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Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes from 2006–2010

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

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Executive Summary

Estuaries support diverse and complex fish assemblages with a broad range of life history strategies. 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 dependant fishes, particularly diadromous species.

The Coorong estuary in south-eastern Australia lies at the terminus of the Murray-Darling river system. The river is highly regulated; natural mean annual discharge has been reduced by 61% and the river now ceases to flow through the river mouth (Murray Mouth) 40% of the time compared to 1% under unregulated conditions. The estuary is also separated from the lower river by a series of tidal barrages that form an abrupt physical and biological barrier. In 2004/2005, three trial fishways were constructed on two of the tidal barrages. Performance assessments of the vertical-slot fishway at Goolwa Barrage and a rock-ramp and vertical-slot fishway at Tauwitchere Barrage were undertaken in 2005 and 2006. These investigations, however, were not designed to provide information on the ecology of fish that may use the fishways. Such data are imperative to inform the design and operation of fishways and the management of environmental flows between the lower Murray River and the Coorong.

The objective of this study was to investigate the migration and recruitment ecology of freshwater, diadromous and estuarine fish in response to variable 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 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 through length-frequency analysis and age determination.

3. Utilise this data to inform barrage gate and fishway operation, including timing and location of freshwater releases.

Over the four-year study period (2006/07–2009/10), freshwater inflows to the estuary diminished and ultimately ceased, disconnecting freshwater and estuarine environments. Salinities immediately downstream of the tidal barrages increased from brackish to marine–hypersaline and species richness and the abundance of freshwater and diadromous species decreased at all sites over time. Species richness was greatest when brackish conditions prevailed and the reduction in species richness was mostly due to the loss of freshwater, diadromous and estuarine species from the assemblage as salinities increased.

As freshwater inflows into the Coorong diminished the abundance of diadromous species decreased dramatically. Anadromous short-headed and pouched lamprey were only collected in 2006 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 significant declines in the abundance of young-of-the-year migrants and contraction of migration and spawning periods. Populations of congolli in the lower Murray River display spatial sexual structuring and obligate catadromy thus are particularly susceptible to altered flow regimes and fragmentation of essential spawning and recruitment habitats. Common galaxias populations in the lower Murray River, however, appear to display greater plasticity in life history strategies with the ability to sustain low levels of recruitment solely within the Lower Lakes when estuarine habitats were unavailable.

The results of our study form an important basis for environmental flow management at the freshwater/marine interface of the Murray River. Freshwater flows during 2006–2007 were low compared with longer-term averages; nevertheless, even small amounts of freshwater discharge (e.g. ~50 ML d^{-1}) delivered through appropriate fish passage structures appear to produce a significant ecological response, promoting diversity in estuarine fish assemblages and protracted spawning and successful recruitment of catadromous fish species.

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 which in turn influence the structure of fish assemblages, which 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 dependant fishes and particularly diadromous species (Lassalle and Rochard 2009).

Throughout the world there is a lack of knowledge on the response of estuary associated fish species to changing river flows (Albaret *et al.* 2004; Whitfield *et al.* 2006). Whilst several studies have reviewed or investigated relationships between river flow and the recruitment of commercially important estuarine and marine fish (Lonergan and Bunn 1999; Shoji *et al.* 2006; Nicholson *et al.* 2008), relationships between flow and non-commercial species remain poorly understood.

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.

Little is known of the biology and ecology of fish that inhabit the Coorong estuary, despite the region supporting a significant commercial fishery (Sloane 2005). Notwithstanding substantial changes in connectivity and freshwater flows, only two species, mulloway (*Argyrosomus japonicus*) and small-mouthed hardyhead (*Atherinosoma microstoma*), have been examined with respect to the potential impacts of altered hydrology (Molsher et al. 1994; Ferguson *et al.* 2008).

In 2004/2005, three trial fishways were constructed on two tidal barrages as part of the Murray-Darling Basin Commission's Sea to Hume Dam Fish Passage program (Barrett and Mallen-Cooper 2006). Performance assessments of the vertical-slot fishway at Goolwa Barrage and a rock-ramp and vertical-slot fishway at Tauwitchere Barrage were undertaken in 2005 and 2006 (Stuart *et al.*, 2005; Jennings *et al.*, 2008). These investigations, however, were not designed to provide information on the ecology of freshwater, estuarine or diadromous fish that may use the fishways. Such data are imperative to inform the design and operation of fishways and the management of environmental flows between the lower Murray River and the Coorong.

The objective of this study was to investigate the migration and recruitment ecology of freshwater, diadromous and estuarine fish in response to variable 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 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 through length-frequency analysis and age determination.

3. Utilise this data to inform barrage gate and fishway operation, including timing and location of freshwater releases.

The transfer of data and knowledge to inform barrage and fishway operation (Aim 3) has been an ongoing process throughout the life of this project and has involved close liaison with the Department for Water (DFW; formerly the Department of Water, Land and Biodiversity and Conservation (DWLBC)), the South Australian Murray-Darling Basin Natural Resources Management Board, the Murray-Darling Basin Authority (MDBA; formerly the Murray-Darling Basin Commission (MDBC)), the Department for Environment and Natural Resources (DENR; formerly the Department for Environment and Heritage (DEH)), SA Water, community groups and national and international researchers. It has also included the publication of two reports (Bice *et al.* 2007; Jennings *et al.* 2008) and a peer reviewed scientific paper (Zampatti *et al.* 2010).

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 ~4723 GL y^{-1} reaches the sea, although over the past decade this has been substantially less and zero on three occasions (Figure 2-2).

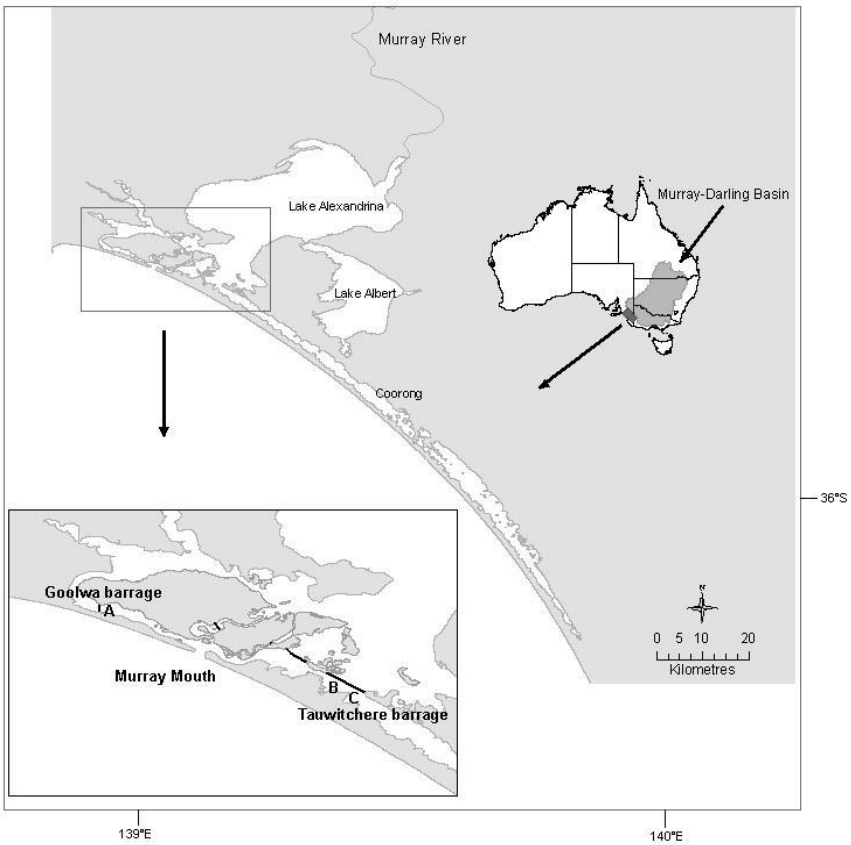


Figure 2-1 A map of the Coorong and Lower Lakes (Lakes Alexandrina and Albert) at the terminus of the Murray River, southern Australia showing the study area in the Coorong estuary, highlighting the Murray Mouth, Goolwa and Tauwitchere barrages and the fish sampling locations (A – Goolwa vertical-slot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

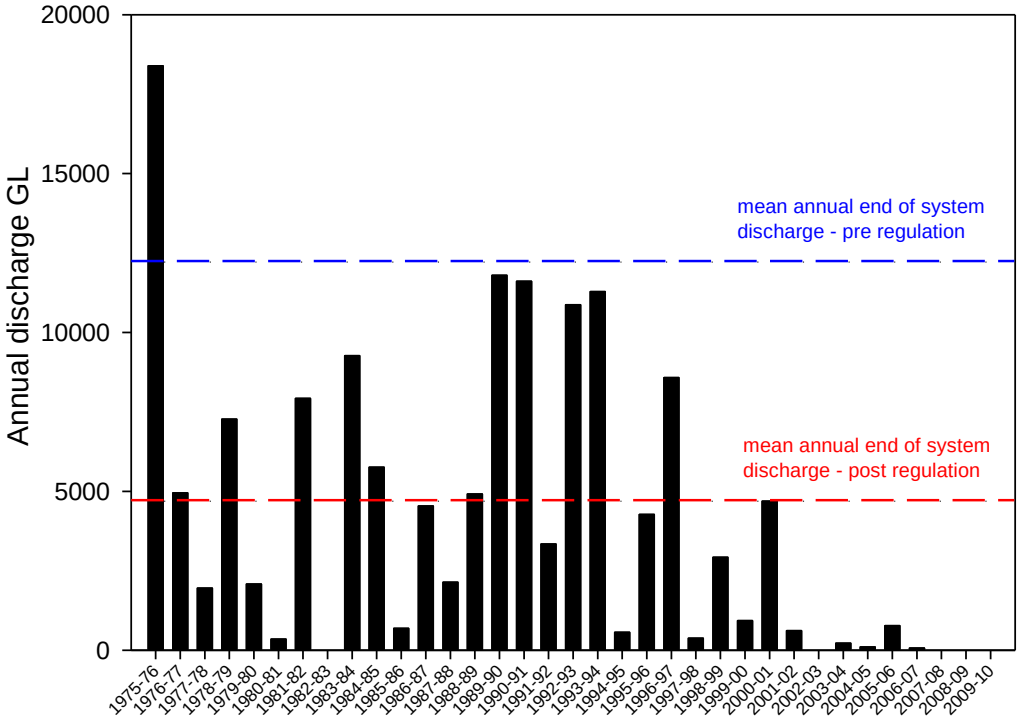


Figure 2-2 Annual freshwater discharge (GL) through the Murray barrages into the Coorong estuary from 1975- August 2010.

