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Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2013/14

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. Freshwater flow and tidal regime determine estuarine salinities, which in turn influence the structure of fish assemblages. Estuaries support diverse fish assemblages which are characterised by a spatio-temporally variable mix of freshwater, diadromous, estuarine and marine fish species. Estuaries also represent 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 river 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 estuarine salinity were accompanied by significant changes in fish assemblage structure. 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 resumption of freshwater flow to the Coorong and a prolonged period (September 2010–April 2011) of high freshwater discharge. Salinities downstream of the barrages decreased and fish assemblages differed significantly from the period 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. Abundance of congolli and common galaxias increased significantly but anadromous lamprey were not sampled. Moderate-

volume freshwater flows continued through 2011/12 with further concurrent changes in fish assemblage structure.

The period 2013/14 represented the fourth consecutive year of freshwater discharge and high levels of hydrological connectivity between the Lower Lakes and Coorong. Annual discharge (~1600 GL) was less than that from 2010–2013 (5200–12,500 $GL.yr^{-1}$), but brackish salinities predominated in the Coorong estuary. 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 Management Plan and aid development of the 'Lakes and Barrages Operating Strategy'. The objective of this study was to further investigate the influence of freshwater inflows and connectivity between the Lower Lakes and Coorong on fish assemblage structure and migration, and diadromous fish recruitment. Using the barrage fishways as a sampling tool we specifically aimed to:

1. Determine the species composition and abundance of fish species immediately downstream of the barrages and/or attempting to move between the Coorong and Lower Lakes via the barrage fishways in 2013/14, and assess spatio-temporal variation in assemblage structure in relation to 2006–2012.
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 2013/14, and in relation to 2006–2012.
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'.*
4. Inform operation of the barrages and development of the 'Lakes and Barrages Operating Strategy'.

The fish assemblage sampled in 2013/14 was diverse (30 species) and similar to that of 2011/12 in regards to species composition, but there were significant changes in the abundance of some species. Total fish abundance was less than 2011/12, primarily due to decreased abundance of the marine migrant sandy sprat (*Hyperlophus vittatus*). Nevertheless, this species still dominated catches, constituting ~53% of the total catch numerically. Several freshwater species remained common (e.g. Australian smelt *Retropinna semoni*) and there were further increases in the abundance of catadromous species (congolli and common galaxias) at most locations.

Abundances of catadromous congolli and common galaxias in 2013/14 were the greatest detected from 2006–2014 and the majority of individuals collected were young-of-the-year. High abundances of congolli and common galaxias in 2013/14 potentially reflected the cumulative benefits of multiple years of freshwater discharge and connectivity. Enhanced recruitment in 2010/11 (relative to previous years), likely led to increases in abundance of the adult spawning population and subsequently, may have resulted in enhanced spawning in 2013/14. 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.

Diadromous species exhibited seasonal peaks in migration, which 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, so freshwater discharge should be limited (where possible) to barrages with effective fish passage.

The results of this investigation present further changes to fish assemblages of the Coorong following prolonged freshwater inflow and hydrological connectivity. In general, the assemblage trended towards the diverse but variable fish assemblages that characterise dynamic estuarine environments under freshwater influence. Abundances of catadromous congolli and common galaxias peaked in 2013/14 following significant declines in recruitment and abundance from 2007–2010 and these data indicates that the target of '*maintain or improve recruitment success of diadromous fish in the Lower Lakes and Coorong'* was achieved. Importantly, continued freshwater flow and connectivity between the Lower Lakes and the Coorong will be essential for the maintenance of populations of diadromous, estuarine and estuarine-dependent marine species and maintaining dynamism in estuarine fish communities. Data collected in this project form a basis for determining the status and trajectories of fish assemblages and populations in the Coorong estuary into the future and synthesis of these data into a series of flow-related 'references' using appropriate metrics (e.g. species richness, probability of encounter and/or relative abundance) remains a priority.

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 regime determine estuarine salinities, 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 two 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 Basin (MDB), 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 sea (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 resulting in reduced inflows to the 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 increases in estuarine salinities 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 (*Mordacia mordax*) and pouched lamprey (*Geotria australis*), present in 2006/07, were absent through 2007–2010.

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 of freshwater to the Coorong from September 2010. Increased freshwater inflows resulted in the reinstatement of connectivity between the Lower Lakes and Coorong, and significantly reduced salinities, with concomitant changes to fish assemblage structure and recruitment. 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.

Medium-volume freshwater flows continued to be delivered to the Coorong throughout 2011/12 (800–36,000 ML.d^{-1}), with further associated changes to the fish assemblage, trending towards a diverse but variable assemblage characteristic of a dynamic estuarine environment (Bice *et al.* 2012). Freshwater species remained present, but were 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.

Low to medium-volume freshwater flows continued in 2012/13 (220–69,000 $ML.d^{-1}$) and 2013/14 (20–18,020 $ML.d^{-1}$). Spring/summer monitoring was not conducted in 2012/13, but 2013/14 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 are used to assess specific ecological targets in the Lower Lakes, Coorong and Murray Mouth Condition Monitoring Plan (Maunsell 2009) and will aid future management of the system, including informing the development of the 'Lakes and Barrages Operating Strategy'.

1.2. Objectives

The objective of this study was to further 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 species immediately downstream of the barrages and/or attempting to move between the Coorong and Lower Lakes via the barrage fishways in 2013/14, and assess spatio-temporal variation in assemblage structure in relation to 2006–2012.
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 2013/14, in relation to 2006–2012.
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'.*
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 is ~12,233 GL but there are strong inter-annual variations in discharge (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 on three occasions (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, with a lower annual discharge in 2013/14 of ~1600 GL.

The Coorong is a narrow (2–3 km wide) estuarine lagoon running southeast from the river mouth and parallel to the coast for ~140 km (Figure 2-1) and 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).

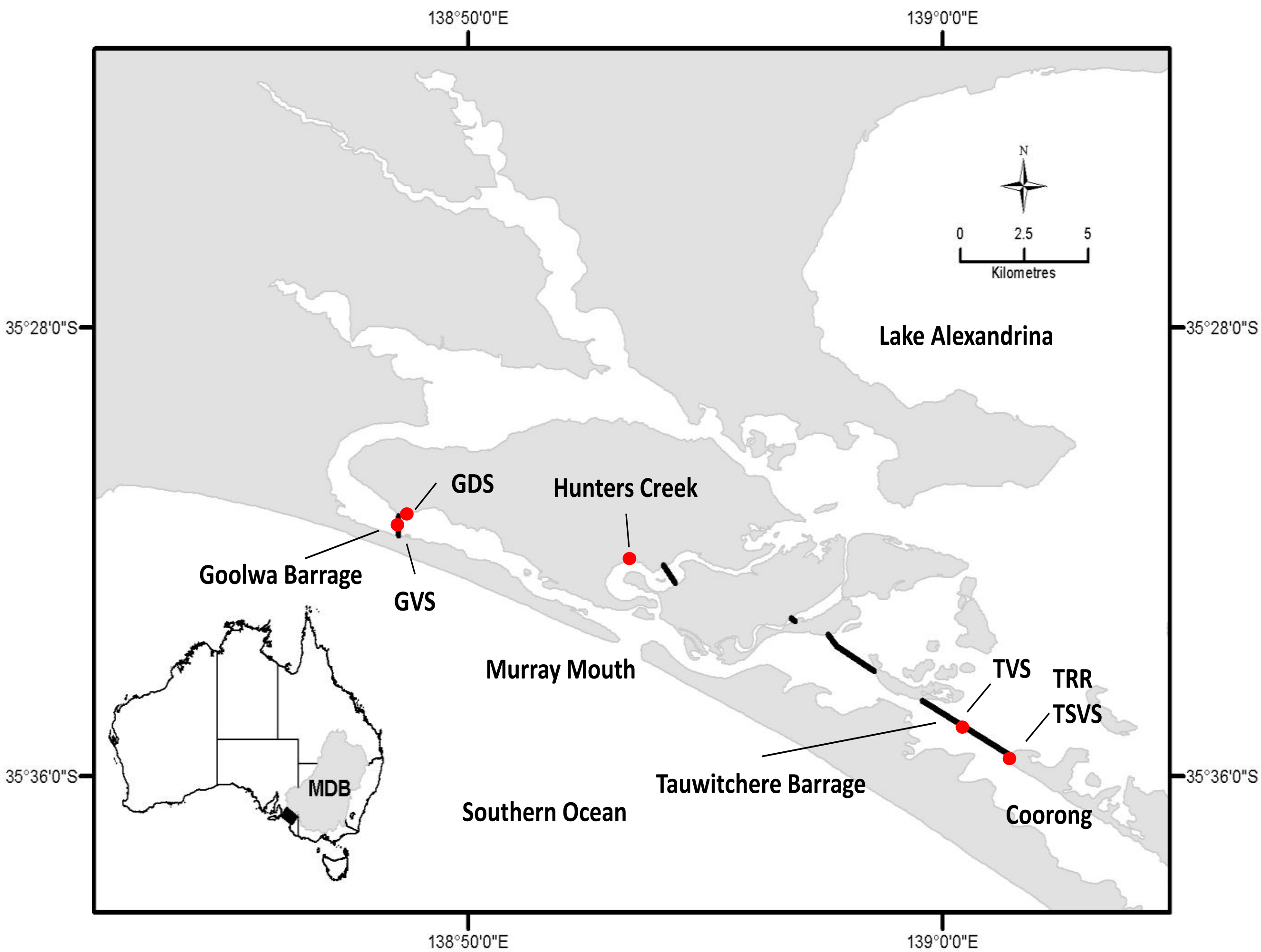

Figure 2-1. A map of the Coorong and Lake Alexandrina at the terminus of the River Murray, southern Australia showing the study area in the Coorong estuary, highlighting the Murray Mouth and Murray Barrages (bold lines). Goolwa and Tauwitchere barrages are identified as are the fish sampling locations (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).

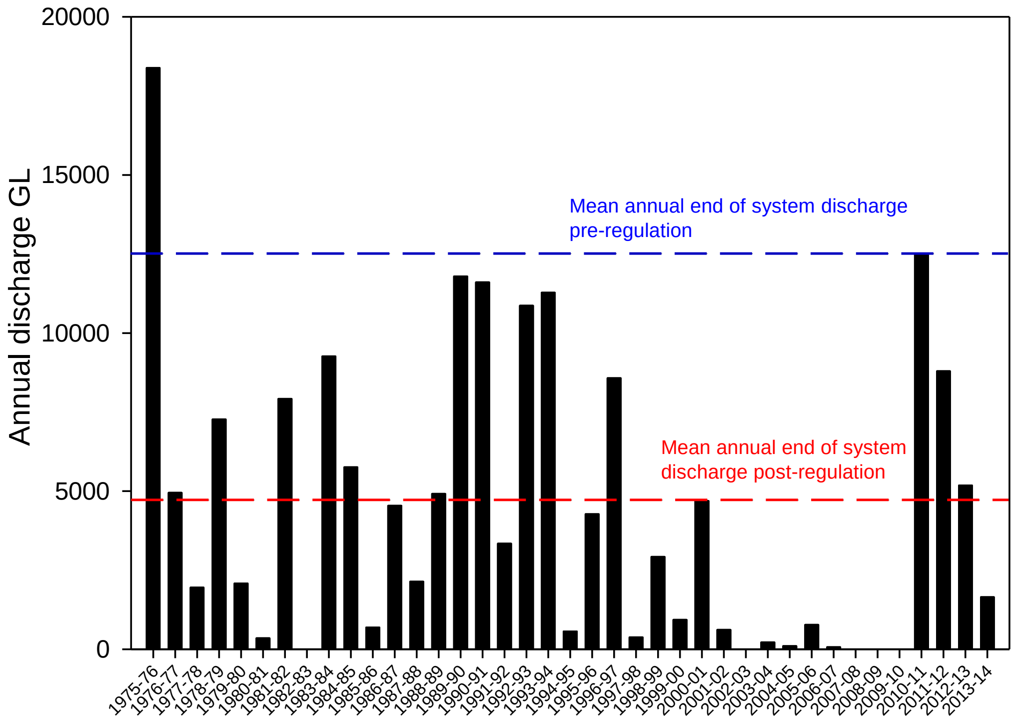

Figure 2-2. Annual freshwater discharge (GL) through the Murray barrages into the Coorong estuary from 1975–March 2014. Dashed lines represent mean annual end of system discharge pre- (blue) and post-regulation (red).

