampatti *et al.* 2012) and thus releases should be prioritised to these two barrages, and in particular, gates near the fishways. Fishways are currently being constructed at Ewe Island, Mundoo and Boundary Creek barrages and thus, freshwater releases from these locations should be avoided or limited (unless releases are planned for other specific environmental objectives) until these fishways are completed, as any discharge will result in the attraction and subsequent accumulation of individuals below these barriers. These fishways, together with additional structures on Goolwa and Tauwitchere Barrages, are planned for completion in 2015/16. Upon assessment of the effectiveness of these new fishways (planned for 2015/16 and 2016/17), and determination of differences in species utilisation between fishways, an operations plan could be developed to inform the order of closing/opening fishways during times of water scarcity, to maximise fish passage benefits.

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

1) Freshwater discharge and operation of all fishways on Goolwa and Tauwitchere Barrages should occur, at a minimum, from October–January to facilitate the upstream migration of YOY congolli and common galaxias (and other species). Where possible, attraction flow should be provided from barrage gates immediately adjacent to each fishway. If discharge is being decreased at Tauwitchere, gates adjacent the small vertical-slot fishway should be the last to 'shut-down' as this fishway is the most effective at passing small-bodied fishes.
2) Freshwater discharge and operation of all fishways on Goolwa and Tauwitchere Barrages should occur from June–August to facilitate the downstream spawning migrations of congolli and common galaxias and the upstream spawning migrations of lamprey. In addition to the fishways, barrage gates should be opened on each of these barrages (and potentially at other barrages), to facilitate downstream migrations of catadromous species and provide attraction flow for upstream migrations of anadromous species.
3) Fishways should remain open for at least two months following the complete closure of barrage gates to facilitate the return migrations of freshwater fishes. Freshwater fish such as Australian smelt, bony herring and flat-headed gudgeon remained common in the Coorong 2014/15, but following the closure of all barrage gates and increasing salinity within the Coorong, will attempt to migrate back into freshwater habitats.
4) Prioritise freshwater discharge at barrages that facilitate effective fish passage. Unless occurring for other specified environmental outcomes, freshwater releases from Ewe Island, Mundoo and Boundary Creek barrages should be limited until fishways are completed on these structures.
5) The 'Lakes and Barrages Operating strategy' should be reviewed following the construction and assessment of new fishways on the Murray Barrages.

5. CONCLUSION

Freshwater flows and connectivity between freshwater and marine environments play a crucial role in structuring the composition of estuarine fish assemblages and facilitating the recruitment of catadromous congolli and common galaxias, and other species, in the Coorong estuary. During 2006–2010, excessive regulation of freshwater inflow to the Coorong estuary led to increases in salinity, a loss of fish species diversity and reduced abundances, particularly in the case of diadromous and estuarine species. The year 2014/15 represented the fifth consecutive year of consistent freshwater inflows post the Millennium Drought and an extended period (March 2007 – September 2010) of no freshwater discharge. Whilst less freshwater was discharged in 2014/15 relative to 2010–2014, brackish salinities prevailed in the Coorong estuary and fish assemblages were typical of a spatio-temporally dynamic temperate estuary under the influence of freshwater flow. Nonetheless, there was some evidence to suggest a trajectory towards the assemblage of 2006/07, which was characterised by decreasing freshwater discharge and increasing salinities prior to the complete closure of the barrages in March 2007. Assemblages will likely continue on this trajectory should discharge remain low.

Abundances of catadromous congolli and common galaxias were the greatest since the inception of the current monitoring program in 2006/07, with the majority of individuals sampled representing newly recruited YOY. Whilst no fish were aged in 2014/15, high levels of connectivity and freshwater inflows throughout 2014/15 likely facilitated protracted spawning seasons and provided conditions conducive to larval/juvenile survival and subsequently recruitment. Furthermore, successful recruitment in 2010/11 and 2011/12 likely led to increases in the adult spawning population of 2014, which in turn led to increased spawning output and subsequent peak abundance of catadromous species in 2014/15. These data indicate that management target F-1 (*'maintain or improve recruitment success of diadromous fish in the Lower Lakes and Coorong'*) of the Lower Lakes, Coorong and Murray Mouth Icon Site Condition Monitoring Plan (Maunsell 2009) was achieved for these two species in 2014/15. Importantly, continuous barrage discharge throughout 2014/15 facilitated the upstream migrations of newly recruited individuals. Further targeted sampling is required to determine the status of lamprey species.