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 of vertical-slot fishways at Tauwitchere (35°35'09.35"S, 139°00'30.58"E) and Goolwa Barrages (35°31'34.44"S, 138°48'31.12"E), adjacent to the rockramp fishway at the southern end of Tauwitchere Barrage (35°35'24.16"S, 139°00'56.83"E) and adjacent to the Hindmarsh Island abutment of the Goolwa Barrage (35°31'24.16"S, 138°48'33.79"E) (Figure 2-1). These samples comprised fish attempting to migrate and/or residing downstream of each barrage. We were not investigating fishway function so samples from the upstream exit of the fishway were not collected.

The entrances of the vertical-slot fishways at Tauwitchere and Goolwa were sampled using aluminium-framed cage traps, designed to fit into the first cell of the fishways (Tauwitchere: 2.30 m long x 3.96 m wide x 2.0 m high, Goolwa: 2.57 m long x 3.58 m wide x 2.0 m height, 0.3 m slot widths) (Figure 2-3a). Each cage trap was 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. 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.

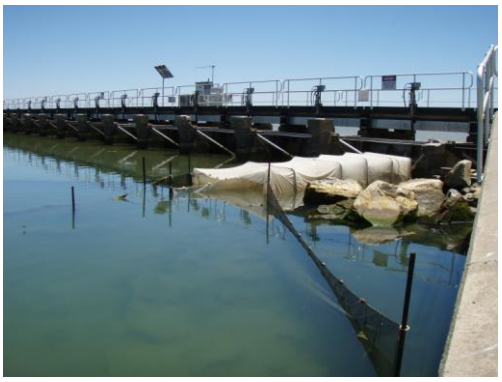
a)  b) 

Figure 2-3. a) Cage trap used to sample the Tauwitchere and Goolwa vertical-slot fishways and b) large fyke net used to sample 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.

Both vertical-slot fishways were designed to facilitate the passage of large-bodied fish and thus have design hydraulics that exceed the swimming abilities of most small-bodied fish (< 40 mm). To mitigate this and enable small-bodied fish to enter the fishways, the head-differential (the difference in water level between the upstream and downstream side of a vertical-slot baffle) at the entrance was reduced to between 0 and 80 mm by placing a perforated screen on the upstream exit. This enabled fish as small as 17 mm to enter the fishways.

In 2006/07 and 2007/08 sampling occurred fortnightly between 19 September 2006 and 16 March 2007 (n = 13) and 10 September 2007 and 25 January 2008 (n = 9) respectively. In 2008/09 and 2009/10 sampling occurred monthly between 17 September 2008 and 10 January 2009 (n = 5) and 24 November 2009 and 21 January 2010 (n = 3). Each site was sampled overnight 1-3 times per sampling trip. Cage traps were deployed and retrieved using a mobile crane (Figure 3a). No sampling was undertaken at the Goolwa vertical-slot fishway in 2007/08 due to restricted access to the Goolwa Barrage. Furthermore, the site adjacent the Hindmarsh Island abutment downstream of the Goolwa Barrage was only sampled in 2008/09 and 2009/10.

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

Temporal variation in the composition of fish assemblages sampled at each location was assessed between years. PRIMER v. 6.12 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. One-way analysis of similarities (ANOSIM) 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 (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 ANOSIM. 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 ($\alpha = 0.05$).

Differences in the standardised abundance (fish.hour^{-1}.trap event^{-1}) of common galaxias and congolli sampled at the Tauwitchere rockramp, Tauwitchere vertical-slot and Goolwa vertical-slot between years were analysed using uni-variate single-factor PERMANOVA (permutational ANOVA and MANOVA) (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 in spawning and hatch date distributions of congolli and common galaxias between years below Tauwitchere and Goolwa Barrage.

2.5 Additional length-frequency data for congolli and common galaxias from Lake Alexandrina in 2009/10

Length-frequency distributions are presented for congolli and common galaxias collected from upstream of the Murray Barrages at sites within Lake Alexandrina upstream of the Murray Barrages. These data were sourced from three additional fish monitoring projects conducted in 2009/10; namely the *Drought Action Plan for South Australian Murray-Darling Basin threatened freshwater fish populations* (Bice et al. 2010a), monitoring to determine the response of fish to the *Goolwa Channel Water Level Management Plan* (Bice *et al.* 2010b) (both projects funded by the Department for Environment and Natural Resources (DENR)) and SARDI unpublished data. Data from different seasons is 'pooled' and thus represents length-frequency distribution through the period 20/08/2009 – 23/04/2010.

3 Results

3.1 Hydrology and salinity

Annual freshwater flow to the Coorong has been well below the post-regulation mean annual flow of ~4723 GL since the mid-1990s and since 2000/2001, discharge has not exceeded 1000 GL y^{-1}. From mid July 2005 to March 2006 and May to August 2006, freshwater flows >1000 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). Freshwater releases continued 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 for the remainder of 2007, 2008, 2009 and beginning of 2010 (Figure 3-1a). Nevertheless, between September 2009 and January 2010, small amounts of freshwater (volumes unknown) were unintentionally released to the Coorong via Goolwa Barrage navigation lock operations and leakage through the Goolwa Barrage when upstream water levels were raised as part of the Goolwa Channel Water Level Management Plan (SA Water 2009).

During the period of consistent 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 55 g L^{-1} for the remainder of the project period (Figure 3-1b). Salinity data for the period April 2007 – February 2008 were unavailable for Goolwa Barrage; nevertheless, salinities beyond February 2008 had increased to ~33 g L^{-1} and remained consistent at this level. Between September 2009 and January 2010, salinity decreased slightly (i.e. <30 g L^{-1}) below Goolwa Barrage (Figure 3-1b) most likely due to some leakage of lower salinity water from the Goolwa Channel upstream of the barrage.

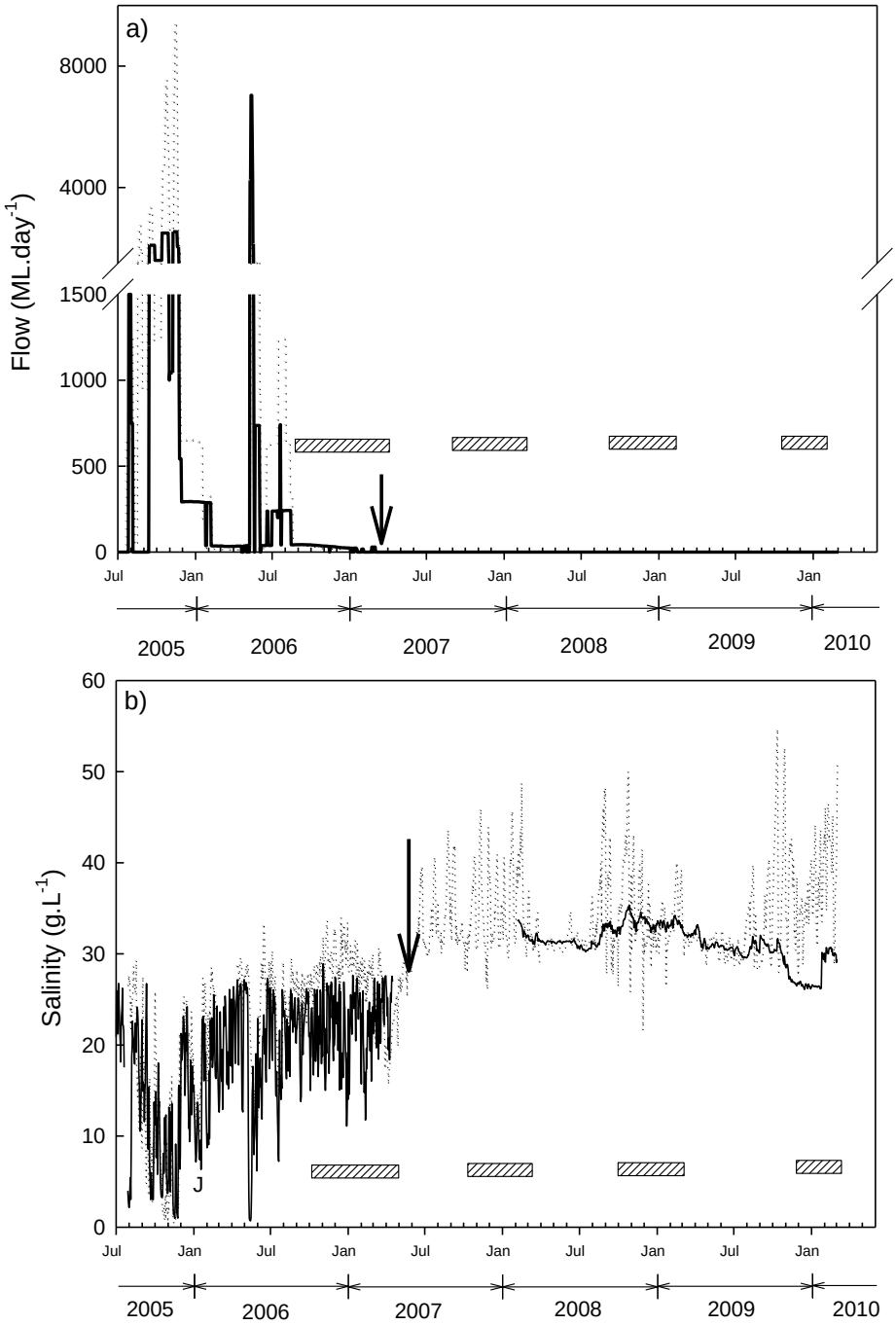


Figure 3-1. a) Mean daily flow (ML day-1) to the Coorong through Tauwitchere (dotted line) and Goolwa (solid line) Barrage from July 2005 – March 2010 and b) Mean daily salinity (g.L-1) of the Coorong below Tauwitchere (dotted line) and Goolwa (solid line) barrage from July 2005 – March 2010. Sampling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

3.2 Catch summary

A total of 367, 938 fish from 46 species (30 families) were sampled over the four year period (Table 1). The marine sandy sprat and estuarine small-mouthed hardyhead were the most abundant species, comprising *c.* 41% and *c.* 38% of the total catch respectively. Sandy sprat was most abundant at Goolwa Barrage, whilst small-mouthed hardyhead was most abundant at Tauwitchere Barrage. Catadromous congolli and common galaxias were the next most abundant species contributing *c.* 7% and *c.* 5% to the total catch, while the remaining 42 species collectively represented just 10% of the total catch (Table 3-1).

Table 3-1. Summary of species and total number of fish sampled from the Tauwitchere rock ramp, Tauwitchere vertical-slot, Goolwa vertical-slot and adjacent Hindmarsh Island abutment of Goolwa Barrage in 2006/07, 2007/08, 2008/09 and 2009/10. Species are categorised using estuarine use functional groups from Elliott *et al.* (2007).

