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George Giatas and David Short

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EXECUTIVE SUMMARY

The Lower Lakes, Coorong and Murray Mouth comprise the terminal system of Australia's Murray-Darling River and plays a significant role in providing ecosystem services. It is a Ramsar wetland and one of the six 'icon sites' identified across the Murray–Darling Basin as part of The Living Murray Program (MDBC 2006). The Coorong estuary supports a diverse range of fish species. Black bream (*Acanthopagrus butcheri*) is an iconic estuarine fish with environmental targets in both State and Commonwealth environmental watering plans, including the Basin-wide Environmental Watering Strategy. This species supports important recreational and commercial fisheries, although the population in the Coorong is currently depleted. In recent years, there has been a concerted effort by water managers to improve the barrage flow regimes, by providing water for the environment to improve connectivity, estuarine habitat condition and enhance recruitment and population resilience of key fish species, including black bream, in the Coorong.

Freshwater flows into estuaries create salt wedges (haloclines), which provide favourable spawning and larval nursery habitats for black bream. More specifically, the salinity gradient is important as it (1) provides a cue for spawning and for locating the spawning ground, (2) provides a cue for larvae and juveniles to locate suitable habitat, and (3) increases food availability for larvae. During 2017-18, successful recruitment of black bream was facilitated by barrage flows, supported by releases of water for the environment to the Coorong.

During spring/summer 2018-19 (i.e. the spawning season for black bream), barrage releases were maintained using Commonwealth environmental water, noting the discharge was substantially lower than in 2017-18. Salt wedge monitoring indicated the presence of some suitable habitat below Goolwa Barrage at low discharge (mean ~400 ML.day^{-1}) during spring–summer; whereas almost no haloclines were present along the Tauwitcherie and Coorong transect at similarly low discharge rates. The overall suitable larval nursery area was much smaller during 2018-19 than 2017-18. Furthermore, calanoid copepods (i.e. *Gladioferens* species and *Sulcanus conflictus*), which are important prey for black bream larvae, were rarely present or absent during 2018-19.

No young-of-year (Age 0+) black bream was detected, suggesting lack of or poor recruitment during 2018-19 in the Coorong. Nevertheless, the black bream collected in 2018-19 were dominated by 1-year olds, which indicated the persistence of the strong 2017-18 cohort. This is an encouraging result and reassures that barrage flow management, supported by water for the environment, can generate favourable habitat conditions (likely including food resources) to facilitate successful recruitment of black bream, which over time should support

the population recovery in the Coorong. In climatically and hydrologically dry years such as 2017-18 and 2018-19, without environmental water, barrage flows would not have been maintained throughout spring−summer, which is the primary reproductive season of black bream and many other estuarine species.

Recruitment of black bream is highly variable in the substantially modified estuary of the Coorong. Recent studies suggest strong cohorts are associated with low to moderate river flows (e.g. up to 12,000 ML day^{-1} in the Coorong). Therefore during dry conditions, when water for the environment plays a critical role in maintaining barrage releases, flow regimes can be managed to increase favourable salt wedge habitat and potentially enhance productivity to promote black bream recruitment. For example, the successful recruits (YOY) in 2017-18 were spawned between late December and early February, which corresponded with barrage releases of 600−5,000 ML day^{-1} and temperature of 18−25°C, and spawning commenced about 1−2 weeks after a ~10,000−12,000 ML day^{-1} barrage flow pulse. Similar flow regimes could be applied in terms of seasonality, volume and release location, with outcomes monitored to improve our learnings and inform management. In addition, consideration should be given to optimise water level regimes in the Lower Lakes to increase productivity of freshwater derived biota. This may provide additional food resource benefits via flow releases to the Coorong to support estuarine fish species including black bream. Furthermore, given the depleted population of black bream in the Coorong, fishery management should continue to seek to protect the remnant spawning biomass and maximise the survival of new recruits to rebuild population abundance and resilience in this region.

The monitoring during 2017-18 and 2018-19 characterised larval nursery habitat for black bream in the Coorong, and collected quantitative data to investigate potential relationships between barrage flows and suitable habitat area. Future research and monitoring will be required, particularly to obtain information on environmental and habitat requirements (including food resources), and how they influence key life history processes (including spawning) and recruitment dynamics for the population of black bream in the Coorong. Such information will support adaptive management of environmental water and inform optimal barrage flow regimes to improve estuarine habitat and enhance the recruitment of black bream and many other estuarine fish in the Coorong.

Keywords: Salt wedge, black bream, recruitment, copepods, environmental water, Coorong estuary.

1. INTRODUCTION

1.1. Background

The Lower Lakes, Coorong and Murray Mouth (LLCMM) are the terminus of the Murray–Darling Basin (MDB), and play a significant role in providing ecosystem services. They have been recognised as a Wetland of International Importance under the Ramsar Convention since 1985 and represents one of the six 'icon sites' identified across the MDB through The Living Murray (TLM) Program (MDBC 2006). There is a diverse fish community inhabiting the LLCMM region, including key commercial/recreational fisheries species (e.g. black bream (*Acanthopagrus butcheri*), mulloway (A*rgyrosomus japonicus*), golden perch (*Macquaria ambigua*)) and those of significant conservation and/or ecological values (e.g. congolli (*Pseudaphritis urvillii*), Murray hardyhead (*Craterocephalus fluviatilis*), Murray cod (*Maccullochella peelii*)). The Coorong and Murray Mouth area (hereafter 'Coorong'), which includes the 'Murray Estuary', 'North Lagoon' and 'South Lagoon' (see Figure 1-1), is the only estuary in the MDB. Many estuarine fish species complete their life cycles in the Coorong, whereas others frequently enter the system, using the Coorong as refuge, nursery and feeding grounds, as well as a migration pathway at certain life history stages.

Freshwater flows to the Coorong are pivotal in facilitating a variety of processes, but most importantly for fish, they influence: 1) the estuarine salinity regime; 2) connectivity between freshwater, estuarine and marine environments; and 3) estuarine productivity by transporting nutrients and/or food resources from upstream. Freshwater flows can affect salt wedge conditions in estuaries, by flowing over the denser marine waters and creating a highly stratified water column at the freshwater and marine interface ('halocline'). The coupling of halocline with primary productivity and zooplankton can benefit larval fish from faster growth due to high prey availability and reduced risk of predation (North and Houde 2003; Islam *et al*. 2006). Therefore, these conditions can influence the location and extent of suitable habitat for spawning and larval development for many estuarine dependent fishes (North and Houde 2003; North *et al*. 2005; Islam *et al*. 2006).

Black bream is a solely estuarine fish species, i.e. it can complete its entire life-cycle within an estuary (Potter *et al.* 2015). Variability of freshwater inflows has been identified as a key factor influencing recruitment success of this species (Sarre and Potter 2000; Nicholson *et al.* 2008; Jenkins *et al.* 2010; Williams *et al.* 2012). However, the flow effects on salinity structure, and consequent recruitment variability, are unique to each estuary based on characteristics of catchment, channel topography and connection to the sea (Jenkins *et al.* 2010). For example, the highest recruitment in Gippsland Lakes often occurred in years of moderate river flows, whereas the timing of strong and weak year classes varied between other Victorian estuaries (Jenkins *et al.* 2010).

Being a multiple batch spawner, black bream has a protracted spawning season, generally ranging from September to late December depending on geographical location (Walker and Neira 2001; Sakabe *et al.* 2011; Cheshire *et al.* 2013). Spawning is triggered by a rise in water temperature (>15^{o} C) and often occurs in the upper reaches of estuaries, near the interface between fresh and brackish waters (Walker and Neira 2001; Nicholson *et al.* 2008; Williams 2013), where the level of salinity stratification (difference between bottom and surface salinity) is at least 10 PSU (Williams *et al.* 2012). The optimal salinity range for egg survival to hatching is from 15−35 PSU (Haddy and Pankhurst 2000; Norris *et al.* 2002).

Haloclines have been identified as critical larval nursery habitat for black bream that could enhance larval fish growth, survival, and ultimately recruitment (William *et al.* 2012; 2013). In the Gippsland Lakes, high concentrations of black bream larvae were found in salinities ranging between 15−30 PSU at sites where the salinity stratification was ≥10 PSU (Williams *et al.* 2013). In the Coorong, studies during 2014-15 (Ye *et al.* 2015a) and 2017-18 (Ye *et al*. 2019) showed that halocline conditions can be provided via manipulating water releases through the Murray barrages, although spatial extent of favourable habitat for black bream may vary due to multi-factorial effects (e.g. barrage discharge, location, tidal and wind conditions). In 2017-18, a strong cohort of black bream young-of-year (YOY, age 0+ years) was detected in the Coorong following freshwater releases (primarily environmental water) through the Murray barrages. The successful spawning period (late December to early February) corresponded with barrage releases of 600−5,000 ML.day^{-1} and temperature of 18−25°C, and commenced about 1−2 weeks after a ~10,000−12,000 ML.day^{-1} flow pulse (Ye *et al.* 2019). In contrast, there were no YOY black bream sampled during 2014-15 despite the presence of a halocline (Ye *et al.* 2019). These suggest a complex mechanism driving recruitment success of black bream, which warrants further study in the Coorong. As 'salt wedge' habitat is dynamic, exhibiting a high degree of temporal and spatial variability, the spawning behaviour and reproductive success of species that are dependent on salt wedge conditions are also likely to be dynamic and highly variable. This may partially explain the variable levels of recruitment of black bream in the Coorong (Ye *et al.* 2015b).

