Fish assemblage response and fishway effectiveness at Goolwa, Tauwitchere and Hunters Creek Barrages in 2010/11

B.P. Zampatti, C.M. Bice and P.R. Jennings

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PO Box 120 Henley Beach SA 5022

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South Australian Research and Development Institute
SARDI Aquatic Sciences
2 Hamra Avenue
West Beach SA 5024

Telephone: (08) 8207 5400
Facsimile: (08) 8207 5406
http://www.sardi.sa.gov.au

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Author(s):	B.P. Zampatti, C.M. Bice and P.R. Jennings
Reviewer(s):	S. Gehrig, J. Nicol and A. Frears
Approved by:	Dr Q. Ye Science Leader – Inland Waters & Catchment Ecology
Signed:	
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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 inflow and tidal regime determine estuarine salinities, which in turn influence the structure of fish assemblages. Estuaries can support diverse fish assemblages which are characterised by a spatio-temporally variable mix of freshwater, 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 Coorong estuary lies at the terminus of Australia's largest river system, the Murray-Darling. The river system 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 richness, 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 and common galaxias were significantly reduced, and migration and spawning seasons contracted. In an attempt to facilitate spawning of congolli in the absence of freshwater flows, the Goolwa Barrage boat lock was operated to enable the downstream passage of female congolli from late July to early September 2010.

Extensive rainfall in the Murray-Darling Basin in winter/spring 2010, led to the resumption of freshwater flow to the Coorong and a prolonged period (September 2010 – April 2011) of high freshwater discharge. In conjunction with increased freshwater flow, the South Australian Department for Water (DFW) and Department of Environment and Natural Resources (DENR) proposed a series of hypotheses generally relating to fish movement through fishways and the response of estuarine fish assemblages to resumption of freshwater flows. In order to address these hypotheses the broad objective of this study was to investigate fish assemblage structure

and movement, and recruitment of diadromous fish, using the barrage fishways as a ready-made sampling tool. We specifically aimed to:

1. Determine the species composition, and spatial and temporal variability of fish assemblages immediately downstream of the barrages and/or attempting to move between the Coorong and Lower Lakes via the barrage fishways.
2. Investigate the ecological response (i.e. spawning and recruitment) of diadromous fish to freshwater inflows.
3. Establish the effectiveness of the modified Goolwa vertical-slot fishway to facilitate the passage of juvenile congolli and the effectiveness of the low discharge/turbulence fishways at Hunters Creek and Tauwitchere to facilitate the passage of all species of fish attempting to migrate from the Coorong to the Lower Lakes.

As freshwater inflows to the Coorong resumed in late 2010, salinities downstream of the barrages decreased. Fish assemblages differed from the period 2006 – early 2010, due to increased abundances of freshwater species and estuarine lagoon goby, and decreased abundances of marine and some estuarine species. Abundances of congolli and common galaxias also increased significantly but anadromous lampreys were not collected. Fish assemblages differed significantly between sites, highlighting the spatially variable nature of fish assemblages in the Coorong. Nevertheless, spatial differences in fish assemblages in the Coorong are also variable across a range of temporal scales. Consequently, we recommend that decisions regarding the release location of water from the barrages for ecological outcomes are not based on data from 2010/11 alone but instead involve ongoing consultation with fish ecologists.

As freshwater inflows into the Coorong resumed, abundances of congolli and common galaxias increased significantly. High abundances of young-of-year (YOY) individuals were most likely a result of improved connectivity between freshwater and marine environments, and increased spawning and/or survival of larvae under brackish salinities. The significant increase in abundance of YOY congolli in 2010/11 may also be attributable to the facilitation of the downstream movement of female congolli via the operation of the Goolwa Barrage boat lock.

The Tauwitchere and Hunters Creek small vertical-slot fishways, and the modified full-depth Goolwa large vertical-slot fishway, effectively facilitated the passage of a broad range of species and sizes of fish. No significant difference was observed in the relative abundance of species, or size ranges (with the exception of Australian smelt) between entrance and exit samples at Tauwitchere and Hunters Creek small vertical-slot fishways suggesting these structures have significantly enhanced fish passage at the Murray Barrages and complement the existing larger vertical-slot fishways. Despite unresolvable problems with effectively trapping the exit of the Goolwa large vertical-slot fishway, it performed substantially better than the original partial depth, 300 mm slot fishway, particularly for small – medium bodied fish. Importantly, the modified fishway facilitated the movement of large numbers of YOY common galaxias and congolli.

The results of this investigation support the hypotheses that (1) diadromous and estuarine species, including high abundances of juvenile congolli, would recruit and utilise the Goolwa Barrage fishway to migrate between the Coorong and Goolwa Channel following an extended period of disconnection and no-flow, (2) diadromous and estuarine fish would move between the Coorong and Lake Alexandrina and (3) fish species would be able to complete their life-cycles during and following freshwater releases. Following high end-of-system flows in the MDB in 2010/11, fish assemblages in the Coorong estuary, immediately downstream of the barrages, trended towards the diverse but variable fish assemblages that characterise dynamic estuarine environments. Furthermore, populations of catadromous congolli and common galaxias in the MDB are in the early stages of recovery following significant declines in recruitment and abundance from 2007 – 2010. Importantly, continuing freshwater flow and connectivity between the Lower Lakes and the Coorong will be essential for the restoration of populations of diadromous and estuarine species and maintaining dynamism in estuarine fish communities.

1 Introduction

Estuaries form a dynamic interface and important conduits 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). Freshwater inflow and tidal regime determine estuarine salinities, influencing the structure of fish assemblages, which inturn 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 Coorong estuary in south-eastern Australia lies at the terminus of Australia's largest river system, the Murray-Darling. 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 river mouth (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 (Murphy and Timbal 2008). 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 of > 1.5 m and the cessation of freshwater flow to Coorong estuary . Disconnection of the Coorong from the freshwater Lower Lakes resulted in increases in estuarine salinities and a concomitant decrease in fish species richness (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, freshwater, diadromous and estuarine species were lost and marine species became more common (Zampatti *et al.* 2010).

As freshwater inflows into the Coorong reduced the abundance of diadromous species decreased dramatically. For instance, in 2006 anadromous short-headed and pouched lampreys were collected when the Coorong and Lower Lakes were hydrologically connected. Both species, however, disappeared from the catch when freshwater inflow ceased. Catadromous congolli and common galaxias exhibited high inter-annual variations in recruitment, with significant declines in the abundance of young-of-the-year migrants and contraction of migration and spawning periods associated with cessation of freshwater flow to the Coorong and loss of longitudinal connectivity (Zampatti *et al.* 2011).

In an effort to restore connectivity between the Lower Lakes and Coorong in the absence of freshwater flows, and to potentially facilitate congolli spawning, the Goolwa Barrage boat lock was operated to enable the downstream passage of reproductively mature female congolli from late July to early September 2010. Subsequently, extensive rainfall in the Murray-Darling Basin, commencing in winter 2010, led to the resumption of freshwater flow from the Lower lakes to the Coorong and a prolonged period (September 2010 – April 2011) of large volumes (peaking at ~80,000 ML.day^{-1}) of freshwater discharge through the barrages and fishways.

The South Australian Department for Water (DFW) and Department of Environment and Natural Resources (DENR) proposed five hypotheses/questions relating to the resumption of freshwater flow through the barrages. In reference to releases of water through the Goolwa Barrage and the Goolwa Vertical slot fishway it was expected that:

1. High abundances of juvenile congolli would utilise the Goolwa Barrage fishway to migrate upstream between the Coorong and Goolwa Channel following an extended period of disconnection and no-flow.
2. Diadromous and estuarine species would recruit and utilise the Goolwa Barrage fishway to migrate between the Coorong and Goolwa Channel following an extended period of disconnection and no-flow.

In reference to releases of water through Tauwitchere Barrage and Hunters Creek and through fishways associated with these structures:

3. Diadromous and estuarine fish would move between the Coorong and Lake Alexandrina.
4. Will species be able to complete their life-cycles during and following releases?
5. Is it possible to assess which release location elicited the best biotic response?

In order to addresses the proposed hypotheses/questions, the broad objective of this study was to investigate fish assemblage structure and migration, and recruitment of diadromous fish, in response to the restoration of freshwater inflow to the Coorong. Using the barrage fishways as a ready-made sampling tool we specifically aimed to:

1. Determine the species composition, and spatial and temporal variability of fish assemblages immediately downstream of the barrages and/or attempting to move between the Coorong and Lower Lakes via the barrage fishways.

2. Investigate the ecological response (i.e. spawning and recruitment) of diadromous fish to freshwater inflows.

3. Establish the effectiveness of the modified Goolwa vertical slot fishway to facilitate the passage of juvenile congolli and the effectiveness of the low discharge/turbulence fishways at Hunters Creek and Tauwitchere to facilitate the passage of all species of fish attempting to migrate from the Coorong to the Lower Lakes.

2 Methods

2.1 Study Site

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 Murray-Darling Basin (MDB) drains an area of ~1,073,000 km^2 and the combined length of the two major rivers, the Murray and the Darling, is ~5,500 km. 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 (Figure 2-1). 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 over the past decade this has been substantially less and zero on three occasions (Figure 2-2).

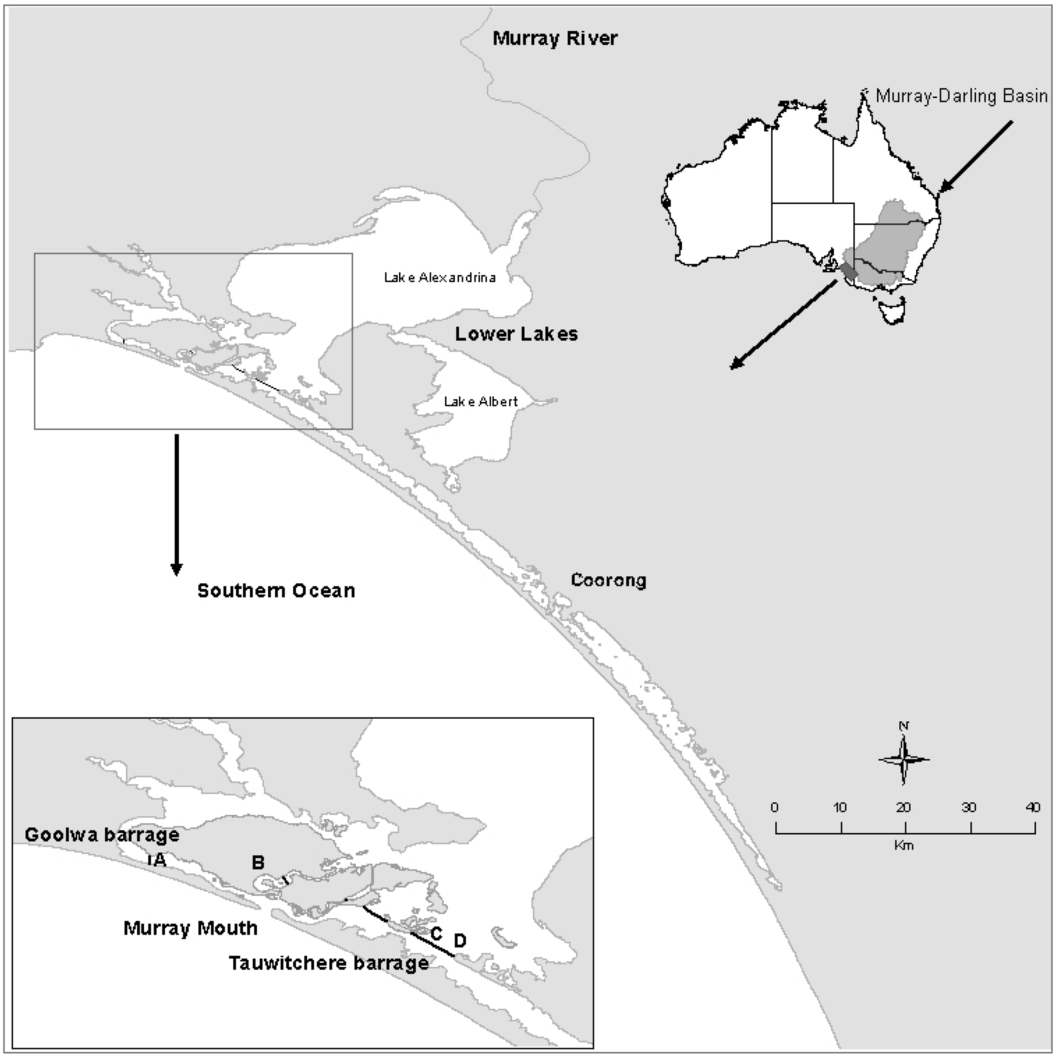

Figure 2-1 A map of the Coorong and Lower Lakes (Lakes Alexandrina and Albert) at the terminus of the Murray River, southern Australia showing the study area in the Coorong estuary, highlighting the Murray Mouth, Goolwa and Tauwitchere barrages and the fish sampling locations (A – Goolwa vertical-slot and adjacent the barrage, B – Hunters Creek vertical slot, C – Tauwitchere large vertical-slot and D – Tauwitchere small vertical-slot and rockramp).

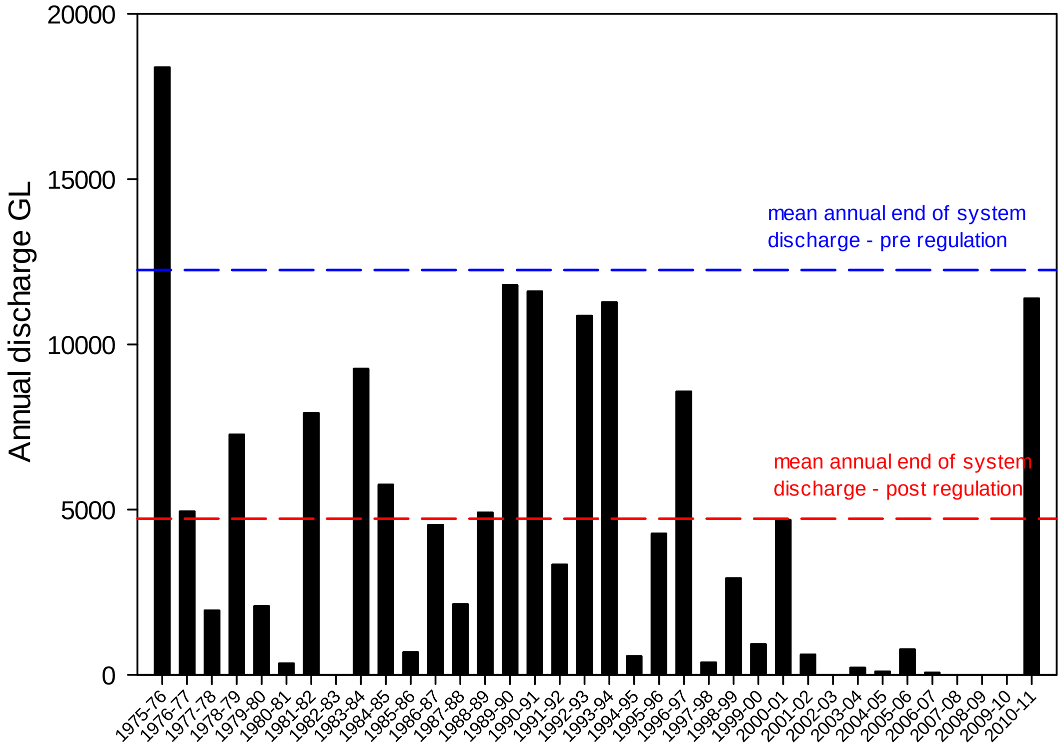

Figure 2-2 Annual freshwater discharge (GL) through the Murray barrages into the Coorong estuary from 1975- May 2011.

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). The Coorong 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 (DEH 2000).

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 water extraction. 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 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).

Water level fluctuations below the Murray Barrages are dynamic and complex. The behaviour of tides is influenced directly by sedimentation and in particular water exchange through the Murray Mouth. Since the construction of the barrages tidal exchange has been reduced by an estimated 87-96%, significantly impacting on the hydrodynamic and littoral transport systems within the estuary (Harvey 1996).

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 hypersaline (> 40 g.L^{-1}) salinities (Geddes 1987; Walker 2002). Typically 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, however, salinities in the northern lagoon can range from fresh to brackish (i.e. 5–30 g.L^{-1}) (Geddes 1987).

2.2 Fish sampling

Samples of fish were collected at the entrance and exit of vertical-slot fishways at Tauwitchere Barrage (35°35'09.35"S, 139°00'30.58"E), Goolwa Barrage (35°31'34.44"S, 138°48'31.12"E) and Hunters Creek (35°32'07.08"S, 138°53'07.48"E), and adjacent to the rockramp fishway at the southern end of Tauwitchere Barrage (35°35'24.16"S, 139°00'56.83"E) and the Hindmarsh Island abutment of the Goolwa Barrage (35°31'24.16"S, 138°48'33.79"E) (Figure 2-1).

Paired replicate samples of the entrance and exit of each vertical–slot fishway were collected 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 and one surface slot 200 mm wide and of variable depth, Appendix 1), 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). At all sites except Tauwitchere large vertical–slot, entrance traps were used to sample the fishway exits. For exit sampling, entrance traps were positioned in the weir pool upstream and orientated to catch all fish which successfully ascended the fishway. At the Tauwitchere large vertical slot fishway a purpose built exit trap was used (2.0 m long x 2.0 m wide x 1.7 m high 0.3 m slot widths).

Traps for the large vertical slot fishways 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 minimize 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 fishway (Coorong side) and adjacent to the Hindmarsh Island abutment of the Goolwa Barrage (Coorong side). At the Tauwitchere rockramp the net was positioned so that one wing crossed in front of the outflow from the fishway thus channelling fish in the vicinity of the fishway into the net (Figure 2-3b). At Goolwa, the net was set adjacent to the barrage to capture fish utilising this area.

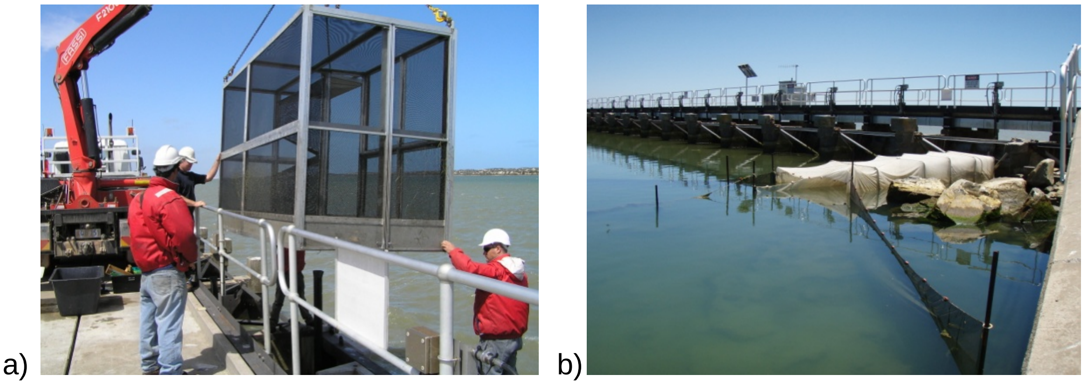

Figure 2-3. a) Cage trap used to sample the Tauwitchere and Goolwa vertical-slot fishways and b) large fyke net used to sample the Tauwitchere rockramp fishway. A net of the same dimensions was also used to sample adjacent the Hindmarsh Island abutment immediately downstream of the Goolwa Barrage.