Common name	Scientific name	Functional group	Tauwitchere rockramp				Tauwitchere vertical-slot				Goolwa vertical-slot			Goolwa Barrage		Total
			06-07	07-08	08-09	09-10	06-07	07-08	08-09	09-10	06-07	08-09	09-10	08-09	09-10	
	Sampling events No. of species		31 28	21 22	11 20	6 21	31 20	12 16	12 8	6 6	35 21	13 15	6 19	11 27	6 23	201 46
Australian smelt	*Retropinna semoni*	Freshwater migrant	1439	12	0	0	522	1	0	0	2426	0	32	0	12	**4444**
Bony herring	*Nematalosa erebi*	Freshwater straggler	60	0	0	0	1	0	0	0	604	0	0	51	0	**716**
Flat-headed gudgeon	*Philypnodon grandiceps*	Freshwater migrant	95	1	0	0	2207	0	0	0	65	1	25	0	0	**2394**
Dwarf flat-headed gudgeon	*Philypnodon macrostomus*	Freshwater straggler	1	0	0	0	0	0	0	0	6	0	0	0	0	**7**
Golden perch	*Macquaria ambigua*	Freshwater straggler	0	0	0	0	0	0	0	0	1	0	0	0	0	**1**
Common carp	*Cyprinus carpio**	Freshwater straggler	1	0	0	0	5	0	0	0	1	0	1	0	0	**8**
Redfin perch	*Perca fluviatilis**	Freshwater straggler	4	0	0	0	3	0	0	0	221	0	0	0	0	**228**
Eastern gambusia	*Gambusia holbrooki**	Freshwater straggler	0	0	0	0	4	0	0	0	0	0	0	0	0	**4**
Common galaxias	*Galaxias maculatus*	Semi-catadromous	254	7	0	0	7697	78	0	0	8683	53	715	0	1	**17488**
Congolli	*Pseudaphritis urvillii*	Semi-catadromous	1514	407	58	21	6066	3	0	6	16839	331	78	237	74	**25634**
Short-headed lamprey	*Mordacia mordax*	Anadromous	13	0	0	0	5	0	0	0	22	0	0	0	0	**40**
Pouched lamprey	*Geotria australis*	Anadromous	1	0	0	0	0	0	0	0	0	0	0	0	0	**1**
Small-mouthed hardyhead	*Atherinosoma microstoma*	Estuarine	83615	44836	1597	2750	1234	360	529	1669	48	19	310	1271	218	**138456**
Tamar River goby	*Afurcagobius tamarensis*	Estuarine	1212	271	135	4	182	97	80	0	141	114	93	1014	1305	**4648**
Blue-spot goby	*Pseudogobius olorum*	Estuarine	931	299	32	1	26	29	7	0	4	1	0	4	23	**1357**
Lagoon goby	*Tasmanogobius lasti*	Estuarine	5145	3	2	0	344	1	0	0	3	0	0	14	2	**5514**
Bridled goby	*Arenogobius bifrenatus*	Estuarine	674	50	29	0	22	0	1	0	8	14	19	515	425	**1757**
Greenback flounder	*Rhombosolea tapirina*	Estuarine	34	27	213	20	0	0	0	0	0	0	0	429	12	**735**
Long-snouted flounder	*Ammotretis rostratus*	Estuarine	15	0	5	7	0	0	0	0	0	0	0	11	2	**40**
Estuary catfish	*Cnidoglanis macrocephalus*	Estuarine	0	0	0	1	0	0	0	0	0	0	0	0	0	**1**

***denotes introduced species**

Table 1 continued.

Common name	Scientific name	Functional group	Tauwitchere rockramp				Tauwitchere vertical-slot				Goolwa vertical-slot			Goolwa Barrage		Total
			06-07	07-08	08-09	09-10	06-07	07-08	08-09	09-10	06-07	08-09	09-10	08-09	09-10	
Yellow-eyed mullet	*Aldrichetta forsteri*	Marine migrant	652	780	1087	81	99	17	35	3	718	69	215	4006	879	**8641**
Flat-tailed mullet	*Liza argentea*	Marine migrant	26	71	1	0	37	1	0	0	390	214	85	5	1	**831**
Black bream	*Acanthopagrus butcheri*	Estuarine	6	0	5	1	2	1	0	4	16	107	6	250	41	**439**
Mulloway	*Argyrosomus japonicus*	Marine migrant	6	1	0	10	1	0	0	0	6	0	0	1	0	**25**
Soldier fish	*Gymnapistes marmoratus*	Marine migrant	24	7	9	1	1	0	2	0	0	3	3	1	8	**59**
Smooth toadfish	*Tetractenos glaber*	Marine migrant	8	7	3	0	0	0	0	0	0	0	3	42	401	**464**
Prickly toadfish	*Contusus brevicaudus*	Marine migrant	0	0	1	44	0	0	0	0	0	0	0	1	0	**46**
King George whiting	*Sillaginodes punctatus*	Marine migrant	1	2	1	20	0	0	0	0	0	0	0	1	0	**25**
Yellowfin whiting	*Sillago schomburgkii*	Marine migrant	0	0	0	1	0	0	0	0	0	0	0		0	**1**
Sea sweep	*Scorpis aequipinnis*	Marine straggler	0	1	0	0	0	1	0	0	0	7	5		0	**14**
Australian herring	*Arripis georgianus*	Marine migrant	7	139	4	98	0	3	0	0	0	0	0	158	14	**423**
Australian salmon	*Arripis trutta*	Marine migrant	54	210	3	190	0	2	0	1	33	1	3	80	52	**629**
Sandy sprat	*Hyperlophus vittatus*	Marine migrant	12591	4311	147	208	4652	17	631	3	29704	62	1008	16290	82462	**152086**
Blue sprat	*Spratelloides robustus*	Marine straggler	0	81	0	0	0	0	0	0	0	0	4	0	7	**92**
Australian anchovy	*Engraulis australis*	Marine straggler	17	495	1	5	0	4	0	0	0	0	0	2	5	**529**
Australian pilchard	*Sardinops sagax*	Marine straggler	0	0	0	0	0	1	0	0	0	0	0	0	0	**1**
Pugnose pipefish	*Pugnaso curtirostris*	Marine straggler	0	0	0	0	0	0	0	0	0	1	0	1	0	**2**
Tuckers pipefish	*Mitotichthys tuckeri*	Marine straggler	0	0	0	2	0	0	0	0	0	0	0	0	0	**2**
Big belly seahorse	*Hippocampus abdominalis*	Marine straggler	0	0	0	1	0	0	0	0	0	0	0	0	0	**1**
Southern garfish	*Hyporhamphus melanchir*	Marine migrant	0	0	4	0	0	0	3	0	0	0		1	0	**8**
Zebra fish	*Girella zebra*	Marine straggler	0	0	0	0	0	0	0	0	0	0	6	0	2	**8**
Tasmanian blenny	*Parablennius tasmanianus*	Marine straggler	0	0	0	0	0	0	0	0	0	0	1	0	0	**1**
Silver spot (kelpfish)	*Threpterius maculosus*	Marine straggler	0	0	0	1	0	0	0	0	0	0	0	0	0	**1**
Bridled leatherjacket	*Acanthaluteres spilomelanurus*	Marine straggler	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
Gummy shark	*Mustelus antarcticus*	Marine migrant	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
Southern eagle ray	*Myliobatis australis*	Marine migrant	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
		Total	**108400**	**52018**	**3337**	**3494**	**23110**	**616**	**1288**	**1686**	**59939**	**997**	**2611**	**24420**	**86022**	**367938**

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 ANOSIM, which detected significant differences in fish assemblages between years at the Tauwitchere rock ramp (R = 0.616, $p < 0.001$), Tauwitchere vertical-slot (R = 0.82, $p < 0.001$) and Goolwa vertical-slot (R = 0.558, p = 0.002) but not adjacent the Hindmarsh Island abutment of Goolwa Barrage (R = 0.22, p = 0.14). Pair-wise comparisons revealed significant differences in fish assemblages between all years at the Tauwitchere rock ramp, with the exception of 2008/09 and 2009/10, whilst fish assemblages sampled at the Tauwitchere vertical-slot in 2006/07 differed significantly from assemblages sampled in 2007/08, 2008/09 and 2009/10 but there were no significant differences between assemblages sampled in these years (Bonferroni corrected α = 0.008) (Table 3-2). At the Goolwa vertical-slot, assemblages differed significantly between 2006/07 and 2008/09 but not between 2006/07 and 2009/10 or 2008/09 and 2009/10 (Bonferroni corrected α = 0.017).

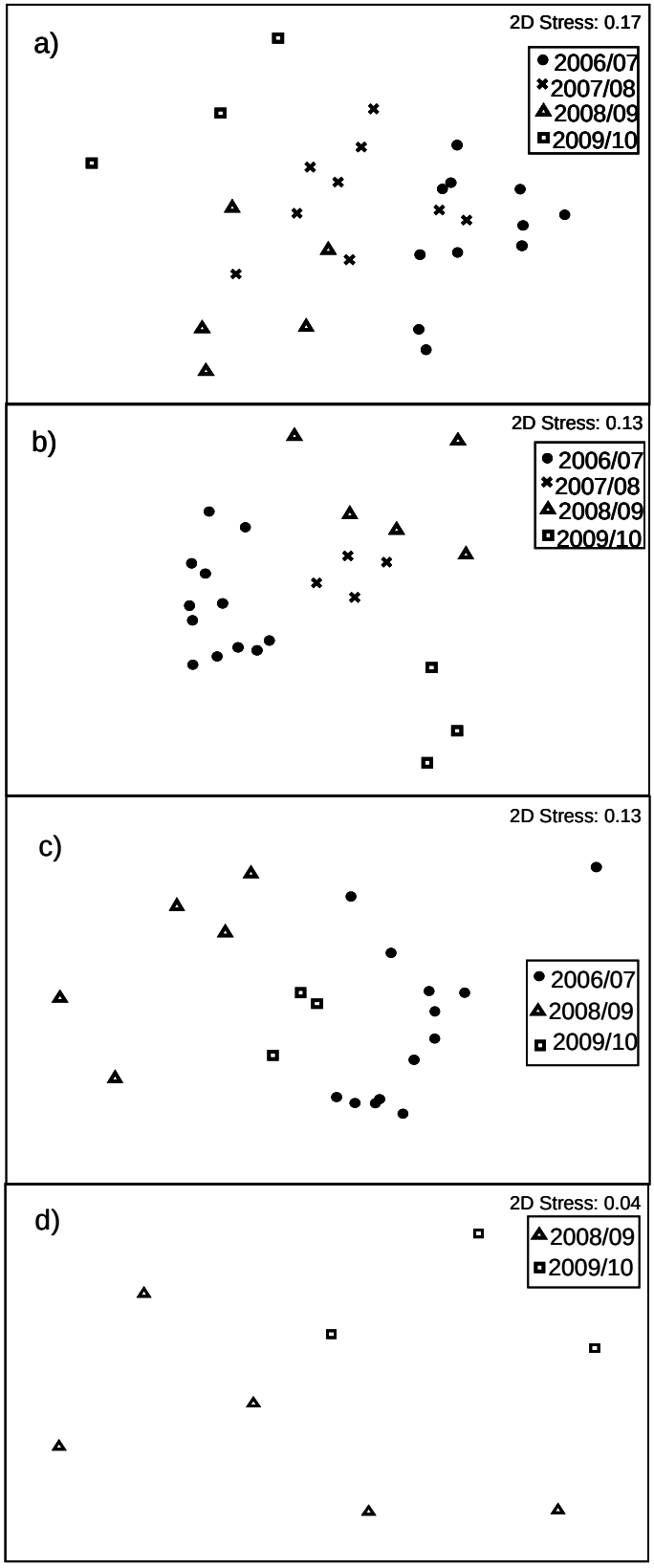


Figure 3-2. MDS ordination plots of fish assemblages sampled at a) Tauwitchere rock ramp, b)Tauwitchere vertical-slot, c) Goolwa vertical-slot and d) adjacent the Hindmarsh Island abutment of Goolwa Barrage, between 2006 and 2010.