Furthermore, food availability is another important factor influencing larval fish survival, growth and ultimately recruitment, therefore food supply has been linked to variable recruitment of black bream (McKinnon and Arnott 1985; Newton 1996; Willis *et al.* 1999). Calanoid copepods are the preferred prey for black bream larvae and have been reported to be re-established following flooding in the Hopkins River (Newton 1996; Willis *et al.* 1999; Williams 2013). This suggests the importance of freshwater flows in driving food resource availability to support black bream recruitment in estuaries. More specifically, *Gladioferens* species and *Sulcanus conflictus* have previously been found as important food resources for black bream (e.g. Norriss *et al.* 2002; Williams *et al.* 2013).

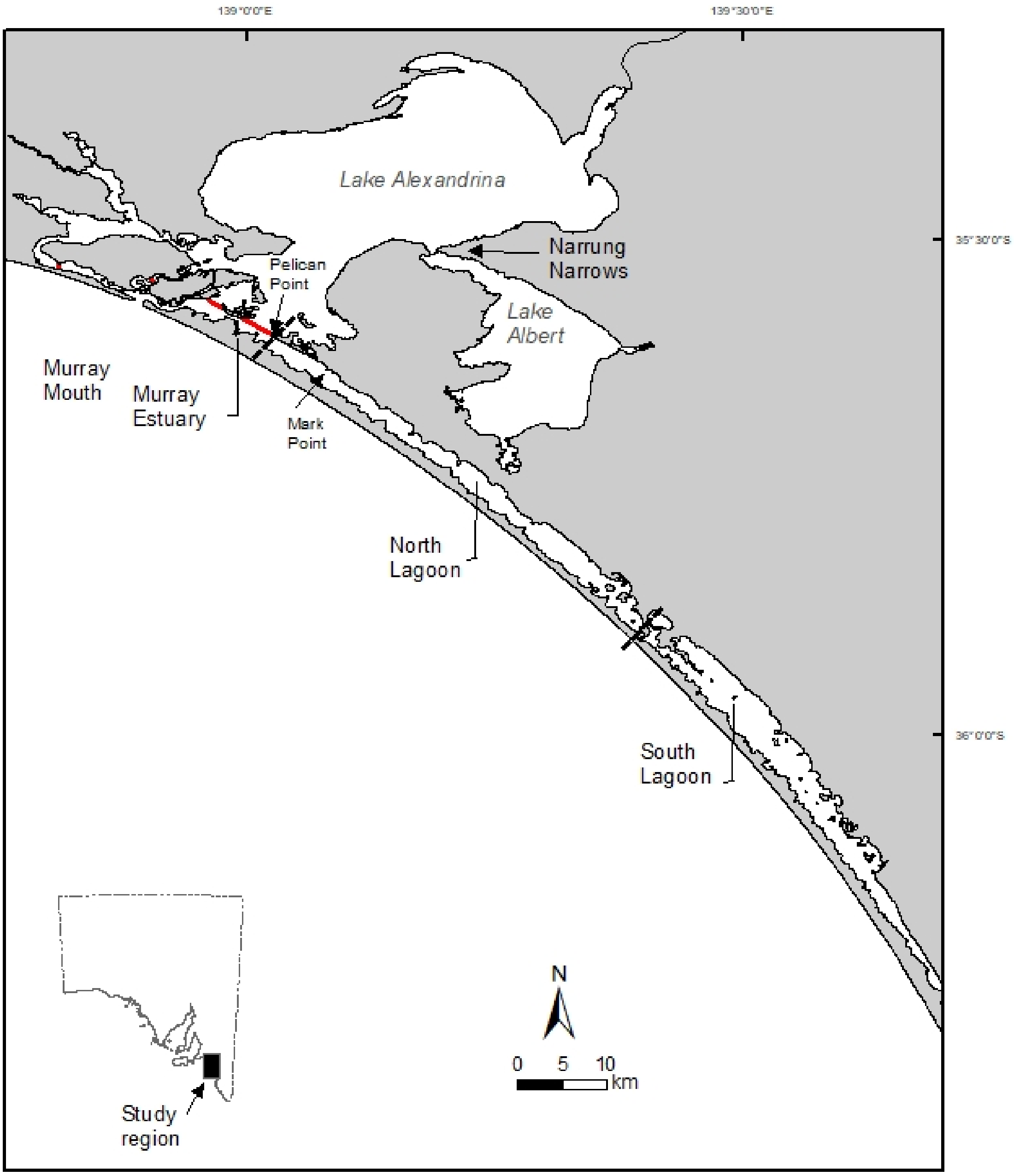

Figure 1-1. Map of the Coorong presenting Murray Estuary, North and South lagoons.

1.2. Need

Black bream is an iconic species with specific ecological objectives and targets under the Murray–Darling Basin-wide Environmental Watering Strategy (MDBA 2014), TLM LLCMM

Condition Monitoring Plan (DEWNR 2017) and South Australian River Murray Long-Term Environmental Watering Plan (DEWNR 2015). The species also supports important commercial and recreational fisheries in the LLCMM region. Currently the population of black bream is depleted in this region (Earl *et al.* 2016; Ye *et al.* 2018; Earl 2019). To facilitate the population recovery, it is important to promote regular recruitment. Barrage releases can be managed to provide favourable habitat (salt wedge conditions) for black bream reproduction to maximise the chance of recruitment success in the Coorong.

Over the last two years, black bream recruitment has been included among a range of targeted ecological outcomes for the Coorong from barrage releases during spring–summer, supported by Commonwealth environmental water. The monitoring during 2017-18 demonstrated the production of a strong cohort of YOY black bream following the managed barrage releases (Ye *et al.* 2019). This project was to continue the monitoring during 2018-19 to evaluate ecological outcomes and collect additional empirical data to improve our understanding of recruitment dynamics and habitat requirements of black bream in the Coorong. Such information will contribute to the underpinning knowledge for improving barrage operations and environmental flow management to achieve targeted ecological outcomes.

1.3. Objectives

The overall aim of this project was to undertake targeted monitoring to assess the salt wedge conditions, food availability and black bream recruitment associated with Murray barrage releases supported by water for the environment during spring and summer 2018-19. Specific objectives were to:

- Characterise salt wedge conditions below the barrages (particularly Goolwa and Tauwitcherie).
- Quantify zooplankton assemblages and assess food availability for black bream larvae with a focus on copepods, including nauplii.
- Determine the relative abundance of YOY black bream in the Coorong during summer/autumn 2018-19.
- Evaluate whether barrage releases supported by water for the environment provided suitable estuarine habitat for black bream recruitment, and provide management recommendations. Evaluation includes comparison of barrage release operations, salt wedge conditions and associated outcomes with those of 2017-18.

2. METHODS

2.1. Salt wedge monitoring

Longitudinal and depth profiles of salinity (practical salinity units, PSU), water temperature (°C) and dissolved oxygen (DO) (mg.L^{-1}) were recorded using a YSI EXO 2 sonde downstream of Goolwa and Tauwitcherie barrages and in the North Lagoon of the Coorong (Table 2-1). Monitoring was conducted on a 3-weekly basis, with a total of seven field trips, between 11 October 2018 and 15 February 2019 (Table 2-2). Measurements were taken using the continuous sampling mode at multiple sites along three transects with ~1 km intervals (Figure 2-1; Appendix A).