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 periods of zero freshwater inflow 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 aimed to produce internal hydraulics that are favourable for the upstream passage of small-bodied fish (i.e. low headloss, velocity and turbulence) and operate with low discharge (<5 $ML.day^{-1}$). Both of these fishways, were found to effectively facilitate the passage of small fish (Zampatti *et al.* 2012).

2.2. Fish sampling

Samples of fish were collected from the entrances of all four vertical-slot fishways in 2013/14 (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 2013/14, 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 area immediately adjacent to the Tauwitchere rock ramp (Coorong side) and adjacent Goolwa Barrage (Coorong side). At both locations, the net was set adjacent to the barrage to capture fish utilising this area.

a) b)

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 adjacent the Tauwitchere rock ramp.

Five weeks of sampling were conducted between 21 October 2013 and 21 February 2014. The sites adjacent the Tauwitchere rock ramp and adjacent Goolwa Barrage were sampled once overnight during each sampling week. All vertical-slot fishway sites were sampled overnight 3 times per sampling week. Cage traps at the large vertical-slot fishways were deployed and retrieved using a mobile crane (Figure 2-3a). All trapped fish were removed and placed in aerated holding tanks. 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.

An additional two sampling weeks were conducted in winter (June/July) 2013, specifically targeting the upstream migration period of anadromous short-headed and pouched lamprey. All vertical-slot fishway sites were monitored during this additional sampling. Given the different season in which this sampling was undertaken (winter sampling was not undertaken in most years), these data are not used in any analysis of fish assemblage structure, but are used solely to determine the presence/absence of lamprey.

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, however, 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. 2006–2014). 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 ($\alpha = 0.05$).

Spatial variation in fish assemblages between sampling locations in 2013/14 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 2013/14, 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 2013/14.

Inter-annual (2006–2014) differences in the standardised abundance (fish.hour^{-1}.trap event^{-1}) of pouched lamprey and short-headed lamprey were qualitatively assessed. Inter-annual (2006–2014) differences in the standardised abundance of common galaxias and congolli (fish.hour^{-1}.trap event^{-1}) sampled at the Tauwitchere rock ramp, Tauwitchere vertical-slot, Goolwa vertical-slot and adjacent Goolwa Barrage were analysed using uni-variate single-factor PERMANOVA (Anderson *et al.* 2008). Data from the Tauwitchere small vertical-slot and Hunters Creek vertical-slot were excluded from this analysis as sampling at these sites only commenced in 2010/11. Intra-annual (monthly) differences in the standardised abundance (fish.hour^{-1}.trap event^{-1}) of common galaxias and congolli sampled at all sites in 2013/14 were analysed using uni-variate single-factor PERMANOVA (Anderson *et al.* 2008).

3. RESULTS

3.1. Hydrology

Estimated daily barrage discharge data were obtained from the Department of Environment, Water and Natural Resources (DEWNR). 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 through barrage ‘gates’ and fishways on Tauwitchere and Goolwa Barrages into the Coorong (Figure 3-1a). At the commencement of sampling 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 conditions 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 were experienced throughout 2013/14 with flow during the sampling season ranging 20–18,020 $ML.d^{-1}$ and a mean daily discharge of 1617 ± 217 $ML.d^{-1}$.

Data on estuarine salinities were sourced from water quality monitoring stations immediately below both Tauwitchere and Goolwa Barrages (DEWNR 2014). During sampling in 2006/07, salinity below Tauwitchere and Goolwa Barrages fluctuated from 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 fluctuated between 30 and 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 from 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 from 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, decreased 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.

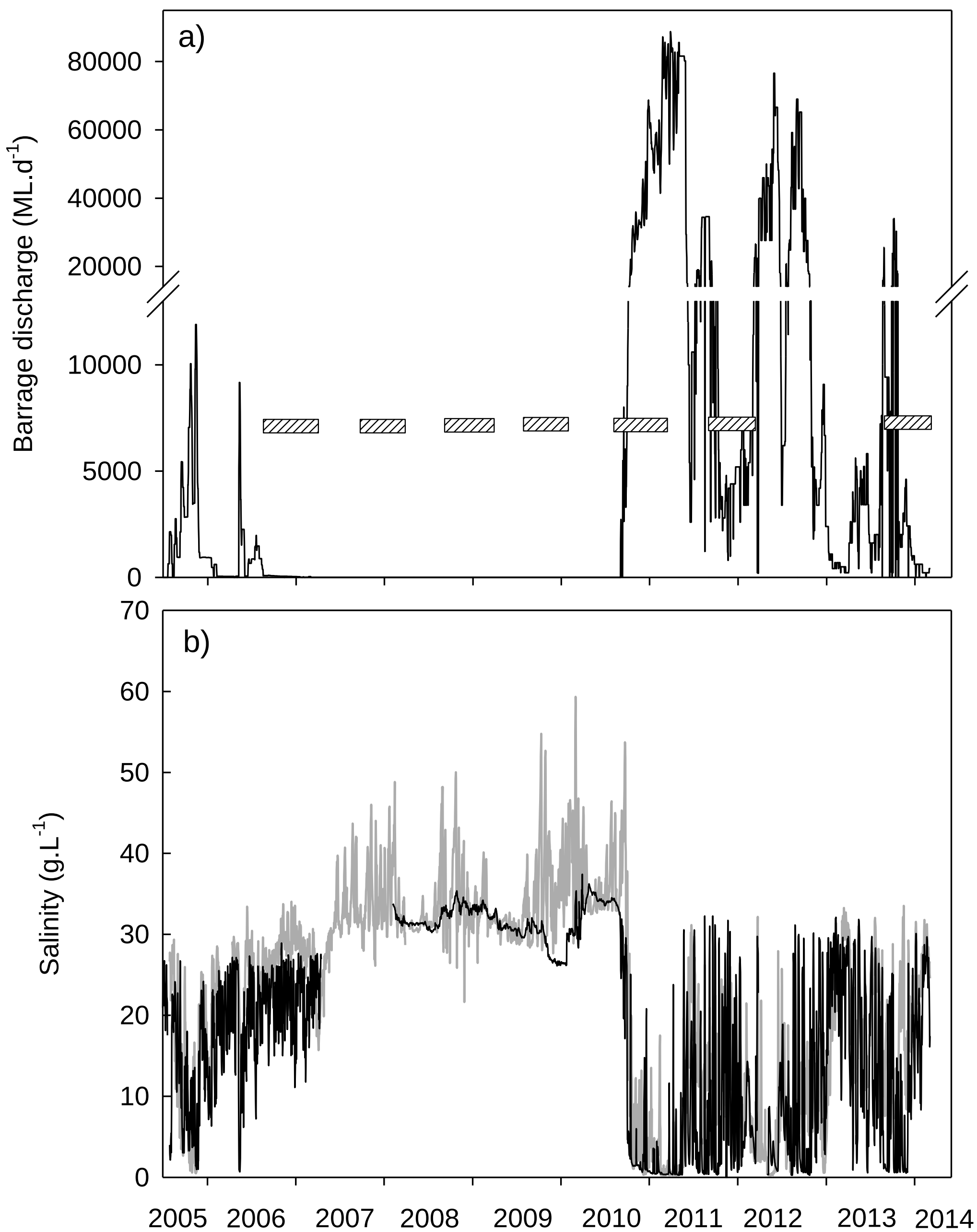

Figure 3-1. a) Mean daily flow (ML.d^{-1}) to the Coorong through the Murray Barrages (all barrages combined) from July 2005–March 2014 and b) Mean daily salinity (g.L^{-1}) of the Coorong below Tauwitchere (grey line) and Goolwa (black line) barrages from July 2005 – March 2010. Sampling periods are 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 2014).

3.2. Catch summary

A total of 581,248 fish from 30 species (20 families) were sampled in 2013/14 (Table 3-1). The marine migrant sandy sprat (*Hyperlophus vittatus*) dominated, comprising ~53% of the total catch. The catadomous congolli and freshwater Australian smelt (*Retropinna semoni*) were also abundant, comprising ~18% and ~16% of the total catch, respectively. The freshwater bony herring (*Nematalosa erebi*; 3.1%) and flat-headed gudgeon (*Philypnodon grandiceps*; 2.4%), catadromous common galaxias (2.7%) and estuarine lagoon goby (*Tasmanogobius lasti*; 2.5%) were the next most abundant species, whilst the remaining 23 species collectively comprised <3% of the total catch numerically.

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 2013/14. 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		14	15	5	15	5	15	
	No. of species		23	11	25	20	25	14	
Australian smelt	*Retropinna semoni*	Freshwater migrant	3381	77386	10516	1285	453	8	**93029**
Unspecked hardyhead	*Craterocephalus stercusmuscarum fulvus*	Freshwater straggler	0	0	2	1	0	0	**3**
Bony herring	*Nematalosa erebi*	Freshwater migrant	1052	257	10767	3993	2066	105	**18240**
Flat-headed gudgeon	*Philypnodon grandiceps*	Freshwater migrant	9665	51	1255	1970	673	151	**13765**
Dwarf flat-headed gudgeon	*Philypnodon macrostomus*	Freshwater straggler	3	0	1	5	2	4	**15**
Carp gudgeon	*Hypseleotris* spp	Freshwater straggler	5	0	0	1	1	0	**7**
Golden perch	*Macquaria ambigua*	Freshwater straggler	5	1	4	2	1	1	**14**
Common carp	*Cyprinus carpio**	Freshwater straggler	30	0	2	9	11	0	**52**
Goldfish	*Carrasius auratus**	Freshwater straggler	0	0	2	1	0	2	**5**
Redfin perch	*Perca fluviatilis**	Freshwater straggler	78	14	501	131	151	0	**875**
Eastern gambusia	*Gambusia holbrooki**	Freshwater straggler	7	0	1	0	0	1	**9**
Common galaxias	*Galaxias maculatus*	Semi-catadromous	3410	6081	1399	2359	1155	1275	**15679**
Congolli	*Pseudaphritis urvillii*	Semi-catadromous	3889	16819	43790	17933	17471	4560	**104462**
Small-mouthed hardyhead	*Atherinosoma microstoma*	Estuarine	25	4	2957	4	220	0	**3210**