Table 3-2. One-way analysis of similarities (ANOSIM) pairwise comparisons between fish assemblages sampled in 2006/07, 2007/08, 2008/09 and 2009/10 at the Tauwitchere rock ramp, Tauwitchere vertical-slot and Goolwa vertical-slot. ANOSIM was performed on Bray-Curtis similarity matrices. After Bonferroni correction, corrected α = 0.008 for the Tauwitchere rock ramp and vertical-slot and α = 0.017 for Goolwa vertical-slot analyses.

Location	**Pairwise comparison**		**Global *R***	***p* value**
	Year	**Year**		
Tauwitchere rock ramp	2006/07	2007/08	0.446	<0.001*
Tauwitchere rock ramp	2006/07	2008/09	0.78	0.002*
Tauwitchere rock ramp	2006/07	2009/10	0.979	0.003*
Tauwitchere rock ramp	2007/08	2008/09	0.407	0.004*
Tauwitchere rock ramp	2007/08	2009/10	0.692	0.005*
Tauwitchere rock ramp	2008/09	2009/10	0.815	0.018 ns
Tauwitchere vertical-slot	2006/07	2007/08	0.767	0.002*
Tauwitchere vertical-slot	2006/07	2008/09	0.91	<0.001*
Tauwitchere vertical-slot	2006/07	2009/10	0.99	0.002*
Tauwitchere vertical-slot	2007/08	2008/09	0.269	0.036 ns
Tauwitchere vertical-slot	2007/08	2009/10	0.926	0.029 ns
Tauwitchere vertical-slot	2008/09	2009/10	0.836	0.018 ns
Goolwa vertical-slot	2006/07	2008/09	0.795	<0.001*
Goolwa vertical-slot	2006/07	2009/10	0.23	0.148 ns
Goolwa vertical-slot	2008/09	2009/10	0.405	0.071 ns

SIMPER results, using a cumulative 40% contribution cut-off, showed that differences in fish assemblages between years 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 greenback flounder (*Rhombosolea tapirina*) and marine Australian salmon (*Arripis truttaceus*), Australian herring (*Arripis georgianus*), mulloway (*Argyrosomus japonicus*) and prickly toadfish (*Contusus brevicausus*) exhibited increases in relative abundance. At the Tauwitchere vertical-slot, differences in fish assemblages between 2006/07 and the following two years were largely attributable to decreases in abundance of catadromous congolli and common galaxias, freshwater flat-headed gudgeon (*Philypnodon grandiceps*) and marine sandy sprat. Differences in assemblages at Goolwa between 2006/07 and 2008/09 were attributed to decreases in relative abundance of congolli, common galaxias, Australian smelt and sandy sprat.

Whilst SIMPER reveals species that contribute substantially to differences in fish assemblages between years detected by ANOSIM, 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 a combination of freshwater (i.e. Australian smelt), diadromous (i.e. short-headed lamprey (*Mordacia mordax*) and common galaxias) and estuarine species (i.e. blue-spot goby, lagoon goby and Tamar River goby) (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, prickly toadfish and yellowfin whiting (*Sillago schomburgkii*) (Table 3-3). At the Tauwitchere vertical-slot, fish assemblages in 2006/07 were characterised by freshwater (i.e. Australian smelt and flat-headed gudgeon), catadromous (i.e. congolli and common galaxias), estuarine (i.e. lagoon goby) and marine species (sandy sprat) (Table 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).

Table 3-3. Indicator species analysis of fish assemblages in the Coorong at the Tauwitchere rockramp, Tauwitchere vertical-slot, Goolwa vertical-slot and downstream of Goolwa Barrage in 2006/07, 2007/08, 2008/09 and 2009/10**.**

Species	Year	Indicator Value	*p* value
Tauwitchere rockramp			
Australian smelt	2006/07	72	0.01
Short-headed lamprey	2006/07	45.5	0.05
Common galaxias	2006/07	96.7	<0.001
Blue-spot goby	2006/07	68.4	0.025
Lagoon goby	2006/07	99.8	<0.001
Tamar River goby	2006/07	59.9	0.003
Blue sprat	2007/08	44.4	0.039
Australian salmon	2009/10	72.2	0.016
Australian herring	2009/10	65.4	0.037
Mulloway	2009/10	98.5	<0.001
Prickly toadfish	2009/10	100	<0.001
Yellowfin whiting	2009/10	44.4	0.014
Tauwitchere vertical-slot			
Australian smelt	2006/07	82.8	0.02
Flat-headed gudgeon	2006/07	100	<0.001
Common galaxias	2006/07	97.3	<0.001
Congolli	2006/07	82.8	0.022
Lagoon goby	2006/07	82.6	0.009
Sandy sprat	2006/07	81.9	0.007
Black bream	2009/10	54.2	0.029
Goolwa vertical-slot			
Australian smelt	2006/07	85.9	0.007
Redfin perch	2006/07	76.9	0.028
Congolli	2006/07	64.3	0.009
Flat-headed gudgeon	2009/10	68.7	0.013
Bridled goby	2009/10	72.2	0.011
Small-mouthed hardyhead	2009/10	95.2	0.001
Zebra fish	2009/10	66.7	0.016
Adjacent the Hindmarsh Island abutment of Goolwa Barrage			
Greenback flounder	2008/09	94.5	0.021
Smooth toadfish	2009/10	98.5	0.040

At the Goolwa vertical-slot, fish assemblages in 2006/07 were characterised by the presence of freshwater (i.e. Australian smelt and redfin perch (*Perca fluviatilis*) and catadromous species (i.e. congolli) (Table 3-3). The Goolwa vertical-slot was not sampled in 2007/08 and there were no significant indicators of the assemblage in 2008/09. In 2009/10 the assemblage was characterised by freshwater (i.e. flat-headed gudgeon), estuarine (i.e. bridled goby (*Arenogobius bifrenatus*) and small-mouthed hardyhead) and marine species (i.e. zebra fish (*Girella zebra*)) (Table 3-3). The Hindmarsh island abutment site immediately downstream of the Goolwa Barrage was not sampled in 2006/07 or 2007/08 but fish assemblages in 2008/09 were characterised by the presence of the estuarine greenback flounder (*Rhombosolea tapirina*) and in 2009/10, by the marine smooth toadfish (*Tetractenos glaber*) (Table 3-3).

3.4 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 and 2009/10.

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, $Pseudo\text{-}F_{3, 65} = 13.42$, $p < 0.001$; common galaxias, $Pseudo\text{-}F_{3, 65} = 21.87$, $p < 0.001$), Tauwitchere vertical-slot (congolli, $Pseudo\text{-}F_{3, 57} = 16.42$, $p < 0.001$; common galaxias, $Pseudo\text{-}F_{3, 57} = 68.94$, $p < 0.001$) and Goolwa vertical-slot (congolli, $Pseudo\text{-}F_{2, 51} = 7.18$, $p = 0.005$; common galaxias, $Pseudo\text{-}F_{2, 51} = 8.82$, $p < 0.001$). Both species were significantly more abundant at all locations in 2006/07 relative to subsequent years (PERMANOVA pairwise comparisons, $\alpha = 0.05$), with the exception of common galaxias at the Goolwa vertical-slot in 2009/10 when abundance was similar to 2006/07 (Figure 3-3).

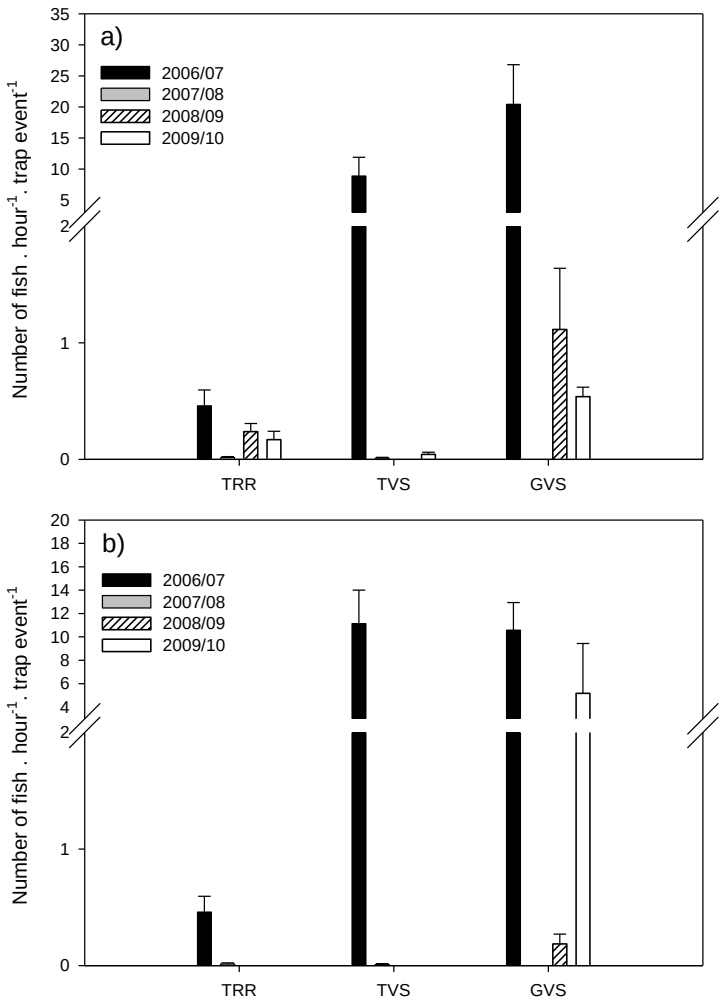


Figure 3-3. Relative abundance (number of fish.hour^{-1}.trap event^{-1}) of a) congolli and b) common galaxias at the Tauwitchere rock ramp (TRR), Tauwitchere vertical-slot (TVS) and Goolwa vertical-slot (GVS) from 2006-2010. Goolwa vertical-slot was not sampled in 2007/08.