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.

REFERENCES

Aldridge, K. T. and Brookes J. D. (2011). The response of water quality and phytoplankton communities in the Northern lagoon of the Coorong and Murray Mouth to barrage releases from the Lower Lakes, November 2010-May 2011. Final Report Prepared for the Department of Environment and Natural Resources and the Department for Water. Adelaide University.

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

Baptista, J., Martinho F., Dolbeth M., Viegas I., Cabral H. and Pardal M. (2010). Effects of freshwater flow on the fish assemblage of the Mondego estuary (Portugal): comparison between drought and non-drought years. *Marine and Freshwater Research* **61**: 490-501.

Barletta, M., Barletta-Bergan A., Saint-Paul U. and Hubold G. (2005). The role of salinity in structuring fish assemblages in a tropical estuary. *Journal of Fish Biology* **66**: 45-72.

Barrett, J. and Mallen-Cooper M. (2006). The Murray River's 'Sea to Hume Dam' fish passage program: Progress to date and lessons learned. *Ecological Management and Restoration* **7**: 173-183.

Beck, M. W., Heck K. L., Able K. W., Childers D. L., Eggleston D. B., Gillanders B. M., Halpern B., Hays C., Hoshino K., Minello T. J., Orth R. J., Sheridan P. F. and Weinstein M. P. (2001). The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates. *Bioscience* **51**: 633-641.

Benjamini, Y. and Yekutieli D. (2001). The control of false discovery rate under dependency. *Annals of Statistics* **29**: 1165-1188.

Bice, C., Jennings P. and Zampatti B. (2007). Fish movement and recruitment in the Coorong and Lower Lakes: 2006/07 progress report. South Australian Research and Development Institute (Aquatic Sciences), Adelaide, 48pp. SARDI Publication No. 2007/000555-1. SARDI Research Report Series No. 232.

Bice, C. and Zampatti B. (2011). Response of fish to the 'Goolwa Channel Water Level Management Plan': 2009-2011. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000703-2. SARDI Research Report Series No. 541, 45 pp.

Bice, C. M., Furst D., Lamontagne S., Oliver R., Revill A. T. and Zampatti B. (In Prep). Science to inform environmental water allocation in the Coorong: Investigation of primary productivity, microbiota community structure and trophic subsidy in the Coorong estuary in relation to low volume freshwater flows. Prepared by the South Australian Research and Development Institute (Aquatic Sciences) for the Goyder Institute for Water Research.

Bice, C. M. and Zampatti B. P. (2014). Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2013/14. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000186-4. SARDI Research Report Series No. 800. 61pp.

Bice, C. M., Zampatti B. P., Jennings P. R. and Wilson P. (2012). Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2011/12. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000186-3. SARDI Research Report Series No. 680. 53pp.

Clay, C. H. (1995). Design of fishways and other fish facilities. Boca Raton, Lewis.

CSIRO (2008). Water availability in the Murray-Darling Basin. Report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia, 67pp.

Day, J. W., Hall C. A. S., Kemp W. M. and Yanez-Aracibia A. (1989). Estuarine Ecology, John Wiley & Sons, New York.

DEWNR (2015). DEWNR Unpublished Data.

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

Elliott, M., Whitfield A. K., Potter I. C., Blaber S. J. M., Cyrus D. P., Nordlie F. G. and Harrison T. D. (2007). The guild approach to categorizing estuarine fish assemblages: a global review. *Fish and Fisheries* **8**: 241-268.

Flemer, D. A. and Champ M. A. (2006). What is the future fate of estuaries given nutrient over-enrichment, freshwater diversion and low flows? *Marine Pollution Bulletin* **52**: 247-258.