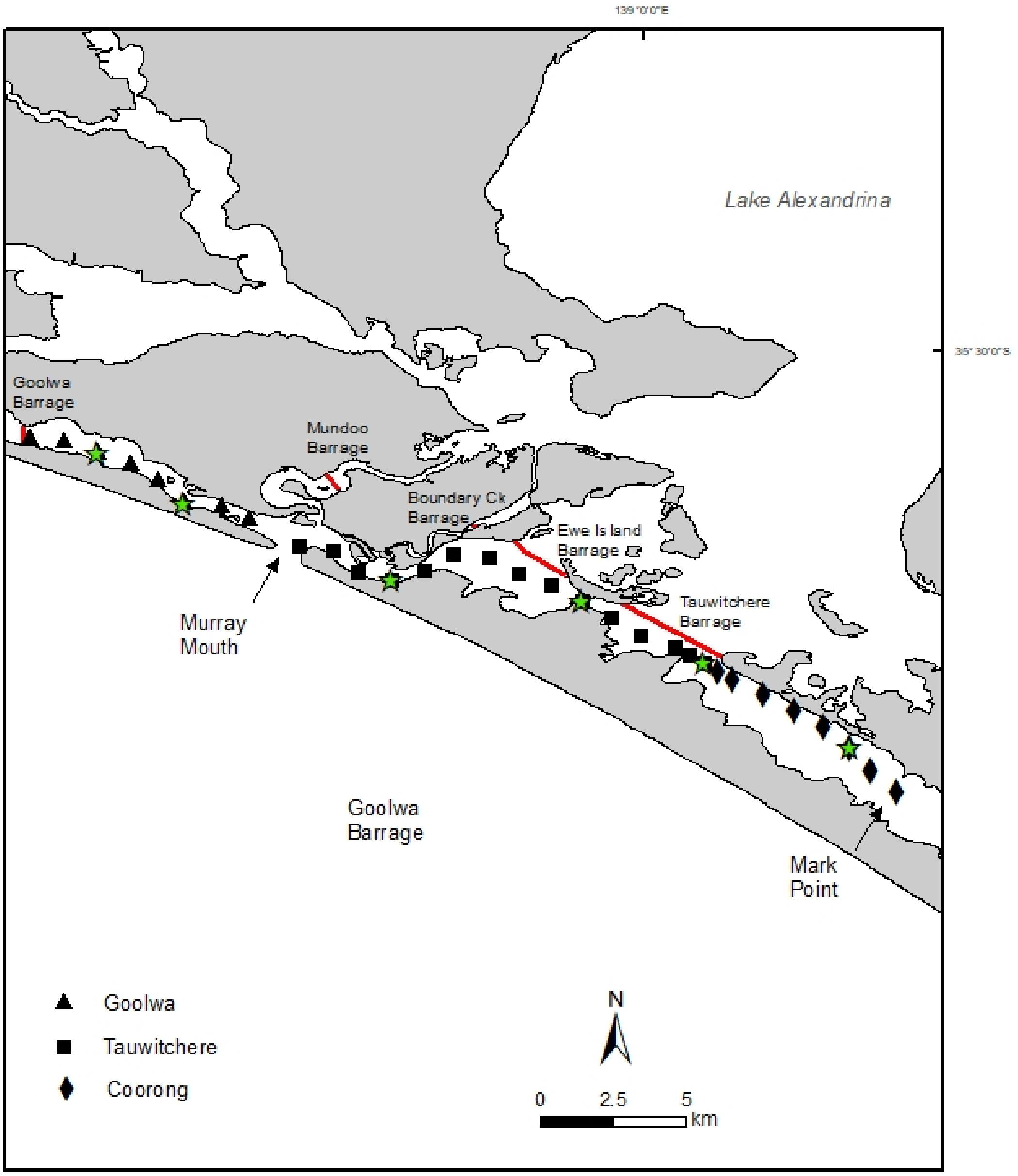

Figure 2-1. Map of the Coorong presenting sites for salinity, water temperature and dissolved oxygen profiling along the Goolwa, Tauwitcherie and Coorong transects. Sites marked with a star represent where zooplankton sampling occurred.

Table 2-1. Information on three transects for salinity, water temperature and dissolved oxygen profiling. Refer to Figure 1-1 for a map of locations.

Transect	**Distance (kms)**	**Location**		**No. sites**
		Start	End	
Goolwa	7	Goolwa Barrage	Murray Mouth	8
Tauwitcherie	13	Tauwitcherie Barrage (Pelican Point end)	Murray Mouth	15
Coorong	7	Tauwitcherie Barrage (Pelican Point end)	Mark Point, North Lagoon	8

Table 2-2. Salt wedge and zooplankton sampling trips and dates during 2018-19.

Trip	**Sampling dates**
1	11–12 October 2018
2	30–31 October 2018
3	25–26 November 2018
4	18–19 December 2018
5	3–4 January 2019
6	22–23 January 2019
7	14–15 February 2019

2.2. Zooplankton assessment

Field sampling

Zooplankton sampling was conducted using a Perspex Haney plankton trap (4.5 L capacity) during each sampling event at six selected sites in the Coorong (two at the Goolwa, three at the Tauwitcherie and one along the Coorong transect) (Figure 2-1). At each site, three replicate samples were taken at the water surface and bottom depths. Additionally, a highly concentrated qualitative zooplankton sample was taken in oblique angle to capture zooplankton from the entire water column. These samples were taken using a 30 µm plankton net to assist with species/genus identification. The total volume of each sample was concentrated to approximately 50 mL by filtering through a 30 µm net. Concentrated samples were then transferred to a 200 mL PET jar and preserved with ~70% ethanol and returned to the laboratory for identification.

Laboratory work

Quantitative samples were inverted three times and a 1 mL sub-sample transferred into a Pyrex gridded Sedgewick-Rafter cell. The entire sub-sample was sorted into taxonomic groups and then counted, and copepods were dissected and identified using a Leica compound microscope. The relative abundance (average density) of zooplankton was calculated and expressed as numbers of individuals per meter cubed (ind.m^{-3}). If no copepods were recorded within a 1 mL count, the entire sample was allowed to settle and the volume pipetted into a 125 mm square gridded Greiner tray and all copepods counted. Qualitative samples were allowed to settle, then the volume pipetted into a 125 mm square gridded Greiner tray. The tray was scanned on an Olympus SZH10 dissecting microscope and copepods were identified to species level where possible, providing a proportional composition and an estimate of species diversity for copepods.

2.3. Sampling YOY black bream

To quantify the abundance of black bream new recruits (YOY), two targeted sampling events (i.e. February and April 2019) were conducted, using fyke nets and a small seine net at multiple sites in the Murray Estuary (8 sites) and North Lagoon (4 sites) of the Coorong (Figure 2-2). The fyke nets were single-wing and 8.6 m long (3 m wing plus 5.6 m funnel) with a mesh size of 8 mm and a hoop diameter of 0.6 m. On each sampling occasion, four replicate fyke nets were set overnight at each site. The small seine net was 8 m long with a 2 m drop and a mesh size of 2 mm. It was hauled through water less than 0.5 m deep over a distance of 20 m by two people walking 5 m apart, thus sampling an area of about 100 m^2. Seine net sampling was replicated by three standard shots at each site.

On each sampling occasion, all fish species were identified and counted. The relative abundance of YOY black bream was based on the estimate of catch per unit effort (CPUE), defined as number of fish per fyke net per night (fish.net $night^{-1}$) or number of fish per seine net shot (fish.net^{-1}).

For age/size composition analyses, additional samples of black bream collected in March 2019 were included. This sampling was part of the TLM Coorong Fish Condition Monitoring, which used large and small seine nets across thirteen sites in the Coorong (for detailed methods refer to Ye *et al.* 2018). For age determination, otoliths (sagittae) were extracted from black bream samples in the laboratory. Transverse sections of otoliths were prepared as described in Ye *et al.* (2002), and the annual increments were counted, representing age in years.

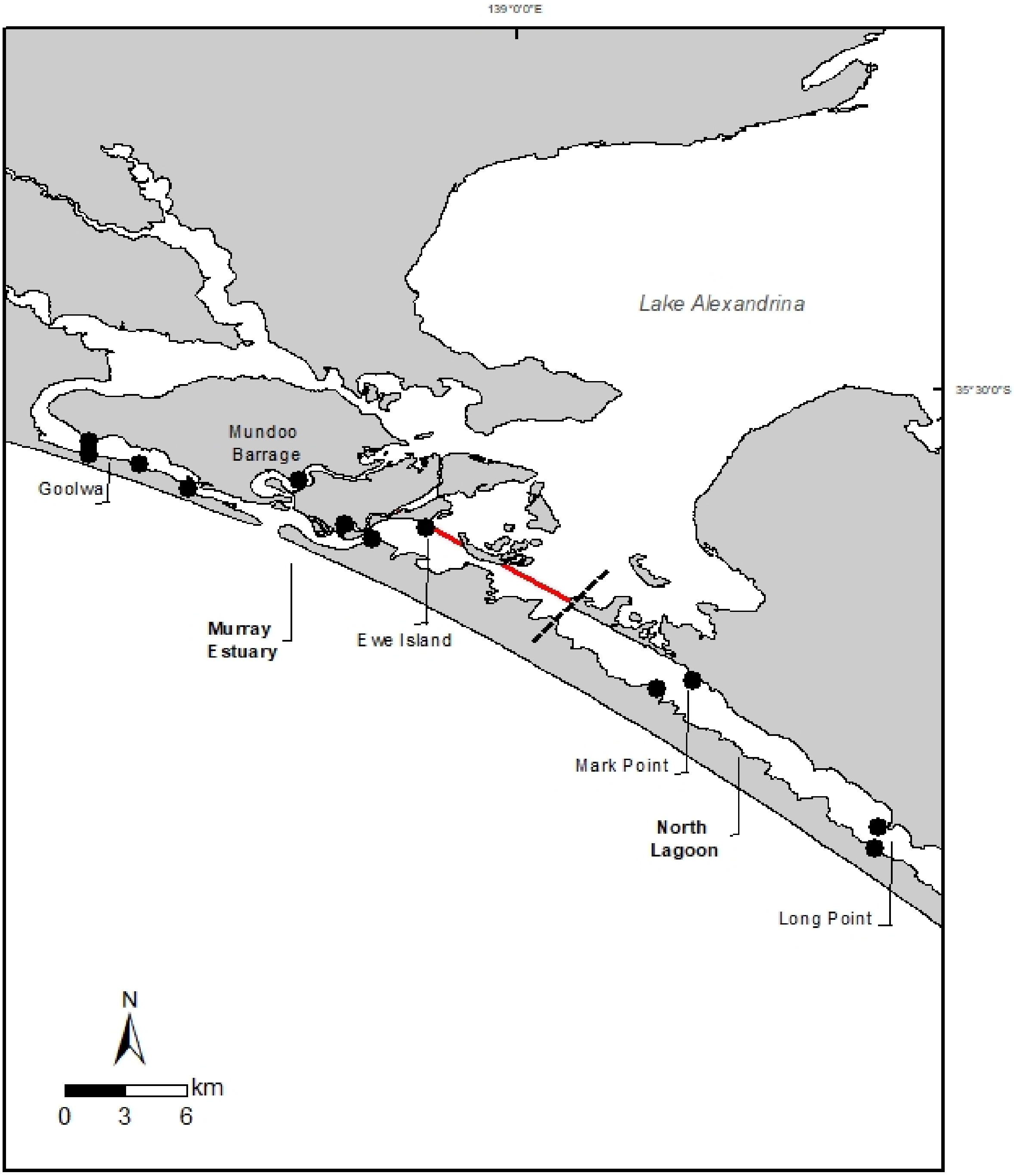

Figure 2-2. Map of the Coorong presenting sampling sites (solid black circles) for YOY black bream using fyke nets and a small seine net. Dashed line indication boundary between Murray Estuary and North Lagoon.