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 3-4a). In November 2006, a 0+ year cohort (< 50 mm TL) comprised > 90% of the population (Figure 3-4a). 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 3-4b). In 2008/09, 0+ congolli were not sampled until December 2008 when just one individual (43 mm TL) was recorded (Figure 7c). The 0+ cohort had increased in proportion by January 2009 (> 50% of the population) but was represented by just eleven individuals (Figure 3-4c). In 2009/10, 0+ congolli were again not

sampled until December 2009 when just two individuals (60 & 62 mm TL) were recorded (Figure 3-4d). No 0+ congolli were detected below Tauwitchere Barrage in January 2010.

Below Goolwa Barrage (Goolwa vertical-slot data) in September and October 2006, congolli exhibited broad length distributions (59-227 mm TL) (Figure 3-5a). In November 2006, a 0+ cohort (< 50 mm TL) comprised > 90% of the population (Figure 3-5a). The abundance of congolli peaked in December 2006 (n = 12, 020) with the 0+ cohort representing 100% of the sampled population (Figure 3-5a). 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 3-5b). 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 3-5a & 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 3-5c) but were sampled in low numbers relative to 2006/07.

Similar to congolli, common galaxias exhibited a broad range of lengths at Tauwitchere in September 2006 (40-114 mm TL) (Figure 3-6a). In October 2006, 0+ fish (< 60 mm TL) comprised > 80% of the population (Figure 3-6a). Numbers of common galaxias peaked in November (n = 3567) with ~95% of these fish represented by the 0+ cohort (Figure 3-69a). In 2007/08, 0+ fish dominated the population in September and October but total numbers had decreased substantially from 2006/07 (Figure 3-6b). No fish were sampled in November 2007 or January 2008 and just two individuals were sampled in December 2007 (Figure 3-6b). No common galaxias were collected downstream of the Tauwitchere barrage during sampling in 2008/09 or 2009/10.

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 3-7a). The abundance of common galaxias peaked in November 2006 (n = 3, 830) with the 0+ cohort representing >99% of the sampled population (Figure 3-7a). This cohort dominated the population for the remainder of sampling (Figure 10a). In September 2008 no common galaxias were sampled and just one adult fish (76 mm TL) was sampled in October 2008 (Figure 3-7b). 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 3-7a & b). A 0+ cohort also represented 100% of the catch in November 2009, December 2009 and January 2010 (Figure 3-7c). Abundance peaked in November 2009 (n = 676) but in December 2009 and January 2010 abundance was diminished relative to 2006/07 (Figure 3-7a & c).

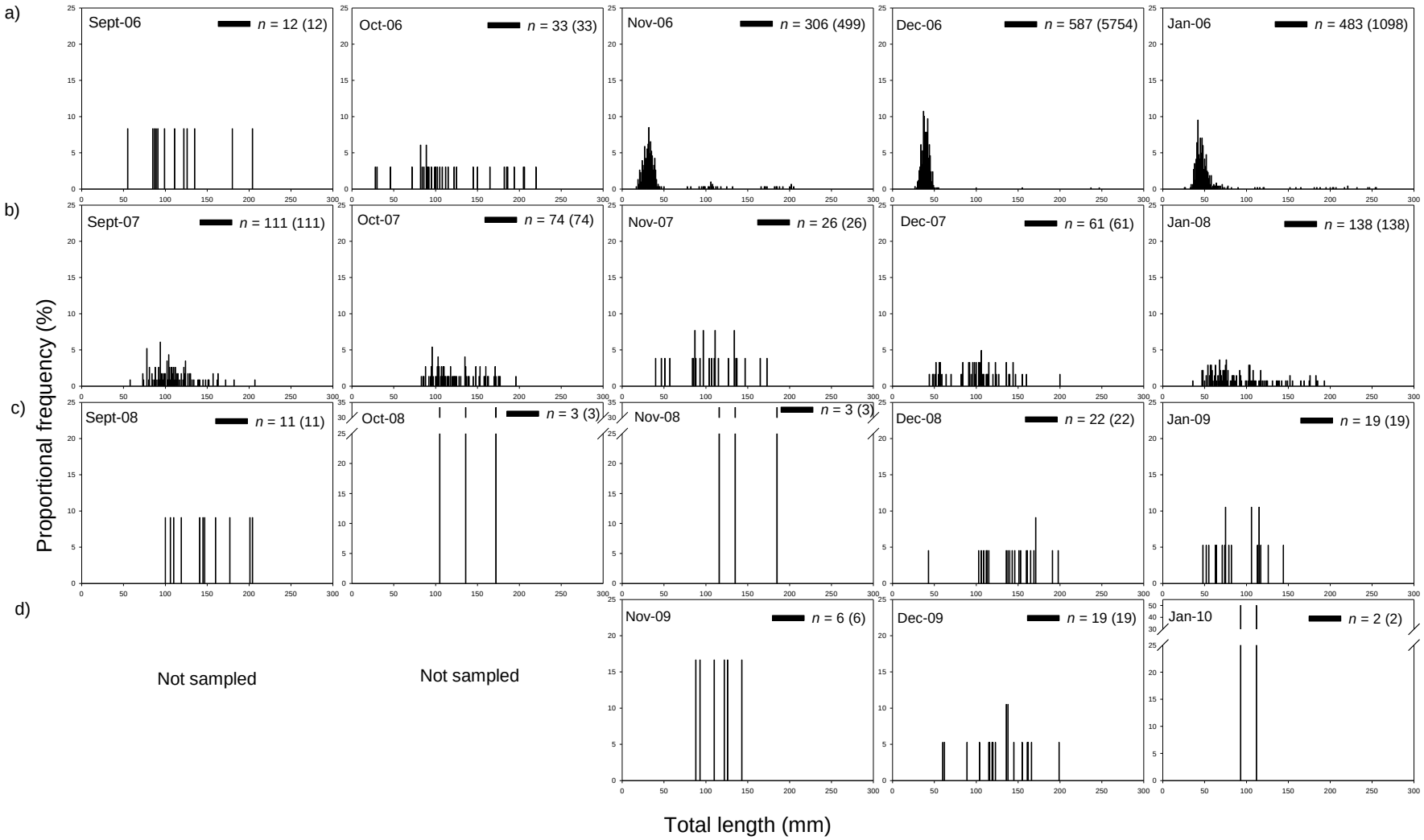


Figure 3-4. Monthly length-frequency distribution histograms (total length, mm) of congolli sampled from below Tauwitchere barrage (Tauwitchere rock ramp and vertical-slot combined) during a) 2006/07, b) 2007/08, c) 2008/09 and d) 2009/10. The number of fish measured and the total number of fish sampled in each month (in brackets) is presented**.**

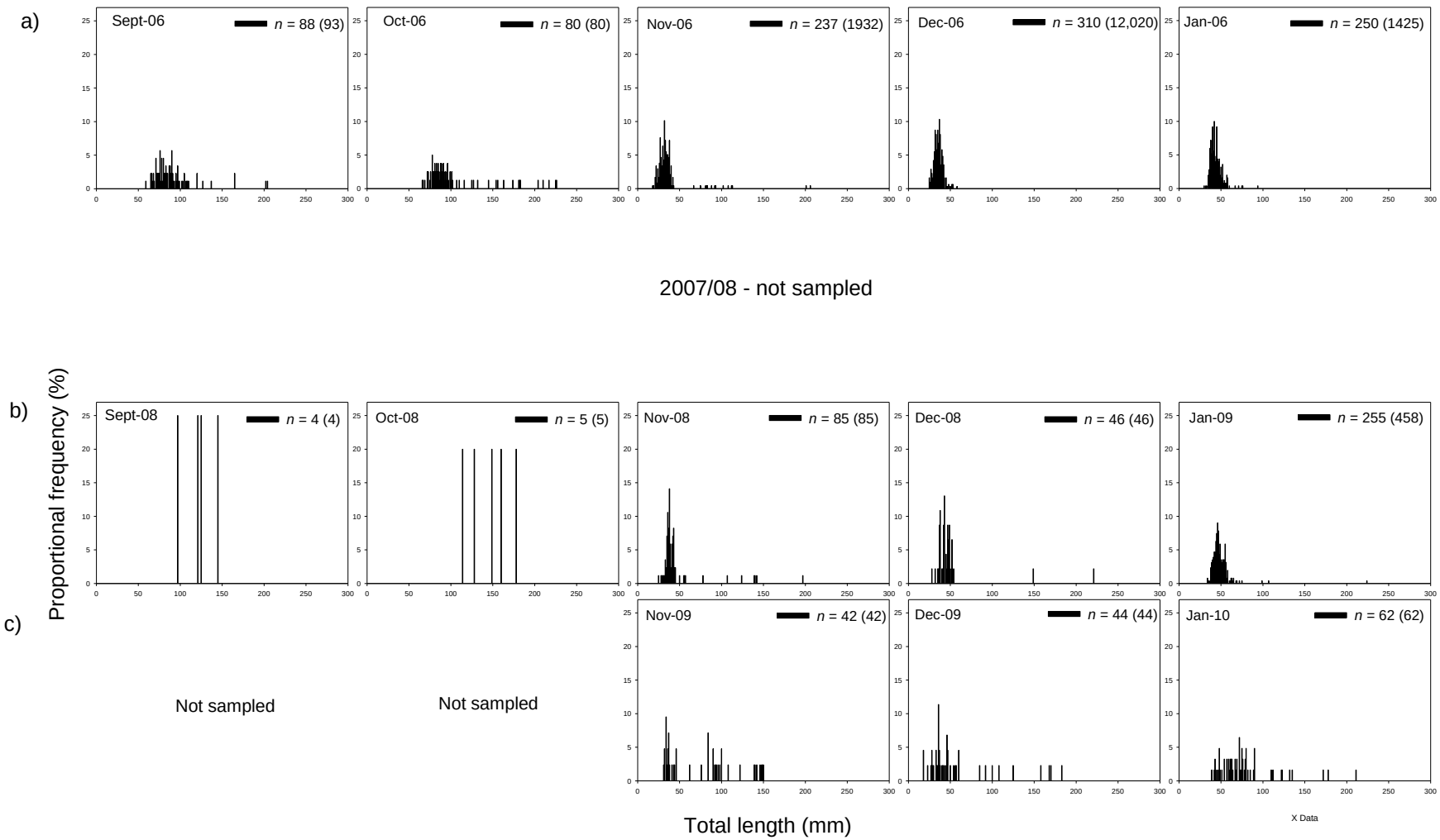


Figure 3-5. Monthly length-frequency distribution histograms (total length, mm) of congolli sampled from below Goolwa Barrage (data from the Goolwa vertical-slot and adjacent the Hindmarsh Island abutment of Goolwa Barrage are combined for 2008/09 and 2009/10) during a) 2006/07, b) 2008/09 and c) 2009/10. The number of fish measured and the total number of fish sampled in each month (in brackets) is presented.