Nine weeks of sampling was conducted between 25 October 2010 and 11 March 2011. Each site was sampled overnight 1-3 times per sampling trip/week. Cage traps at the large vertical slot fishways were deployed and retrieved using a mobile crane (Figure 3a). All trapped fish were removed and placed in large aerated holding tanks. Each individual was then identified to species and counted. For the catadromous species, congolli (*Pseudaphritis urvillii*) and common galaxias (*Galaxias maculatus*), a random sub-sample of 50 individuals were measured to the nearest mm (total length, TL) to represent the size structure of the population. Furthermore, sub-samples of congolli and common galaxias were collected every year, when present, for ageing via otolith microstructure analysis.

2.3 Otolith preparation and interpretation of microstructure

Where possible, 50 juvenile congolli and common galaxias were selected randomly from Tauwitchere (vertical-slot and rockramp site combined) and Goolwa Barrage (vertical-slot and Hindmarsh Island abutment site combined) to represent year for otolith analysis. Fish were thawed, measured for length (total length (TL), mm) and sagittae were extracted under a dissecting microscope.

Sagittae were embedded in crystal bond™, then ground and polished from the anterior side towards the core with 30 µm and 9 µm lapping film. The ground surface was then glued to the centre of a microscope slide and then further ground and polished from the posterior side, to produce sections of 50 - 100 µm thickness. Two readers examined each otolith on separate occasions and each reader performed two counts of the increments. Counts from each reader were compared and if they differed by more than 5% the otolith was rejected, but if count variation was within 5%, the mean of all counts was accepted as the best estimate of daily increment number.

Daily increment formation in post larval common galaxias otoliths has been validated previously by McDowall *et al.* (1994). Similar to McDowall *et al.* (1994), pre-hatch increments in common galaxias sections in this study were laid down at such fine resolution they are difficult to interpret consistently using standard light microscopy techniques. Alternatively, an easily identifiable hatch mark identified by McDowall *et al.* (1994) was evident on all sectioned otoliths, providing a reliable reference point to begin increment counts. Thus in the current study, daily increment counts for common galaxias were made from the hatch mark along the maximum growth axis towards the ventral apex. The estimates of individual age and collection dates were used to calculate the date on which successful recruits were hatched.

Daily increment formation in post larval congolli otoliths has been validated previously by Cheshire (2005). Daily increments for congolli were easily interpreted and counts were made from the primordium along the maximum growth axis towards the ventral apex. Daily increment counts were subtracted from individual capture dates to identify the date successful recruits were spawned.

2.4 Data analysis

Spatio-temporal variation in fish assemblages

Temporal variation in the composition of fish assemblages sampled at each location was assessed between years. The statistical software package PRIMER v. 6.12 & PERMANOVA+ was used to perform statistical comparisons on fourth-root transformed relative abundance (number of fish.hour^{-1}.trip^{-1}) and species composition data (after Clarke and Warwick 2001). Non-Metric Multi-Dimensional Scaling (MDS) generated from Bray-Curtis similarity matrices were used to graphically represent assemblages from different years in two dimensions. PERMANOVA (permutational ANOVA and MANOVA) 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 Bonferroni correction was adopted ($\alpha = 0.05/n_{comparisons}$). 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 2005). 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 (Dufrêne 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 2010/11 was also investigated using MDS, PERMANOVA and ISA. MDS plots generated from Bray-Curtis similarity matrices was used to graphically represent assemblages from different locations in two dimensions and PERMANOVA was used to detect differences in assemblages between locations. ISA was then used to determine what species characterised assemblages at the different sampling locations in 2010/11.

Differences between years in the standardised abundance (fish.hour^{-1}.trap event^{-1}) of common galaxias and congolli sampled at the Tauwitchere rockramp, Tauwitchere vertical-slot, Goolwa vertical-slot and adjacent the Hindmarsh Island abutment of Goolwa Barrage were analysed using uni-variate single-factor PERMANOVA (Anderson *et al.* 2008). This routine tests the response of a variable (e.g. 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.

The Kolmogorov-Smirnov 'goodness-of-fit' test was used to determine differences between years in spawning and hatch date distributions of congolli and common galaxias below Tauwitchere and Goolwa Barrage.

Fishway assessments

To assess fishway efficiency, PERMANOVA, based on Bray-Curtis similarity matrices and fourth root transformed relative abundance data (fish.hour^{-1}.trap event^{-1}), was used to determine differences in fish assemblages between entrance and exit samples at both the Hunters Creek and Tauwitchere small-bodied vertical-slot fishways. MDS ordinations generated from the same similarity matrices were used to graphically represent fish assemblages from entrance and exit traps. The relative abundance of the most abundant species sampled at each fishway was compared between entrance and exit samples using uni-variate single-factor PERMANOVA.

The Kolmogorov-Smirnov 'goodness-of-fit' test was used to determine differences between entrance and exit samples in length-frequency distributions of the most abundant species sampled at each fishway.

3 Results

3.1 Hydrology and salinity

From mid July 2005 to March 2006 and May to August 2006, low-volume freshwater flows of 1000 – 12,000 ML.d^{-1} were consistently released into the Coorong (Figure 3-1a). Water was released through barrage 'gates' and fishways on Tauwitchere and Goolwa Barrages. 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}; Figure 3-1a) until March 2007, when all fishways were closed due to receding water levels in the Lower Lakes. Persistent drought conditions in the Murray-Darling Basin resulted in no freshwater being released to the Coorong from March 2007 – September 2010 (Figure 3-1a). 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 Barrage's, with cumulative flow across the barrages peaking at ~80,000 ML.d^{-1} and consistently >40,000 ML.d^{-1} over the sampling period (Figure 3-1a).

During the period of low-volume freshwater releases (July 2005 – March 2007) salinity below Tauwitchere and Goolwa Barrages fluctuated from 1 – 34 g.L^{-1} and 1 – 27 g.L^{-1} respectively but regularly ranged from 15 – 25 g.L^{-1} at both locations (Figure 3-1b). Following the cessation of freshwater releases in March 2007, mean daily salinities at Tauwitchere increased and fluctuated between 30 and 60 g.L^{-1} until September 2010 (Figure 3-1b). Similarly, salinities at Goolwa Barrage between March 2007 and September 2010 ranged 28 – 37 g.L^{-1}. Following significant increases in freshwater releases to the Coorong in September 2010 (Figure 3-1a), salinities over the 2010/11 sampling period ranged 0.3 – 25 g.L^{-1} at Goolwa Barrage and 0.2 – 27 g.L^{-1} at Tauwitchere Barrage; however, salinities were predominantly <1 g.L^{-1} at both locations (Figure 3-1b).

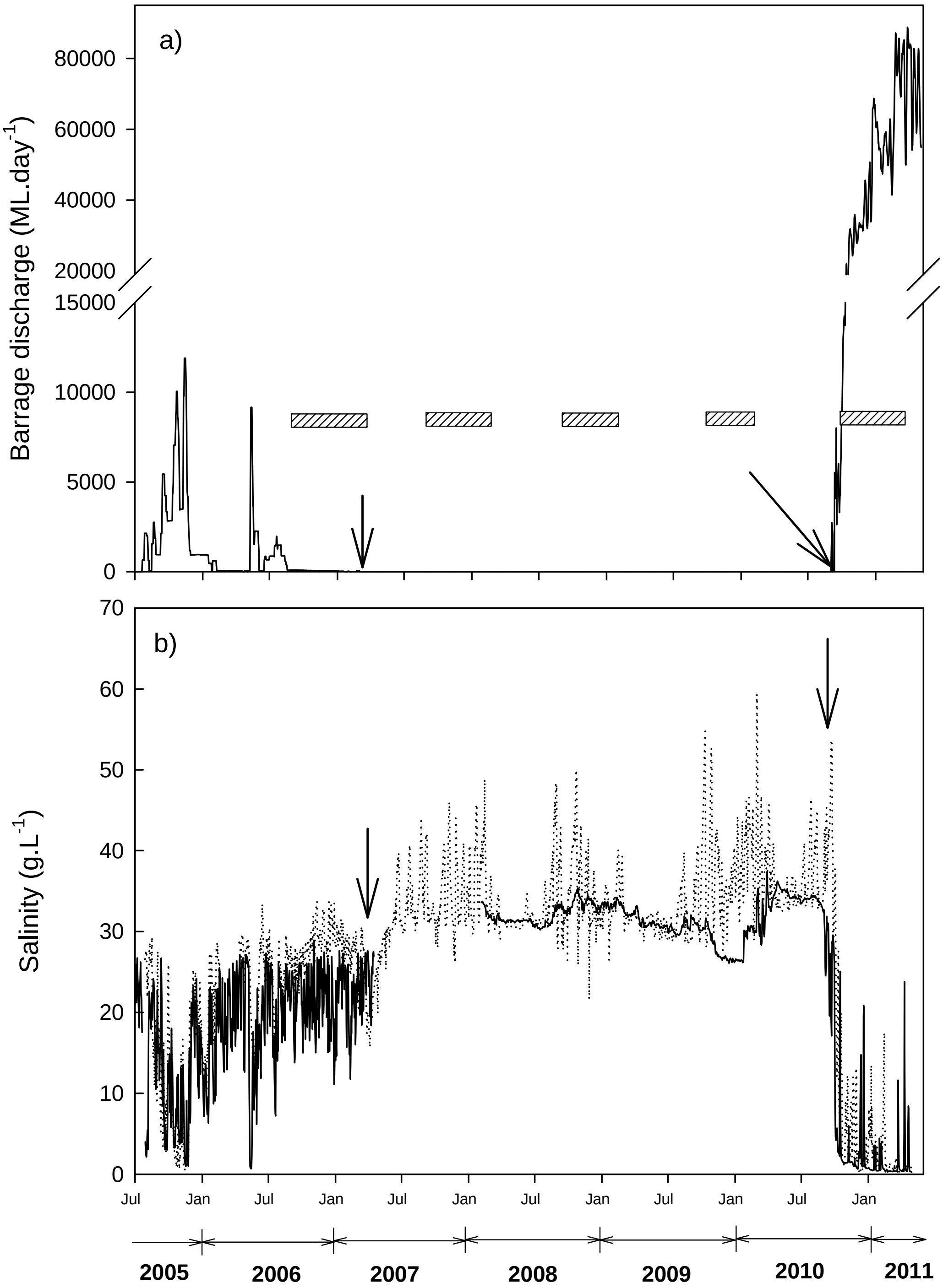

Figure 3-1. a) Mean daily flow (ML.d^{-1}) to the Coorong through Tauwitchere (dotted line) and Goolwa (solid line) Barrage from July 2005 – March 2010 and b) Mean daily salinity (g.L-1) of the Coorong below Tauwitchere (dotted line) and Goolwa (solid line) barrage from July 2005 – March 2010. Sampling periods are represented by hatched bars. Black arrows indicate closure and reopening of the barrages/fishways.

3.2 Catch summary

A total of 1, 747, 531 fish from 31 species (19 families) were sampled in 2010/11 (Table 3-1). The freshwater Australian smelt, non-native freshwater redfin perch and marine sandy sprat were the most abundant species, comprising *c.* 26%, *c.* 25% and *c.* 20% of the total catch respectively. Australian smelt were most abundant at Tauwitchere, whilst redfin perch and sandy sprat were abundant across all sampling locations. The freshwater flat-headed gudgeon and bony herring, and estuarine lagoon goby and small-mouthed hardyhead were the next most abundant species contributing *c.* 9%, *c.* 7%, *c.* 6% and *c.* 2% to the total catch, while the remaining 24 species collectively represented <4% of the total catch (Table 3-1).

Table 3-1. Summary of species and total number of fish sampled from the entrances and exits 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 Hindmarsh Island abutment of Goolwa Barrage in 2010/11. Species are categorised using estuarine use functional groups from Elliott *et al.* (2007).

**denotes introduced species*

			Tauwitchere large vertical-slot		**Tauwitchere small vertical-slot**		**Tauwitchere rock-ramp**	**Goolwa vertical-slot**		**Goolwa downstream**	**Hunters Creek**		**Total**
Common name	**Scientific Name**	**Functional group**	**entrance**	**exit**	**entrance**	**exit**		**entrance**	**exit**		**entrance**	**exit**	
	Sampling events No. of species		16 15	17 19	17 18	17 15	9 26	22 23	11 17	9 25	17 18	17 16	
Australian smelt	*Retropinna semoni*	Freshwater migrant	135948	92715	14345	14522	147904	33170	5501	10975	5	4	**455,089**
Murray hardyhead	*Craterocephalus fluviatilis*	Freshwater straggler	0	0	0	0	0	0	1	0	0	2	**3**
Bony herring	*Nematalosa erebi*	Freshwater straggler	6843	10518	180	29	59401	1097	289	26529	7709	10145	**122,740**
Flat-headed gudgeon	*Philypnodon grandiceps*	Freshwater migrant	5780	1233	2222	3273	102469	685	216	30845	5849	5339	**157,911**
Dwarf flat-headed gudgeon	*Philypnodon macrostomus*	Freshwater straggler	0	0	0	0	4	2	2	2	0	0	**10**
Carp gudgeon	*Hypseleotris* spp	Freshwater straggler	2	7	18	198	438	5	0	149	18	13	**848**
Golden perch	*Macquaria ambigua*	Freshwater migrant	2	18	8	35	3575	28	0	183	0	11	**3860**
Common carp	*Cyprinus carpio**	Freshwater straggler	141	646	86	286	9985	61	0	788	1698	1711	**15,402**
Goldfish	*Carrasius auratus**	Freshwater straggler	0	2	4	12	101	1	0	33	439	220	**812**
Redfin perch	*Perca fluviatilis**	Freshwater straggler	2944	5107	51727	92524	149998	495	108	19824	71963	47985	**442,675**
Eastern gambusia	*Gambusia holbrooki**	Freshwater straggler	0	0	0	0	0	0	0	0	2	0	**2**
Common galaxias	*Galaxias maculatus*	Semi-catadromous	39	62	362	1454	429	2599	37	26	669	1789	**7466**
Congolli	*Pseudaphritis urvillii*	Semi-catadromous	200	203	1184	780	5467	266	54	552	960	1234	**10,900**
Small-mouthed hardyhead	*Atherinosoma microstoma*	Estuarine	472	448	17	27	27551	427	119	10170	347	250	**39,828**
Southern long-finned goby	*Favonigobius lateralis*	Estuarine	1	1	1	0	172	1	0	2	0	0	**178**
Tamar River goby	*Afurcagobius tamarensis*	Estuarine	41	31	2	5	143	89	61	4380	14	2	**4768**

Table 1 continued.

			Tauwitchere large vertical-slot		**Tauwitchere small vertical-slot**		**Tauwitchere downstream**	**Goolwa vertical-slot**		**Goolwa downstream**	**Hunters Creek**		**Total**
Common name	**Scientific Name**	**Functional group**	**entrance**	**exit**	**entrance**	**exit**		**entrance**	**exit**		**entrance**	**exit**	
	Sampling events No. of species												
Blue-spot goby	*Pseudogobius olorum*	Estuarine	7	54	18	8	215	18	1	139	25	19	**504**
Lagoon goby	*Tasmanogobius lasti*	Estuarine	2663	1632	286	24	83901	1353	757	9922	267	268	**101,173**
Bridled goby	*Arenogobius bifrenatus*	Estuarine	0	3	0	1	88	111	174	22344	24	16	**22,761**
Greenback flounder	*Rhombosolea tapirina*	Estuarine	0	1	0	0	47	1	1	1531	0	0	**1581**
Long-snouted flounder	*Ammotretis rostratus*	Estuarine	0	1	1	0	5	0	0	4	0	0	**11**
Southern garfish	*Hyperhamphus melanchir*	Marine migrant	0	0	0	0	3	0	0	0	0	0	**3**
River garfish	*Hyperhamphus regularis*	Estuarine	0	0	2	0	356	1	0	16	1	0	**376**
Yellow-eyed mullet	*Aldrichetta forsteri*	Marine migrant	0	0	0	0	5	1	1	5	0	0	**13**
Flat-tailed mullet	*Liza argentea*	Marine migrant	0	0	0	0	0	0	1	0	1	0	**2**
Black bream	*Acanthopagrus butcheri*	Estuarine	0	0	0	0	0	0	0	38	0	0	**38**
Soldier fish	*Gymnapistes marmoratus*	Marine migrant	0	0	0	0	2	1	0	7	0	0	**10**
Prickly toadfish	*Contusus brevicaudus*	Marine migrant	0	0	0	0	3	0	0	0	0	0	**3**
Australian herring	*Arripis georgianus*	Marine migrant	0	0	0	0	0	0	0	1	0	0	**1**
Sandy sprat	*Hyperlophus vittatus*	Marine migrant	2273	9	18	0	161293	936	282	193835	14	0	**358,660**
Zebra fish	*Girella zebra*	Marine straggler	0	0	0	0	0	2	0	0	0	0	**2**
		Total	**157,356**	**112,691**	**70,481**	**113,178**	**753,555**	**41,350**	**7605**	**332,301**	**90,005**	**69,009**	**1,747,531**

3.3 Temporal variation in fish assemblages

MDS ordination plots show distinct groupings of fish assemblages by year at each sampling location (Figure 3-2). These groupings are supported by PERMANOVA, which detected significant differences in fish assemblages between years at the Tauwitchere rock ramp ($Pseudo\text{-}F_{4,\ 36} = 14.882$, $p < 0.001$), Tauwitchere vertical-slot ($Pseudo\text{-}F_{4,\ 31} = 14.294$, $p < 0.001$), Goolwa vertical-slot ($Pseudo\text{-}F_{3,\ 29} = 8.011$, $p < 0.001$) and adjacent the Hindmarsh Island abutment of Goolwa Barrage ($Pseudo\text{-}F_{2,\ 16} = 11.467$, $p < 0.001$).