2.4. Data analysis

Salinity, temperature and DO stratifications

Calculations were performed using R language (R Core Team 2017) and geometry operations with R package rgeos (Bivand and Rundel 2017). The profile data for salinity, temperature and DO concentration were converted into three joint longitudinal sections of Goolwa, Tauwitcherie and Coorong. Grids were created by interpolating values at one centimeter vertical distance from sonde profiles using a cubic smoothing spline. In addition, the salinity gradient was calculated along the sections. Based on the results of published research (Hassell *et al.* 2008a; 2008b; Williams *et al.* 2013), environmental criteria were selected for further analysis to identify favourable spawning and larval nursery habitat for black bream. These included salinity within a range of 15−30 PSU, combined with salinity stratification (gradient) ≥10 PSU, temperature >15°C and DO >65% saturation level (i.e. >5 $mg.L^{-1}$ at 25 PSU and 20°C). In the next step, polygons were obtained from the grids for individual areas where salinity, temperature and DO met these criteria. Finally, the areas of suitable habitat were computed by intersection of salinity, temperature and DO polygons as well as salinity gradient requirement.

Linking larval nursery areas with barrage flows

The areas (longitudinal section) of suitable larval nursery habitat for black bream along the Goolwa, Tauwitcherie and Coorong transects were plotted against prior 7-day discharge (i.e. mean daily discharge of previous seven days including the sampling day) for each barrage. Data from 2017-18 and 2018-19 were combined for the transects sampled in both years (note Mundoo transect was only sampled in 2017-18). The patterns of the scatterplots were analysed to explore the potential relationships between nursery area and barrage releases. For the Goolwa and Coorong transects, the discharges from Goolwa and Tauwitcherie barrages, respectively, were used, whereas for the Tauwitcherie transect (i.e. Pelican Point to Murray Mouth), the total discharges from Tauwitcherie and Ewe Island were used.

3. RESULTS

3.1. Barrage releases and water for the environment

From 2003-04 to 2018-19, freshwater discharge via barrage releases to the Coorong was highly variable (Figure 3-1). Annual discharge remained <940 GL year^{-1} between 2003-04 and 2009-10, with no flow from 2007-08 to 2009-10. In 2010-11 and 2011-12 (high flow years), discharge increased substantially to >9,000 GL year^{-1}. Following a gradual decrease in the subsequent four years, the discharge peaked again (~6,500 GL) in 2016-17 (another high flow year), but then decreased to ~850 GL in 2017-18 and further reduced to 377 GL in 2018-19.

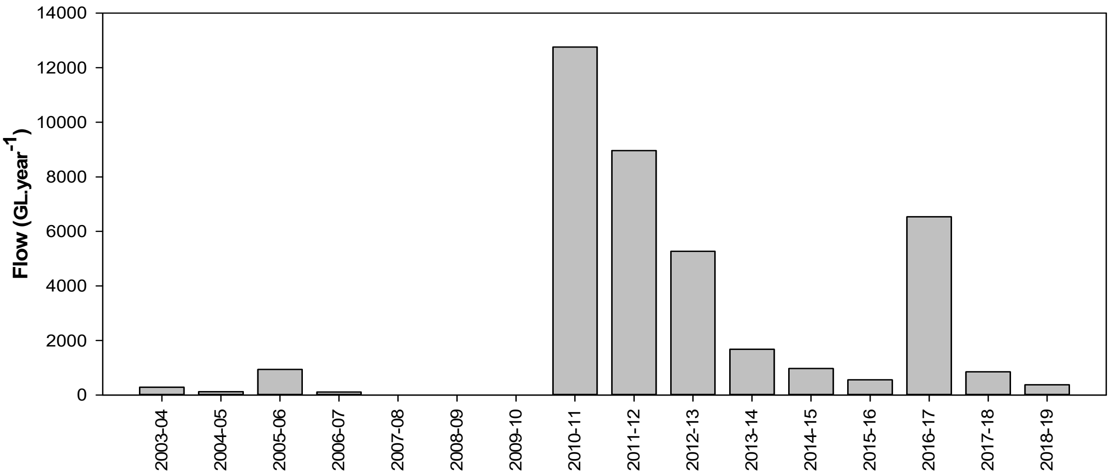

Figure 3-1. Total annual flow discharge to the Coorong (GL.year^{-1}). Discharge from 2003-04 to 2012-13 were modelled data (Data source: MDBA) and from 2013-14 to 2018-19 were calculated dashboard data (Data source: DEW).

Although 2018-19 was a year of low flow, Commonwealth environmental water was used to maintain barrage releases at low volumes to the Coorong between October 2018 and March 2019, with a total discharge of ~135 GL (Figure 3-2). During this six-month period, the majority of discharge was through Tauwitcherie (56%) and Goolwa (39%) barrages. Mundoo and Ewe Island barrages together had 4.8% of the discharge whilst Boundary Creek Barrage had minor releases (0.2%) (Figure 3-2). Prior to October, total daily barrage discharge peaked at ~9,800 ML.day^{-1} in August 2018.

At Goolwa Barrage, the mean discharge was 290 ML.day^{-1} (SE ± 18) between October 2018 and March 2019 (Figure 3-2a). From early October 2018 to January 2019, the mean discharge was 390 ML.day^{-1} (± 21), but then declined to 87 ML.day^{-1} (± 10) in February and March 2019. At Tauwitcherie Barrage, the mean discharge was 408 ML.day^{-1} (± 19) between October 2018 and March 2019. The mean discharge during October 2018 was relatively high at ~817 ML.day^{-1} (± 28); it then reduced to 325 ML.day^{-1} (± 16) during November and December 2018, before increasing to 713 ML.day^{-1} by 11 January 2019. From then, flow steadily declined and was low (182 ML.day^{-1} ± 18) in February 2019 before increasing to 1,497 ML.day^{-1} in late March 2019 (507 ML.day^{-1} ± 76 in March).

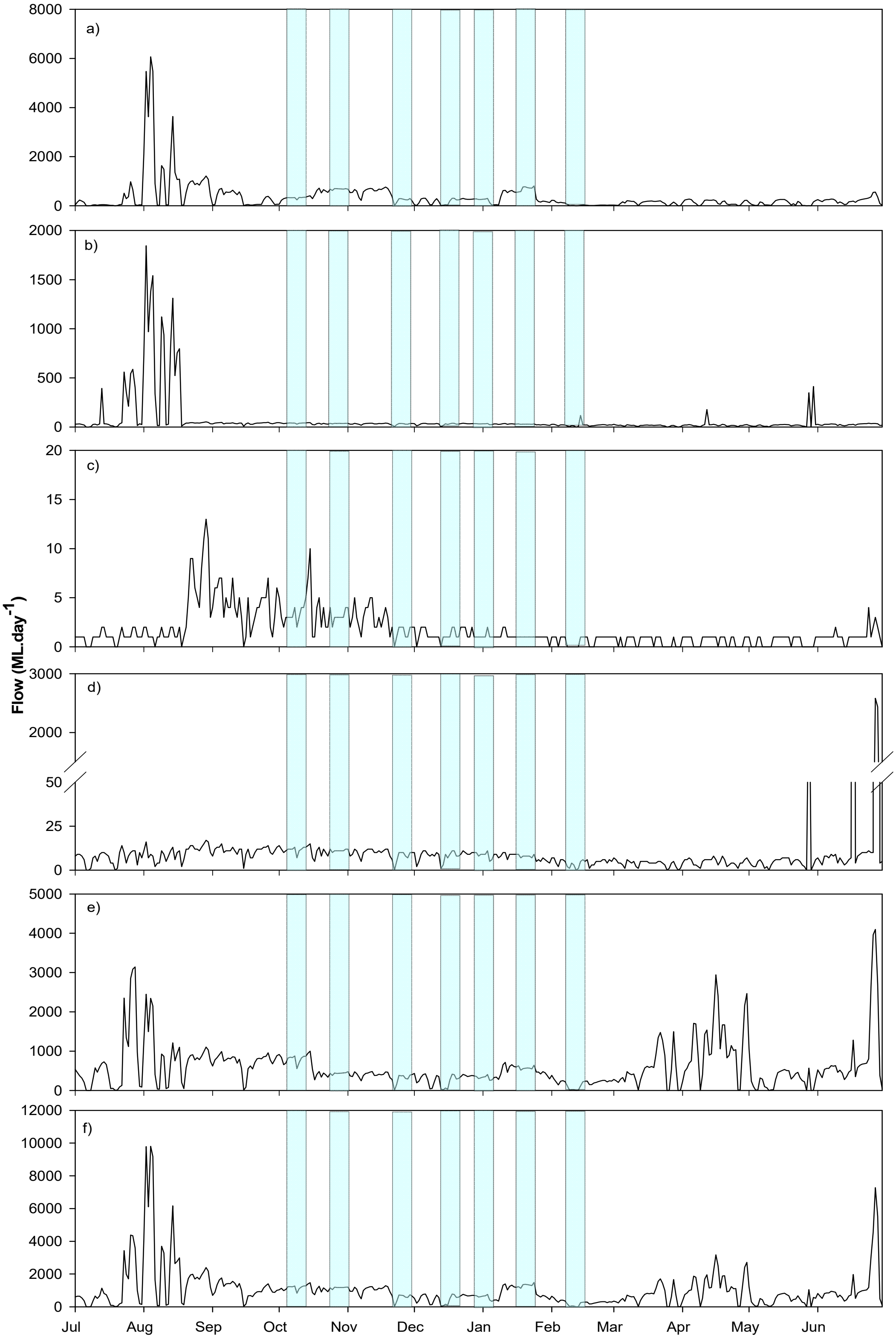

Figure 3-2. Daily flow discharge by individual barrages (ML.day^{-1}) for 2018-19. a) Goolwa barrage, b) Mundoo barrage, c) Boundary Creek barrage, d) Ewe Island barrage, e) Tauwitcherie barrage and f) Combined discharge (five barrages). Blue bars are the timing of field trips. Data source: DEW.