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	236	3	1528	184	2695	19	**4665**
Blue-spot goby	*Pseudogobius olorum*	Estuarine	6	0	53	0	31	12	**102**
Lagoon goby	*Tasmanogobius lasti*	Estuarine	3279	1	9590	205	1246	2	**14323**
Bridled goby	*Arenogobius bifrenatus*	Estuarine	342	0	282	1	43	4	**672**
Greenback flounder	*Rhombosolea tapirina*	Estuarine	6	0	15	1	107	0	**129**
Long-snouted flounder	*Ammotretis rostratus*	Estuarine	16	0	33	4	31	0	**84**
River garfish	*Hyperhamphus regularis*	Estuarine	1	0	190	0	1	0	**192**
Black bream	*Acanthopagrus butcheri*	Estuarine	1	0	0	0	1	0	**2**
Yellow-eyed mullet	*Aldrichetta forsteri*	Marine migrant	3	0	1	108	33	1	**146**
Mulloway	*Argyrosomus japonicas*	Marine migrant	0	0	3	0	18	0	**21**
Soldier fish	*Gymnapistes marmoratus*	Marine migrant	1	0	0	0	0	0	**1**
Smooth toadfish	*Tetractenos glaber*	Marine migrant	1	0	2	0	5	0	**8**
Blue sprat	*Spratelloides robustus*	Marine migrant	0	0	0	0	32	0	**32**
Sandy sprat	*Hyperlophus vittatus*	Marine migrant	28611	1	160405	510	121976	0	**311503**
Zebra fish	*Girella zebra*	Marine migrant	0	0	1	0	0	0	**1**
Pug nose pipefish	*Pugnaso curtirostris*	Marine straggler	0	0	0	0	2	0	**2**
		Total	**54053**	**100618**	**243300**	**28707**	**148425**	**6145**	**581248**

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 2013/14 (Figure 3-2), with significant differences between years detected at the Tauwitchere rock ramp (*Pseudo-*$F_{6, 49}$ = 17.338, p < 0.001), Tauwitchere vertical-slot (*Pseudo-*$F_{6, 42}$ = 11.471, p < 0.001) and Goolwa vertical-slot (*Pseudo-*$F_{5, 40}$ = 2.561, p = 0.05), but not adjacent Goolwa Barrage (*Pseudo-*$F_{4, 29}$ = 2.477, p = 0.073). The Tauwitchere small vertical-slot and Hunters Creek vertical-slot have only been sampled since 2010 and are included for completeness (Figure 3-2a). Nonetheless, the mean number of fish sampled at these sites varied significantly between years (TSVS: *Pseudo-*$F_{2, 56}$ = 3.486, p = 0.037, Hunters: *Pseudo-*$F_{2, 57}$ = 3.339, p = 0.030). Patterns of temporal variability in total fish abundance were similar at all locations, with significant 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. Abundance remained high in 2013/14, but typically less so than the preceding two years. Abundance peaked at the Tauwitchere vertical-slot in 2010/11 and at the rock ramp in 2011/12, with abundance >100 and >150 times greater than was recorded at each respective location in 2008/09.

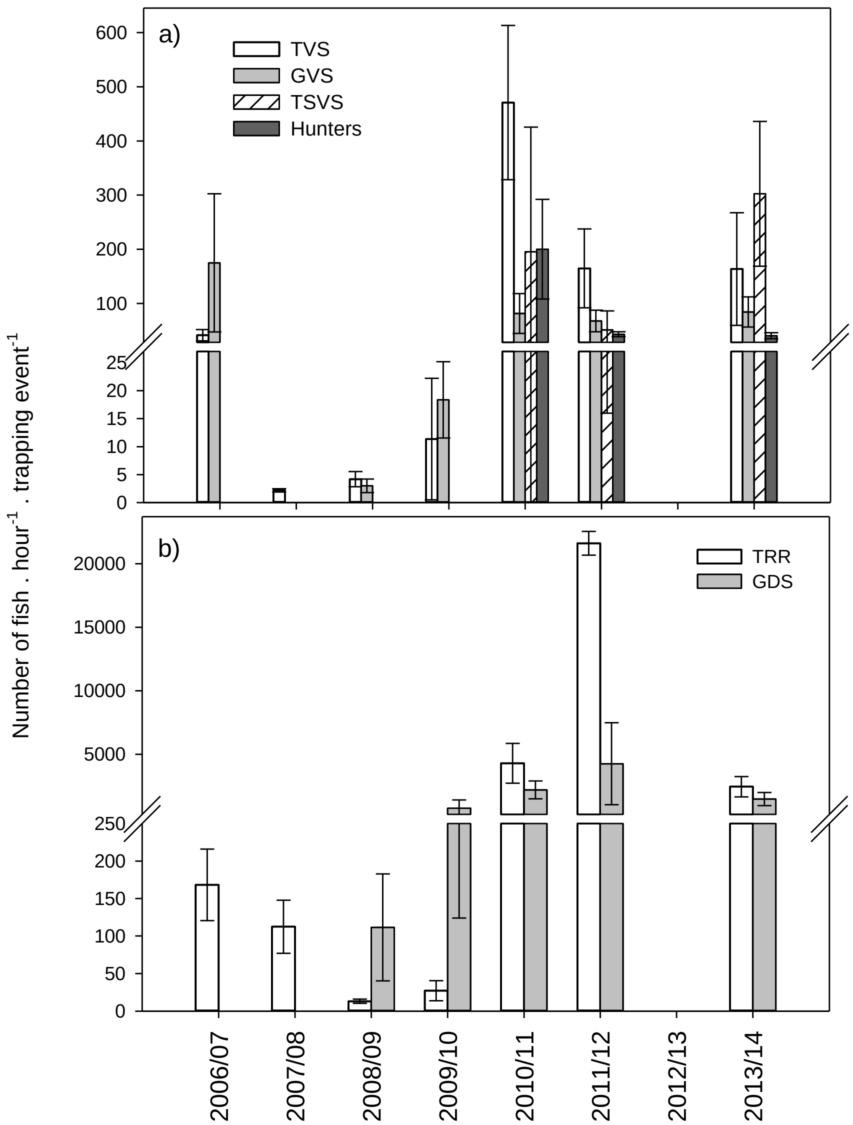

Figure 3-2. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of fish (all species combined) sampled at a) the Tauwitchere large vertical-slot (TVS), Goolwa vertical-slot (GVS), Tauwitchere small vertical-slot and Hunters Creek vertical-slot (Hunters), and b) the Tauwitchere rock ramp (TRR) 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) did not vary greatly between years, except for 2007/08 when just 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 (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 2010–2014 (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 2010–2014 (n = 7–11). The number of diadromous species was reduced during 2007–2010 (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).

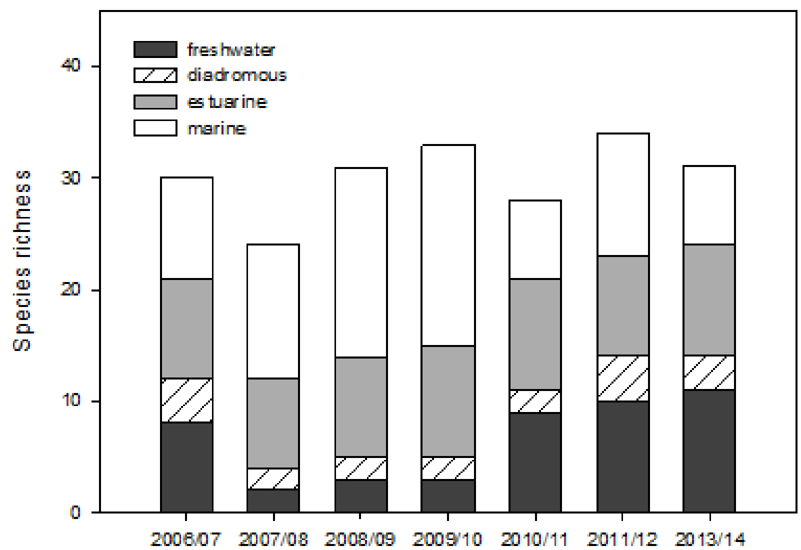

Figure 3-3. Species richness (i.e. the number of species) of fish assemblages sampled (all sites combined) from 2006–2014, including the contribution of species from different estuarine-use guilds, i.e. freshwater (freshwater migrants and stragglers combined), diadromous (catadromous and anadromous combined), estuarine and marine (marine migrants and stragglers combined).

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 ($Pseudo\text{-}F_{6,\ 49}$ = 17.602, p <

0.001), Tauwitchere large vertical-slot (*Pseudo-$F_{6, 42}$* = 12.343, *p* < 0.001), Tauwitchere small vertical-slot (*Pseudo-$F_{2, 21}$* = 3.557, *p* = 0.003), Goolwa vertical-slot (*Pseudo-$F_{5, 40}$* = 6.692, *p* < 0.001), adjacent Goolwa Barrage (*Pseudo-$F_{4, 29}$* = 8.472, *p* < 0.001) and Hunters Creek vertical-slot (*Pseudo-$F_{2, 21}$* = 7.016, *p* < 0.001).

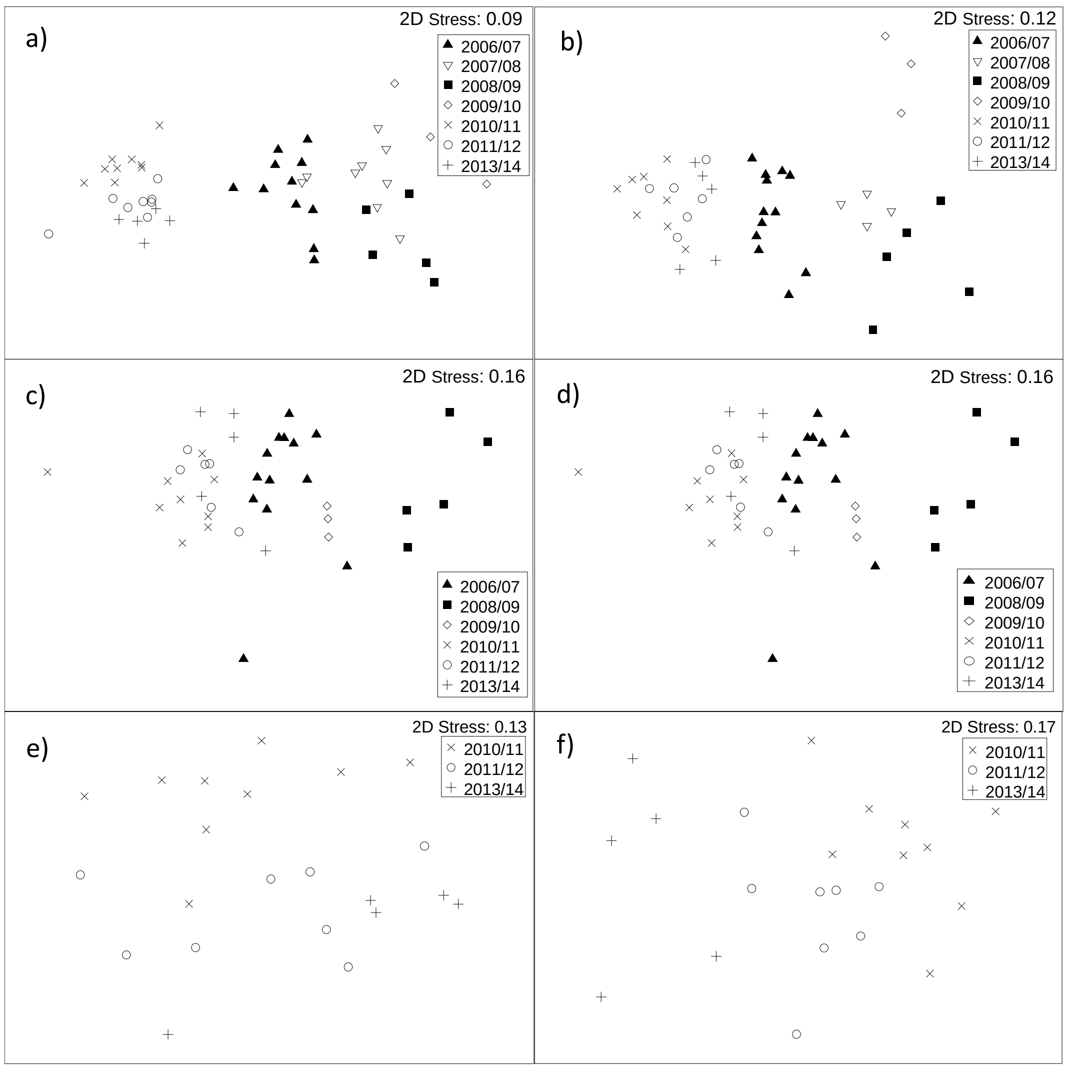

Figure 3-4. MDS ordination plots of fish assemblages sampled at a) Tauwitchere rock ramp, b) Tauwitchere large vertical-slot, c) Goolwa vertical-slot, d) adjacent Goolwa Barrage, e) Tauwitchere small vertical-slot and f) Hunters Creek vertical-slot, between 2006 and 2014.