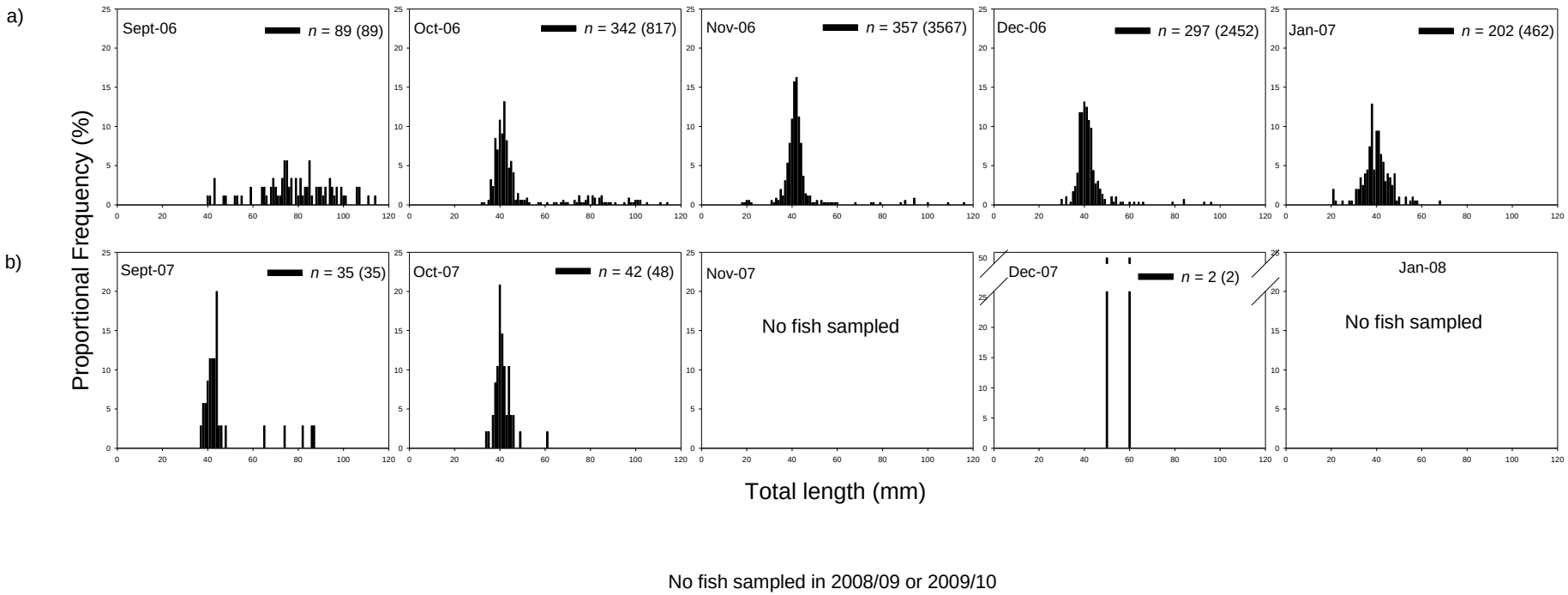


Figure 3-6. Monthly length-frequency distribution histograms (total length, mm) of common galaxias sampled from below Tauwitchere barrage (Tauwitchere rock ramp and vertical-slot combined) during a) 2006/07, b) 2007/08, c) 2008/09 and d) 2009/10. The number of fish measured and the total number of fish sampled in each month (in brackets) is presented.

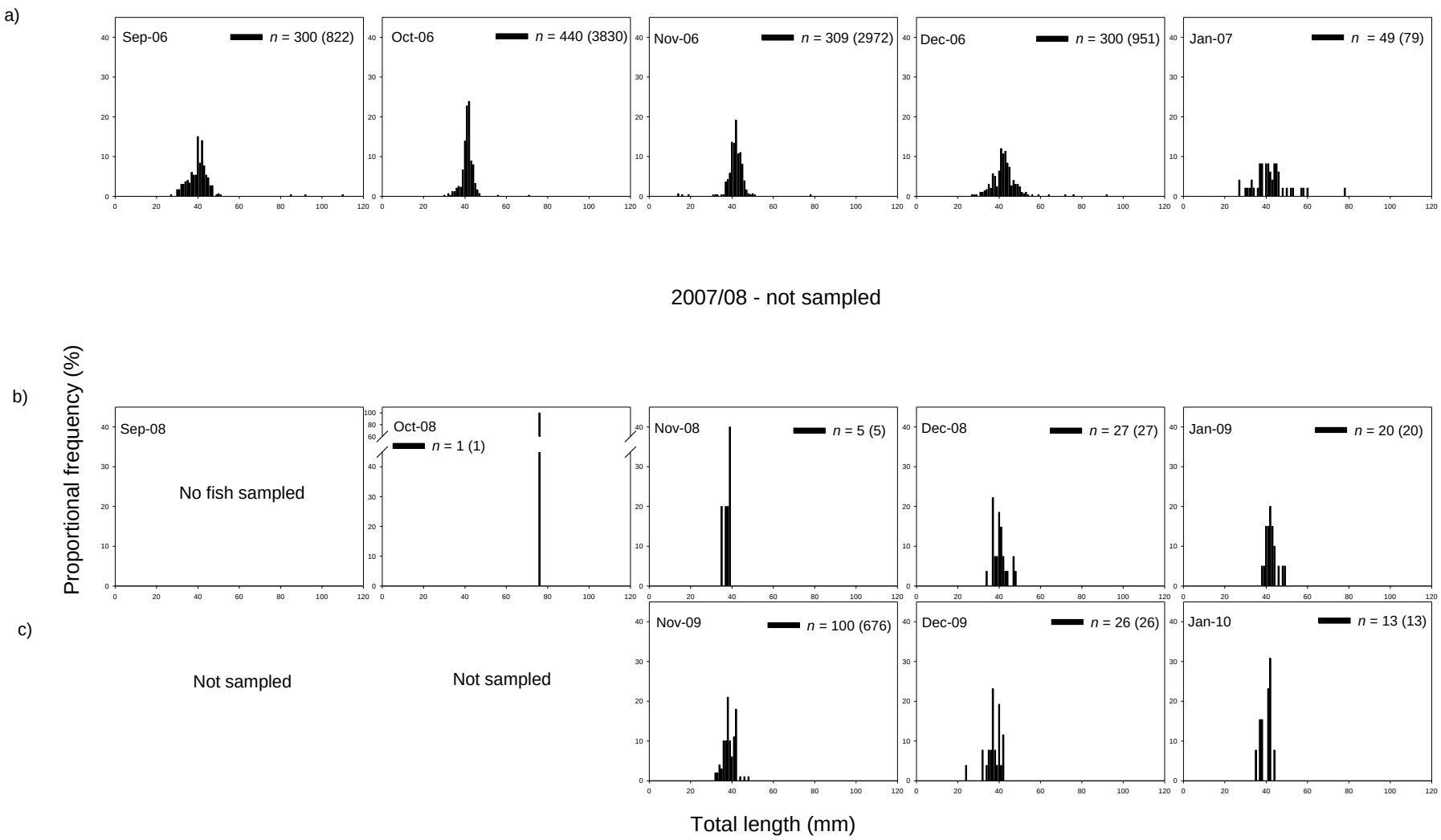


Figure 3-7. Monthly length-frequency distribution histograms (total length, mm) of common galaxias sampled from below Goolwa Barrage (data from the Goolwa vertical-slot and adjacent the Hindmarsh Island abutment of Goolwa Barrage are combined for 2008/09 and 2009/10) during a) 2006/07, b) 2008/09 and c) 2009/10. The number of fish measured and the total number of fish sampled in each month (in brackets) is presented.

3.5 Determination of spawning and hatch dates

3.5.1 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 3-8a). At Tauwitchere, successful recruits were derived from spawning that occurred over a ~88 day period from 4 July to 29 September 2006 (Figure 3-8a). 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 3-8a). 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 in mid and late July.

In 2007/08 a contracted distribution was evident at Tauwitchere (Figure 3-8b). Successful recruits were derived from spawning that occurred over a significantly shorter period of ~44 days, from 19 July to 31 August 2007 (D = 0.38, p = 0.016) (Figure 3-8b). In 2008/09 at Tauwitchere, spawning occurred over a similarly restricted season of ~36 days, which began on the same day as the previous year, from 19 July 2008 to 23 August 2008 (Figure 3-8c). In 2009/10 just three recruits were sampled and aged, these fish were spawned between 11 July and 23 July (Figure 3-8d). Sample sizes in 2008/09 and 2009/10 were too small to allow statistical comparison of spawn date distributions with previous years.

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 3-8c). 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 3-8d). A peak period of spawning success occurred in late July and early August (Figure 3-8d).