3.2. Characterising salt wedge conditions

Salinities of 15–30 PSU with high stratification (≥10 PSU) were consistently present below Goolwa Barrage (i.e. along the Goolwa transect) during most of the sampling periods (from Trip 1 to Trip 6 between mid-October 2018 and late January 2020) (Figure 3-3). During the last sampling trip (Trip 7 in mid-February 2019), there was a substantial reduction in areas with favourable salinity and stratification, which were confined to the vicinity below Goolwa Barrage. In contrast, along the Tauwitcherie and Coorong transects, suitable salinities were only present on some occasions (e.g. Trip 2 in late October 2018, and Trips 5 and 6 during January 2019), but noting minimum salinities were generally higher than 15 PSU, and salinity stratification of ≥10 PSU rarely occurred throughout the sampling period (except for small areas during Trips 5 and 6).

Water temperature was >15°C across all sites throughout most of the sampling period, with the exception of Trip 1 (early October 2018) when large deep areas were <15°C (Figure 3-4). Warmest temperatures (>20°C) were present throughout the water column during Trips 5 and 6 (January 2019).

DO levels generally remained favourable (>5 mg.L^{-1}) across the sampling sites/trips (Figure 3-5). However, some deep areas along Goolwa and Coorong transects occasionally had DO ≤5 mg.L^{-1} (Figure 3-5). This was particularly noticeable during Trip 4 (mid-December 2018) below Goolwa Barrage.

Overall, suitable areas of larval nursery habitat for black bream (using the defined criteria of salinities 15−30 PSU, salinity gradient ≥10 PSU, temperature >15°C and DO >5 mg.L^{-1}) were present below Goolwa Barrage from Trip 1 to Trip 6 (October 2018 to January 2019), although the extent of the area varied between trips. With the reduction of barrage discharge, suitable habitat area contracted to a very small area below the Goolwa Barrage during Trip 7 (mid-February 2019) (Figure 3-6). In contrast, no larval nursery habitat was present along Tauwitcherie and Coorong transects during the study period except for small patchy areas during Trip 6 (late January 2019) and a very small area during Trip 5 (mid-January 2019).

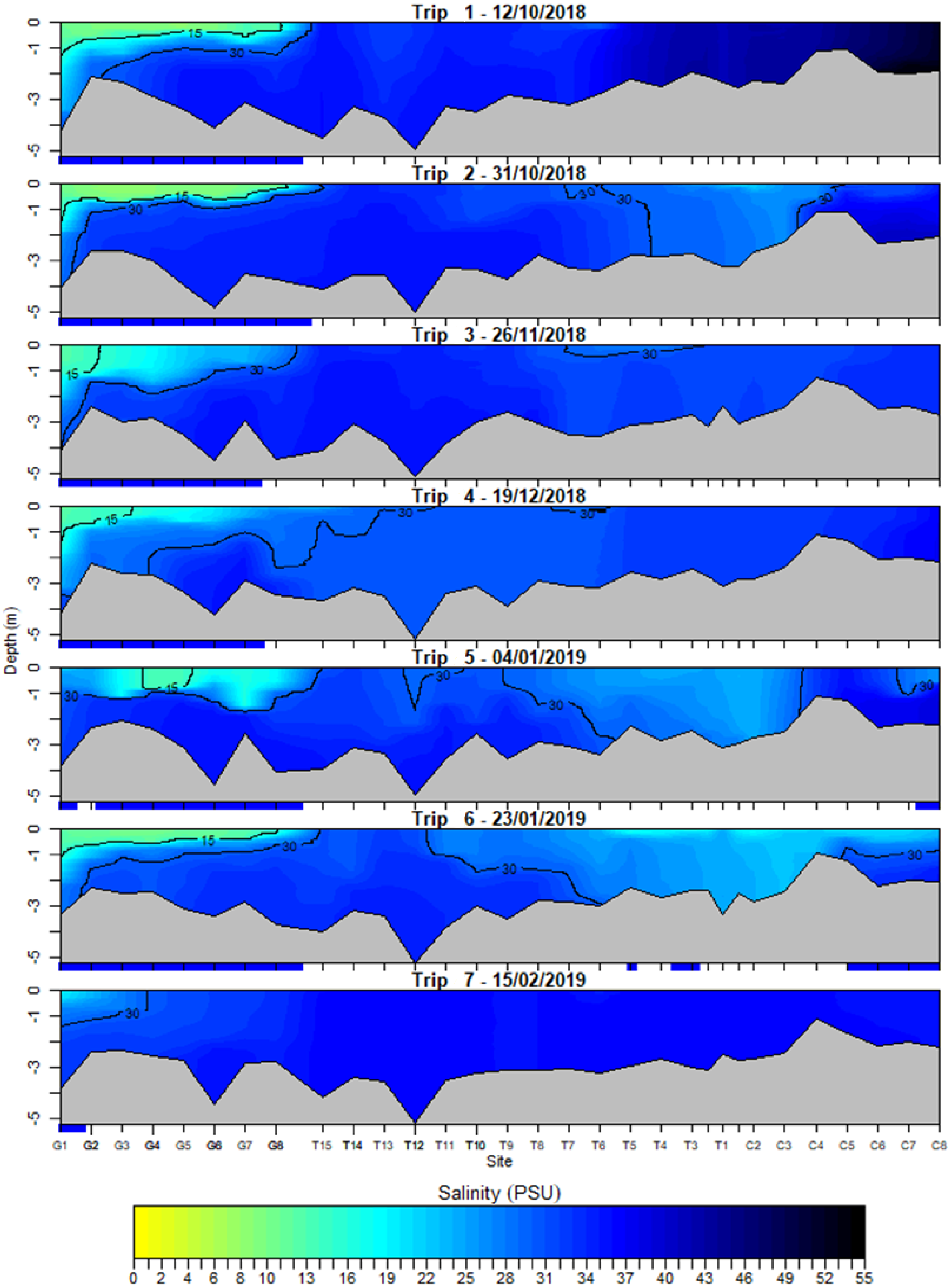

Figure 3-3. The longitudinal and depth profile of salinities measured at multiple sites with ~1 km interval along the Goolwa (G1−G8), Tauwitcherie (T1−T15) and Coorong (C1−C8) transects in the Murray Estuary and North Lagoon of the Coorong during seven trips between 12 October 2018 and 15 February 2019. Blue highlighting below the x-axis indicates areas with salinity stratification ≥10 PSU. G1: below Goolwa Barrage; T1: Pelican Point end of the Tauwitcherie Barrage; C8: Mark Point; and Murray Mouth: between G8 and T15. Salinity contours of 15 PSU and 30 PSU are shown.