Pair-wise comparisons revealed significant differences in fish assemblages at the Tauwitchere rock ramp between 2006/07 and all subsequent years, and between 2010/11 and all preceding years. No significant difference in fish assemblages was detected at the Tauwitchere rock ramp between 2007/08, 2008/09 and 2009/10 (Table 3-2). Fish assemblages sampled at the Tauwitchere vertical-slot in 2006/07 also differed significantly from assemblages sampled in all subsequent years. Assemblages sampled in 2010/11 differed significantly from assemblages in all preceding years, with the exception of 2009/10. No significant difference was detected between assemblages sampled in 2007/08, 2008/09 and 2009/10 (Bonferroni corrected $\alpha = 0.005$) (Figure 3-2).

Pair-wise comparisons revealed significant differences in fish assemblages at the Goolwa vertical-slot between 2006/07 and 2008/09 but not between 2006/07 and 2009/10 or 2008/09 and 2009/10 (Bonferroni corrected $\alpha = 0.008$) (Table 3-2). Fish assemblages sampled in 2010/11, however, differed significantly from all preceding years. Fish assemblages adjacent the Hindmarsh Island abutment of Goolwa Barrage did not differ significantly between 2008/09 and 2009/10 but assemblages sampled in 2010/11 differed significantly from both preceding years (Table 3-2).

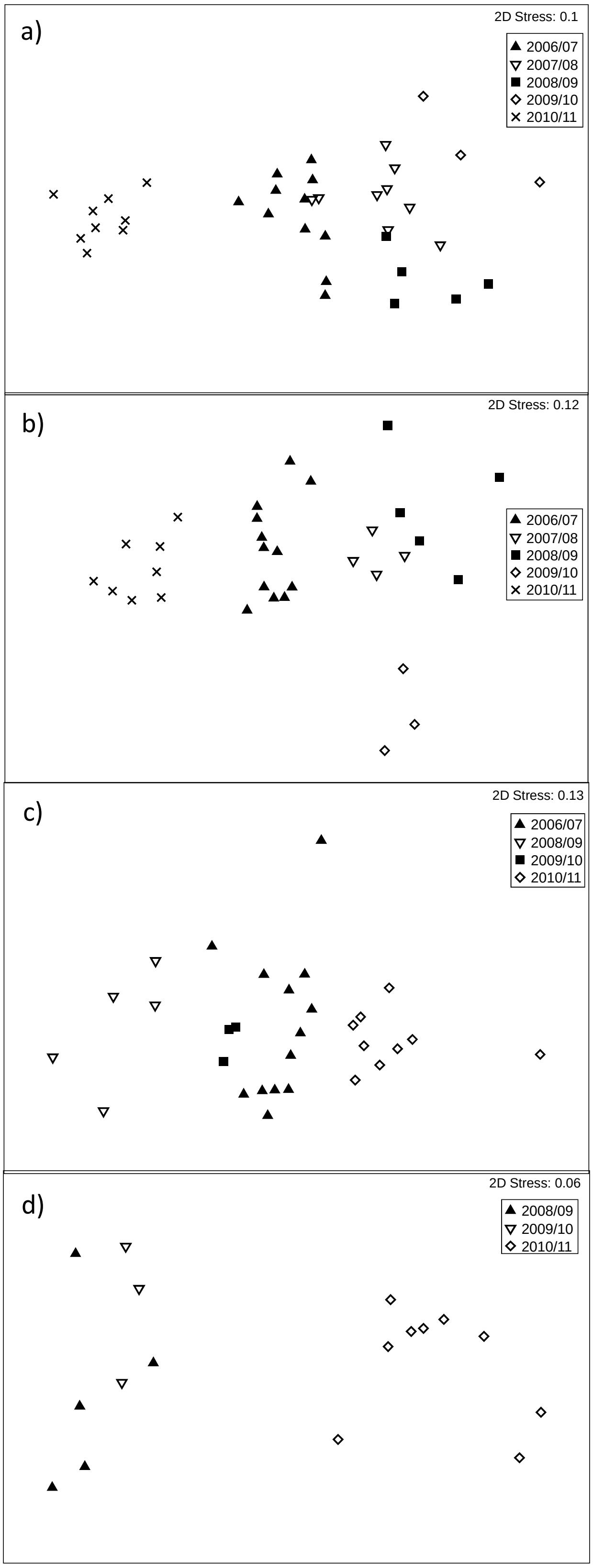

Figure 3-2. MDS ordination plots of fish assemblages sampled at a) Tauwitchere rock ramp, b) Tauwitchere vertical-slot, c) Goolwa vertical-slot and d) adjacent the Hindmarsh Island abutment of Goolwa Barrage, between 2006 and 2011.

Table 3-2. PERMANOVA pair-wise comparisons between fish assemblages sampled in 2006/07, 2007/08, 2008/09, 2009/10 and 2010/11 at the Tauwitchere rock ramp, Tauwitchere vertical-slot, Goolwa vertical-slot and adjacent the Hindmarsh Island abutment of Goolwa Barrage. PERMANOVA was performed on Bray-Curtis similarity matrices. After Bonferroni correction, corrected α = 0.005 for the Tauwitchere rock ramp and vertical-slot and α = 0.008 for Goolwa vertical-slot analyses.

Location	**Pairwise comparison**		***t***	***p* value**
	Year	**Year**		
TRR	2006/07	2007/08	2.281	<0.001*
TRR	2006/07	2008/09	2.775	<0.001*
TRR	2006/07	2009/10	3.064	0.005*
TRR	2006/07	20010/11	5.202	<0.001*
TRR	2007/08	2008/09	1.772	0.01 ns
TRR	2007/08	2009/10	2.144	0.009 ns
TRR	2007/08	2010/11	6.044	<0.001*
TRR	2008/09	2009/10	2.086	0.018 ns
TRR	2008/09	2010/11	5.532	0.002*
TRR	2009/10	2010/11	5.303	0.004*
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	0.004*
TVS	2006/07	2010/11	4.527	<0.001
TVS	2007/08	2008/09	1.597	0.021 ns
TVS	2007/08	2009/10	2.622	0.029 ns
TVS	2007/08	2010/11	5.45	0.004*
TVS	2008/09	2009/10	2.439	0.017 ns
TVS	2008/09	2010/11	4.963	0.002*
TVS	2009/10	2010/11	4.914	0.01 ns
GVS	2006/07	2008/09	2.805	0.002*
GVS	2006/07	2009/10	1.72	0.024 ns
GVS	2006/07	2010/11	2.977	<0.001*
GVS	2008/09	2009/10	1.865	0.039 ns
GVS	2008/09	2010/11	3.974	<0.001*
GVS	2009/10	2010/11	2.64	0.006*
GDS	2008/09	2009/10	1.319	0.137 ns
GDS	2008/09	2010/11	4.172	<0.001*
GDS	2009/10	2010/11	3.337	0.004*

SIMPER results, using a cumulative 40% contribution cut-off, showed that differences in fish assemblages between 2006/07 and the years 2007/08 – 2009/10 at the Tauwitchere rock ramp were primarily due to decreasing relative abundances of the estuarine small-mouthed hardyhead, lagoon goby (*Tasmanogobius lasti*), blue-spot goby (*Pseudogobius olorum*) and Tamar River goby (*Afurcagobius tamarensis*), marine sandy sprat and freshwater Australian smelt (*Retropinna semoni*) across the four years. Conversely the estuarine yellow-eyed mullet (*Aldrichetta forsteri*) and marine Australian salmon (*Arripis truttaceus*) and Australian herring (*Arripis georgianus*) exhibited increases in relative abundance. In 2010/11, assemblages differed from previous years primarily due to increases in the abundance of the freshwater Australian smelt, flat-headed gudgeon (*Philypnodon grandiceps*), bony herring (*Nematalosa erebi*) and redfin perch (*Perca fluviatilis*) and estuarine lagoon goby. At the Tauwitchere vertical-slot, differences in fish assemblages between 2006/07 and subsequent years were largely attributable to decreases in abundance of catadromous congolli and common galaxias, freshwater flat-headed gudgeon (*Philypnodon grandiceps*) and marine sandy sprat. Assemblages in 2010/11 differed from preceding years due to increases in the freshwater Australian smelt, bony herring and flat-headed gudgeon.

Differences in assemblages at the Goolwa vertical-slot between 2006/07 and 2008/09 were attributed to decreases in relative abundance of catadromous congolli and common galaxias, freshwater Australian smelt and marine sandy sprat. Assemblages in 2010/11, differed from previous years due to decreases in the abundance of the marine sandy sprat and estuarine flat-tail mullet (*Liza argentea*), and increases in the abundance of the freshwater Australian smelt, bony herring, flat-headed gudgeon and redfin perch, and estuarine lagoon goby. Furthermore, the difference between 2010/11 and 2006/07 was partially driven by decreases in the abundance of catadromous congolli and common galaxias. Differences in fish assemblages adjacent the Hindmarsh Island abutment of Goolwa Barrage between 2010/11 and 2008/09 – 2009/10, were primarily driven by increases in the abundance of freshwater Australian smelt, bony herring, flat-headed gudgeon and redfin perch and marine sandy sprat.

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 indicator species analysis (Dufrêne and Legendre 1997) was carried out to determine species that 'characterised' assemblages in different years at each site.

At the Tauwitchere rock ramp, fish assemblages in 2006/07 were characterised by the presence of the anadromous short-headed lamprey (*Mordacia mordax*) (Table 3-3). In 2007/08 fish assemblages were characterised by the presence of the marine blue sprat (*Spratelloides robustus*), whilst there were no significant indicators of the assemblage in 2008/09 (Table 3-3). In 2009/10 the assemblage was characterised by several marine species; namely Australian salmon, Australian herring, mulloway (*Argyrosomous japonicas*), prickly toadfish (*Contusus brevicaudus*) and yellowfin whiting (*Sillago schomburgkii*) (Table 3-3). In 2010/11 fish assemblages were characterised predominantly by freshwater species (i.e. golden perch (*Macquaria ambigua*), carp gudgeon (*Hypseleotris* spp), bony herring, Australian smelt, flat-headed gudgeon, redfin perch, common carp (*Cyprinus carpio*) and goldfish (*Carrassius auratus*)), together with catadromous (i.e. common galaxias and congolli), estuarine (i.e. river garfish (*Hyporhamphus regularis*), lagoon goby and southern longfin goby (*Favonigobius lateralis*)) and marine species (i.e. sandy sprat) (Table 3-3).

At the Tauwitchere vertical-slot, fish assemblages in 2006/07 were characterised by two catadromous species, namely congolli and common galaxias (Table 3-3). There were no significant indicators of fish assemblages in 2007/08 or 2008/09 but fish assemblages in 2009/10 were characterised by the presence of the estuarine black bream (*Acanthopagrus butcheri*) (Table 3-3). Assemblages in 2010/11 were characterised by the freshwater bony herring, Australian smelt, redfin perch and common carp, and estuarine lagoon goby.

Table 3-3. Indicator species analysis of fish assemblages in the Coorong at the Tauwitchere rockramp and Tauwitchere large vertical-slot in 2006/07, 2007/08, 2008/09, 2009/10 and 2010/11. Only significant indicators (p <0.05) have been presented.

Species	**Year**	**Indicator Value**	***p* value**
Tauwitchere rockramp			
Short-headed lamprey	2006/07	45.5	0.027
Blue sprat	2007/08	44.4	0.02
Australian salmon	2009/10	72.2	0.006
Australian herring	2009/10	65.4	0.009
Mulloway	2009/10	98.5	<0.001
Prickly toadfish	2009/10	93.3	<0.001
Yellowfin whiting	2009/10	62.8	0.006
Golden perch	2010/11	66.7	0.003
Carp gudgeon complex	2010/11	88.3	<0.001
Bony herring	2010/11	100	<0.001
Australian smelt	2010/11	99.7	<0.001
Flat-headed gudgeon	2010/11	100	<0.001
Redfin perch	2010/11	88.9	0.006
Common carp	2010/11	100	<0.001
Goldfish	2010/11	55.6	0.01
Common galaxias	2010/11	72.4	0.032
Congolli	2010/11	90.2	<0.001
River garfish	2010/11	88.9	0.001
Lagoon goby	2010/11	98.1	<0.001
Southern longfin goby	2010/11	88.9	0.001
Sandy sprat	2010/11	96.7	<0.001
Tauwitchere vertical-slot			
Common galaxias	2006/07	96.2	<0.001
Congolli	2006/07	76.4	0.025
Black bream	2009/10	54.2	0.014
Bony herring	2010/11	100	<0.001
Australian smelt	2010/11	99.8	<0.001
Redfin perch	2010/11	99.9	<0.001
Common carp	2010/11	99.2	<0.001
Lagoon goby	2010/11	96.6	<0.001

At the Goolwa vertical-slot, fish assemblages in 2006/07 were characterised by the presence of the anadromous short-headed lamprey and catadromous congolli (Table 3-4). The Goolwa vertical-slot was not sampled in 2007/08 but in 2008/09, the assemblage was characterised by black bream. In 2009/10 the assemblage was characterised by the estuarine small-mouthed hardyhead and two marine species, namely zebra fish (*Girella zebra*) and soldier fish (*Gymnapistes marmoratus*) (Table 3-4). In 2010/11, the assemblage was characterised by several freshwater species (i.e. Australian smelt, bony herring, flat-headed gudgeon, redfin perch and common carp) and the estuarine lagoon goby (Table 3-4).

The Hindmarsh island abutment site immediately downstream of the Goolwa Barrage was not sampled in 2006/07 or 2007/08 and in 2008/09 there were no significant indicators of the fish assemblage. In 2009/10 fish assemblages were characterised by the marine smooth toadfish (*Tetractenos glaber*) (Table 3-4). In 2010/11, fish assemblages were predominantly characterised by freshwater species (i.e. golden perch, carp gudgeon, bony herring, Australian smelt, flat-headed gudgeon, redfin perch and common carp), together with catadromous (i.e. common galaxias and congolli) and estuarine species (i.e. small-mouthed hardyhead, bridled goby (*Arenogobius bifrenatus*) and lagoon goby) (Table 3-4).

Table 3-4. Indicator species analysis of fish assemblages in the Coorong at the Goolwa vertical-slot and the Hindmarsh island abutment site immediately downstream of the Goolwa Barrage in 2006/07, 2008/09, 2009/10 and 2010/11**.**

Species	**Year**	**Indicator Value**	***p* value**
Goolwa vertical-slot			
Short-headed lamprey	2006/07	46.2	0.04
Congolli	2006/07	90.4	0.001
Black bream	2008/09	65.4	0.015
Small-mouthed hardyhead	2009/10	68.4	0.017
Zebra fish	2009/10	61.3	0.007
Soldier fish	2009/10	44.5	0.046
Bony herring	2010/11	62.7	0.046
Australian smelt	2010/11	95.4	<0.001
Flat-headed gudgeon	2010/11	85.6	<0.001
Redfin perch	2010/11	75.9	0.003
Common carp	2010/11	52.2	0.044
Lagoon goby	2010/11	99.9	<0.001
Adjacent the Hindmarsh Island abutment of Goolwa Barrage			
Smooth toadfish	2009/10	98.5	0.002
Golden perch	2010/11	66.7	0.037
Bony herring	2010/11	99.9	<0.001
Carp gudgeon	2010/11	77.8	0.046
Australian smelt	2010/11	99.9	<0.001
Flat-headed gudgeon	2010/11	100	<0.001
Redfin perch	2010/11	88.9	0.001
Common carp	2010/11	66.7	0.034
Common galaxias	2010/11	63	0.044
Congolli	2010/11	71.1	0.013
Small-mouthed hardyhead	2010/11	81.3	0.040
Bridled goby	2010/11	96.2	<0.001
Lagoon goby	2010/11	99.9	<0.001

3.4 Spatial variation in fish assemblages in 2010/11

MDS ordination of fish assemblage data from 2010/11 shows distinct groupings of fish assemblages by capture location (Figure 3-3), supported by PERMANOVA, which detected significant differences in fish assemblages between capture locations (*Pseudo-*$F_{5,\,52}$ = 12.177, $p < 0.001$). Pair-wise comparisons indicated that assemblages differed significantly between all capture locations, with the exception of the Goolwa vertical-slot and Tauwitchere small-bodied vertical-slot (Table 3-5).

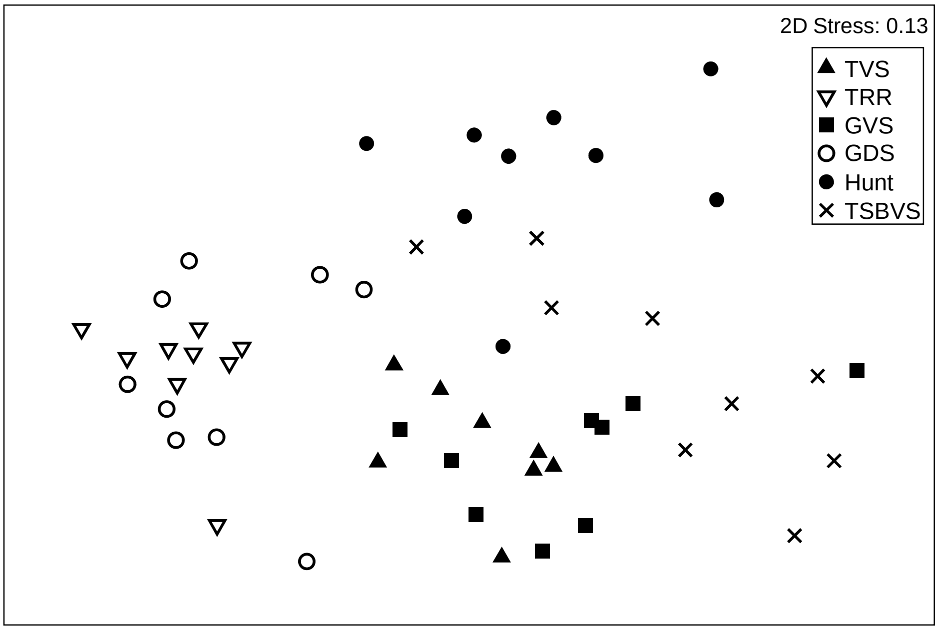

Figure 3-3. MDS ordination plot of fish assemblages sampled at the Tauwitchere large vertical-slot (TVS), Tauwitchere rockramp (TRR), Tauwitchere small vertical-slot (TSBVS), Goolwa vertical-slot (GVS), Hindmarsh island abutment site immediately downstream of the Goolwa Barrage (GDS) and Hunters Creek vertical-slot (Hunt) in 2010/11.

Table 3-5. PERMANOVA pair-wise comparisons of fish assemblages from the Tauwitchere rockramp (TRR), Tauwitchere large vertical-slot (TVS), Tauwitchere small vertical-slot (TSBVS), Goolwa vertical-slot (GVS), Hindmarsh island abutment site immediately downstream of the Goolwa Barrage (GDS) and Hunters Creek vertical-slot (Hunters) in 2010/11. PERMANOVA was performed on bray-curtis similarity matrices. After Bonferroni correction, corrected α = 0.003.