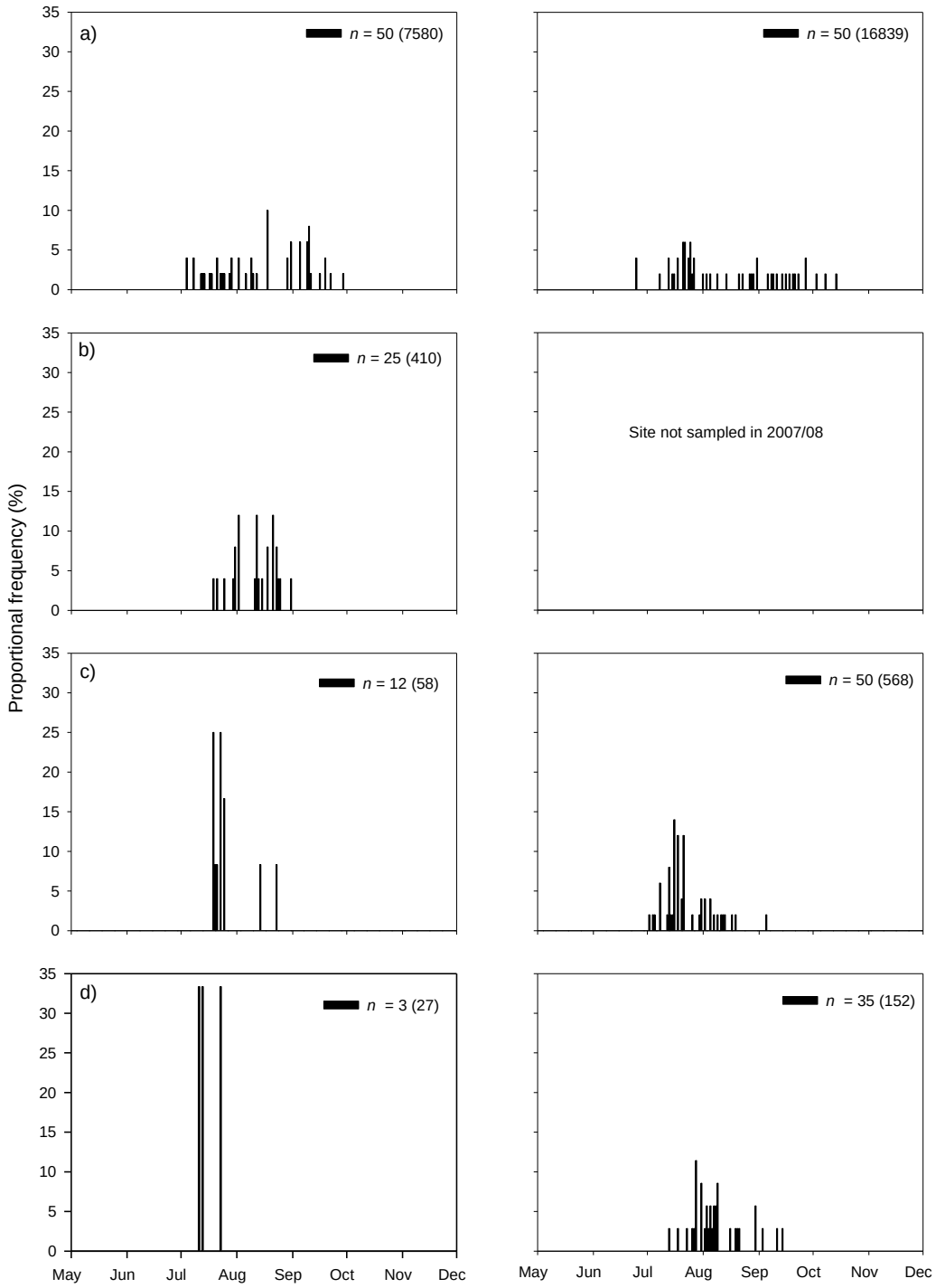


Figure 3-8. Estimated spawn date-frequency distributions of post-larval congolli sampled at Tauwitchere (left-hand side; rock ramp and vertical-slot sites combined) and Goolwa Barrages (right-hand side; vertical-slot and adjacent the Hindmarsh Island abutment of Goolwa Barrage sites combined) in (a) 2006/07, (b) 2007/08, (c) 2008/09 and (d) 2009/10. *n* is the number of fish that were aged at each location within each year and the total number of individuals sampled from each location is presented in brackets.

3.5.2 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 3-9a). 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 3-9a).

In 2007/08 hatch date distribution had contracted and was significantly different from 2006/07 at Tauwitchere ('Kolmogorov-Smirnov' (K-S), $D = 0.88$, $p < 0.001$) (Figure 3-9b). 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 3-9c & d).

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 3-9c). In 2009/10, spawning period had increased to ~82 days, hatching from 2 August to 21 October (Figure 3-9d), 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 ($D = 0.21$, $p = 0.36$).

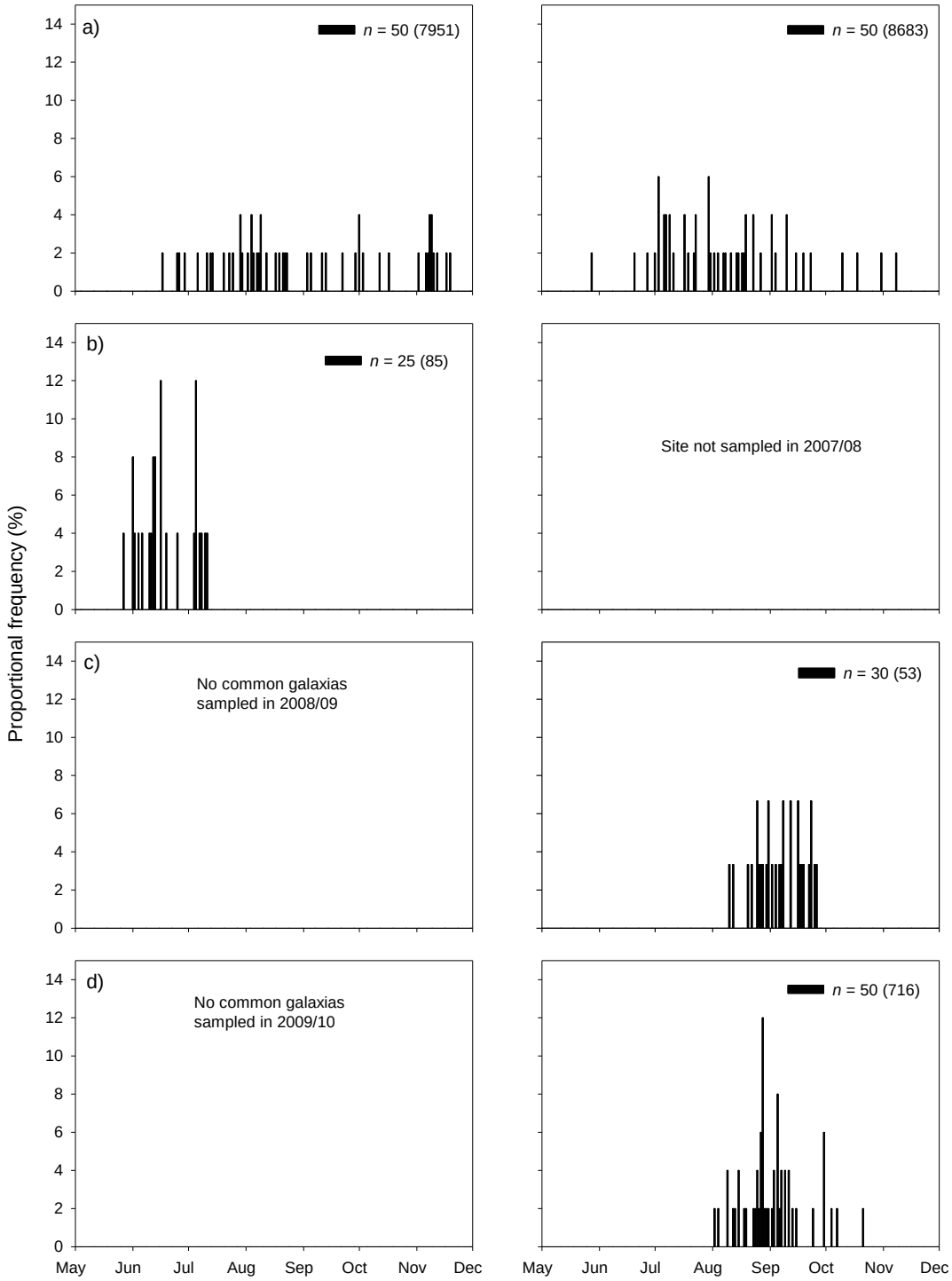


Figure 3-9. Estimated hatch date-frequency distributions of post-larval common galaxias sampled at Tauwitchere (left-hand side; rockramp and vertical-slot sites combined) and Goolwa Barrage (right-hand side; vertical-slot and adjacent the Hindmarsh Island abutment of Goolwa Barrage sites combined) in (a) 2006/07, (b) 2007/08, (c) 2008/09 and (d) 2009/10. n is the number of fish that were aged at each location within each year and the total number of individuals sampled from each location is presented in brackets.

3.6 Additional length-frequency data for congolli and common galaxias from Lake Alexandrina in 2009/10

The congolli population upstream of the Murray Barrages in 2009/10 was dominated (>80% of catch) by large (>200 mm TL) adult fish (Figure 3-10a). There was limited indication of recruitment with just two (<3 % of catch) young-of-year individuals (i.e. < 55 mm TL) sampled (Figure 3-10a). Conversely, common galaxias exhibited successful recruitment upstream of the Murray Barrages with young-of-year (i.e. <60 mm TL) comprising the majority of individuals sampled in 2009/10 (Figure 3-10b).

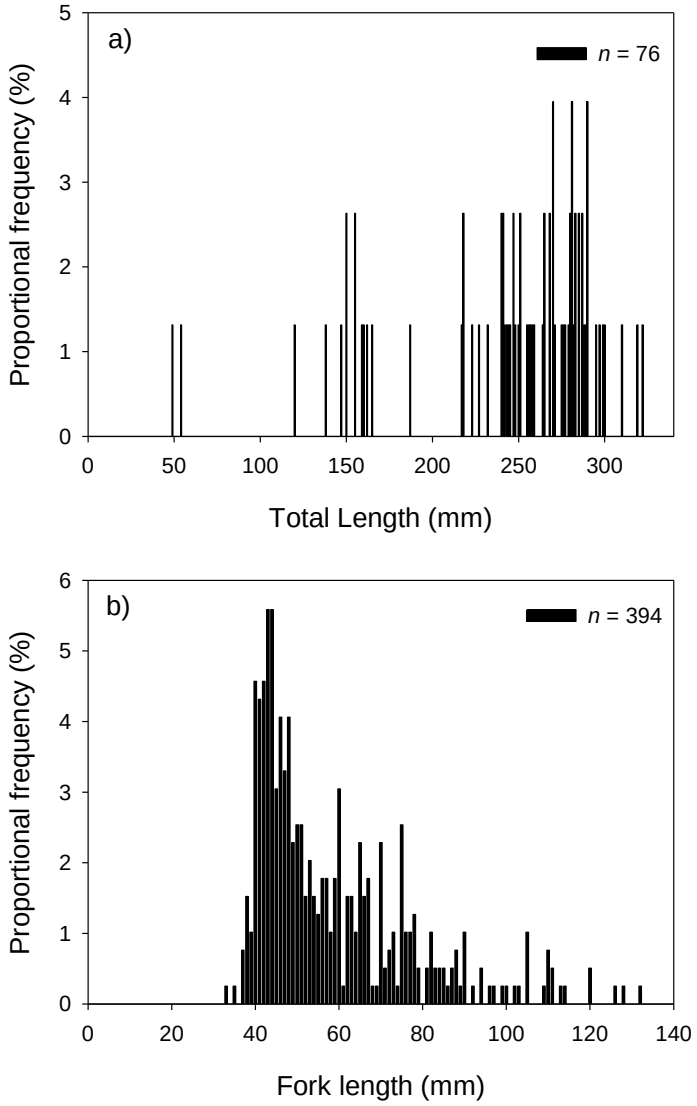


Figure 3-10. Length-frequency distributions of (a) congolli and (b) common galaxias sampled in Lake Alexandrina in 2009/10 by other fish monitoring projects; namely Bice et al. (2010a), Bice et al. (2010b) and SARDI unpublished data.