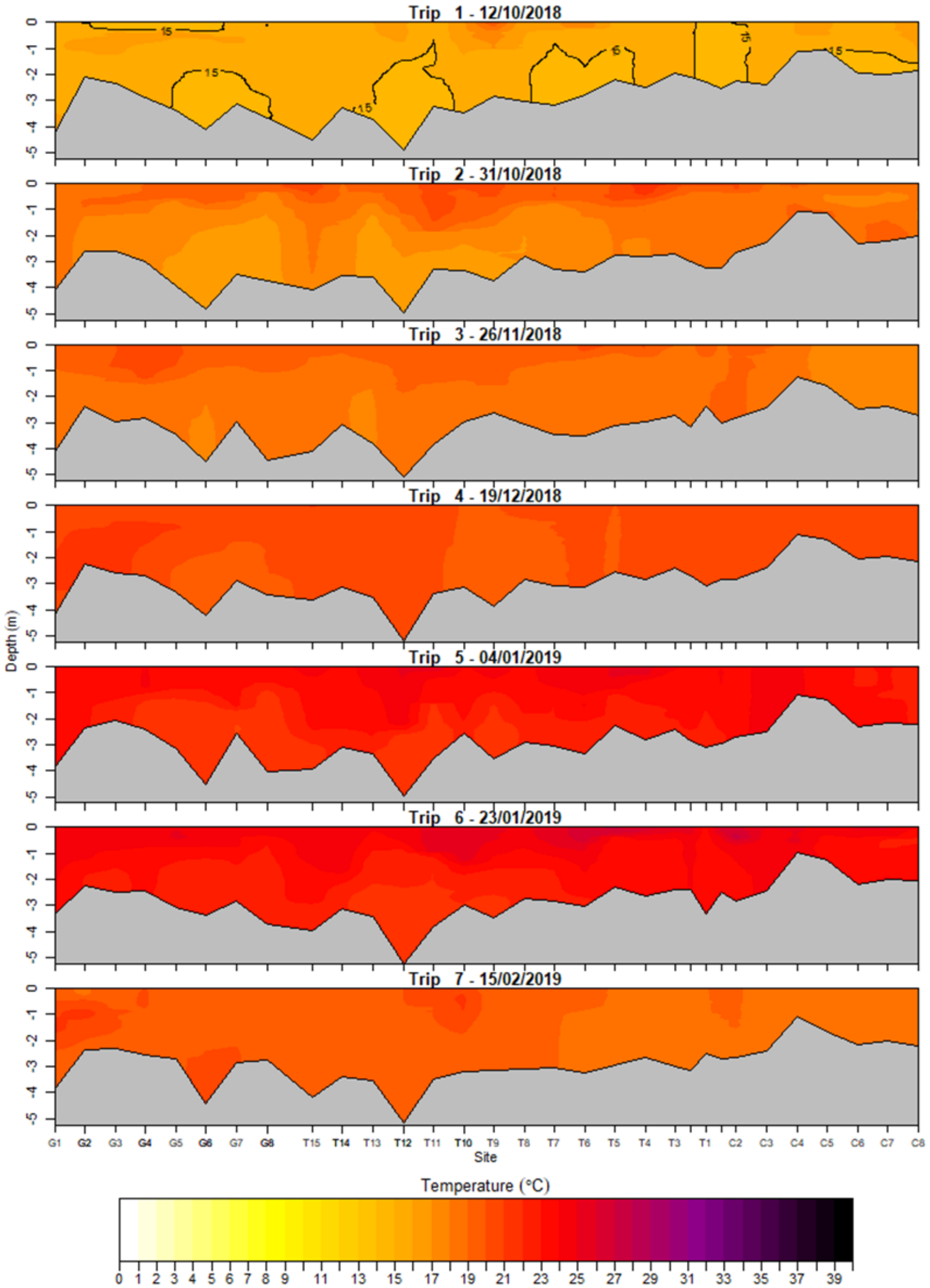

Figure 3-4. The longitudinal and depth profile of water temperature measured at multiple sites with ~1 km interval along the Goolwa (G1−G8), Tauwitcherie (T1−T15) and Coorong (C1−C8) transects in the Murray Estuary and North Lagoon of the Coorong during seven trips between 12 October 2018 and 15 February 2019. G1: below Goolwa Barrage; T1: Pelican Point end of the Tauwitcherie Barrage; C8: Mark Point; and Murray Mouth: between G8 and T15.

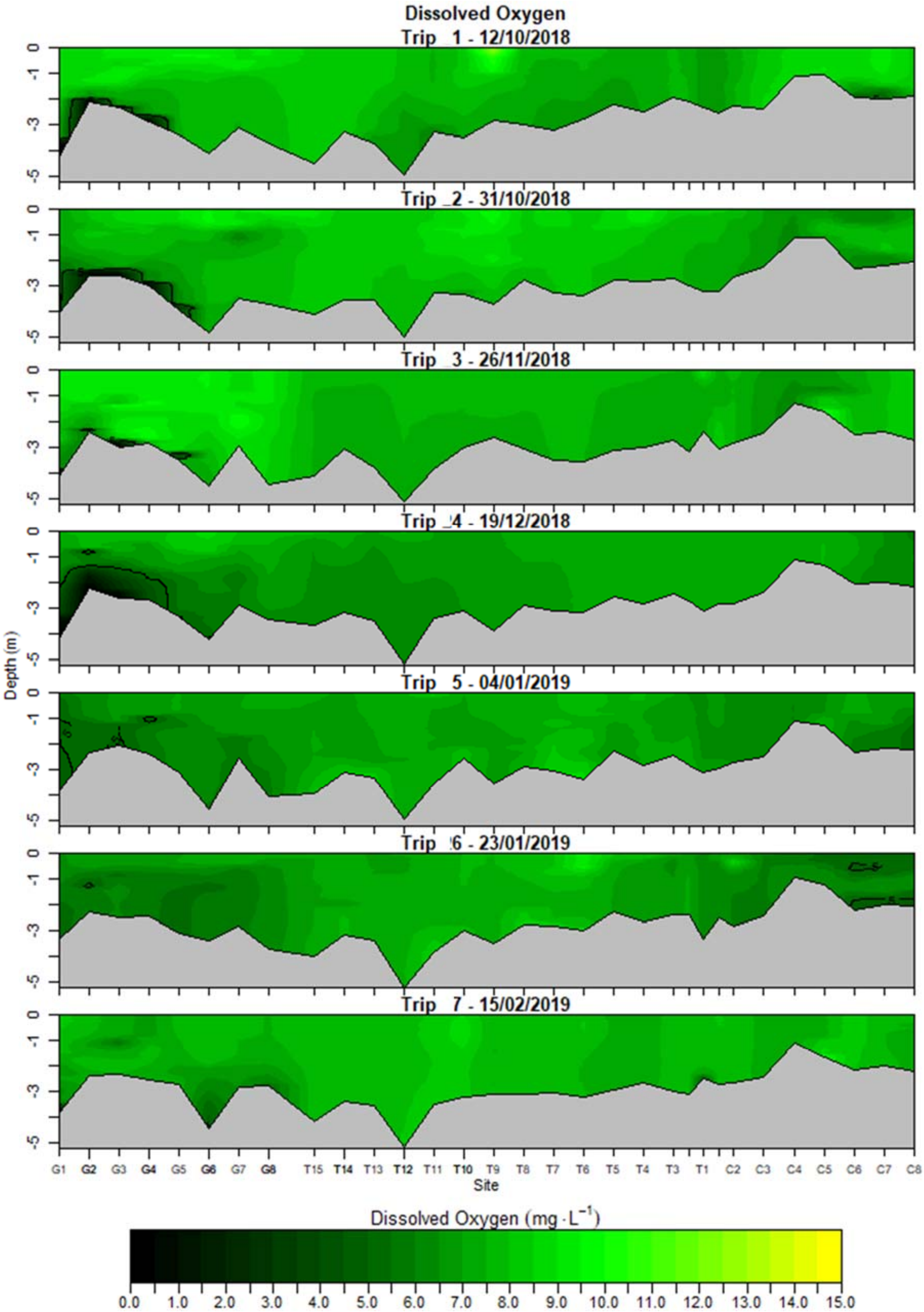

Figure 3-5. The longitudinal and depth profile of dissolved oxygen measured at multiple sites with ~1 km interval along the Goolwa (G1−G8), Tauwitcherie (T1−T15) and Coorong (C1−C8) transects in the Murray Estuary and North Lagoon of the Coorong during seven trips between 12 October 2018 and 15 February 2019. G1: below Goolwa Barrage; T1: Pelican Point end of the Tauwitcherie Barrage; C8: Mark Point; and Murray Mouth: between G8 and T15. DO contour of 5 mg.L^{-1} is shown.