Pairwise comparison		*t*	***p* value**
Location	**Location**		
TRR	TVS	4.337	<0.001*
TRR	GVS	4.613	<0.001*
TRR	GDS	2.274	<0.001*
TRR	Hunters	4.848	<0.001*
TRR	TSBVS	4.642	<0.001*
TVS	GVS	2.004	0.003*
TVS	GDS	3.733	<0.001*
TVS	Hunters	3.543	<0.001*
TVS	TSBVS	2.351	0.002*
GVS	GDS	3.707	<0.001*
GVS	Hunters	2.977	<0.001*
GVS	TSBVS	1.777	0.018 ns
GDS	Hunters	4.059	<0.001*
GDS	TSBVS	3.910	<0.001*
Hunters	TSBVS	2.565	<0.001*

Indicator species analysis was used to determine species that characterised assemblages at different sampling locations in 2010/11. Of 32 species sampled, 18 were deemed to be significant indicators of the fish assemblage at a particular location (Table 3-6). The estuarine black bream, greenback flounder (*Rhombosolea tapirina*) and bridled goby characterised the assemblage at the Hindmarsh Island abutment site immediately downstream of the Goolwa Barrage, whilst a range of freshwater (i.e. golden perch, carp gudgeon, bony herring, flat-headed gudgeon, Australian smelt, common carp and eastern gambusia (*Gambusia holbrooki*)), catadromous (i.e. congolli) and estuarine species (river garfish, long-snouted flounder (*Ammosetris rostratus*), blue-spot goby (*Pseudogobius olorum*) and lagoon goby) characterised the assemblage at the Tauwitchere rock ramp site (Table 3-6). There were no significant indicators from the Tauwitchere large vertical-slot, Tauwitchere small-bodied vertical-slot, Goolwa vertical-slot or Hunters Creek vertical-slot.

Table 3-6. Indicator species analysis of fish assemblages in the Coorong at the Tauwitchere rockramp (TRR), Tauwitchere vertical-slot (TVS), Tauwitchere small-bodied vertical-slot (TSBVS), Goolwa vertical-slot (GVS), Hindmarsh island abutment site immediately downstream of the Goolwa Barrage (GDS) and Hunters Creek vertical-slot (Hunters) in 2010/11.

Species	**Location**	**Indicator value**	***p* value**
Black bream	GDS	77.8	<0.001
Greenback flounder	GDS	95.3	<0.001
Bridled goby	GDS	99.4	<0.001
Golden perch	TRR	62.1	0.006
Carp gudgeon complex	TRR	63.8	0.002
Bony herring	TRR	61.5	0.005
Flat-headed gudgeon	TRR	69.4	0.002
Australian smelt	TRR	59.6	<0.001
Common carp	TRR	84.7	<0.001
Eastern gambusia	TRR	88.5	<0.001
Congolli	TRR	75.2	<0.001
River garfish	TRR	85	<0.001
Long-snout flounder	TRR	28.4	0.016
Blue-spot goby	TRR	54.5	0.003
Lagoon goby	TRR	85.5	<0.001

Given the much greater numbers of fish sampled at the Tauwitchere rock ramp site and the Hindmarsh island abutment site immediately downstream of the Goolwa Barrage, and the likelihood of masking differences between the vertical-slot fishways, a second ISA was run using only data from the vertical-slot fishways. This analysis revealed that amongst the vertical-slot fishways, the assemblage at the Tauwitchere large vertical-slot was characterised by the freshwater Australian smelt and estuarine lagoon goby, whilst the Goolwa vertical-slot assemblage was characterised by the estuarine bridled goby and the Hunters Creek vertical-slot assemblage by freshwater common carp (Table 3-7).

Table 3-7. Indicator species analysis of fish assemblages in the Coorong at the Tauwitchere large vertical-slot (TVS), Tauwitchere small vertical-slot (TSBVS), Goolwa vertical-slot (GVS) and Hunters Creek vertical-slot (Hunters) in 2010/11.

Species	**Location**	**Indicator value**	***p* value**
Australian smelt	TVS	79.6	<0.001
Lagoon goby	TVS	75.6	0.008
Bridled goby	GVS	73.7	0.002
Common carp	Hunters	80.1	0.001

3.5 Temporal variation in abundance and recruitment of diadromous species

Lamprey

Upstream adult migrants of anadromous short-headed lamprey (*Mordacia mordax*) were collected from the Tauwitchere rock ramp (*n*=13), Tauwitchere vertical slot (*n*=5) and Goolwa vertical slot (*n*=22) between mid September and mid November 2006. One adult pouched lamprey (*Geotria australis*) was also collected at the Tauwitchere rock ramp in September 2006. No lamprey were sampled in 2007/08, 2008/09, 2009/10 or 2010/11.

Congolli and common galaxias

The abundance of the catadromous congolli and common galaxias differed significantly between years at the Tauwitchere rock ramp (uni-variate single-factor PERMANOVA: congolli, $Pseudo\text{-}F_{4,\ 77} = 39.26$, $p < 0.001$; common galaxias, $Pseudo\text{-}F_{4,\ 77} = 18.51$, $p < 0.001$), Tauwitchere vertical-slot (congolli, $Pseudo\text{-}F_{4,\ 76} = 13.69$, $p < 0.001$; common galaxias, $Pseudo\text{-}F_{4,\ 76} = 60.83$, $p < 0.001$), Goolwa vertical-slot (congolli, $Pseudo\text{-}F_{3,\ 75} = 11.56$, $p < 0.001$; common galaxias, $Pseudo\text{-}F_{3,\ 75} = 5.65$, $p = 0.002$) and at the Hindmarsh island abutment site immediately downstream of the Goolwa Barrage (congolli, $Pseudo\text{-}F_{2,\ 25} = 3.41$, $p = 0.049$; common galaxias, $Pseudo\text{-}F_{2,\ 25} = 10.61$, $p = 0.003$) (Figure 3-4).

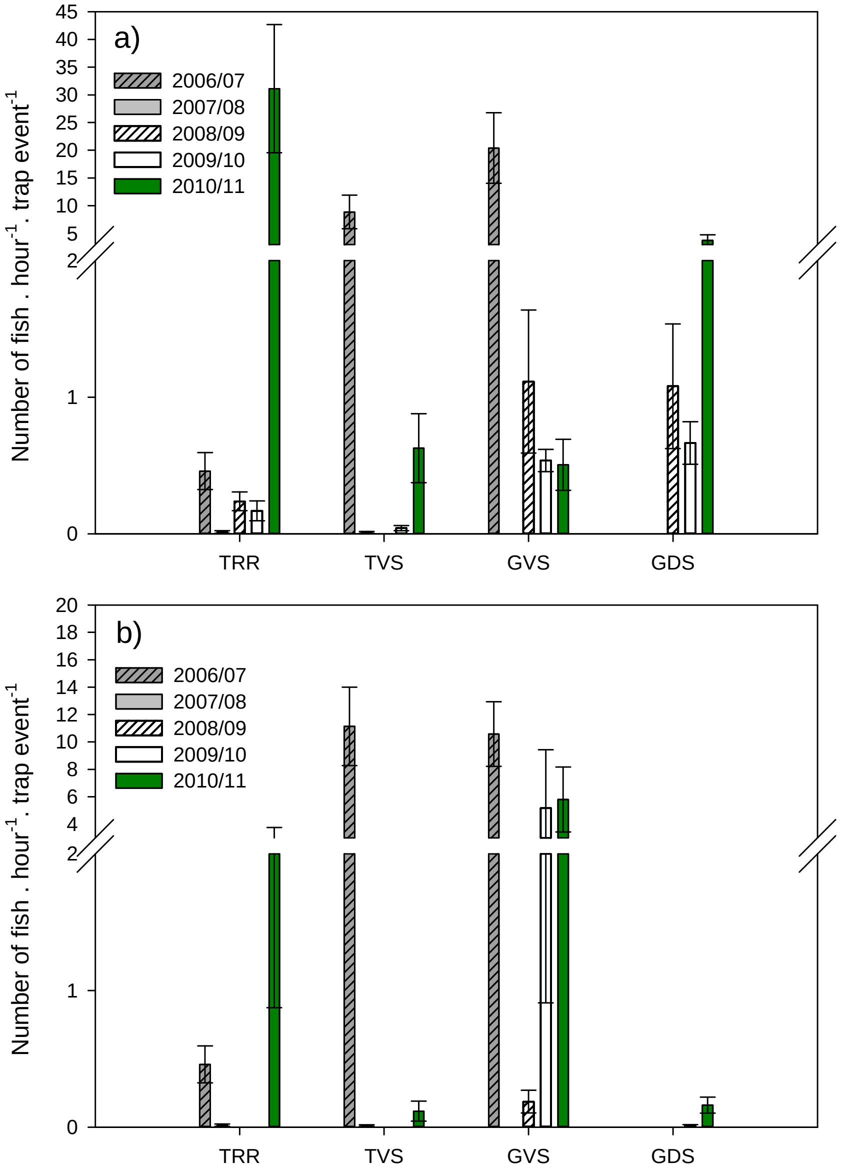

Figure 3-4. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of a) congolli and b) common galaxias at the Tauwitchere rockramp (TRR), Tauwitchere vertical-slot (TVS), Goolwa vertical-slot (GVS) and the Hindmarsh island abutment site immediately downstream of the Goolwa Barrage (GDS) from 2006 – 2011. 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.

Congolli were significantly more abundant at the Tauwitchere rock ramp in 2010/11, relative to all other years and significantly less abundant in 2007/08, relative to all other years (PERMANOVA pairwise comparisons, Bonferroni corrected $\alpha = 0.005$) (Figure 3-4a and Table 3-8). Similarly, abundance at the Hindmarsh island abutment site immediately downstream of the Goolwa Barrage was greatest in 2010/11 (Figure 3-4a and Table 3-8). Conversely, at the Tauwitchere vertical-slot, congolli were significantly more abundant in 2006/07, relative to all other years and significantly more abundant in 2010/11 relative to 2007/08 and 2008/09 (Figure 3-4a and Table 3-8). At the Goolwa vertical-slot, congolli were significantly more abundant in 2006/07, relative to 2007/08, 2008/09 and 2009/10. Abundances increased slightly in 2010/11, albeit without statistical significance (Figure 3-4a and Table 3-8).

The abundance of common galaxias at the Tauwitchere rock-ramp was the greatest in 2010/11 but was not significantly different from abundance in 2006/07 (Figure 3-4b and Table 3-9). Abundances in both 2006/07 and 2010/11, however, were significantly greater than in all intervening years. Correspondingly abundance at the Hindmarsh island abutment site immediately downstream of the Goolwa Barrage was significantly greater in 2010/11, relative to 2008/09 and 2009/10 (Figure 3-4b and Table 3-9). At the Tauwitchere vertical-slot, common galaxias abundance was greatest in 2006/07 before a significant decrease in abundance in 2007/08 and absence in 2008/09 and 2009/10 (Figure 3-4b and Table 3-9). A significant increase in abundance was evident in 2010/11 but abundance was significantly less than in 2006/07. Similarly, at the Goolwa vertical-slot, peak abundance in 2006/07 was followed by a significant decrease in abundance in 2008/09 (no sampling was conducted at this site in 2007/08) (Figure 3-4b and Table 3-9). Nonetheless, abundance increased in 2009/10 and 2010/11, and was similar to abundance in 2006/07.

Table 3-8. PERMANOVA pairwise comparisons of congolli relative abundance (fish.hour^{-1}.trap^{-1}) sampled in 2006/07, 2007/08, 2008/09, 2009/10 and 2010/11 at the Tauwitchere rock ramp, Tauwitchere large vertical-slot, Goolwa vertical-slot and Hindmarsh Island abutment site immediately downstream of the Goolwa Barrage. PERMANOVA was performed on Bray-Curtis similarity matrices. After Bonferroni correction, corrected α = 0.005 for the Tauwitchere rock ramp and vertical-slot and α = 0.008 for Goolwa vertical-slot analyses.

Location	**Pairwise comparison**		***t***	***p* value**
	Year	**Year**		
TRR	2006/07	2007/08	5.663	<0.001*
TRR	2006/07	2008/09	0.195	0.836 ns
TRR	2006/07	2009/10	0.453	0.638 ns
TRR	2006/07	2010/11	7.644	<0.001*
TRR	2007/08	2008/09	6.711	<0.001*
TRR	2007/08	2009/10	4.273	0.002*
TRR	2007/08	2010/11	10.704	<0.001*
TRR	2008/09	2009/10	0.740	0.489 ns
TRR	2008/09	2010/11	5.610	<0.001*
TRR	2009/10	2010/11	4.411	0.002*
TVS	2006/07	2007/08	4.515	<0.001*
TVS	2006/07	2008/09	5.056	<0.001*
TVS	2006/07	2009/10	2.549	0.014 ns
TVS	2006/07	20010/11	2.784	0.010 ns
TVS	2007/08	2008/09	1.915	0.230 ns
TVS	2007/08	2009/10	1.915	0.062 ns
TVS	2007/08	2010/11	3.076	0.003*
TVS	2008/09	2009/10	4.515	0.002*
TVS	2008/09	2010/11	4.090	0.002*
TVS	2009/10	2010/11	1.160	0.246 ns
GVS	2006/07	2008/09	3.259	0.004*
GVS	2006/07	2009/10	2.081	0.029 ns
GVS	2006/07	2010/11	4.880	<0.001*
GVS	2008/09	2009/10	0.429	0.669 ns
GVS	2008/09	2010/11	0.850	0.399 ns
GVS	2009/10	2010/11	1.372	0.166 ns
GDS	2008/09	2009/10	0.039	0.980 ns
GDS	2008/09	2010/11	2.188	0.044*
GDS	2009/10	2010/11	1.949	0.057 ns

Table 3-9. PERMANOVA pairwise comparisons of common galaxias relative abundance (fish.hour^{-1}.trap^{-1}) sampled in 2006/07, 2007/08, 2008/09, 2009/10 and 2010/11 at the Tauwitchere rock ramp, Tauwitchere vertical-slot, Goolwa vertical-slot and Hindmarsh island abutment site immediately downstream of the Goolwa Barrage. PERMANOVA was performed on Bray-Curtis similarity matrices. After Bonferroni correction, corrected α = 0.005 for the Tauwitchere rock ramp and vertical-slot and α = 0.008 for Goolwa vertical-slot analyses.

Location	**Pairwise comparison**		***t***	***p* value**
	Year	**Year**		
TRR	2006/07	2007/08	5.663	<0.001*
TRR	2006/07	2008/09	5.109	<0.001*
TRR	2006/07	2009/10	3.760	<0.001*
TRR	2006/07	2010/11	1.710	0.088 ns
TRR	2007/08	2008/09	1.298	0.382 ns
TRR	2007/08	2009/10	0.953	0.576 ns
TRR	2007/08	2010/11	5.698	<0.001*
TRR	2008/09	2009/10	N/A	N/A
TRR	2008/09	2010/11	5.080	<0.001*
TRR	2009/10	2010/11	3.681	0.002*
TVS	2006/07	2007/08	8.764	<0.001*
TVS	2006/07	2008/09	9.684	<0.001*
TVS	2006/07	2009/10	6.821	<0.001*
TVS	2006/07	2010/11	8.438	<0.001*
TVS	2007/08	2008/09	1.915	0.208 ns
TVS	2007/08	2009/10	1.333	0.445 ns
TVS	2007/08	2010/11	1.436	0.153
TVS	2008/09	2009/10	N/A	N/A
TVS	2008/09	2010/11	2.735	0.021 ns
TVS	2009/10	2010/11	1.913	0.101 ns
GVS	2006/07	2008/09	4.169	<0.001*
GVS	2006/07	2009/10	0.861	0.393 ns
GVS	2006/07	2010/11	1.909	0.061 ns
GVS	2008/09	2009/10	2.881	0.006*
GVS	2008/09	2010/11	2.324	0.018 ns
GVS	2009/10	2010/11	0.329	0.749 ns
GDS	2008/09	2009/10	1.393	0.361 ns
GDS	2008/09	2010/11	4.310	0.002*
GDS	2009/10	2010/11	2.349	0.035*

Below Tauwitchere Barrage (Tauwitchere rock ramp and vertical-slot data combined) in September and October 2006, congolli exhibited broad length distributions (28-220 mm TL) (Figure 3-5a). In November 2006, a 0+ year cohort (< 50 mm TL) comprised > 90% of the population (Figure 3-5a). The abundance of congolli peaked in December 2006 (*n* = 5754) with the 0+ cohort representing *c.* 99% of the population. In 2007/08, congolli were sampled in substantially lower numbers, and whilst a 0+ cohort did appear, these fish represented < 50% of the population from November through to January (Figure 3-5b). In 2008/09, 0+ congolli were not sampled until December 2008 when just one individual (43 mm TL) was recorded (Figure 3-5c). The 0+ cohort had increased in proportion by January 2009 (> 50% of the population) but was represented by just eleven individuals (Figure 3-5c). In 2009/10, 0+ congolli were again not sampled until December 2009 when just two individuals (60 & 62 mm TL) were recorded (Figure 3-5d). No 0+ congolli were detected below Tauwitchere Barrage in January 2010. In 2010/11, 0+ congolli were sampled from October – January (Figure 3-5e). Peak abundance occurred in November (*n* = 2269) and the 0+ cohort represented 100% of the sampled population (Figure 3-5e)

Congolli exhibited broad length distributions below Goolwa Barrage in September and October 2006 (59-227 mm TL) (Figure 3-6a). In November 2006, a 0+ cohort (< 50 mm TL) comprised > 90% of the population (Figure 3-6a). The abundance of congolli peaked in December 2006 (*n* = 12, 020) with the 0+ cohort representing 100% of the sampled population (Figure 3-6a). Sites at Goolwa Barrage were not sampled in 2007/08. In November 2008 below Goolwa Barrage (data from Goolwa vertical-slot and adjacent the Hindmarsh Island abutment of Goolwa Barrage combined), a 0+ cohort (< 50 mm TL) comprised *c.*90% of the population (Figure 3-6b). This cohort continued to dominate the population in December 2008 and January 2009 despite the species being sampled in far lower numbers than in 2006/07 (Figure 3-6a and b). In November 2009, December 2009 and January 2010, 0+ cohorts were present and represented *c.* 45%, 80% and 85% of the population respectively (Figure 3-6c) but were sampled in low numbers relative to 2006/07. In 2010/11, the 0+ cohort dominated the population in all months from October – January (Figure 3-6d). Abundance of the 0+ cohort had also increased relative to 2008/09 and 2009/10 (Figure 3-6b, c and d).