Tauwitchere sites

Pair-wise comparisons revealed significant differences in fish assemblages at the Tauwitchere rock ramp between all years, except for 2008/09 and 2009/10, and 2009/10 and 2013/14 (B-Y method corrected α = 0.015; 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 = 0.015; Table 3-3). No significant difference was detected between assemblages sampled in 2007/08, 2008/09 and 2009/10. Assemblages sampled in 2010/11 and 2011/12 were not significantly different but both years were significantly different from all other 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. Fish assemblages at the Tauwitchere small vertical-slot differed significantly between 2010/11 and all proceeding years, but assemblages sampled in 2011/12 and 2013/14 were not significantly different (B-Y method corrected α = 0.027; Table 3-3).

Table 3-2. PERMANOVA pair-wise comparisons between fish assemblages sampled in 2006/07, 2007/08, 2008/09, 2009/10, 2010/11, 2011/12 and 2013/14 at the Tauwitchere rock ramp (TRR). PERMANOVA was performed on Bray-Curtis similarity matrices. After B-Y method FDR correction α = 0.015.

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	0.003*
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	2007/08	2008/09	1.772	0.007*
TRR	2007/08	2009/10	2.144	0.004*
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	2008/09	2009/10	2.086	0.02 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	0.004*
TRR	2009/10	2010/11	5.303	0.004*
TRR	2009/10	2011/12	5.277	0.007*
TRR	2009/10	2013/14	5.046	0.018 ns
TRR	2010/11	2011/12	2.445	<0.001*
TRR	2010/11	2013/14	2.765	<0.001*
TRR	2011/12	2013/14	1.763	0.002*

Table 3-3. PERMANOVA pair-wise comparisons between fish assemblages sampled in 2006/07, 2007/08, 2008/09, 2009/10, 2010/11, 2011/12 and 2013/14 at the Tauwitchere vertical-slot (TVS), and in 2010/11, 2011/12 and 2013/14 at the Tauwitchere small vertical-slot (TSVS). PERMANOVA was performed on Bray-Curtis similarity matrices. After B-Y method FDR correction α = 0.015 at the vertical-slot and α = 0.027 at the small vertical-slot.

Location	Pairwise comparison		*t*	*p* value
	Year	Year		
TVS	2006/07	2007/08	2.784	<0.001*
TVS	2006/07	2008/09	3.447	<0.001*
TVS	2006/07	2009/10	3.637	0.002*
TVS	2006/07	2010/11	4.527	<0.001
TVS	2006/07	2011/12	3.506	<0.001*
TVS	2006/07	2013/14	1.879	0.005*
TVS	2007/08	2008/09	1.597	0.023 ns
TVS	2007/08	2009/10	2.622	0.036 ns
TVS	2007/08	2010/11	5.45	0.002*
TVS	2007/08	2011/12	4.567	0.007*
TVS	2007/08	2013/14	3.551	0.008*
TVS	2008/09	2009/10	2.439	0.023 ns
TVS	2008/09	2010/11	4.963	0.002*
TVS	2008/09	2011/12	4.439	0.003*
TVS	2008/09	2013/14	3.506	0.008*
TVS	2009/10	2010/11	4.914	0.004*
TVS	2009/10	2011/12	4.232	0.010*
TVS	2009/10	2013/14	3.589	0.015 ns
TVS	2010/11	2011/12	1.665	0.017 ns
TVS	2010/11	2013/14	2.319	<0.001*
TVS	2011/12	2013/14	1.399	0.099 ns
TSVS	2010/11	2011/12	1.793	0.013*
TSVS	2010/11	2013/14	2.310	0.003*
TSVS	2011/12	2013/14	1.476	0.074 ns

SIMPER analysis, adopting a cumulative 40% contribution cut-off for all comparisons, showed 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 (*Retropinna semoni*), estuarine small-mouthed hardyhead (*Atherinosoma microstoma*), lagoon goby (*Tasmanogobius lastii*), blue-spot goby (*Pseudogobius olorum*) and Tamar River goby (*Afurcagobius tamarensis*) and marine migrant sandy sprat (*Hyperlophus vitattus*), 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 preceding and proceeding years due to greater abundances of freshwater species; namely Australian smelt, flat-headed gudgeon (*Philypnodon grandiceps*), bony herring (*Nematalosa erebi*), 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 and 2013/14, with high abundance of Australian smelt and bony herring, together with the estuarine lagoon goby and marine migrant sandy sprat, driving differences in assemblages in these years from preceding years (i.e. 2006–2010). Differences in assemblages between 2010/11, 2011/12 and 2013/14 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 (*Pseudaphritis urvillii*) in 2013/14.

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 years 2011/12 and 2013/14 were not significantly different, but the assemblage sampled in 2013/14 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. Assemblage variation between 2013/14 and 2010/11 was driven by greater abundance of Australian smelt in 2010/11 and greater abundance of catadromous common galaxias and marine migrant sandy sprat in 2013/14.

The difference in fish assemblage structure between 2010/11 and both 2011/12 and 2013/14 at the Tauwitchere small vertical-slot was primarily due to greater abundance of redfin perch in 2010/11 and slightly greater abundance of catadromous common galaxias and congolli in 2011/12 and 2013/14, respectively.

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*) (Table 3-4). In contrast, estuarine, marine migrant and marine straggler species characterised the assemblages in 2007/08 (flat-tailed mullet (*Liza argentea*) and Australian anchovy (*Engraulis australis*)), 2008/09 (black bream (*Acanthopagrus butcheri*)) and 2009/10 (yellowfin whiting (*Sillago schomburgkii*), Australian herring, prickly toadfish (*Contusus brevicaudus*) and mulloway (*Argyrosomus japonicus*)). The assemblage sampled in 2010/11 was characterised by a suite of eight freshwater species including golden perch (*Macquaria ambigua ambigua*), carp gudgeon complex (*Hypseleotris* spp.), bony herring, Australian smelt, flat-headed gudgeon, redfin perch, common carp and goldfish (*Carrasius auratus*)) and one marine migrant species (i.e. southern longfin goby (*Favonigobius lateralis*)). The assemblage in 2011/12 was characterised by the estuarine river garfish (*Hyperhamphus melanchir*), whilst the assemblage in 2013/14 was characterised by the catadromous common galaxias and three estuarine species; Tamar River goby, bridled goby (*Arenogobius bifrenatus*) and long-snouted flounder (*Ammosetris rostratus*).

At the Tauwitchere large vertical-slot, assemblages in 2006/07 were also characterised by the anadromous short-headed lamprey (*Mordacia mordax*) (Table 3-4). There were no significant indicators of the assemblage in 2007/08 and 2008/09, but in 2009/10 the assemblage was characterised by the estuarine resident black bream and small-mouthed hardyhead. Assemblages in 2010/11 were characterised by a range of freshwater species, namely bony herring, Australian smelt, redfin perch and common carp. The assemblage in 2011/12 was characterised by the estuarine river garfish, whilst the assemblage in 2013/14 was characterised by the catadromous congolli and freshwater dwarf flat-headed gudgeon (*Philypnodon macrostomus*).

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 and lagoon goby. There were no significant indicators of the assemblage in 2011/12, but in 2013/14 the assemblage was characterised by the catadromous congolli and common galaxias.

Table 3-4. Indicator species analysis of fish assemblages in the Coorong at the Tauwitchere rock ramp, and large vertical-slot from 2006–2014, 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		**Year**	**Indicator Value**	***p* value**
Tauwitchere rockramp	**Guild**			
Short-headed lamprey	Anadromous	2006/07	45.5	0.015
Australian anchovy	Marine straggler	2007/08	52.8	0.050
Flat-tailed mullet	Marine migrant	2007/08	42.0	0.020
Black bream	Estuarine	2008/09	33.5	0.037
Mulloway	Marine migrant	2009/10	94.0	0.002
Prickly toadfish	Marine straggler	2009/10	93.3	0.002
Yellowfin whiting	Marine straggler	2009/10	62.8	0.004
Australian herring	Marine straggler	2009/10	65.4	0.006
Golden perch	Freshwater straggler	2010/11	63.9	0.014
Carp gudgeon complex	Freshwater straggler	2010/11	88.1	<0.001
Bony herring	Freshwater migrant	2010/11	44.9	0.036
Australian smelt	Freshwater migrant	2010/11	57.0	0.007
Flat-headed gudgeon	Freshwater migrant	2010/11	95.1	<0.001
Redfin perch	Freshwater straggler	2010/11	82.6	0.016
Common carp	Freshwater straggler	2010/11	98.7	<0.001
Goldfish	Freshwater straggler	2010/11	50.5	0.019
Southern longfin goby	Marine migrant	2010/11	88.3	<0.001
River garfish	Estuarine	2011/12	62.6	0.018
Common galaxias	Semi-catadromous	2013/14	69.3	<0.001
Tamar River goby	Estuarine	2013/14	54.7	0.002
Bridled goby	Estuarine	2013/14	54.2	0.017
Long-snouted flounder	Estuarine	2013/14	63.8	0.008
Tauwitchere large vertical-slot				
Short-headed lamprey	Anadromous	2006/07	33.3	0.050
Black bream	Estuarine	2009/10	50.1	0.011
Small-mouthed hardyhead	Estuarine	2009/10	62.0	0.050
Bony herring	Freshwater migrant	2010/11	72.0	0.020
Australian smelt	Freshwater migrant	2010/11	74.0	<0.001
Redfin perch	Freshwater straggler	2010/11	83.7	0.012
Common carp	Freshwater straggler	2010/11	51.3	0.026
River garfish	Estuarine	2011/12	45.4	0.033
Congolli	Semi-catadromous	2013/14	56.1	0.016
Dwarf flat-headed gudgeon	Freshwater straggler	2013/14	40.0	0.033
Tauwitchere small vertical-slot				
Redfin perch	Freshwater straggler	2010/11	99.9	<0.001
Flat-headed gudgeon	Freshwater migrant	2010/11	94.9	<0.001
Blue-spot goby	Estuarine	2010/11	44.4	0.040
Lagoon goby	Estuarine	2010/11	64.9	0.035
Congolli	Semi-catadromous	2013/14	91.4	0.027
Common galaxias	Semi-catadromous	2013/14	74.6	0.020

Goolwa sites

Pair-wise comparisons revealed that fish assemblages sampled at the Goolwa vertical-slot in 2013/14 were not significantly different from those in 2006/07 and 2009/10, but that these years differed significantly from all other years (B-Y method corrected α = 0.015; 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 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 = 0.017; Table 3-5), or between 2009/10 and 2013/14, but all other comparisons were statistically significant.

Table 3-5. PERMANOVA pair-wise comparisons between fish assemblages sampled in 2006/07, 2008/09, 2009/10, 2010/11, 2011/12 and 2013/14 at the Goolwa vertical-slot (GVS) and in 2008/09, 2009/10, 2010/11, 2011/12 and 2013/14 adjacent Goolwa Barrage (GDS). PERMANOVA was performed on Bray-Curtis similarity matrices. After B-Y method FDR correction α = 0.015 at the vertical-slot and α = 0.017 adjacent Goolwa Barrage.