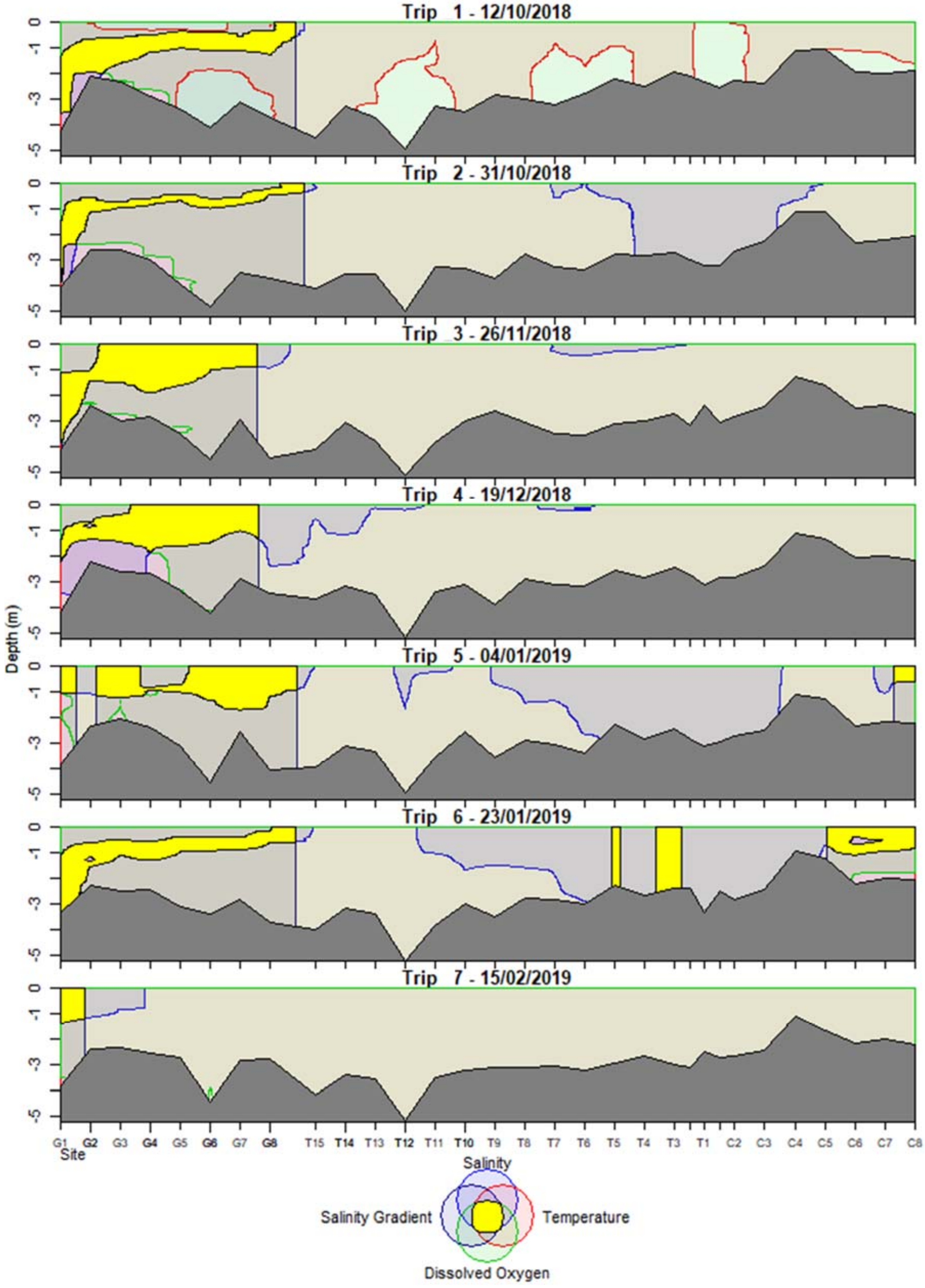

Figure 3-6. Integrated values for salinity, temperature and dissolved oxygen showing longitudinal sections of suitable areas (in yellow) for black bream larval nursery habitat (using environmental criteria of salinities 15−30 PSU, salinity gradient ≥10 PSU, temperature >15°C and DO >5 mg.L^{-1}) along the Goolwa (G1−G8), Tauwitcherie (T1−T15) and Coorong (C1−C8) transects in the Coorong during seven trips between 12 October 2018 and 15 February 2019. G1: below Goolwa Barrage; T1: Pelican Point end of the Tauwitcherie Barrage; C8: Mark Point; and Murray Mouth: between G8 and T15.

3.3. Linking flow discharge with suitable larval habitat area

Scatter plots of the extent (area) of suitable larval nursery habitat for black bream against daily barrage discharge (prior 7-day mean) are shown for different transects in the Coorong (Figure 3-7). No clear relationship could be discerned for the Goolwa transect, and data points for the Mundoo transect were limited with only one year of data (2017-18). However, a ‘dome shape’ pattern was revealed with a significant model ($P \leq 0.005$) for the Tauwitcherie, Coorong and all transects combined and R^2 (goodness of model fit) for most relationships >0.50 (Figure 3-7); this suggests that larval nursery area could be enhanced/improved for the respective transect at barrage discharge rates of 4,500 $ML.day^{-1}$ (from the Tauwitcherie and Ewe Island barrages), 3,000 $ML.day^{-1}$ (from the Tauwitcherie Barrage) and 6,000 $ML.day^{-1}$ (from all barrages combined).

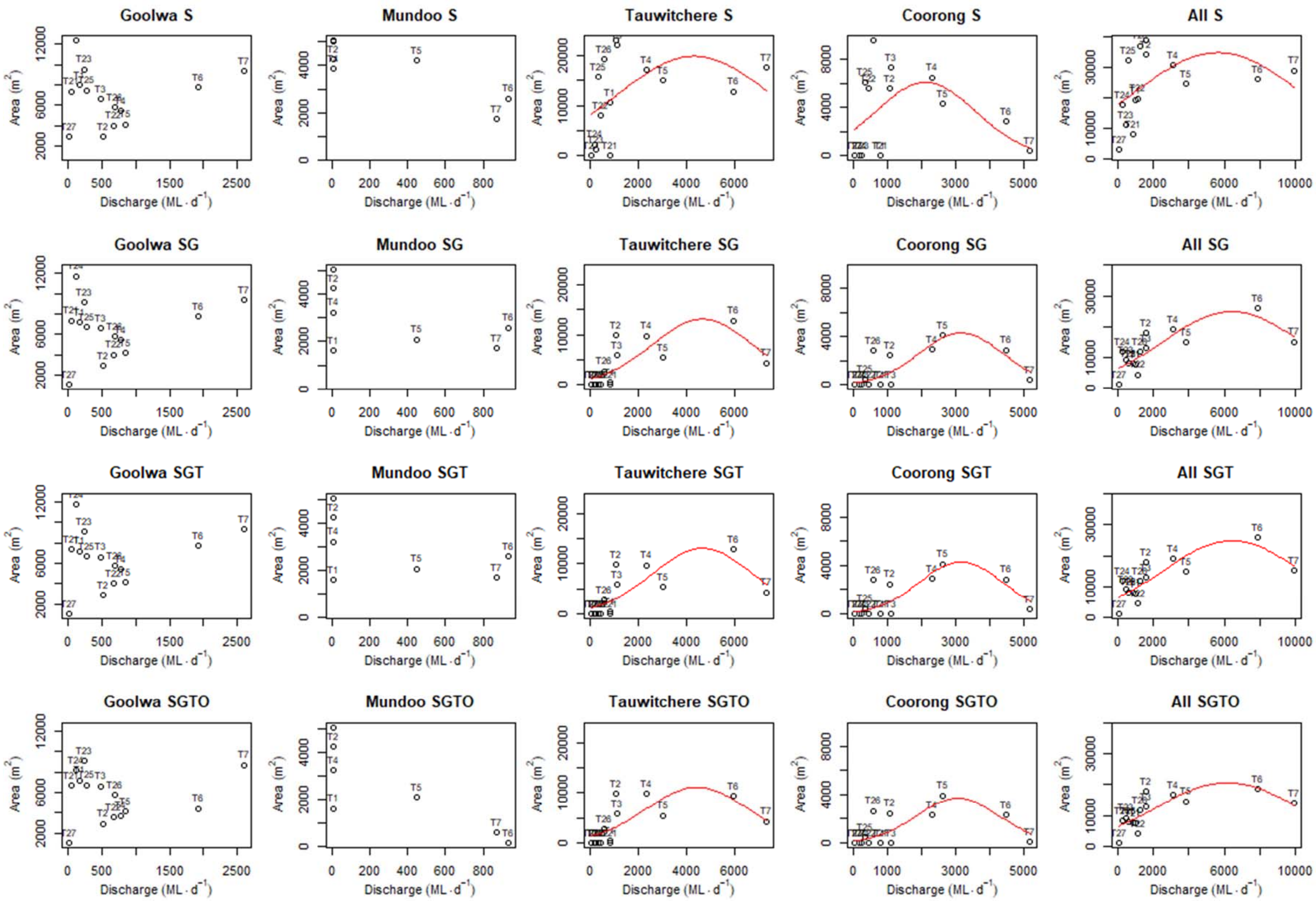

Figure 3-7. Scatterplots of suitable areas (longitudinal section) of larval nursery habitat for black bream, using interpolated environmental criteria of salinities (S) 15−30 PSU, depth gradient (G) ≥10 PSU, temperature (T) >15°C and DO (O) >5 mg.L^{-1}, against prior 7-day's mean barrage discharge (including the sampling day) along the Goolwa, Tauwitcherie, Coorong and Mundoo transects and the joint results of the first three transects (All) based on data collected in the Coorong during November–December 2017-18 and October–February 2018-19. Note: The total discharge through Tauwitcherie and Ewe Island barrages was used in the plots for the Tauwitcherie transect (Pelican Point to Murray Mouth), whereas the discharge through Goolwa, Mundoo and Tauwitcherie barrages were used in the plots of Goolwa, Mundoo and Coorong transects, respectively. Redlines showing significant relationships (*P*≤0.005) and the goodness of fit R^2>0.50 for all except for the top three panels.

3.4. Assessing larval fish food resources

Copepod assemblages

In this study, two calanoid copepod, eight harpacticoid copepod and seven cyclopoid copepod species were identified in the Coorong during spring–summer 2018-19 (Tables 3-1; 3-2). Approximately 75–100% copepod abundance was comprised of marine or marine/brackish species across all trips (Appendix B). The highest copepod diversity of nine species was recorded during Trip 3 (late November 2018), the only trip in which *Gladioferens* taxa was found (Table 3-1).

Typical of prolonged periods of low freshwater discharge, the abundance of copepods was generally low throughout the study period. Each of the major groups of copepods, including nauplii, demonstrated higher abundance during Trip 2 (late October 2018) (Figure 3-8), when a small yet distinct freshwater plume that extended from below Goolwa Barrage (G1) through to near the Murray Mouth (G8) was present (Figure 3-3) and the temperature throughout water column was >15°C (Figure 3-4). During Trip 2, the discharge (prior 7-day's mean including the sampling day) through Goolwa Barrage increased to 1,174 ML.day^{-1} (± 7) compared to 892 ML.day^{-1} (± 11) during Trip 1 (mid-October 2018). Copepod nauplii reached their maximum abundance (239,000 ind.m^{-3}) during Trip 2 for the study. Peaks of copepod nauplii abundance generally aligned with peaks in harpacticoid copepod abundance (Figure 3-8 c-d). Therefore, the majority of the copepod nauplii were likely also harpacticoids, making them the most abundant order of copepod present during the study.