Gaughan, D. J., Fletcher W. J., Tregonning R. J. and Goh J. (1996). Aspects of the biology and stock assessment of the whitebait, *Hyperlophus vittatus*, in South Western Australia. WA Fisheries Research Report 108. 127 pp.

Geddes, M. C. (1987). Changes in salinity and in the distribution of macrophytes, macrobenthos and fish in the Coorong Lagoons, South Australia, following a period of River Murray flow. *Transactions of the Royal Society of South Australia* **108**: 173-181.

Geddes, M. C. and Butler A. J. (1984). Physicochemical and biological studies on the Coorong Lagoons, South Australia, and the effect of salinity on the distribution of the macrobenthos. *Transactions of the Royal Society of South Australia* **108**: 51-62.

Giatas, G. C. and Ye Q. (2015). Diet of mulloway, congolli and Australian salmon in the Coorong. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2015/000479-1. SARDI Research Report Series No. 858. 81pp.

Gillanders, B. and Kingsford M. (2002). Impacts of changes in flow of freshwater on estuarine and open coastal habitats and the associated organism. *Oceanography and Marine Biology: an Annual Review* **40**: 233-309.

Goecker, M. E., Valentine J. F., Sklenar S. A. and Chaplin G. I. (2009). Influence from hydrological modification on energy and nutrient transference in a deltaic food web. *Estuaries and Coasts* **32**: 173-187.

Gomon, M., Bray D. and Kuiter R., Eds. (2008). Fishes of Australia's Southern Coast, Reed, New Holland, Sydney.

Hortle, M. (1978). The ecology of the sandy, *Pseudaphritis urvillii,* in south-east Tasmania, Honours thesis, University of Tasmania.

Jennings, P., Zampatti B. and Bice C. (2008a). Fish movement and recruitment in the Coorong and Lower Lakes 2007/08 Progress Report. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. 47pp

Jennings, P., Zampatti B., Stuart I. G. and Baumgartner L. J. (2008b). Fish passage at the Murray barrages. In *The sea to Lake Hulme: Restoring fish passage in the Murray River*, Murray-Darling Basin Commission, Canberra. MDBC publication No. 32/08**:** 62-77.

Kingsford, R. T., Walker K. F., Lester R. E., Young W. J., Fairweather P. G., Sammut J. and Geddes M. C. (2011). A Ramsar wetland in crisis - the Coorong, Lower Lakes and Murray Mouth Australia. *Marine and Freshwater Research* **62**: 255-265

Kocovsky, P. M., Ross R. M. and Dropkin D. S. (2009). Prioritising removal of dams for passage of diadromous fishes on a major river system. *River Research and Applications* **25**: 107-117.

Kupschus, S. and Tremain D. (2001). Associations between fish assemblages and environmental factors in nearshore habitats of a subtropical estuary. *Journal of Fish Biology* **58**: 1383-1403.

Lamberth, S. J., van Niekerk L. and Hutchings K. (2008). Comparison of and the effects of altered freshwater inflow on fish assemblages of two contrasting South African estuaries: The cool-temperate Oliphants and the warm-temperate Breede. *African Journal of Marine Science* **30**: 311-336.

Larinier, M. and Marmulla G. (2004). Fish passages: types, principles and geographical distribution - an overview. In *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries. RAP publication 2004/17, vol. II. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand, pp 183-206*. R. L. Welcomme and T. Petr.

Lassalle, G. and Rochard E. (2009). Impact of twenty-first century climate change on diadromous fish spread over Europe, North Africa and the Middle East. *Global Change Biology* **15**: 1072-1089.

Lonergan, N. R. and Bunn S. E. (1999). River flows and estuarine ecosystems: implications for coastal fisheries from a review and a case study of the Logan River, southeast Queensland. *Australian Journal of Ecology* **24**: 431-440.

Lucas, M. and Baras E. (2001). Migration of Freshwater Fishes, Blackwell Sciences, Oxford.