4 Discussion

4.1 Fish assemblage

In a four-year period characterised by declining freshwater inflows, 46 species of fish were sampled at four sites immediately downstream of the Murray Barrages in the Coorong estuary. Species richness was greater than that reported by Eckert and Robinson (1990) and Noell *et al.* (2009) (33 and 26 species respectively), and substantially greater than the 16 species collected in the Coorong during a high freshwater discharge event in 1984 (Geddes 1987). Greater species richness reflects the presence of a number of marine migrant and straggler species not typically sampled in the Coorong. Nonetheless, species richness was 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).

The overall catch was dominated by the estuarine atherinid small-mouthed hardyhead and marine clupeid sandy sprat. Estuarine fish assemblages in temperate Australia are typically characterised by large abundances of atherinids (Potter *et al.* 1986). Small-mouthed hardyhead are considered one of the most abundant fish in the Coorong (Molsher *et al.* 1994), most likely due to their ability to tolerate the highly variable salinities that occur in the system (lower-upper LD_{50} 3.3–108 L^{-1}) (Lui 1969).

Catadromous congolli and common galaxias were also abundant, particularly in the first year of sampling (2006/07) when there were freshwater inflows to the Coorong. During this time the vast majority (> 90% of the total catch) of individuals collected for both species were juveniles (0+ year class) attempting to migrate into freshwater.

4.2 Temporal variation in fish assemblages

From 2006–2010 fish assemblages at the Tauwitchere rock ramp, Tauwitchere vertical-slot and Goolwa vertical-slot changed significantly. In general, species richness and the abundance of freshwater and diadromous species decreased at all sites over time. Species richness was greatest when brackish conditions prevailed and the reduction in species richness was mostly due to the loss of freshwater, diadromous and estuarine species from the assemblage as salinities increased.

Brackish regions, frequently in the upper reaches of estuaries, are often associated with greatest species richness, reflecting the penetration of both freshwater and marine species in conjunction with resident estuarine species (Barletta-Bergan *et al.* 2002). Whitfield *et al.* (2006) report high species diversity in the St Lucia estuary in South Africa when salinities are brackish; conversely,

hypersaline salinities result in declines in diversity of freshwater, estuarine and marine fish species. Similarly, in the Mondego estuary, Portugal, an extreme drought event resulted in decreased freshwater runoff and the incursion of saline water corresponding with a depletion of freshwater fish species, an increase in marine species and reduced abundances of estuarine species (Martinho *et al.* 2007).

Overall, differences in fish assemblages in the Coorong estuary between years 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. We used indicator species analysis (Dufrêne and Legendre 1997) to determine those species that characterised fish assemblages at each site over time. In 2006/07 the last year of freshwater discharge into the Coorong, and the year of lowest salinities, fish assemblages were generally characterised by a diverse range of freshwater, diadromous, estuarine and marine species. In comparison, in 2009/10, three years after freshwater discharge had ceased and salinity had increased fish assemblages were characterised by the estuarine black bream, small-mouthed hardyhead and bridled goby and a suite of seven marine species, namely Australian salmon, Australian herring, mulloway, prickly toadfish, smooth toadfish, yellowfin whiting and zebrafish.

4.3 Abundance and recruitment of diadromous fish

As freshwater inflows into the Coorong diminished the abundance of diadromous fish decreased dramatically. Adult upstream migrants of short-headed and pouched lamprey were collected below Tauwitchere and Goolwa Barrages between September and November 2006 when low volumes of freshwater were being released into the Coorong. No lamprey were collected, however, from 2007–2010 following cessation of freshwater inflows. The biology of both lamprey species has not been investigated in the Murray-Darling Basin; nevertheless, studies in North America suggest that migratory adult sea lamprey (*Petromyzon marinus*) select spawning rivers based on larval pheromonal odours in river outflows (Bjerselius *et al.* 2000). In the absence of hydrological connectivity between the Murray River and the sea and/or absence of larvae (due to recruitment failure) such olfactory cues may have been unavailable to stimulate upstream riverine migration of adult lamprey.

Below Tauwitchere Barrage in 2006/07, catadromous congolli and common galaxias each comprised ~6% of the total catch. The vast majority (>90%) of these individuals were young-of-year. In 2007/08 and 2008/09, congolli comprised ~0.01% of the total catch and the proportion of young-of-year had decreased substantially. Similarly, common galaxias comprised just 0.002% of the total catch in 2007/08, with a severely diminished proportion of young-of-year, and no common galaxias were collected in 2008/09. Recruitment of catadromous species was most likely

affected by a reduction in connectivity impeding obligate migratory movements and decreased spawning and/or survival of larvae under increasingly saline conditions.

The highest abundances of common galaxias occurred between September and January in all years, suggesting a peak upstream migratory period for juveniles. Similar periods of peak movement in spring and summer have been documented in other coastal populations in south-eastern Australia and New Zealand (McDowall *et al.* 1994; Zampatti *et al.* 2003). Timing of migration varied between Tauwitchere and Goolwa in 2006/07. Catadromous populations of common galaxias have a marine larval phase and delayed migration at Tauwitchere, relative to Goolwa, may have been due to the greater distance of this barrage from the estuary mouth (~14 km) and the diffuse nature of attraction flows to orientate immigration.

Congolli abundances peaked between November and February at both Goolwa and Tauwitchere. Similar timing of migrations has been observed in spring and summer in other coastal systems in south-eastern Australia (Hortle 1978; Andrews 1996). A previous assessment of fish passage at the Tauwitchere vertical-slot fishway from January–February 2005 detected higher abundances of migrating young-of-the-year congolli than the current study (Stuart *et al.* 2005). Freshwater flows to the Coorong in 2004 and 2005, however, were significantly higher than in 2006 and may have facilitated higher levels of spawning and/or recruitment.

Successful recruitment of common galaxias in 2006/07 resulted from spawning throughout a protracted period from mid May to late November 2006. Congolli recruits in the same year had a similar protracted spawning season from late June to mid October. Spawning was continuous in both species, and whilst no spawning peaks were observed for common galaxias, congolli did exhibit discrete periods of higher spawning success. This suggests that continuous low volume freshwater flow and connectivity facilitated successful spawning and recruitment for both species in 2006. Reflecting the significant declines in the abundance of recruits in both species, successful spawning periods in 2007, 2008 and 2009 were severely contracted following cessation of freshwater flows into the Coorong and loss of connectivity between freshwater and estuary habitats after March 2007.

Spawning and recruitment dynamics, timing of adult and post-larval migrations and growth in common galaxias may differ substantially between populations (Morgan and Beatty 2006). Although there is evidence to suggest common galaxias are capable of spawning year round in some lacustrine populations (Chapman *et al.* 2006), coastal populations typically exhibit more defined spawning seasons. McDowall *et al.* (1994) reported spawning of common galaxias in coastal streams of New Zealand between March and June, occurring earlier but overlapping with

spawning observed in this study. Our results suggest that, under favourable conditions of freshwater inflows and connectivity, spawning of common galaxias in the Coorong occurs over a period of approximately seven months. This implies a much longer spawning season than previously suggested for coastal populations of Australian common galaxias (McDowall *et al.* 1994; Allen *et al.* 2002) with spawning potentially occurring throughout autumn, winter and spring.

Protracted spawning was also evident in congolli; however, unlike common galaxias, congolli likely spawn in the outer estuary or coastal zone to disperse pelagic eggs (Hortle 1978; Crook *et al.* 2010). Episodic and pulsed egg production is common in temperate fish where spawning often occurs over protracted periods, with distinct periods resulting in successful recruitment (Secor and Rooker 2005). The fate of larvae and juveniles therefore, has the potential to differ substantially and is likely dependent upon seasonal and inter–annual environmental fluctuations (Secor 2007). More defined periods of spawning success in congolli compared to the continuous, consistent hatching events for common galaxias, suggests a spawning strategy that is less resilient to temporal variations in early survival conditions.

In congolli populations, smaller males and individuals of indeterminate sex predominate in coastal and estuarine zones and larger females mostly inhabit freshwater habitats in rivers (Hortle 1978). This implies an obligate catadromous life history highly susceptible to fragmentation. Prior to the construction of the Murray barrages, large downstream migrations of reproductively mature female congolli, from freshwater reaches to the Coorong, were commonly observed during autumn and winter. These migrations supported a seasonal component of the regions commercial fishery (Eckert and Robinson 1990; Evans 1991) but have since declined significantly and are now no longer observed.

In coastal drainages in Victoria, Australia, female congolli undertake rapid and synchronised downstream spawning migrations in autumn and winter (Crook *et al.* 2010). Females leave the estuary and are thought to spawn at sea. No corresponding movements back to the estuary or freshwater reaches have been observed post–spawning. Consequently, disconnection of freshwater and estuarine habitats in the present study likely disrupted adult migrations, potentially contributing to reductions in spawning period.

Alternatively, populations of adult common galaxias are sexually mixed and in fragmented systems migratory and non-migratory individuals may occur sympatrically (Chapman *et al.* 2006). We observed common galaxias recruiting in low abundances upstream of the Murray barrages suggesting catadromy may be facultative in freshwater habitats of the lower Murray River. Many

diadromous fish populations possess similar plasticity in life history strategies, recruiting without diadromy provided suitable larval and juvenile habitats are present (Closs *et al.* 2003). Such a mechanism has likely conferred resilience on populations of common galaxias in the Coorong and Lower Lakes, although the prognosis for congolli populations remains more uncertain.

5 Conclusions

Freshwater inflows and connectivity between freshwater and marine environments play a crucial role in structuring the composition of fish assemblages and facilitating the recruitment of catadromous congolli and common galaxias, and anadromous lamprey in the Coorong estuary. Over a four year period (2006/07–2009/10), excessive regulation of freshwater inflow to the Coorong estuary led to a loss of fish species diversity and the potential elimination of some estuarine and diadromous fish species. Specifically, cessation of freshwater inflow and disconnection of the Coorong estuary from the freshwater Lower Lakes resulted in increases in estuarine salinities and a concomitant decrease in species richness. 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.

As freshwater inflows into the Coorong diminished the abundance of diadromous species decreased dramatically. Anadromous short-headed and pouched lamprey were only collected in 2006 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. Populations of congolli in the lower Murray River display spatial sexual structuring and obligate catadromy thus are particularly susceptible to altered flow regimes and fragmentation of essential spawning and recruitment habitats. Common galaxias populations in the lower Murray River, however, appear to display greater plasticity in life history strategies with the ability to sustain low levels of recruitment solely within the Lower Lakes when estuarine habitats were unavailable.

The results of our study form an important basis for environmental flow management at the freshwater/marine interface of the Murray River. Freshwater flows during 2006–2007 were low compared with longer-term averages; nevertheless, even small amounts of freshwater discharge (e.g. ~50 ML d^{-1}) delivered through appropriate fish passage structures appear to produce a significant ecological response, promoting diversity in estuarine fish assemblages and protracted spawning and successful recruitment of catadromous fish species.

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