Similar to congolli*,* common galaxias exhibited a broad range of lengths at Tauwitchere in September 2006 (40-114 mm TL) (Figure 3-7a). In October 2006, 0+ fish (< 60 mm TL) comprised > 80% of the population (Figure 3-7a). Numbers of common galaxias peaked in November (*n* = 3567) with ~95% of these fish represented by the 0+ cohort (Figure 3-7a). In 2007/08, 0+ fish dominated the population in September and October but total numbers had decreased substantially from 2006/07 (Figure 3-7b). No fish were sampled in November 2007 or January 2008 and just two individuals were sampled in December 2007 (Figure 3-7b). No common galaxias were collected downstream of the Tauwitchere barrage during sampling in 2008/09 or 2009/10. Common galaxias were again sampled below

Tauwitchere Barrage in 2010/11 from October – January (Figure 3-7c). The population was dominated by a 0+ cohort but abundance remained considerably less than in 2006/07 but (Figure 3-7).

In contrast to Tauwitchere Barrage, common galaxias sampled below Goolwa Barrage (Goolwa vertical-slot data) in September 2006 were dominated by a 0+ cohort (< 50 mm TL) (Figure 3-8a). The abundance of common galaxias peaked in November 2006 (*n* = 3, 830) with the 0+ cohort representing >99% of the sampled population (Figure 3-8a). This cohort dominated the population for the remainder of sampling (Figure 3-8a). In September 2008 no common galaxias were sampled and just one adult fish (76 mm TL) was sampled in October 2008 (Figure 3-8b). A 0+ cohort represented 100% of the catch in November 2008, December 2008 and January 2009 but abundances were severely diminished relative to 2006/07 (Figure 3-8a and b). A 0+ cohort also represented 100% of the catch in November 2009, December 2009 and January 2010 (Figure 3-8c). Abundance peaked in November 2009 (*n* = 676) but in December 2009 and January 2010 abundance was diminished relative to 2006/07 (Figure 3-8a and c). In 2010/11, similar to previous years, a 0+ cohort dominated the population sampled below Goolwa Barrage from October – January (Figure 3-8d). Abundance increased relative to 20078/09 and 2009/10 but remained below that of 2006/07 (Figure 3-8).

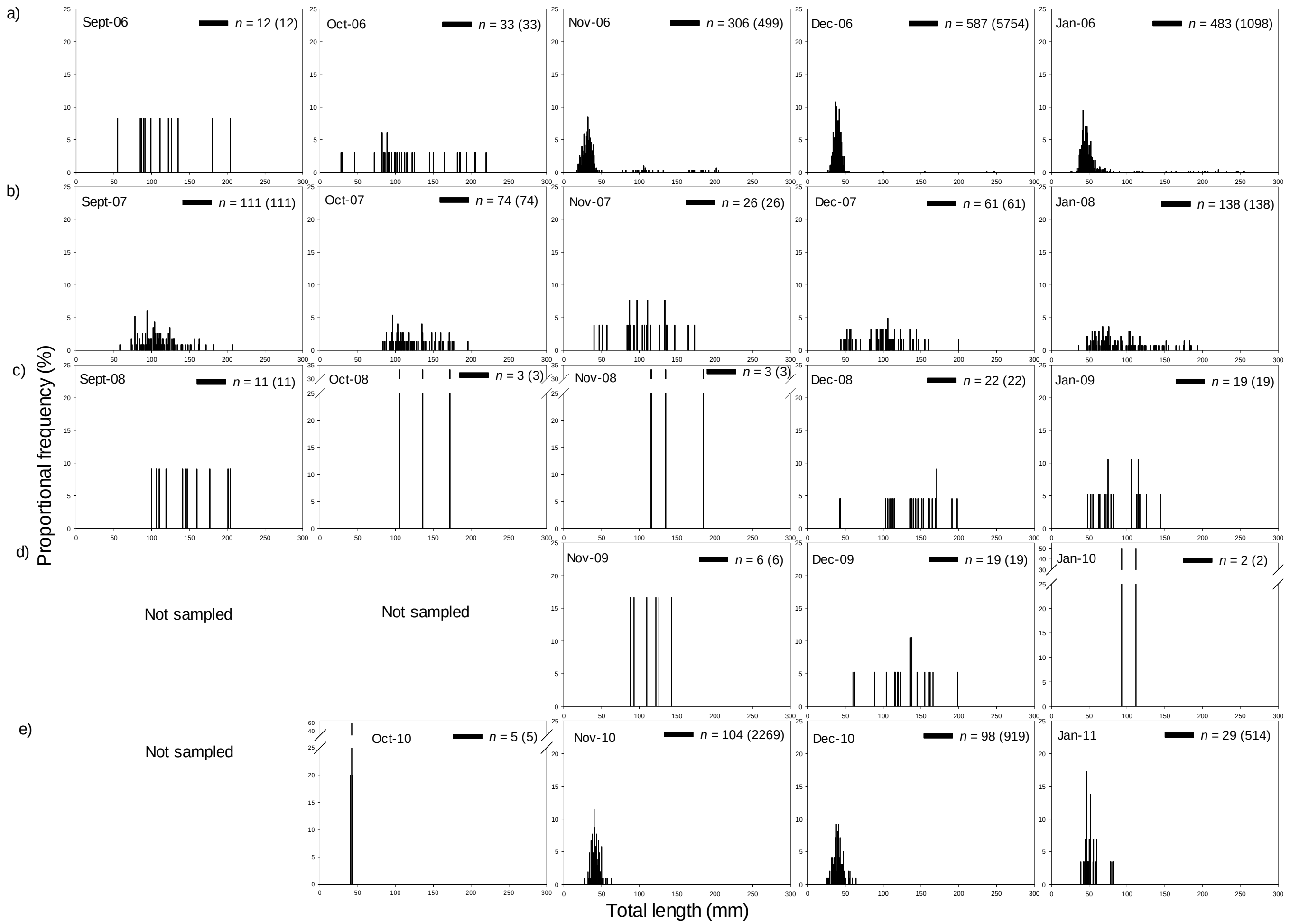

Figure 3-5. Monthly length-frequency distributions (total length, mm) of congolli sampled below Tauwitchere Barrage (rockramp and vertical-slot combined) during a) 2006/07, b) 2007/08, c) 2008/09, d) 2009/10 and e) 2010/11. *n* is the number of fish measured and the total number of fish is presented in brackets.

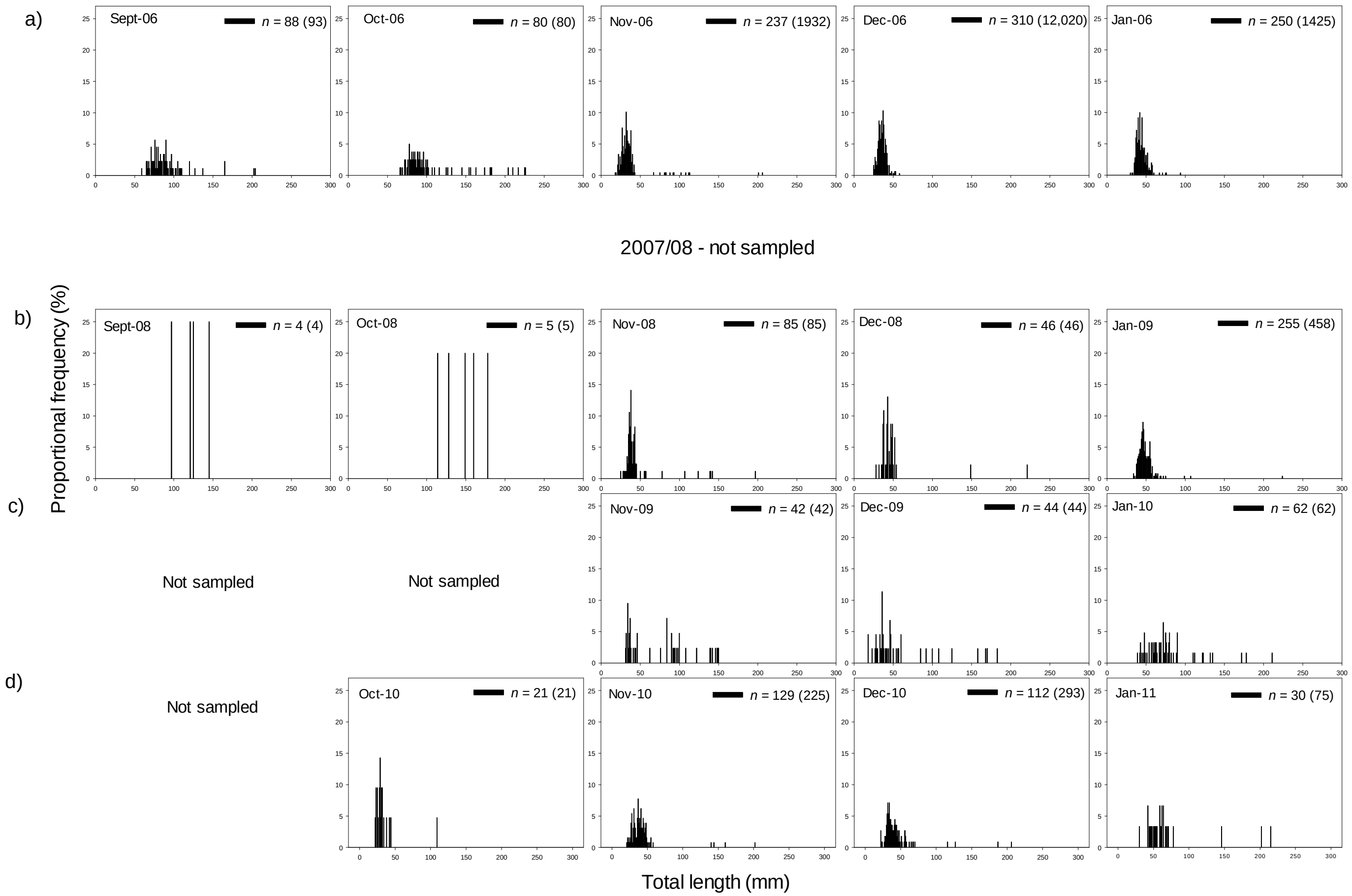

Figure 3-6. Monthly length-frequency distributions (total length, mm) of congolli sampled below Goolwa Barrage (vertical-slot and Hindmarsh Island abutment side of Goolwa Barrage site combined) during a) 2006/07, b) 2008/09, d) 2009/10 and e) 2010/11. *n* is the number of fish measured and the total number of fish is presented in brackets.

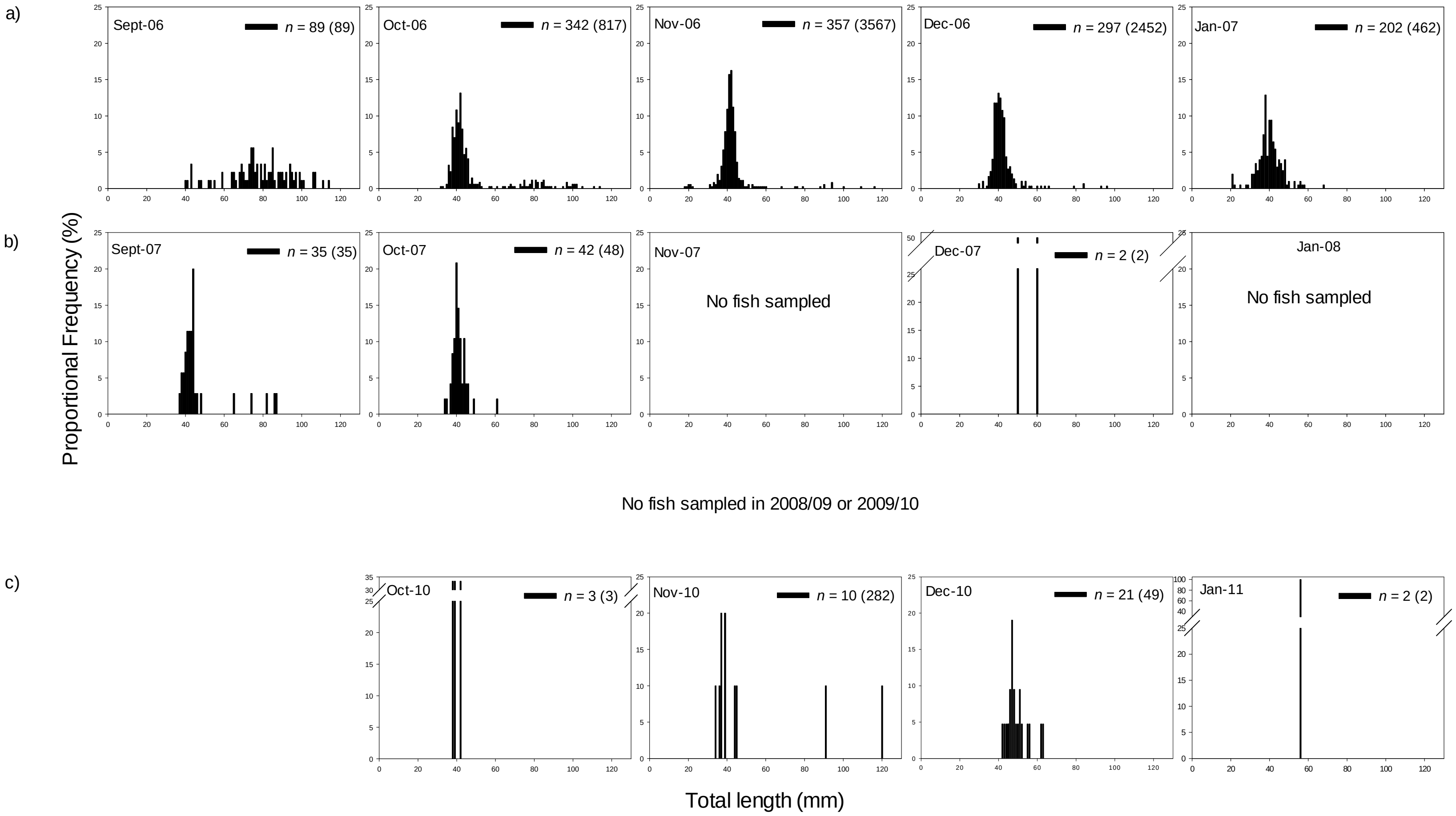

Figure 3-7. Monthly length-frequency distributions (total length, mm) of common galaxias sampled below Tauwitchere Barrage (rockramp and vertical-slot combined) during a) 2006/07, b) 2007/08 and c) 2010/11. No individuals were sampled in 2008/09 or 2009/10. *n* is the number of fish measured and the total number of fish is presented in brackets.

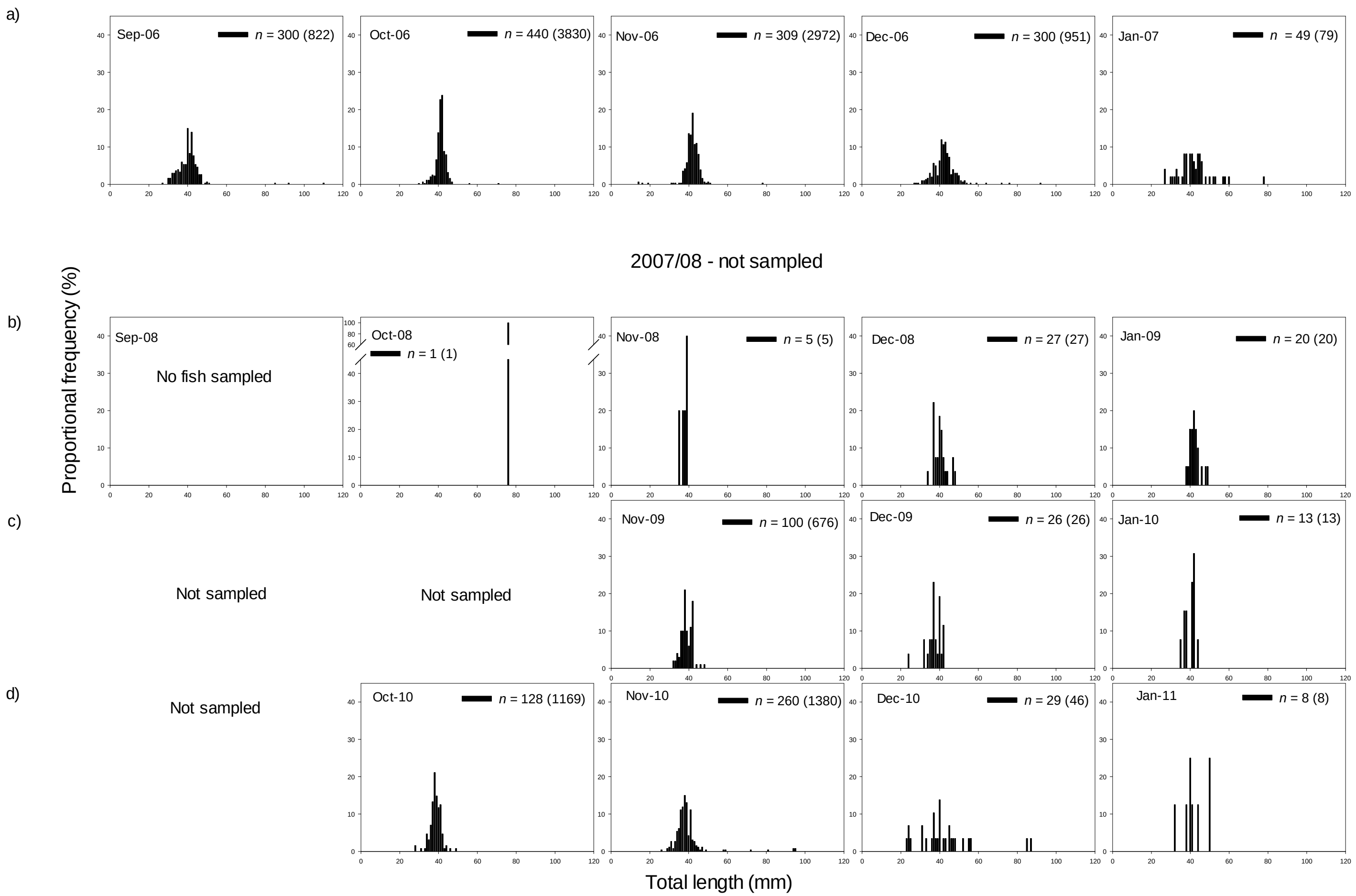

Figure 3-8. Monthly length-frequency distributions (total length, mm) of common galaxias sampled below Goolwa Barrage (vertical-slot and Hindmarsh Island abutment side of Goolwa Barrage site combined) during a) 2006/07, b) 2008/09, d) 2009/10 and e) 2010/11. *n* is the number of fish measured and the total number of fish is presented in brackets.