Mallen-Cooper, M. (2001). Fish passage options for the Murray Barrages. Fishways Consulting Services, Sydney

Martinho, F., Leitao R., Viegas I., Dolbeth M., Neto J. M., Cabral H. N. and Pardal M. A. (2007). The influence of an extreme drought event in the fish community of a southern Europe temperate estuary. *Estuarine, Coastal and Shelf Science* **75**: 537-546.

Maunsell (2009). Lower Lakes, Coorong and Murray Mouth Icon Site Condition Monitoring Plan. Maunsell Australia, Adelaide.

McCune, B. and Mefford M. (2006). PC-ORD. Multivariate Analysis of Ecological Data, Version 5.0. MjM Software Design, Glendon Beach, Oregon.

McDowall, R. M. (1988). Diadromy in Fishes - Migrations between Freshwater and Marine Environments, Croom Helm, London, UK.

McDowall, R. M., Ed. (1996). Freshwater fishes of south-eastern Australia. Sydney, Reed.

Narum, S. R. (2006). Beyond Bonferroni: Less conservative analyses for conservation genetics. *Conservation Genetics* **7**: 783-787.

Phillips, W. and Muller K. (2006). Ecological Character Description of the Coorong, Lakes Alexandrina and Albert Wetland of International Importance. Department of Environment and Heritage.

Puckridge, J. T., Sheldon F. and Walker K. F. (1998). Flow variability and the ecology of large rivers. *Marine and Freshwater Research* **49**: 55-72.

Shiel, R. J. and Aldridge K. T. (2011). The response of zooplankton communities in the North Lagoon of the Coorong and Murray Mouth to barrage releases from the Lower Lakes, November 2010-April 2011. Final Report to the Department of Environment and natural Resources and Department for Water. Adelaide University.

Stuart, I. G., Ye Q., Higham J. and O'Brien T. (2005). Fish Migration at Tauwitchere Barrage: new options for fish passage. Murray-Darling Basin Commission, Canberra, 33pp.

Van Dijk, A., Beck H. E., Crosbie R. S., de Jeu R. A. M., Liu Y. Y., Podger G. M., Timbal B. and Viney N. R. (2013). The millenium drought in southeast Australia (2001-2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. *Water Resources Research* **49**: 1040-1057.

Walker, D. (2002). What is possible: hydrology and morphology. In 'The Murray Mouth: exploring implications of closure or restricted flow. A report prepared for the Murray-Darling Basin Commission and Department of Water Land and Biodiversity Conservation.

Whitfield, A. K. (1994). Abundance of larval and 0+ juvenile marine fishes in the lower reaches of three southern African estuaries with differing freshwater inputs *Marine Ecology Progress Series* **105**: 257-267.

Whitfield, A. K. (1999). Icthyofaunal assemblages in estuaries: A South African case study. *Reviews in Fish Biology and Fisheries* **9**: 151-186.

Ye, Q., Bucater L., Short D. and Livore J. (2012). Fish response to barrage releases in 2011/12, and recovery following the recent drought in the Coorong. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2012/000357-1. SARDI Research Report Series No. 665. 81pp.

Zampatti, B. P., Bice C. M. and Jennings P. R. (2010). Temporal variability in fish assemblage structure and recruitment in a freshwater deprived estuary: The Coorong, Australia. *Marine and Freshwater Research* **61**: 1298-1312.

Zampatti, B. P., Bice C. M. and Jennings P. R. (2011a). Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes from 2006-2010. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000186-1. SARDI Research Report Series No. 569. 43p.

Zampatti, B. P., Bice C. M. and Jennings P. R. (2011b). Movements of female congolli (*pseudaphritis urvillii*) in the Coorong and Lower Lakes of the River Murray South Australian Research and Development Institiute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000333-1. SARDI Research Report Series No. 577. 32pp.

Zampatti, B. P., Bice C. M. and Jennings P. R. (2012). Fish assemblage response and fishway effectiveness at Goolwa, Tauwitchere and Hunters Creek Barrages in 2010/11. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000186-2. SARDI Research Report Series No. 605. 66pp.