Location	**Pairwise comparison**		***t***	***p* value**
	Year	**Year**		
GVS	2006/07	2008/09	2.805	<0.001*
GVS	2006/07	2009/10	1.72	0.018 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	0.017 ns
GVS	2008/09	2009/10	1.865	0.032 ns
GVS	2008/09	2010/11	3.974	<0.001*
GVS	2008/09	2011/12	3.745	0.003*
GVS	2008/09	2013/14	3.142	0.009*
GVS	2009/10	2010/11	2.64	0.004*
GVS	2009/10	2011/12	3.044	0.016*
GVS	2009/10	2013/14	2.580	0.024 ns
GVS	2010/11	2011/12	1.456	0.057 ns
GVS	2010/11	2013/14	2.089	0.001*
GVS	2011/12	2013/14	1.615	0.008*
GDS	2008/09	2009/10	1.295	0.161 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	0.01*
GDS	2009/10	2010/11	3.334	0.007*
GDS	2009/10	2011/12	2.519	0.006*
GDS	2009/10	2013/14	2.614	0.021 ns
GDS	2010/11	2011/12	2.731	<0.001*
GDS	2010/11	2013/14	2.390	<0.001*
GDS	2011/12	2013/14	1.959	0.005*

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 and 2009/10 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 (*Liza argentea*) and slightly diminished abundance of catadromous congolli and common galaxias relative to 2006/07. Differences in assemblages between 2013/14 and preceding years (with the exception of 2006/07), was primarily due to elevated abundance of the catadromous congolli and common galaxias in 2013/14.

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. Assemblages sampled in 2010/11, 2011/12 and 2013/14 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 in 2011/12 and greater abundance of the catadromous congolli in 2013/14.

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, whilst the assemblage in 2009/10 was characterised by the marine sea sweep (*Scorpis aequipinnis*) and soldier fish (*Gymnapistes marmoratus*), and estuarine small-mouthed hardyhead. The assemblage in 2010/11 was characterised by the estuarine bridled goby and lagoon goby and the 2011/12 assemblage by the freshwater goldfish. The assemblage in 2013/14 was characterised by the catadromous congolli.

The assemblage sampled adjacent Goolwa Barrage in 2008/09 was characterised by the estuarine black bream and marine migrant yellow-eyed mullet (*Aldrichetta forsteri*), 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 four freshwater species, namely carp gudgeon (*Hypseleotris* spp.), Australian smelt, flat-headed gudgeon, and redfin perch and two estuarine species; bridled goby and small-mouthed hardyhead. The assemblage sampled in 2011/12 was characterised by the two marine migrants; mulloway and Australian salmon. The assemblage sampled in 2013/14 was characterised by the catadromous congolli and common galaxias.

Table 3-6. Indicator species analysis of fish assemblages in the Coorong at the Goolwa vertical slot from 2006–2014 and adjacent Goolwa Barrage from 2008–2014. Only significant indicators (i.e. $p < 0.05$) are presented. Species are categorised using estuarine use guilds from Elliott *et al.* (2007).

Species		**Year**	**Indicator Value**	***p* value**
Goolwa vertical-slot	**Guild**			
Short-headed lamprey	Anadromous	2006/07	46.2	0.014
Black bream	Estuarine	2008/09	65.4	0.005
Zebra fish	Marine straggler	2009/10	61.3	0.002
Soldier fish	Marine migrant	2009/10	44.5	0.023
Small-mouthed hardyhead	Estuarine	2009/10	67.4	0.005
Lagoon goby	Estuarine	2010/11	70.2	0.029
Bridled goby	Estuarine	2010/11	55.5	0.030
Goldfish	Freshwater straggler	2011/12	48.6	0.005
Congolli	Semi-catadromous	2013/14	69.8	0.005
Adjacent Goolwa Barrage				
Black bream	Estuarine	2008/09	64.9	0.045
Yellow-eyed mullet	Marine migrant	2008/09	68.1	0.014
Smooth toadfish	Marine migrant	2009/10	96.1	<0.001
Carp gudgeon	Freshwater straggler	2010/11	76.5	0.014
Flat-headed gudgeon	Freshwater migrant	2010/11	93.7	<0.001
Redfin perch	Freshwater straggler	2010/11	85.2	<0.001
Australian smelt	Freshwater migrant	2010/11	79.3	<0.001
Small-mouthed hardyhead	Estuarine	2010/11	78.6	0.011
Bridled goby	Estuarine	2010/11	95.8	<0.001
Mulloway	Marine migrant	2011/12	59.8	0.015
Australian salmon	Marine migrant	2011/12	94.3	<0.001
Common galaxias	Semi-catadromous	2013/14	91.5	<0.001
Congolli	Semi-catadromous	2013/14	94.6	<0.001

Hunters Creek

Pair-wise comparisons revealed that fish assemblages sampled at the Hunters Creek vertical-slot differed significantly between all years (B-Y method corrected α = 0.027) (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. Variation in assemblages between 2011/12 and 2013/14 was primarily driven by greater abundances of the freshwater redfin perch and common carp in 2011/12 and greater abundances of the catadromous congolli in 2013/14. Furthermore, ISA determined that the assemblage sampled in 2010/11 was characterised by the freshwater carp gudgeon and flat-headed gudgeon, and estuarine small-mouthed hardyhead (Table 3-8). In 2011/12 the assemblage was characterised by the freshwater golden perch (*Macquaria ambigua ambigua*) and Australian smelt, whilst there were no significant indicators of the assemblage in 2013/14.

Table 3-7. PERMANOVA pairwise comparisons between fish assemblages sampled in 2010/11, 2011/12 and 2013/14 at the Hunters Creek vertical-slot fishway. PERMANOVA was performed on Bray-Curtis similarity matrices. After B-Y method FDR correction α = 0.027.

Location	**Pairwise comparison**		***t***	***p* value**
	Year	**Year**		
Hunters	2010/11	2011/12	2.209	<0.001*
Hunters	2010/11	2013/14	3.049	<0.001*
Hunters	2011/12	2013/14	2.637	<0.001*

Table 3-8. Indicator species analysis of fish assemblages at the Hunters Creek 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**
Carp gudgeon	Freshwater straggler	2010/11	53.7	0.017
Flat-headed gudgeon	Freshwater migrant	2010/11	92.8	<0.001
Small-mouthed hardyhead	Estuarine	2010/11	66.8	0.046
Golden perch	Freshwater straggler	2011/12	72.0	0.002
Australian smelt	Freshwater migrant	2011/12	53.5	0.028

3.4. Spatial variation in fish assemblages in 2013/14

MDS ordination of fish assemblage data from the vertical-slot fishways exhibited groupings of fish assemblages by capture location (Figure 3-5a), supported by PERMANOVA, which detected significant differences in fish assemblages between capture locations (*Pseudo-*$F_{3, 19}$ = 2.824, $p < 0.001$). Pair-wise comparisons indicated that assemblages sampled at Hunters Creek were different from all other vertical-slot fishways, with the exception of the Tauwitchere small vertical-slot (Table 3-9). All other comparisons were non-significant (Table 3-9). MDS ordination of fish assemblage data from the Tauwitchere rock ramp and adjacent Goolwa Barrage (GDS) exhibited interspersion (Figure 3-5b) and PERMANOVA suggested assemblages sampled from these locations were not significantly different (*Pseudo-*$F_{1, 9}$ = 2.02, $p = 0.074$).

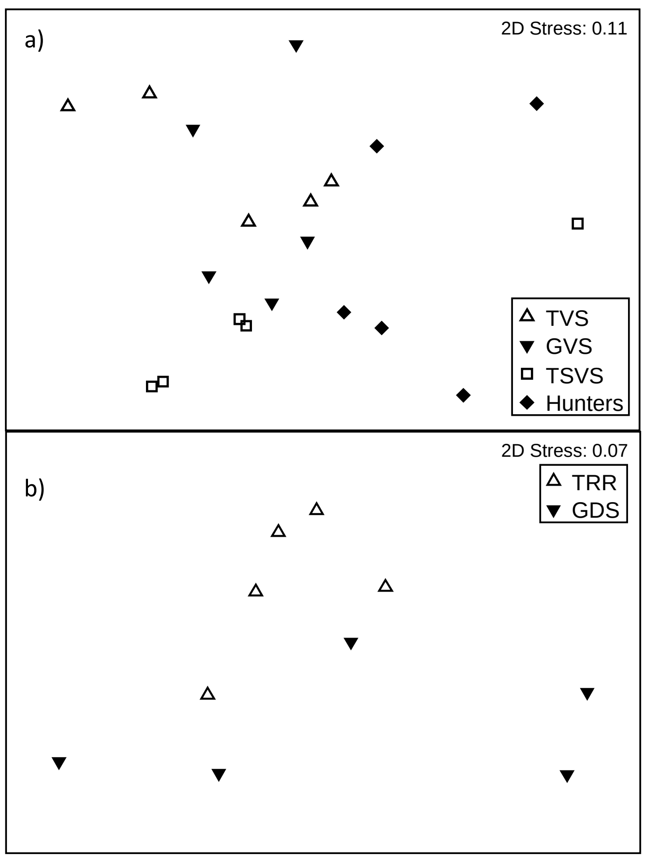

Figure 3-5. MDS ordination plot of fish assemblages sampled at the Tauwitchere large vertical-slot (TVS), Tauwitchere rock ramp (TRR), Tauwitchere small vertical-slot (TSVS), Goolwa vertical-slot (GVS), adjacent Goolwa Barrage (GDS) and Hunters Creek vertical-slot (Hunters) in 2013/14.

Table 3-9. PERMANOVA pair-wise comparisons of fish assemblages from the Tauwitchere rock ramp (TRR), Tauwitchere large vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS), Goolwa vertical-slot (GVS), adjacent Goolwa Barrage (GDS) and Hunters Creek vertical-slot (Hunters) in 2013/14. PERMANOVA was performed on bray-curtis similarity matrices. B-Y method corrected α = 0.02.

Pairwise comparison		***t***	***p* value**
Location	**Location**		
TVS	GVS	0.896	0.582 ns
TVS	TSVS	1.658	0.033 ns
TVS	Hunters	2.029	0.009*
GVS	Hunters	1.823	0.007*
GVS	TSVS	1.589	0.044 ns
Hunters	TSVS	1.802	0.026 ns

Indicator species analysis was used to determine species that characterised assemblages at the different vertical-slot fishways in 2013/14. Of 30 species sampled, three were deemed to be significant indicators of the fish assemblage at a particular location (Table 3-10). The freshwater common carp and estuarine lagoon goby characterised the assemblage at the Tauwitchere large vertical-slot, whilst the freshwater Australian smelt characterised the assemblage at the Tauwitchere small vertical-slot rock ramp site.

Table 3-10. Indicator species analysis of fish assemblages in the Coorong at the Tauwitchere rockramp (TRR), Tauwitchere vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS), Goolwa vertical-slot (GVS), Hindmarsh Island abutment site immediately downstream of the Goolwa Barrage (GDS) and Hunters Creek vertical-slot (Hunters) in 2013/14.

Species		**Location**	**Indicator Value**	***p* value**
Common carp	Freshwater straggler	TVS	64.6	0.017
Lagoon goby	Estuarine	TVS	94.1	0.010
Australian smelt	Freshwater migrant	TSVS	94.1	0.018

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

Inter-annual variation in abundance

Lamprey

No short-headed lamprey (*Mordacia mordax*) or pouched lamprey (*Geotria australis*) were captured during sampling in spring/summer 2013/14. Nevertheless, two individual pouched lamprey were captured at the Goolwa vertical-slot fishway during targeted sampling in June/July 2013 (Figure 3-6a). This species was sampled in similarly low numbers in 2006/07, from the Tauwitchere rock ramp, but was sampled in greater abundance, across four locations in 2011/12. Short-headed lamprey, sampled in moderate abundance across three locations in 2006/07, were sampled in low abundance adjacent Goolwa Barrage in 2011/12 but were absent from all sampling in 2013/14 (Figure 3-6b).