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3.6 Determination of spawning and hatch dates

3.6.1 Congolli

In 2006/07, spawn date distributions for congolli at both Tauwitchere and Goolwa Barrage indicated an extended reproductive season with distinct periods of higher spawning success (Figure 3-9a). At Tauwitchere, successful recruits were derived from spawning that occurred over a ~88 day period from 4 July to 29 September 2006 (Figure 3-9a). Peak periods in spawning success were observed during late August and early September. At Goolwa successful recruits resulted from spawning that occurred for a duration of ~112 days (Figure 3-9a). Spawning occurred earlier than observed at Tauwitchere, commencing on 25 June 2006 and continuing through to 14 October 2006. Peak periods in spawning success were observed from mid – late July.

In 2007/08 at Tauwitchere (Figure 3-9b), successful recruits were derived from spawning that occurred over a significantly contracted period of ~44 days, from 19 July to 31 August 2007 ($D = 0.38$, $p = 0.016$) (Figure 3-9b). In 2008/09 at Tauwitchere, spawning occurred over a similarly restricted season of ~36 days, from 19 July 2008 to 23 August 2008 (Figure 3-9c). In 2009/10 just three recruits were sampled and aged; these fish were spawned between 11 July and 23 July (Figure 3-9d). In 2010/11, however, spawning again occurred over a protracted duration, similar to 2006/07 ($D_{50, 19} = 0.162$, $p = 0.92$), of ~75 days from 10 July – 21 September (Figure 3-9e).

In 2008/09 at Goolwa, successful recruits originated from a significantly contracted spawning season ($D = 0.44$, $p < 0.001$) that occurred over a period of ~66 days, from 2 July to 5 September 2008, with a peak period in spawning success in mid July (Figure 3-9c). Similarly, in 2009/10 spawning occurred over a significantly contracted spawning season ($D = 0.32$, $p = 0.03$), relative to 2006/07, of ~64 days from 13 July to 14 September (Figure 3-9d). In 2010/11, however, spawning again occurred over a protracted period of ~104 days from 21 July – 1 November (Figure 3-9e). Whilst spawning in 2010/11 occurred over a similar duration to 2006/07, spawn-frequency distributions differed significantly ($D_{50, 32} = 0.338$, $p = 0.023$) with spawning beginning later in 2010/11 (Figure 3-9a and e).

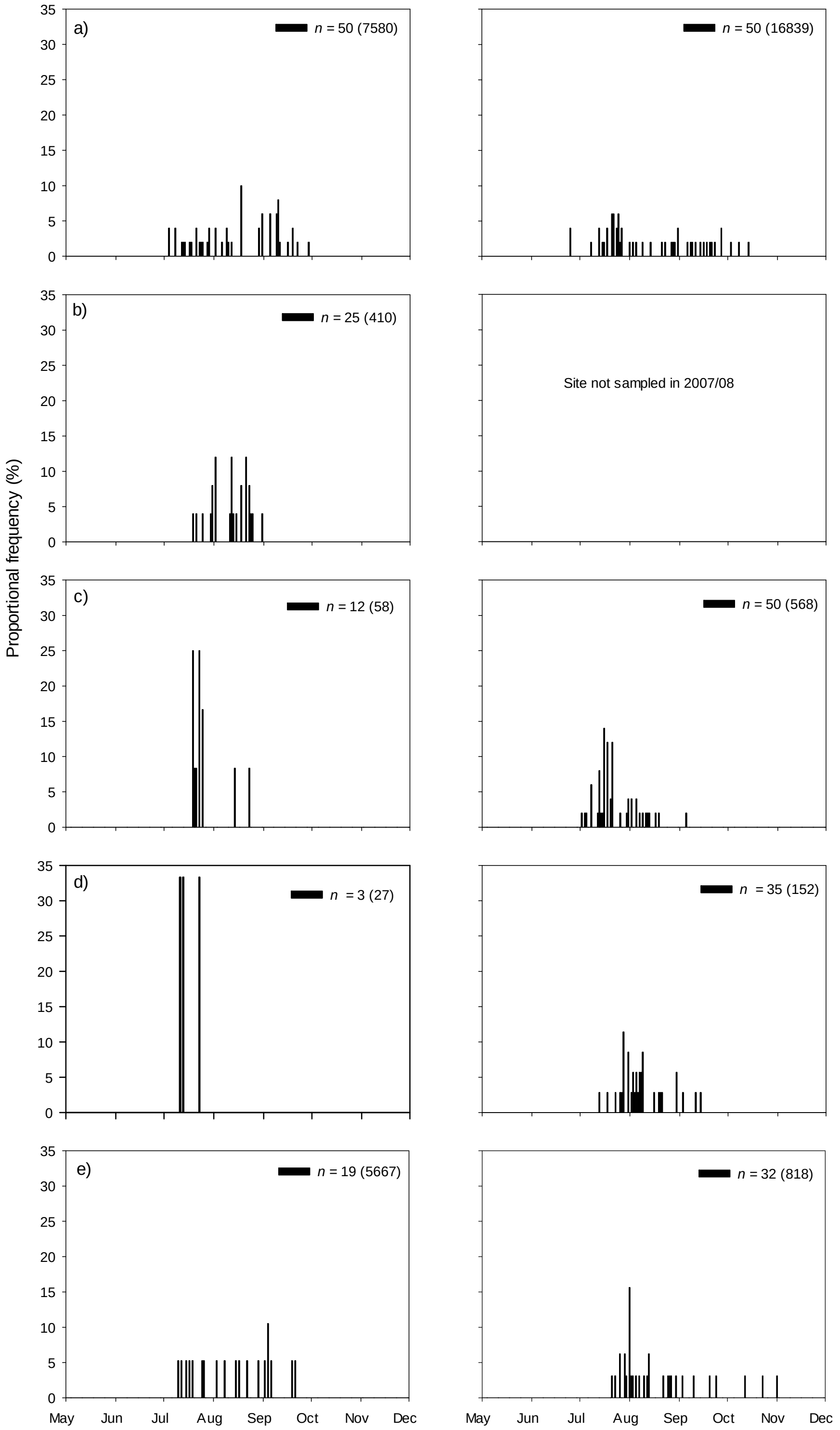

Figure 3-9. Estimated spawn-date frequency of post-larval congolli sampled from downstream Tauwitchere (left-hand side; rockramp and vertical-slot entrance sites combined) and Goolwa Barrages (right-hand side; vertical-slot entrance and Hindmarsh Island abutment of Goolwa Barrage sites combined) in a) 2006/07, b) 2007/08, c) 2008/09, d) 2009/10 and e) 2010/11. *n* is the number fish that were aged from each location within each year. The total number of individuals sampled from each location is presented in brackets.

3.6.2 Common galaxias

In 2006/07 hatch dates for common galaxias at Tauwitchere and Goolwa exhibited broad flat distributions, evidence of an extended spawning season with continuous recruitment success (Figure 3-10a). At Tauwitchere successful recruits were derived from spawning that occurred over a period of ~156 days, hatching from 17 June 2006 to 19 November 2006. At Goolwa successful recruits resulted from spawning that occurred for a similar duration of ~165 days, although hatching occurred earlier on 28 May 2006 and continued to 8 November 2006 (Figure 3-10a).

In 2007/08 hatch date distribution had contracted and was significantly different from 2006/07 at Tauwitchere ($D = 0.88$, $p < 0.001$) (Figure 3-10b). Recruits were derived from spawning that occurred over a substantially shorter period of ~46 days, hatching from 27 May to 11 July 2007. In 2008/09 and 2009/10 recruits were absent from Tauwitchere (Figure 3-10c and d). In 2010/11, however, recruits were again present and were derived from a contracted hatching season relative to 2006/07, albeit without statistical significance ($D = 0.297$, $p = 0.147$), of ~68 days from 21 July to 26 September

At Goolwa in 2008/09 successful recruits were derived from spawning that occurred over a significantly shorter period than 2006/07 ($D = 0.63$, $p < 0.001$) of ~48 days, hatching from 10 August to 26 September 2008 (Figure 3-10c). In 2009/10, spawning period had increased to ~82 days, hatching from 2 August to 21 October (Figure 3-10d), but remained significantly less than that exhibited in 2006/07 ($D = 0.52$, $p < 0.001$) and did not differ significantly from the hatch date distribution of 2008/09 ($D = 0.21$, $p = 0.36$). In 2010/11, hatching occurred over a similar duration to 2009/10, over ~85 days from 18 July to 10 October, but peak hatching occurred earlier than in 2009/10 in early August ($D = 0.454$, $p = 0.002$) (Figure 3-10d and e). Hatching in 2010/11 occurred over a significantly shorter period than 2006/07 ($D = 0.403$, $p = 0.008$) (Figure 3-10a and e).

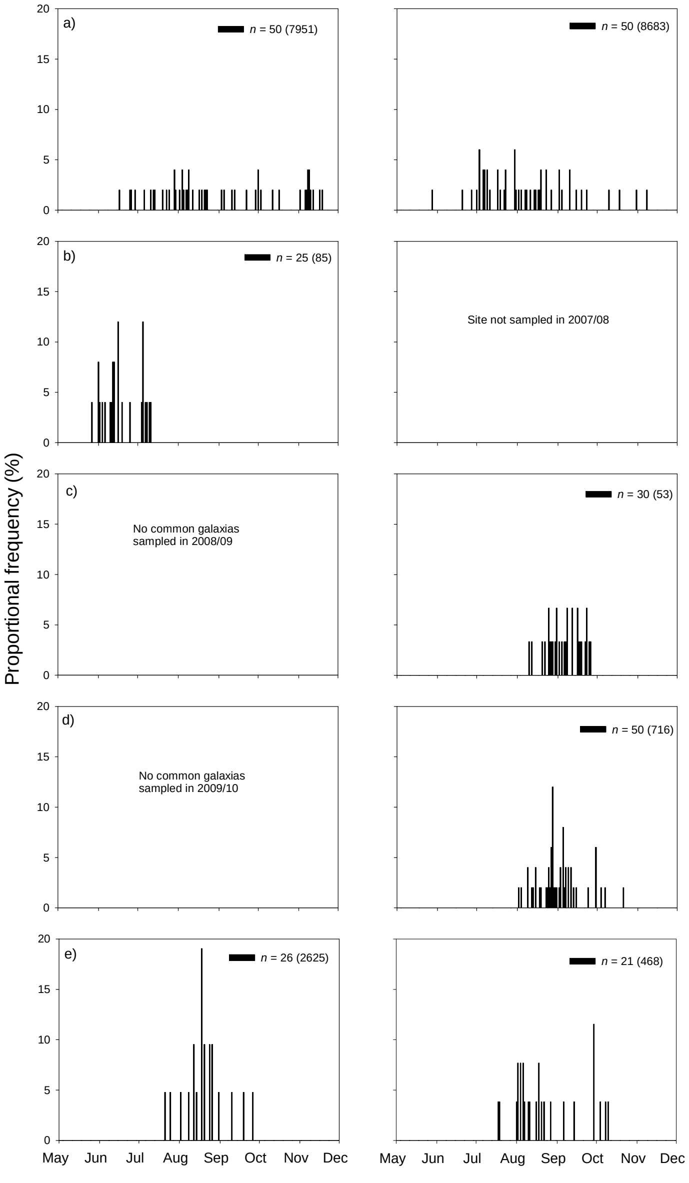

Figure 3-10. Estimated hatch-date frequency of post-larval common galaxias sampled from downstream Tauwitchere (left-hand side; rockramp and vertical-slot entrance sites combined) and Goolwa Barrages (right-hand side; vertical-slot entrance and Hindmarsh Island abutment of Goolwa Barrage sites combined) in a) 2006/07, b) 2007/08, c) 2008/09, d) 2009/10 and e) 2010/11. *n* is the number fish that were aged from each location within each year. The total number of individuals sampled from each location is presented in brackets.

3.7 Fishway assessments

Species ascending the Hunters Creek vertical-slot and Tauwitchere small vertical-slot fishways

A total of 159,014 fish (entrance: *n* = 90,005, exit: *n* = 69,009) from 20 species were sampled at the Hunters Creek vertical-slot fishway (Figure 3-11). Catches were dominated by a non-native freshwater species; redfin perch (*n* = 119,948). The freshwater bony herring (*n* = 17,854) and flat-headed gudgeon (*n* = 11,188), non-native common carp (*n* = 3,409), and catadromous congolli (*n* = 2,194) and common galaxias (*n* = 2,458) were also abundant. These six species represented ~99% of the total catch.

A total of 183,659 fish (entrance: *n* = 70,481, exit: *n* = 113,178) from 19 species were sampled at the Tauwitchere small vertical-slot fishway (Table 3-1). Catches were dominated by non-native redfin perch (*n* = 144,251), together with two native freshwater species, Australian smelt (*n* = 28,867) and flat-headed gudgeon (*n* = 4,495) and two catadromous species, congolli (*n* = 1,964) and common galaxias (*n* = 1816). These five species cumulatively represented ~99% of the total catch.

MDS ordination of fish assemblage data from exit and entrance trapping at both the Hunters Creek vertical-slot and Tauwitchere small vertical-slot did not indicate any grouping of sampling events by sampling location (i.e. entrance or exit) (Figure 3-11). This was supported by PERMANOVA, which indicated that fish assemblages sampled at entrances and exits did not differ significantly at the Hunters Creek vertical-slot ($Pseudo\text{-}F_{1,\,33} = 0.305$, $p = 0.911$) or at the Tauwitchere small vertical-slot ($Pseudo\text{-}F_{1,\,31} = 1.031$, $p = 0.362$).

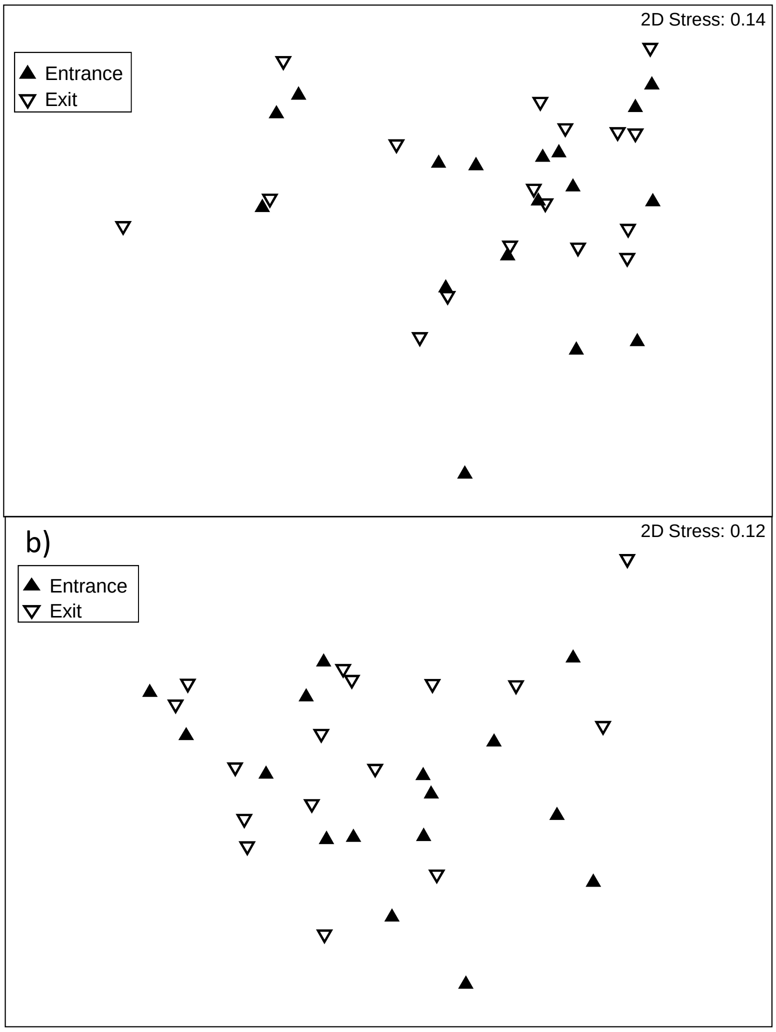

Figure 3-11. MDS ordination plots of fish assemblages sampled at the entrance and exit of the a) Hunters Creek vertical-slot and b) Tauwitchere small-bodied vertical-slot.

Uni-variate PERMANOVA was used to determine if there were differences in the relative abundance between entrance and exit samples of the most abundant species at the Hunters Creek vertical-slot and Tauwitchere small vertical-slot. At the Hunters Creek vertical-slot there was no significant difference in the abundance of common galaxias ($Pseudo\text{-}F_{1,\ 33} = 1.727$, $p = 0.186$), congolli ($Pseudo\text{-}F_{1,\ 33} = 0.23$, $p = 0.646$), bony herring ($Pseudo\text{-}F_{1,\ 33} = 0.066$, $p = 0.798$), flat-headed gudgeon ($Pseudo\text{-}F_{1,\ 33} = 0.003$, $p = 0.96$), redfin perch ($Pseudo\text{-}F_{1,\ 33} = 0.023$, $p = 0.879$) or common carp ($Pseudo\text{-}F_{1,\ 33} = 0.525$, $p = 0.469$) between entrance and exit samples (Figure 3-12a). Similarly, at the Tauwitchere small-bodied vertical-slot, there was no significant difference in the abundance of common galaxias ($Pseudo\text{-}F_{1,\ 31} = 2.331$, $p = 0.146$), congolli ($Pseudo\text{-}F_{1,\ 31} = 0.332$, $p = 0.57$), Australian smelt ($Pseudo\text{-}F_{1,\ 31} = 0.257$, $p = 0.627$), flat-headed gudgeon ($Pseudo\text{-}F_{1,\ 31} = 0.64$, $p = 0.429$) or redfin perch ($Pseudo\text{-}F_{1,\ 31} = 0.207$, $p = 0.651$) between entrance and exit samples (Figure 3-12b).