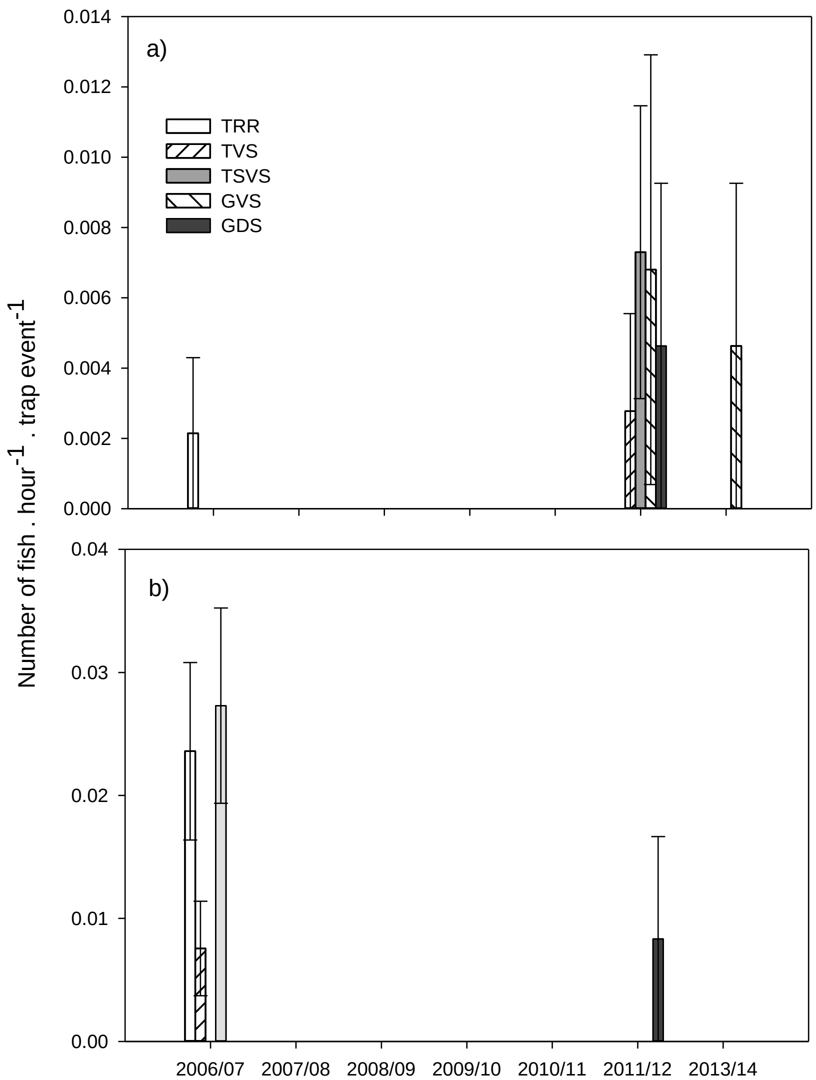

Figure 3-6. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of a) pouched lamprey and b) short-headed lamprey at the Tauwitchere rock ramp (TRR), Tauwitchere large vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS), Goolwa vertical-slot (GVS) and adjacent Goolwa Barrage (GDS) from 2006–2014. 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.

Congolli and common galaxias

The abundance of the catadromous congolli and common galaxias differed significantly between years at the Tauwitchere rock ramp, Tauwitchere vertical-slot, Goolwa vertical-slot and adjacent Goolwa Barrage (Table 3-11). The abundances of congolli recorded in 2013/14 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. Slight increases in abundance were evident in 2010/11, except at the Tauwitchere rock ramp and adjacent Goolwa Barrage, where abundances increased substantially. Abundances remained similar at these two sites in 2011/12 but increased further at both the Tauwitchere large vertical slot and Goolwa vertical-slot, returning to levels similar to those recorded in 2006/07. Abundances increased further at all sites in 2013/14.

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 2006–2014 at the Tauwitchere rock ramp (TRR), Tauwitchere vertical-slot (TVS), Goolwa vertical-slot (GVS) and adjacent Goolwa Barrage (GDS). PERMANOVA was performed on Euclidean Distance similarity matrices. A = 0.05.

		Congolli		**Common galaxias**	
Site	**df**	***Pseudo-F***	***P* value**	***Pseudo-F***	***P* value**
TRR	6, 90	29.88	<0.001*	25.79	<0.001*
TVS	6, 106	17.12	<0.001*	43.73	<0.001*
GVS	5, 107	18.47	<0.001*	4.10	0.003*
GDS	4, 38	11.97	<0.001*	17.27	<0.001*

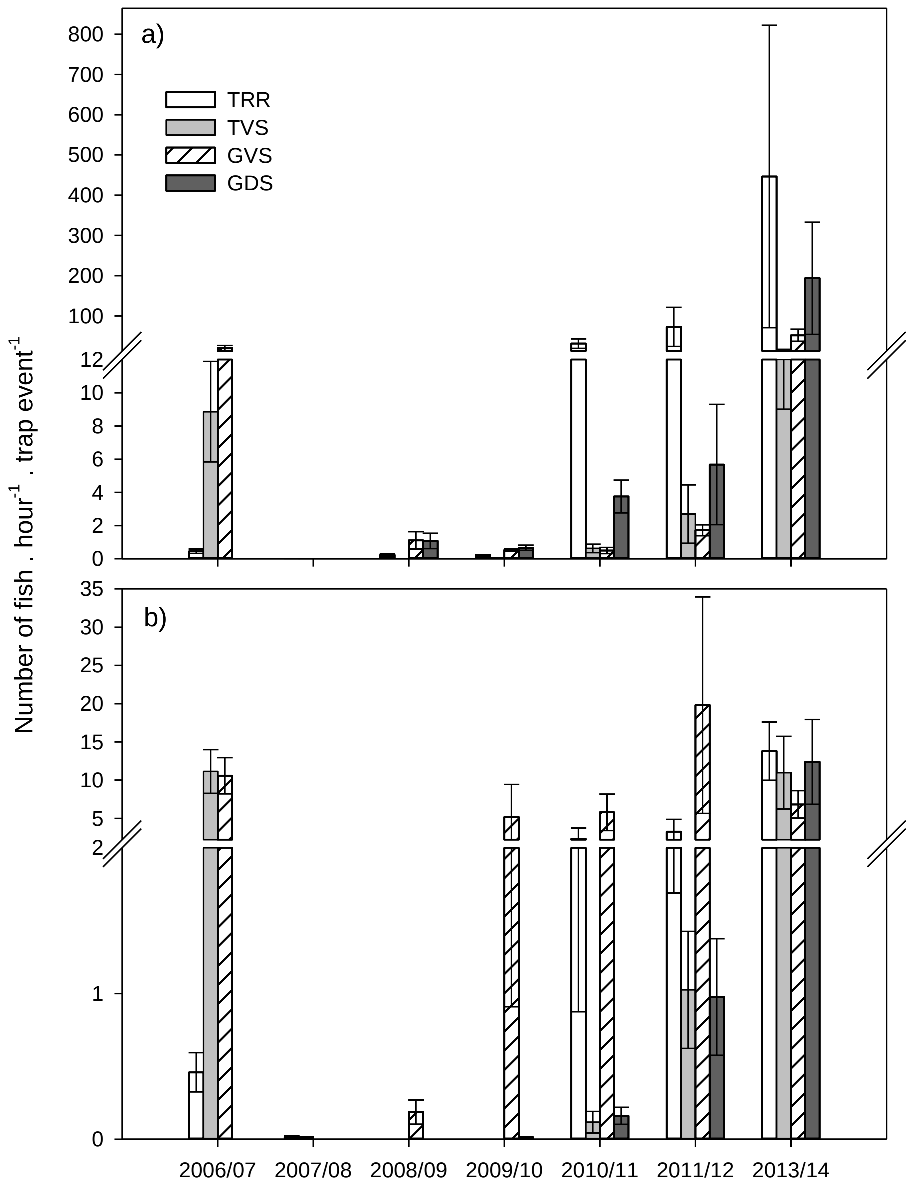

Figure 3-7. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of a) congolli and b) common galaxias at the Tauwitchere rock ramp (TRR), Tauwitchere vertical-slot (TVS), Goolwa vertical-slot (GVS) and the Hindmarsh island abutment site immediately downstream of the Goolwa Barrage (GDS) from 2006–2014. Goolwa vertical-slot was not sampled in 2007/08 and the Hindmarsh island abutment site immediately downstream of the Goolwa Barrage was not sampled in 2006/07 and 2007/08. All sites were not sampled in 2012/13. The Hunters Creek vertical-slot and Tauwitchere small vertical-slot were not included in these analyses as they have only been sampled since 2010.

A similar pattern was evident for common galaxias in 2013/14, which was sampled in greatest abundances, relative to all previous years, at the Tauwitchere rock ramp and adjacent Goolwa Barrage. Abundances at the large vertical-slots at Tauwitchere and Goolwa, however, were similar to those recorded in 2006/07 (Figure 3-7b). 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 year, with further increases in abundance occurring at the Tauwitchere rock-ramp, Tauwitchere large vertical-slot, and adjacent Goolwa Barrage in 2011/12 and then 2013/14.

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*-$F_{4,\ 14}$ = 5.24, p = 0.017), Tauwitchere small vertical-slot (*Pseudo*-$F_{4,\ 14}$ = 6.62, p = 0.014) and Hunters Creek vertical-slot (*Pseudo*-$F_{4,\ 14}$ = 18.30, p = 0.002), but not at the Tauwitchere large vertical-slot (*Pseudo*-$F_{4,\ 13}$ = 2.51, p = 0.131). 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 the greatest number of congolli detected at all sites in December, with moderate abundances in both November and January, and low numbers in October and February (Figure 3-8a). Whilst abundance did vary between sites, congolli was most abundant at both Tauwitchere and Goolwa barrages, with lower numbers sampled at Hunters Creek.

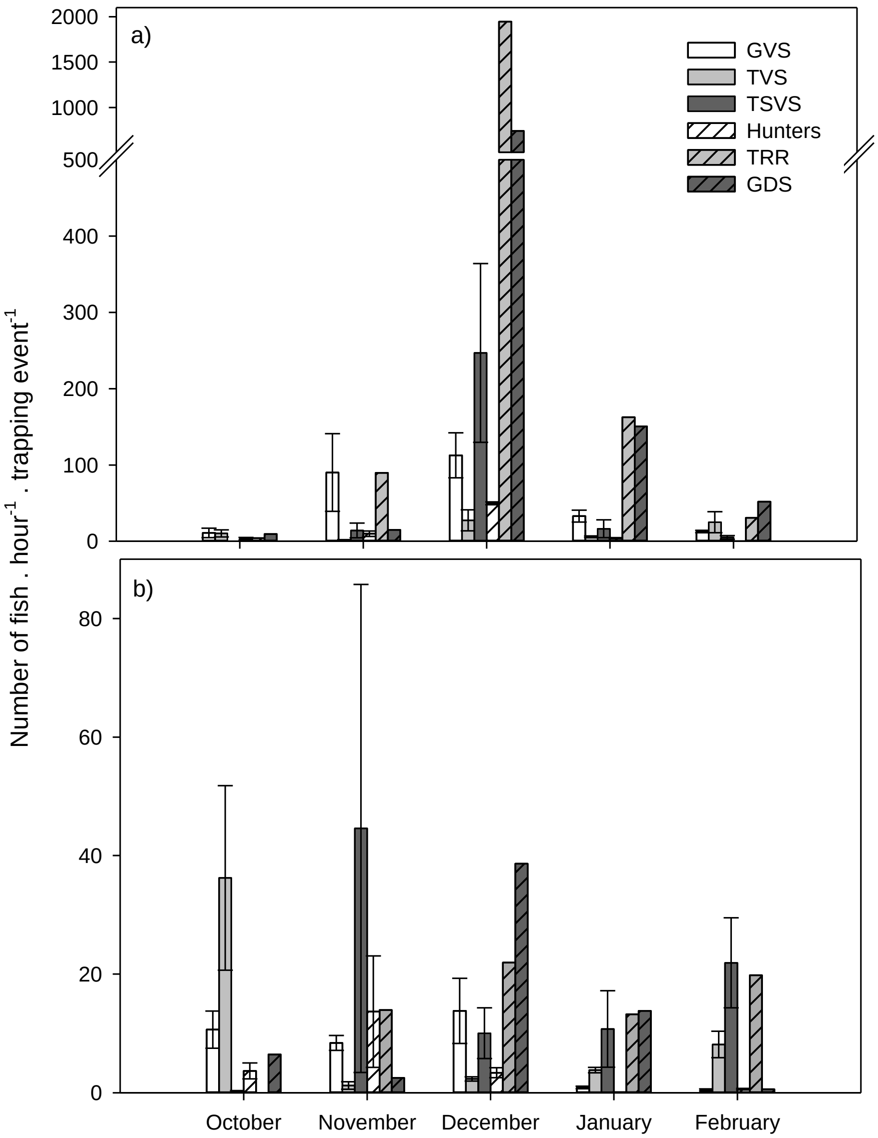

Figure 3-8. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of a) congolli and b) common galaxias at the Hindmarsh island abutment site immediately downstream of the Goolwa Barrage (GDS), Goolwa vertical-slot (GVS), Tauwitchere rock ramp (TRR), Tauwitchere vertical-slot (TVS), Tauwitchere small vertical-slot (TSVS) and Hunters Creek vertical-slot (Hunters) from October 2013–February 2014.

The abundance of upstream migrating common galaxias was significantly different between months at the Goolwa vertical-slot (*Pseudo*-$F_{4, 14}$ = 17.32, p = 0.002), Tauwitchere large vertical-slot (*Pseudo*-$F_{4, 14}$ = 11.29, p < 0.001) and Hunters Creek vertical-slot (*Pseudo*-$F_{4, 14}$ = 6.50, p = 0.002), but not at the Tauwitchere small vertical-slot (*Pseudo*-$F_{4, 13}$ = 2.77, p = 0.091). 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 at Goolwa, but was similar between months at the Tauwitchere rock ramp. In contrast to congolli, intra-annual variation in abundance did not follow a consistent pattern across sites (Figure 3-8b). The abundance of common galaxias peaked at the Tauwitchere rock ramp, Goolwa vertical-slot and adjacent Goolwa Barrage in December, at the Tauwitchere large vertical-slot in October, and at both the Tauwitchere small vertical-slot and Hunters Creek vertical-slot in November. Similar to congolli, whilst there were specific spatial differences in abundance, common galaxias were moderately to highly abundant at all sites.

Below Tauwitchere Barrage (Tauwitchere rock ramp, large vertical-slot and small vertical-slot data combined) in October and November 2013, congolli exhibited broad length distributions (i.e. 19–171 mm TL and 22–201 mm TL respectively) (Figure 3-9a). A newly recruited 0+ year cohort ranging 19–42 mm TL (whilst fish were not aged in 2013/14, fish of this size have been determined to represent a 0+ cohort in previous years; see Bice *et al.* 2012) was present in October 2013, comprising ~48% of the sampled population. This cohort increased in both size and dominance of the sampled population throughout sampling period, representing ~60% of the population by November 2013. Abundance peaked in December 2013 (Figure 3-8a), with the 0+ cohort representing >90% of the sampled population. Further growth of this cohort was evident in January and February 2014, when abundance began to decrease, but the 0+ cohort still comprised >90% of the population.

A similar pattern was evident below Goolwa Barrage (vertical-slot and adjacent Goolwa Barrage data combined), but larger fish (i.e. >100 mm TL) comprised a smaller proportion of the population in October and November 2013 than at Tauwitchere (Figure 3-9a&b). In October 2013, a 0+ cohort, ranging 16–42 mm TL, was present and comprised >90% of the population. Growth of this cohort was evident through the following months, comprising ~90% and ~95% of the population in November and December respectively. Similar to Tauwitchere, abundance began to decline in January, but the proportion of the population represented by the 0+ cohort was maintained at >95%.

Dissimilar to both Tauwitchere and Goolwa, the 0+ cohort of congolli (<60 mm TL) was dominant throughout 2013/14 sampling at Hunters Creek, with no fish sampled >100 mm TL for the entire sampling season (Figure 3-9c). Indeed the 0+ cohort represented 95–100% of the sampled population during all sampling events. This is, however, not unexpected given all fish sampled at this site were sampled within the entrance of the fishway hence are undertaking 'driven' upstream migrations (i.e. typically juveniles). 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. As per the previous two locations, growth of the 0+ cohort was clearly evident through the sampling season, with abundance peaking in December (*n* = 3490), before declining through January and February.

Common galaxias ranged 30–103 mm TL at Tauwitchere in October 2013 but a 0+ cohort (30–45 mm TL; whilst fish were not aged in 2013/14, fish of this size have been determined to represent a 0+ cohort in previous years; see Bice *et al.* 2012) comprised ~98% of the sampled population (Figure 3-10a). Whilst, abundance peaked in November (*n* = 3747), the species was abundant (e.g. >1000 individuals sampled per month) throughout the sampling season. The size of the 0+ cohort lengthened and broadened through the sampling season, suggesting a protracted spawning season, and represented >90% of the sampled population in each sampling month.

At Goolwa in October 2013, the length range (35–58 mm TL) of the 0+ cohort of common galaxias was greater than that at Tauwitchere, but also comprised >95% of the sampled population (Figure 3-10b). Abundance peaked in December 2013 (*n* = 1627), before declining through January and February. As at Tauwitchere, 0+ fish (<60 mm TL) dominated the sampled population throughout sampling, comprising >90% from November 2013 through January 2014, and >70% of the sampled population in February 2014.

The length-frequency distributions for common galaxias at Hunters Creek in 2013/14 were similar to Tauwitchere and Goolwa, in that the 0+ cohort (<60 mm TL) comprised >80% of the sampled population in all months (Figure 3-10c). Abundance peaked at Hunters Creek in November (*n* = 792), similar to Tauwitchere, but earlier than at Goolwa.

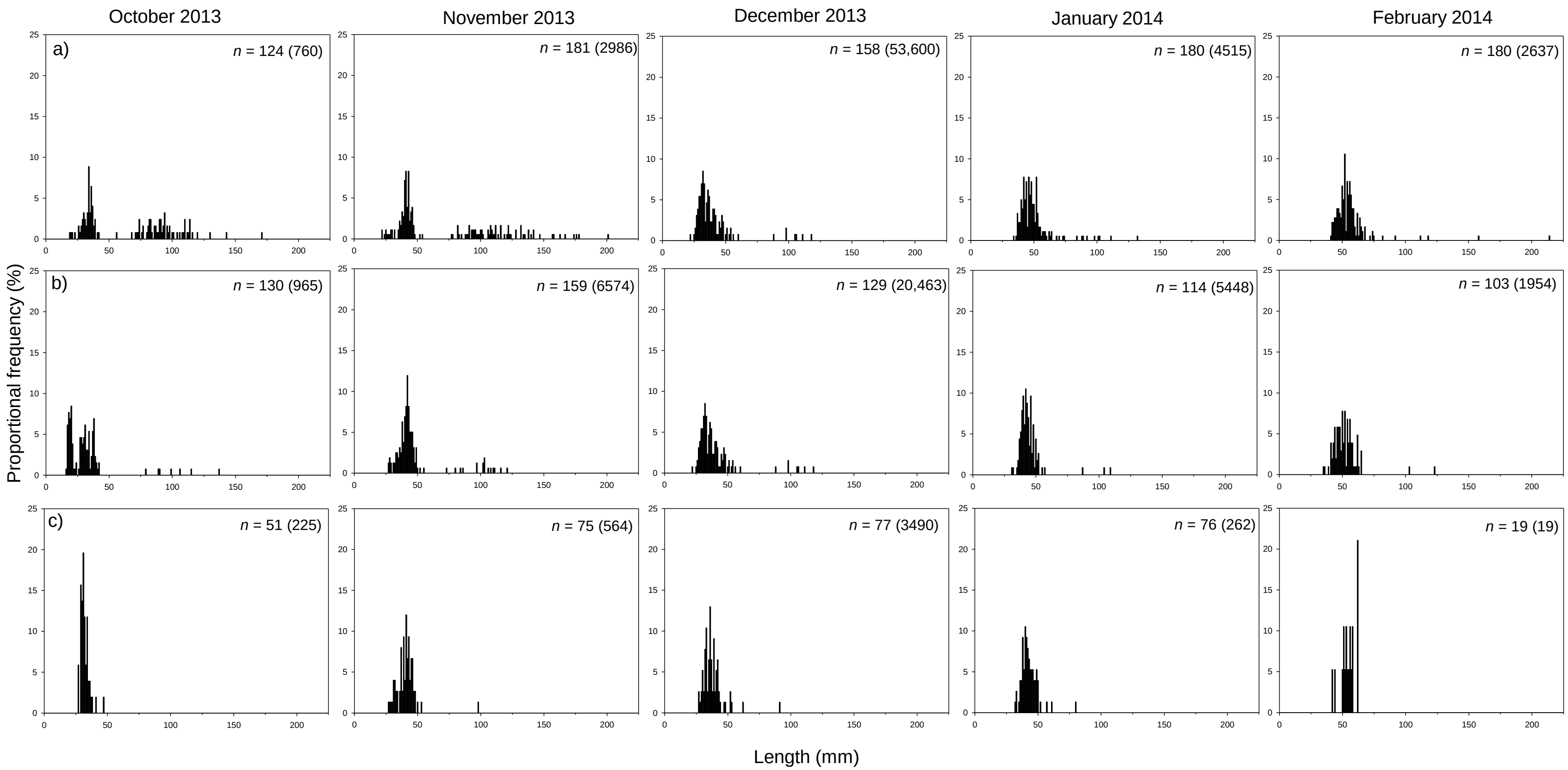

Figure 3-9. Monthly length-frequency distributions (total length, mm) of congolli sampled below a) Tauwitchere Barrage (rock ramp, large vertical-slot and small vertical-slot combined) b) Goolwa Barrage (vertical-slot and adjacent Goolwa Barrage combined) and c) at the entrance of the Hunters Creek vertical-slot from October 2013–February 2014. *n* is the number of fish measured and the total number of fish collected in each month at each site is presented in brackets.