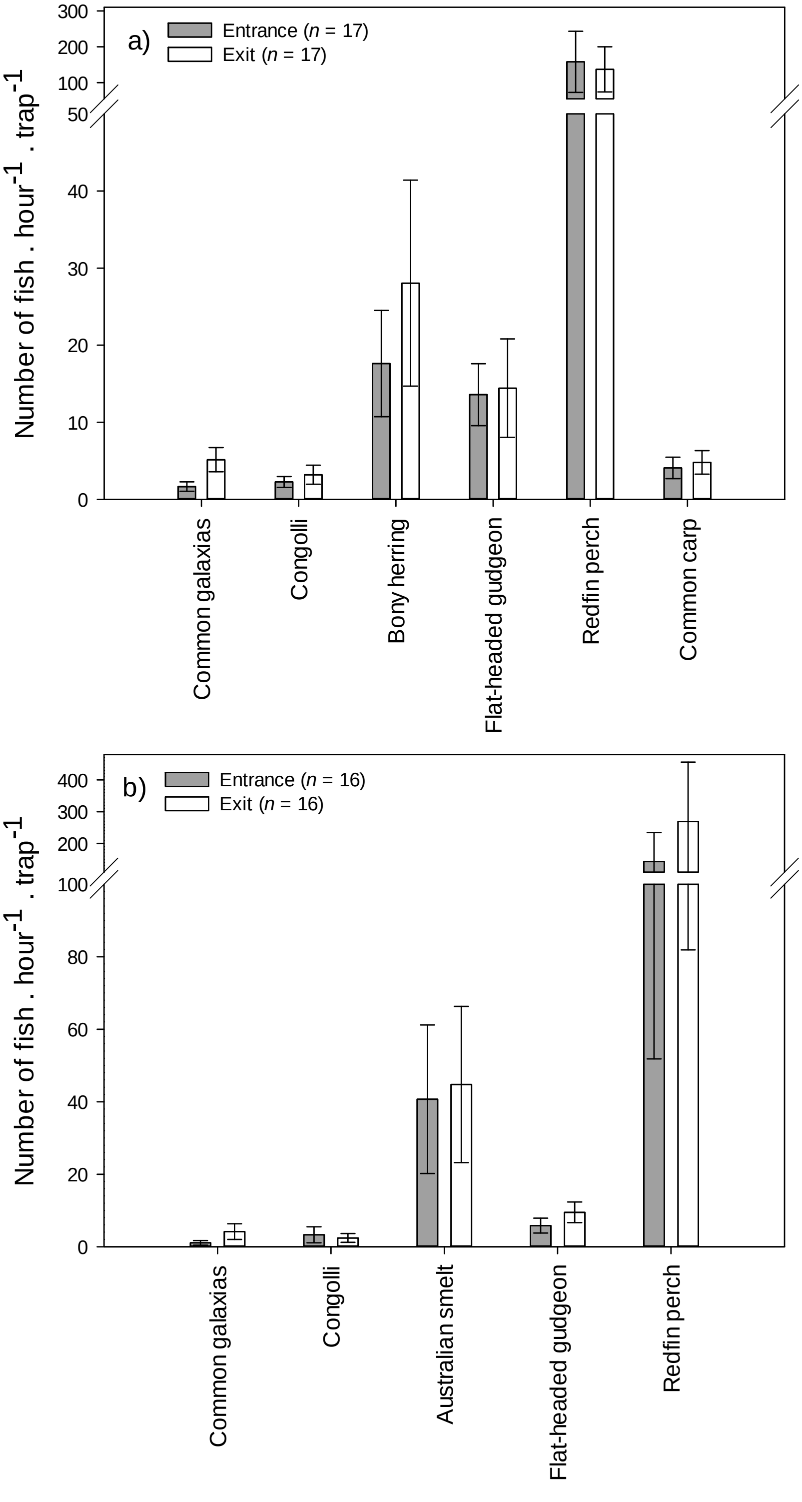

Figure 3-12. Relative abundance (number of fish.hour^{-1}.trapping event^{-1}) of the most abundant species, sampled at the entrance and exit of a) the Hunters Creek vertical-slot fishway and b) the Tauwitchere small-bodied vertical-slot fishway in 2010/11.

Size of fish ascending the Hunters Creek vertical-slot and Tauwitchere small vertical-slot fishways

Common galaxias sampled at the entrance to the Hunters Creek vertical-slot fishway ranged from 25 – 104 mm TL, compared to 32 – 90 mm TL at the exit (Figure 3-13a). Length-frequency distributions differed significantly ($D_{291, 256} = 0.178$, $p < 0.001$), likely due to a greater proportion of individuals 40 – 44 mm TL at the entrance. Congolli (entrance: 28 – 108 mm TL, exit: 30 – 86 mm TL), bony herring (entrance: 33 – 166 mm FL, exit: 32 – 121 mm FL) and common carp (entrance: 9 – 90 mm FL, exit: 8 – 162 mm FL) all appear to exhibit length-frequency distributions that are similar between entrance and exit samples (Figure 3-13b, c and f); however marginally higher proportions of small individuals were sampled at the entrance (congolli: $D_{349, 343} = 0.155$, $p < 0.001$, bony herring: $D_{316, 296} = 0.127$, $p = 0.015$, common carp: $D_{325, 326} = 0.177$, $p < 0.001$). There was no difference in length-frequency distributions of flat-headed gudgeon (entrance: 30 – 86 mm TL, exit: 28 – 77 mm TL. $D_{403, 425} = 0.065$, $p = 0.344$) or redfin perch (entrance: 21 – 93 mm FL, exit: 18 – 100 mm FL. $D_{374, 356} = 0.081$, $p = 0.185$) between entrance and exit samples (Figure 3-13d and e).

Length-frequency distributions of congolli at the Tauwitchere small-bodied vertical-slot differed significantly between entrance and exit samples ($D_{137, 227} = 0.176$, $p = 0.01$). Exit trapping yielded a greater range of lengths (i.e. entrance: 18 – 70 mm TL, exit: 24 – 107 mm TL) and a greater proportion of individuals 25 – 34 mm TL (Figure 3-14b). The length-frequency distribution of Australian smelt also differed between entrance (range: 19 – 75 mm FL) and exit samples (range: 23 – 69 mm FL) ($D_{331, 349} = 0.154$, $p < 0.001$). A greater proportion of smaller Australian smelt, 19 – 29 mm FL, were sampled from the entrance (Figure 3-14c). No significant difference in length-frequency distributions was detected between entrance and exit samples for common galaxias (entrance: 31 – 128 mm TL, exit: 32 – 112 mm TL. $D_{79, 205} = 0.066$, $p = 0.959$), flat-headed gudgeon (entrance: 18 – 81 mm TL, exit: 24 – 90 mm TL. $D_{337, 350} = 0.091$, $p = 0.116$) or redfin perch (entrance: 24 – 315 mm FL, exit: 21 – 280 mm FL. $D_{333, 334} = 0.062$, $p = 0.543$) (Figure 3-14a, d and e).

Length-frequency distributions of common galaxias differed significantly between entrance and exit samples at the Goolwa vertical-slot fishway ($D_{114, 25} = 0.313$, $p = 0.036$). Entrance trapping yielded a greater range of lengths (i.e. entrance: 23 – 95 mm FL, exit: 33 – 82 mm TL) and a greater proportion of individuals <40 mm FL (Figure 3-15a). Similarly, length-frequency distributions of congolli differed significantly between entrance and exit samples ($D_{119, 54} = 0.266$, $p = 0.025$), with entrance trapping yielding a greater range of lengths (i.e. entrance: 21 – 146 mm FL, exit: 23 – 78 mm TL) (Figure 3-15b). The minimum size of congolli in entrance and exit samples did not differ markedly but a greater proportion of individuals 30 – 34 mm TL were sampled at the entrance (Figure 3-15b). Australian smelt also exhibited significantly different length-frequency distributions between entrance and exit samples ($D_{362, 175} = 0.151$, $p = 0.009$), with fish ranging 22 – 71 mm FL and 28 – 66 mm FL respectively and greater proportion of individuals <30 mm FL sampled from the exit (Figure 3-15c). No significant difference in length-frequency distributions was detected between entrance and exit samples for bony herring (entrance: 18 – 251 mm FL, exit: 28 – 196 mm FL. $D_{293, 145} = 0.132$, $p = 0.068$), lagoon goby (entrance: 17 – 54 mm TL, exit: 16 – 53 mm TL. $D_{212, 123} = 0.133$, $p = 0.127$) or sandy sprat (entrance: 21 – 56 mm FL, exit: 20 – 55 mm FL. $D_{132, 97} = 0.121$, $p = 0.391$) (Figure 3-15d – f).

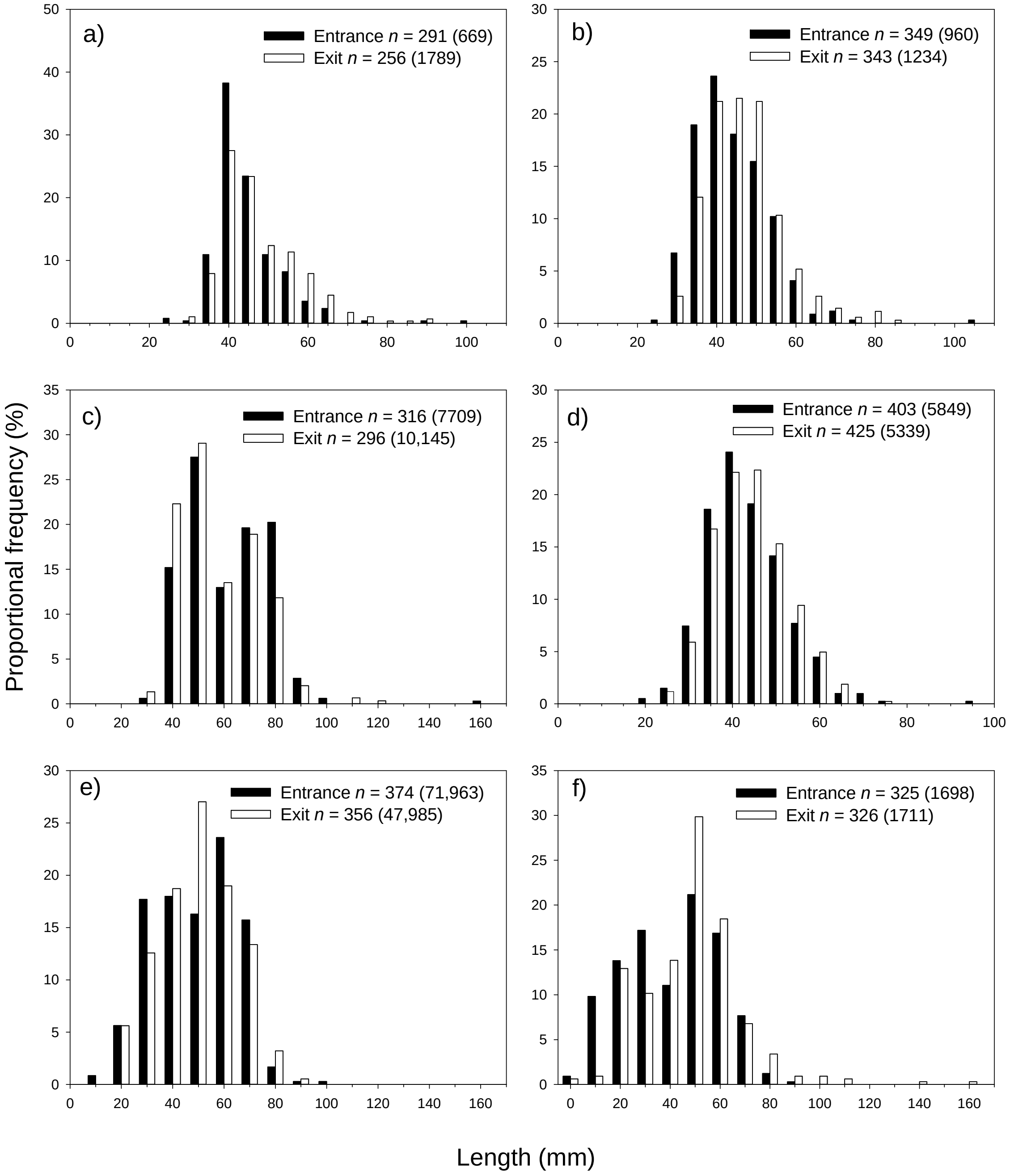

Figure 3-13. Length-frequency distributions of a) common galaxias, b) congolli, c) bony herring, d) flat-headed gudgeon, e) redfin perch and f) common carp sampled from the entrance (shaded bar) and exit (unshaded bar) of the Hunters Creek vertical-slot fishway in 2010/11.

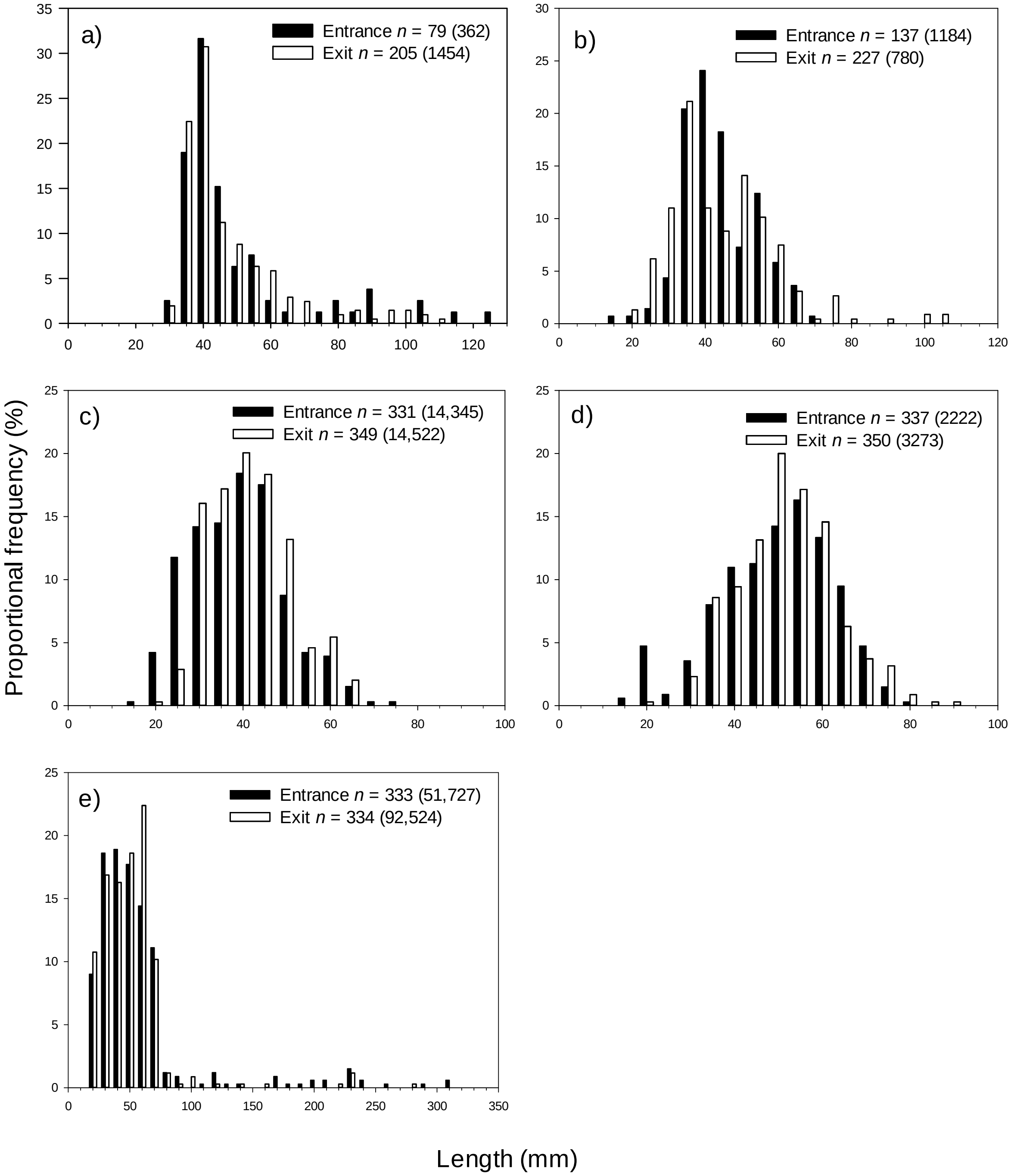

Figure 3-14. Length-frequency distributions of a) common galaxias, b) congolli, c) Australian smelt, d) flat-headed gudgeon and e) redfin perch sampled from the entrance (shaded bar) and exit (unshaded bar) of the Tauwitchere small vertical-slot fishway in 2010/11.

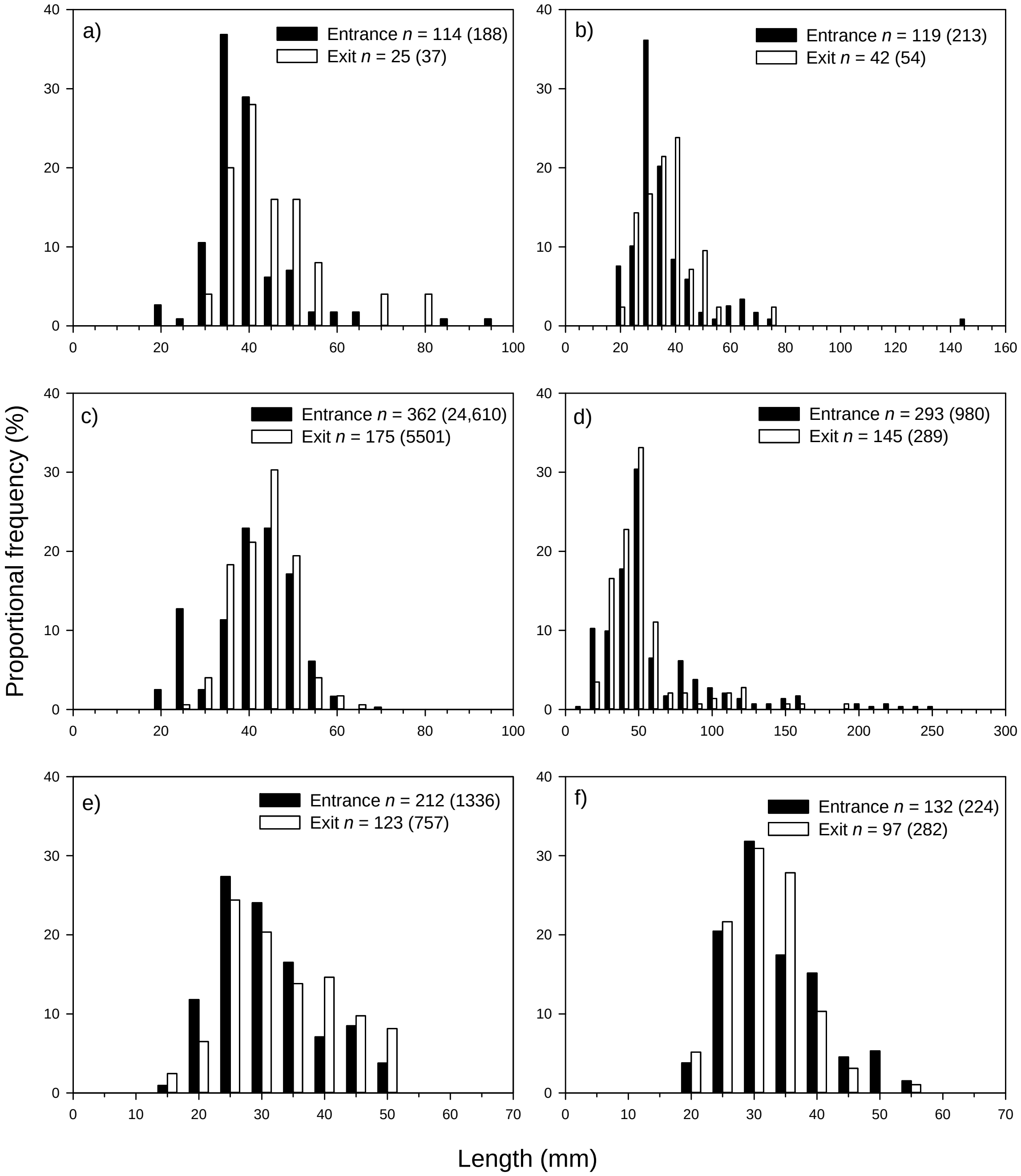

Figure 3-15. Length-frequency distributions of a) common galaxias, b) congolli, c) Australian smelt, d) bony herring, e) lagoon goby and f) sandy sprat sampled from the entrance (shaded bar) and exit (unshaded bar) of the Goolwa vertical-slot fishway in 2010/11.