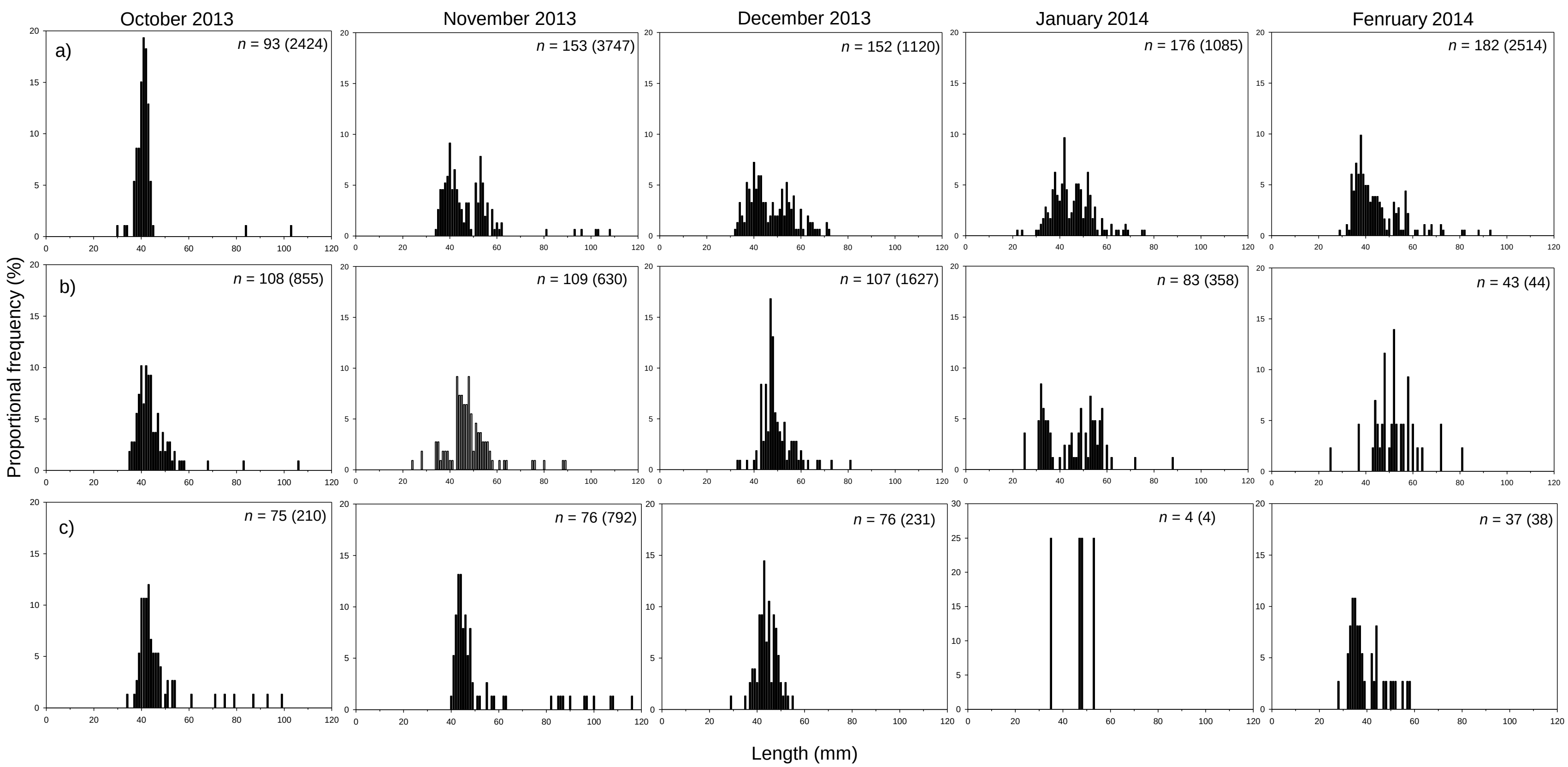

Figure 3-10. Monthly length-frequency distributions (total length, mm) of common galaxias sampled below a) Tauwitchere Barrage (rock ramp, large vertical-slot and small vertical-slot combined) b) Goolwa Barrage (vertical-slot and adjacent Goolwa Barrage combined) and c) at the entrance of the Hunters Creek vertical-slot from October 2013–February 2014. *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 led to the cessation of freshwater discharge to the Coorong, disconnection of the Lower Lakes and Coorong, and elevated estuarine salinities, to the detriment of a range of native flora and fauna (Kingsford *et al.* 2011). Nonetheless, 2013/14 represented the fourth consecutive year of continuous freshwater discharge to the Coorong, promoting connectivity between the Coorong and Lower Lakes and persistence of an estuarine salinity gradient (predominantly 'brackish') in the Coorong estuary. These conditions were reflected in the structure of fish assemblages in 2013/14, which were 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 2013/14, 30 fish species, representing 20 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). It contrasts the depauperate assemblage during the extended period (2007–2010) of no freshwater release 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 also highly 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 2013/14 was similar to that in 2011/12, excepting lower total fish abundance in 2013/14 (particularly due to lower abundances of sandy sprat) and increased abundance of catadromous species. Despite declines in abundance relative to 2011/12, the marine migrant sandy sprat dominated the catch (~53% of the total 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, 2010/11, 2011/12 and 2013/14) and lowest during years of low or zero freshwater inflow (2007–2010) (Zampatti *et al.* 2011a, Bice *et al.* 2012, Zampatti *et al.* 2012). 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 autochthonous production of zooplankton as a result of elevated phytoplankton and nutrient loads (Aldridge and Brookes 2011, Shiel and Aldridge 2011). The species was most abundant in 2011/12 and whilst still abundant in 2013/14, declines relative to 2011/12 may reflect declining freshwater discharge and estuarine productivity.

Studies in other parts of southern Australia have shown sandy sprat to be an important food source for larger piscivorous fishes (e.g. Australian salmon; Hoedt and Dimmlich 1994) and piscivorous birds such as little penguins (*Eudyptula minor*; Klomp and Wooller 1988) and little terns (*Sterna albifrons sinensis*; Taylor and Roe 2004). Deegan *et al.* (2010) also present some evidence suggesting that sandy sprat is preyed upon by both mulloway and black bream within the Coorong. Given the high abundance of this species, it is likely to be important to trophic dynamics within the Coorong, particularly in the River Murray estuary reach (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 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 2006–2014, 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 and 2013/14, 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 2013/14, 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 except the Tauwitchere small vertical-slot. Hunters Creek is a small stream (~5 m wide) and thus, during times of freshwater discharge, is characterised by generally 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. Similarities in the assemblages at this fishway and the Tauwitchere small vertical-slot are likely a result of similarities in the design of these fishways (i.e. to produce low velocities) and target of facilitating the passage of small-bodied (<150 mm TL) fish.

Whilst not compared statistically, the assemblages sampled at the vertical-slot fishways and sites adjacent the barrages (i.e. the 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, Bice *et al.* 2012, Zampatti *et al.* 2012). Indeed, species richness and overall fish abundance varied from 11 species at the Tauwitchere small vertical-slot and 6145 individuals (1% of all fish sampled in 2013/14) at the entrance of the Hunters Creek vertical-slot to 25 species and 243,300 individuals (42% of all fish sampled in 2013/14) 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 2013/14, but two individual pouched lamprey were sampled at the Goolwa vertical-slot fishway during specific monitoring in June/July 2013. Failure to detect lamprey species in spring/summer is not surprising 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 over the winter period.

Despite the low numbers of lamprey, further records of the species from the region in June/July 2013 are encouraging following an extended absence from sampling from 2007–2011 (Bice *et al.* 2012). Relative abundance remains lower than recorded in 2006/07 (Bice *et al.* 2007), but as these species are generally rare, determining trends in abundance is difficult. Both short-headed and pouched lamprey do not metamorphose into adult forms and migrate downstream until 3–4 years of age and the age of adults during upstream migrations is unclear. Given the potentially long lifespan of these species, it may take several years for numbers to return to that observed pre-2007.

Abundances of congolli in 2013/14, at all sampling locations, were the highest recorded since the inception of this monitoring program in 2006/07 (Zampatti *et al.* 2010, 2011a, Bice *et al.* 2012). Indeed, congolli was the second most abundant species sampled in 2013/14 after sandy sprat. Common galaxias was also highly abundant, sampled in the greatest abundances at the Tauwitchere rock ramp and adjacent Goolwa Barrage, relative to all previous sampling years. Whilst no ageing of fish was conducted in 2013/14, length-at-age data from previous years (Zampatti *et al.* 2010, 2011a, Bice *et al.* 2012), indicate the vast majority of individuals sampled for both species were newly recruited young-of-the-year (YOY).

Successful recruitment of catadromous species in 2013/14 was likely a result of high levels of hydrological connectivity between freshwater and marine environments throughout 2013/14 and potentially, increased spawning and/or survival of larvae and juveniles under brackish salinities (Whitfield 1994, Gillanders and Kingsford 2002). Increased abundance in 2013/14, relative to other years with freshwater discharge and high levels of connectivity (2010/11 and 2011/12), was likely due to the cumulative benefits of multiple consecutive years of such conditions. The lack of connectivity and reduced recruitment of congolli from 2007–2010 may have resulted in a limited 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 2013 was likely abundant and comprised, in part, of fish that were recruited in 2010/11. 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 2013 (Wedderburn and Barnes 2013, 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.

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

Data collected from this project from 2006–2014 ((Bice *et al.* 2007, Jennings *et al.* 2008a, Zampatti *et al.* 2010, 2011a, Bice *et al.* 2012, Zampatti *et al.* 2012) 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 prioritized for freshwater releases and fishway operation.

Newly recruited YOY congolli and common galaxias migrate upstream during spring/summer, but there are subtle differences in the timing of peak migration. Peak migration of congolli in 2013/14 occurred at all sites during December, with moderate abundance in November and January. This is in concurrence with monitoring during previous years of freshwater flow and connectivity (i.e. 2006/07 and 2010–2012) when peak abundances were observed in November and December (Bice *et al.* 2007, Bice *et al.* 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, as well as at Hunters Creek, potentially reflects consistent freshwater discharge, and thus attraction, at all 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 successfully facilitate the upstream passage of YOY common galaxias and congolli and thus releases should be prioritised to these two barrages. Fishways have yet to be 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) as any discharge will result in the attraction and subsequent accumulation of individuals below these barriers.

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). Fishways must be operated and where possible, attraction flow provided from barrage gates adjacent to each fishway. If discharge is being decreased at Tauwitchere, gates adjacent the small vertical-slot fishway should be the last to be 'shut-down' as this fishway is the most effective at passing small-bodied fishes and thus, attraction flow at this fishway should be maintained.
2) Freshwater discharge and operation of all fishways on Goolwa and Tauwitchere Barrages from June–August to facilitate the downstream spawning migrations of congolli and common galaxias and the upstream spawning migrations of lamprey species. In addition to the fishways, barrage gates should also 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 2013/14, 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. CONCLUSIONS

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. Over a four year period (2006/07–2009/10), 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 2013/14 represented the fourth consecutive year of consistent freshwater inflows and high levels of hydrological connectivity following the no flow period and discharge of large volumes of freshwater in 2010/11. Whilst less freshwater was discharged in 2013/14 relative to 2010–2013, 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.

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 2013/14, high levels of connectivity and freshwater inflows throughout 2013/14 likely facilitated protracted spawning seasons and provided conditions conducive to larval/juvenile survival and subsequently recruitment. Furthermore, successful recruitment in 2010/11 likely led to increases in the adult spawning population of 2013, which in turn led to increased spawning output and subsequent peak abundance of catadromous species in 2013/14. 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 2013/14. 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. Due to the temporal variability in freshwater discharge from the River Murray (Puckridge *et al.* 1998) and the dynamism inherent to estuarine systems, typical baselines or 'absolute standards' are not applicable to estuarine associated fishes in the

Coorong (Sheaves *et al.* 2012). Rather, change in assemblage structure due to management interventions or the use of fish as indicators of ecosystem 'health' in the Coorong, requires knowledge of a historical sequence of assemblage structure and population dynamics. The data analysed in this project represents such knowledge and synthesis of these data into a series of meaningful flow-related 'references', using appropriate metrics (e.g. species richness, probability of encounter and/or relative abundance) is a priority.

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