4 Discussion

4.1 Fish assemblage

Temporal Variation

In 2010/11, 31 species of fish were sampled at six sites immediately downstream of the Murray Barrages in the Coorong estuary. Species richness was greater than that recorded from late 2007 – early 2010 but similar to that recorded in 2006/07 (Zampatti *et al.* 2011). The overall catch in 2010/11 was numerically dominated by freshwater Australian smelt and redfin perch (an introduced species), and the marine migrant sandy sprat. Catadromous congolli and common galaxias were also abundant with the vast majority (> 90% of the total catch) of individuals collected for both species being juveniles (0+ year class) attempting to migrate upstream.

The predominance of freshwater species in 2010/11 reflects the large volumes of freshwater discharged through the barrages and the displacement/range expansion of freshwater species. It contrasts the fish assemblage observed during an extended period (2007 – early 2010) of no freshwater release to the Coorong when marine migrant and estuarine species were most abundant, and during low volume freshwater releases in 2006/07 when estuarine, catadromous and marine migrant species dominated the catch.

Overall, differences in fish assemblages in the Coorong estuary between 2006 and 2010 were the result of decreasing relative abundances of small-bodied estuarine (e.g. goby species), catadromous and freshwater fishes, and increasing relative abundances of medium-bodied marine and estuarine species (Zampatti *et al.* 2011). In 2010/11, assemblages differed from previous years as the freshwater species (i.e. Australian smelt, flat-headed gudgeon, bony herring and redfin perch) and estuarine lagoon goby increased in abundance.

We used indicator species analysis (Dufrêne and Legendre 1997) to determine those species that characterised fish assemblages at each site over time. In 2010/11, as freshwater discharge into the Coorong increased significantly and salinities decreased, fish assemblages were predominantly characterised by freshwater species (i.e. golden perch, carp gudgeon, bony herring, Australian smelt, flat-headed gudgeon, redfin perch common carp and goldfish) but also catadromous (i.e. common galaxias and congolli), estuarine (i.e. river garfish, lagoon goby and longfin goby) and marine migrant species (i.e. sandy sprat).

The influence of salinity on spatio-temporal variation in estuarine fish assemblage structure has been documented widely (Lonergan *et al.* 1986; Barletta *et al.*, 2005; Baptista *et al.* 2010). At a range of spatial and temporal scales, low salinities caused by high freshwater flows generally result in low species diversity and high abundances of a few freshwater and estuarine dependent species (Lamberth et al. 2008). Brackish salinities result in high species diversity, with a range of freshwater, estuarine and marine migrant and vagrant species present (Baptista *et al.* 2010), and high salinities (i.e. marine) caused by diminished freshwater inflows result in decreased species diversity characterised by the loss of freshwater species and increases in marine species (Martinho *et al.* 2007). The current study indicates that such general patterns also apply to the Coorong.

Species richness in the Coorong is similar to that observed in other temperate estuaries in southern Australia (Humphries *et al.* 1992; Potter and Hyndes 1999 and references therein) and South Africa (Whitfield 1999; Lamberth *et al.* 2008). Estuarine fish assemblages are inherently variable with changes occurring at scales ranging from days to years (Methven *et al.* 2001); Nevertheless, fish species richness and diversity in the Coorong appears to be greatest when freshwater flow through the barrages generates connectivity between the Southern Ocean, Coorong and Lower Lakes, and brackish but variable salinities prevail (e.g. 2006/07 and 2010/11).

Spatial Variation

In 2010/11, fish assemblages differed significantly between all capture locations, with the exception of the Goolwa large vertical-slot and Tauwitchere small vertical-slot. Species richness varied from 15 species at the entrance of the Tauwitchere large vertical-slot to 23 species at the entrance of the Goolwa vertical-slot. Large and diverse catches at the two sites immediately downstream of Goolwa and Tauwitchere barrages masked differences in the fish assemblages between the fishway entrances, therefore we analysed fishway sites independent of downstream sites.

In general the Goolwa large vertical-slot fishway was characterised by high abundances of freshwater, estuarine, catadromous and marine migrant species, the Tauwitchere large and small vertical-slot fishways by freshwater and catadromous species and the estuarine lagoon goby, and Hunters Creek vertical-slot fishway by freshwater and catadromous species. Spatial differences in fish assemblages at fishways, and sites immediately downstream of the barrages, may reflect spatio-temporal variation in salinity at these sites, connectivity between the open waters of Lake Alexandrina (e.g. Tauwitchere) or more confined channels (e.g. Goolwa and Hunters Creek) and proximity to the Murray mouth.

4.2 Abundance and recruitment of diadromous fish

As freshwater inflows into the Coorong resumed (September 2010) the abundance of catadromous congolli and common galaxias increased significantly at all sites in comparison to the low inflow period of 2007/08 – 2009/10. Abundances at the Tauwitchere rockramp were also greater than in 2006/07 (Zampatti *et al.* 2011). Nevertheless, two species of anadromous lamprey (*Mordacia mordax* and *Geotria australis*), last captured in 2006/07, remained absent from the catch.

Like 2006/07, the majority (>90%) of congolli and common galaxias collected in 2010/11 were young-of-year (YOY). Improved recruitment of catadromous species was most likely a result of improved connectivity between freshwater and marine environments and increased spawning and/or survival of larvae under brackish salinities (Whitfield 1994; Gillanders and Kingsford 2002). The abundance of YOY congolli peaked between November and December 2010 at both Goolwa and Tauwitchere similar to that recorded in 2006/07 but unlike 2006 did not extend through December (Zampatti *et al.* 2011).

Congolli exhibit an obligate catadromous life history that is highly susceptible to fragmentation (Crook *et al.* 2010; Zampatti *et al.* 2011). Females reside in freshwater habitats and undertake a pre-spawning migration to estuarine/marine habitats where male fish predominate (Hortle, 1978; Crook *et al.*, 2010). Recruitment failure in the MDB from 2007 – 2010 was primarily a result of the disruption of the downstream migration of females (Zampatti *et al.* 2010; Zampatti *et al.* 2011). If juvenile congolli exhibit natal homing, the significant increase in abundance of YOY congolli in 2010/11 may be attributable to the operation of the Goolwa Barrage boat lock to facilitate the downstream migration of reproductively mature female congolli from July – early September 2010. Without this intervention female congolli would have again been prevented from spawning in the Coorong estuary/Southern Ocean.

The highest abundances of YOY common galaxias in 2010/11 were captured at Goolwa Barrage between October and November, similar to 2006/07 but, like congolli, abundances decreased in December. Only low abundances of YOY common galaxias were collected at Tauwitchere in 2010/11, unlike 2006/07 when YOY were collected in similar abundance to Goolwa from October – December (Zampatti *et al.* 2011). Based on monitoring data alone it is difficult to elucidate the reasons for the decreased abundance of common galaxias at Tauwitchere and decreased abundances of common galaxias and congolli in December 2011 compared to 2006. It is possible that the large volume of freshwater flow (~70,000 ML/d) in December 2010 and the large number (200+) of barrage gates open made the fishways difficult for fish to locate. Furthermore, open barrage bays may have facilitated fish passage during periods of low head differential between the Lower Lakes and Coorong. High flow may also create hydraulic conditions that exceed the swimming abilities of YOY congolli and common galaxias hence fish may be prevented from approaching the barrage, with the exception of the littoral regions, during these periods.

Back calculated spawn and hatch dates for YOY congolli and common galaxias respectively were established by interpreting otolith microstructure (i.e. daily increment formation). Both species exhibited protracted spawning/hatch periods in 2010. Congolli spawned over a similar duration to 2006/07 (i.e. 3 – 4 months from mid July to late October) and considerably longer than that observed from 2007 – 2009. Common galaxias, however, hatched over a noticeably contracted season (July – October) in 2010 in comparison to June – November in 2006. The hatch season in 2011 was, however, broader than that observed from 2007 – 2009. Protracted spawning seasons enable the early life stages of fish to be exposed to a broader range of environmental conditions hence maximising the prospects of survival and hence recruitment (Secor 2007).

Spawning was essentially continuous over the spawning period for both species, although spawning intensity appeared greatest for congolli in late July/early August 2010 and hatch intensity for common galaxias in August 2010. There is some inter-annual variation in peak spawning/hatch activity for congolli and common galaxias but the key spawning /hatch periods appear to be July – October and July – November respectively (Zampatti *et al.* 2011). To enable the spawning and recruitment of catadromous congolli and common galaxias the provision of freshwater flow to the Coorong and adequate downstream and upstream fish passage through the tidal barrages is essential during these periods. Provision of such will also cater for the life history processes of anadromous lamprey.

4.3 Fishway performance

The Tauwitchere and Hunters Creek small vertical-slot fishways effectively facilitated the passage of a diverse range of fish (19 and 20 species respectively). Large numbers of catadromous (i.e. congolli and common galaxias), native freshwater species (i.e. flat-headed gudgeon, Australian smelt and bony herring) and non-native freshwater species (i.e. redfin perch and common carp) successfully ascended both fishways with no difference in the relative abundance of these species between entrance and exit samples. Furthermore, fish <30 mm in length successfully ascended both fishways. Of the abundant species, Australian smelt at the Tauwitchere small vertical-slot and Common galaxias, congolli, bony herring, and common carp at the Hunters Creek vertical-slot exhibited potential size related variation in passage success. Differences in length frequency distributions from the entrances and exits for these species, however, were marginal with slightly higher proportions of small fish at the entrances. The Hunters Creek vertical-slot fishway facilitated the upstream passage of a considerable number of fish <20 mm in length (minimum 8 mm), which are among the smallest fish successfully passed by pool-type fishways in Australia or globally (Jansen *et al.* 1999; Stuart and Berghuis 2002; Stuart *et al.* 2008).

The Tauwitchere small vertical-slot and Hunters Creek vertical-slot fishways have enhanced fish passage at the Murray Barrages and complement the existing larger vertical-slot fishways. Previous assessments at the Goolwa large vertical-slot, Tauwitchere large vertical-slot and Tauwitchere rock-ramp fishways indicated that these structures were not adequately facilitating the passage of some species and size classes of small and medium-bodied fish (Jennings *et al.* 2008). The small vertical slot fishways at Hunters Creek and Tauwitchere fulfil this role, passing a range of small-bodied species and in particular facilitating the upstream passage of the juvenile life-stages of catadromous common galaxias and congolli. Both of these fishways, however, did not attract or facilitate passage for adults of large-bodied species (e.g. golden perch, >300 mm TL), emphasizing the complementary roles of both the large and small vertical-slot fishways on the Murray Barrages.

An additional benefit of the Hunters Creek and Tauwitchere small vertical-slot fishways is they require only low volumes of water (<10 $ML.d^{-1}$) to operate effectively when compared to the large vertical-slot fishways. Thus, at times of limited water availability, these fishways may be operated with minimal water resources (given favourable Lake and Coorong water levels) and provide connectivity between the Coorong and Lake Alexandrina for diadromous fish species.

The effectiveness of the modified Goolwa large vertical-slot fishway was also assessed in 2010/11 but the assessment was compromised due to trapping limitations. Excessive growth of the encrusting estuarine tube worm, *Ficopomatus enigmaticus,* on the upstream exit baffle of the fishway obstructed the bottom half of the 'dual trap' set-up and thus only the top trap could be set. Therefore the fishway exit was not completely 'sealed' and fish could exit the fishway without entering the trap. Consequently, the abundance of fish entering the fishway from downstream could not be statistically compared with the abundance of fish exiting the fishway upstream. Despite this, substantial numbers of fish from 17 different species successfully ascended the fishway suggesting that fishway performance had improved following modification.

Assessment of the partial depth Goolwa large vertical-slot fishway in 2005/06 indicated the total number of fish sampled at the exit was ~5% of total entrance number (Jennings *et al.* 2008). In 2010/11, despite reduced trapping efficiency, the total number of fish sampled at the exit was ~18% of the total number at the entrance. Furthermore, in 2010/11 the minimum size of the most abundant species (i.e. congolli, bony herring, lagoon goby and sandy sprat) was similar at both the entrance and exit of the fishway and there was no size related variation in passage success. Only a limited proportion of small common galaxias (<33 mm FL) and Australian smelt (<28 mm FL) appeared unable to ascend the fishway. Fish <20 mm in length (minimum 16 mm) successfully ascended the Goolwa vertical-slot fishway in 2010/11, which, similar to the two small vertical-slot fishways, are among the smallest fish successfully passed by pool type fishways in Australia or globally (Jansen *et al.* 1999; Stuart and Berghuis 2002; Stuart *et al.* 2008)). Importantly significant numbers of YOY common galaxias and congolli were able to ascend the fishway. Similar modifications, including decreasing slot width and installing baffles, could be considered at the Tauwitchere large vertical-slot fishway to potentially increase passage success for small-bodied fish species but this may compromise passage of large bodied fish.

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 anadromous lamprey in the Murray-Darling Basin. 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 of diadromous and some estuarine species. When brackish conditions prevailed, fish assemblages were characterised by a diversity of freshwater, diadromous, estuarine and marine species. As salinities increased, however, freshwater, diadromous and estuarine species were lost and marine species became more common (Zampatti *et al.* 2010; Zampatti *et al.* 2011).

As freshwater inflows to the Coorong resumed in late 2010, salinities downstream of the barrages decreased and ranged between freshwater and brackish. Fish assemblages were significantly different from 2006 – early 2010, due to increased abundances of freshwater species and estuarine lagoon goby, and decreased abundances of marine and some estuarine species. Abundances of catadromous congolli and common galaxias also increased significantly but anadromous lampreys were not collected. Freshwater flow through the barrages generates brackish salinities in the Coorong and connectivity between the Southern Ocean, Coorong and Lower Lakes, in turn promoting high species diversity in the Coorong and high abundances of YOY catadromous species. Nevertheless, when high volumes of freshwater flow into the Coorong, fish assemblages may be dominated by freshwater species.

In 2010/11, fish assemblages differed significantly between sites, with the exception of the Goolwa large vertical-slot and Tauwitchere small vertical-slot fishways. In general the Goolwa large vertical-slot fishway was characterised by freshwater, estuarine, catadromous and marine migrant species, the Tauwitchere large and small vertical-slot fishways by freshwater and catadromous species and the estuarine lagoon goby, and Hunters Creek vertical-slot fishway by freshwater and catadromous species. Fish assemblages in the Coorong, however, are spatially variable at temporal scales ranging from hours to years. Consequently, we recommend that decisions regarding the release location of water from the barrages should not be based on the data from 2010/11 alone and instead, where possible, long-term (i.e. multi-year) datasets are considered.

As freshwater inflows into the Coorong resumed, abundances of catadromous congolli and common galaxias increased significantly. The majority (>90%) of congolli and common galaxias collected in 2010/11 were young-of-year and improved recruitment of catadromous species was most likely a result of improved connectivity between freshwater and marine environments and increased spawning and/or survival of larvae under brackish salinities. The significant increase in abundance of YOY congolli in 2010/11 may be attributable to the operation of the Goolwa Barrage boat lock to facilitate the downstream migration of reproductively mature female congolli from July – early September 2010. Without this intervention female congolli would have again been prevented from spawning in the Coorong estuary/Southern Ocean.

The Tauwitchere and Hunters Creek small vertical-slot fishways effectively facilitated the passage of a broad range of species and sizes of fish. Large numbers of catadromous, and native and non-native freshwater species successfully ascended both fishways with no difference in the relative abundance of these species, or size ranges (with the exception of Australian smelt) between entrance and exit samples. The Tauwitchere small vertical-slot and Hunters Creek vertical-slot fishways have significantly enhanced fish passage at the Murray Barrages and complement the existing larger vertical-slot fishways.

The modified full-depth Goolwa large vertical-slot fishway also effectively passed a diverse range of species and broad size range of fish. Despite unresolvable problems with effectively trapping the exit of the fishway, the fishway performed substantially better than the original partial depth, 300 mm slot fishway, particularly for small – medium bodied fish. Importantly, large numbers of YOY common galaxias and congolli were able to ascend the modified fishway.

The results of this investigation support the hypotheses proposed by DFW and DENR that (1) high abundances of juvenile congolli and (2) diadromous and estuarine fish species, would recruit and utilise the Goolwa Barrage fishway to migrate between the Coorong and Goolwa Channel following an extended period of disconnection and no-flow, (3) diadromous and estuarine fish would move between the Coorong and Lake Alexandrina and (4) fish species would be able to complete their life-cycles during and following freshwater releases. We could not, however, assess which release location elicited the best biotic response (question 5). Whilst there was spatial variation in fish assemblage structure, positive biotic responses were exhibited by fish species at all release locations relative to preceding years. In a situation of broad-scale, large-volume releases, such as those experienced in 2010/11, differentiating the benefit of different release locations is difficult. The utilisation of multiple release locations and operation of multiple fishways (i.e. Goolwa, Tauwitchere and Hunters Creek), however, is likely to provide the greatest scope for fish movement between the Coorong and Lower Lakes.

Following high end-of-system flows in the MDB in 2010/11, fish assemblages in the Coorong estuary, immediately downstream of the Murray Barrages, trended towards the diverse but variable fish assemblages that characterise dynamic estuarine environments. Furthermore, populations of catadromous congolli and common galaxias in the MDB are in the early stages of recovery following significant declines in recruitment and abundance from 2007 – 2010. Importantly, continuing freshwater flow and connectivity between the Lower Lakes and the Coorong will be essential for the restoration of populations of diadromous and estuarine species and maintaining dynamism in estuarine fish communities.

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Appendix 1. Modified Goolwa large vertical-slot fishway baffles.