Each group also demonstrated a peak in abundance during, one or more of, Trips 4, 5 and 6 (from December 2018 to January 2019), when water temperature was greatest and there were larger areas of lower salinity habitat present in the Coorong compared to other trips. This included calanoid copepodites peak abundance during Trip 5 (early January 2019) at Site T12 (near the Boundary Creek mouth and ~3 km from the Murray Mouth), and cyclopoid copepods which reached their maximum abundance (11,000 ind.m^{-3}) during Trip 6 (late January 2019) at Site T12 (Appendix B). All groups demonstrated consistently higher abundances at the bottom in comparison to the surface of the water column (Figure 3-8).

Calanoid copepods

This group, reported as the preferred prey for black bream larvae (Newton 1996; Williams 2013), had two species identified in this study. The *Gladioferens* taxa, a known important food source, were recorded only during Trip 3 (late November 2018) at 2 km downstream of Goolwa Barrage (G3) and at very low abundance (~70 ind.m^{-3}) (Table 3-1; Figure 3-8). The *Acartia* taxa were present during Trip 7 (mid-February 2019) at Site T12 (Table 3-2; Figure 3-8) also at very low abundance (~70 ind.m^{-3}). Additionally, unidentified calanoid copepodites (juvenile copepod) were recorded in all trips mainly at sites along Goolwa and Tauwitcherie transects. They reached their maximum abundance (8,400 ind.m^{-3}) during Trip 5 (early January 2019) at T12. *Sulcanus conflictus*, another previously reported food source for black bream larvae, were not found during this study.

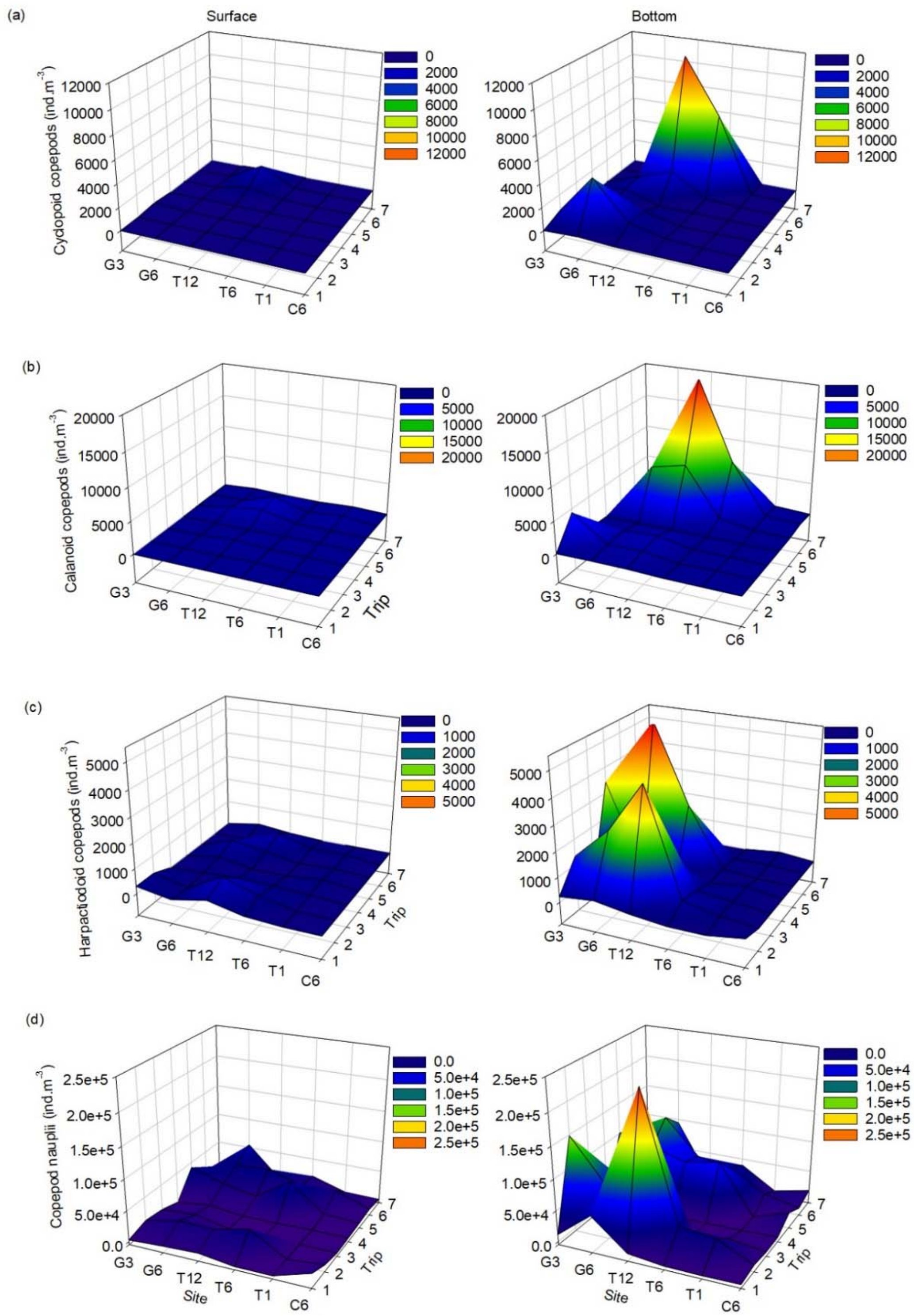

Figure 3-8. Differences in average number of (a) cylopoid copepods, (b), calanoid copepods, (c) harpacticoid copepods and (d) copepod nauplii per cubic meter (ind.m^{-3}) at the surface and the bottom of the water column across all sites across trips.

Table 3-1. Summary of the species identified at each site during sampling Trips 1, 2 and 3 and their preferred environment where F = fresh, M = marine and B = brackish. Grey shading indicates that the species was only found in the bulk sample, not within the quantitative counts.

		Trip 1							Trip 2							Trip 3						
	Habitat	G3	G6	T1	T6	T12	C6	TOTAL	G3	G6	T1	T6	T12	C6	TOTAL	G3	G6	T1	T6	T12	C6	TOTAL
HARPACTICOIDS																						
Mesochra parva	B	*	*		*	*	*	*	*	*			*		*			*	*	*		*
Euterpina acutifrons	M/B										*	*	*		*		*					*
cf. *Quinquelaophonte* sp.	M																					
cf. *Robertsonia* sp	M												*		*			*				*
Species a	-												*		*							
Species b	-																*					*
Species c	-					*	*	*											*			*
CYCLOPOIDS																						
Oithona cf. *plumifera*	M/B		*					*	*	*		*	*		*			*		*	*	*
Oithona cf. *atlantica*	M/B									*					*							
Oithona cf. *simplex*	M/B	*						*		*					*			*				*
Oithona cf. *rigida*	M/B																			*		*
cf. *Cyclopetta orientalis*	M/B															*	*					*
Unidentified	-																					
CALANOIDS																						
Gladioferens pectinatus	M															*						*
Acartia cf. *fancetti*	M/B																					
Unidentified juveniles	-	*	*	*		*		*	*	*	*	*	*		*		*	*	*	*		*
CLADOCERA																						
Total taxa identified		3	3	1	1	3	2	5	3	5	2	3	6	0	8	2	4	5	3	4	1	11

Table 3-2. Summary of the species identified at each site during sampling Trips 4, 5, 6 and 7. Grey shading indicates that the species was only found in the bulk sample, not within the quantitative counts.

	Trip 4							Trip 5							Trip 6							Trip 7						
	G3	G6	T1	T6	T12	C6	TOTAL	G3	G6	T1	T6	T12	C6	TOTAL	G3	G6	T1	T6	T12	C6	TOTAL	G3	G6	T1	T6	T12	C6	TOTAL
HARPACTICOIDS																												
Mesochra parva			*	*			*																			*		*
Euterpina acutifrons	*	*					*		*	*	*	*		*	*	*	*	*	*		*							
cf. *Quinquelaophonte* sp.																								*				*
cf. *Robertsonia* sp																							*					*
Species a																												
Species b																								*				*
Species c			*				*										*				*							
CYCLOPOIDS																												
Oithona cf. *plumifera*		*					*									*	*	*			*		*					*
Oithona cf. *atlantica*																												
Oithona cf. *simplex*											*			*					*		*							
Oithona cf. *rigida*									*			*		*					*		*							
cf. *Cyclopetta orientalis*																												
Unidentified																										*		*
CALANOIDS																												
Gladioferens pectinatus																												
Acartia cf. *fancetti*																										*		*
Unidentified juveniles			*	*			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*				*
Total taxa identified	1	2	3	2	0	0	5	1	3	2	3	3	1	4	2	3	4	3	4	1	6	0	3	3	0	3	0	8

3.5. Black bream recruitment

Catch and CPUE of YOY

A total of six black bream were sampled during the targeted sampling event in April 2019, whereas none were caught in February 2019. All six fish were collected by fyke net (nil from the small seine net). An additional 56 black bream were caught by large seine net during the TLM Fish Condition Monitoring survey in March 2019. None of the black bream sampled in 2019 were YOY (i.e. age 0+ years) (Table 3-3; Figure 3-10), confirmed by age determination using otoliths. The mean CPUE of YOY black bream in this year was among the lowest comparing with the data over the last eleven years (2009–2019), based on catch data from four regular sampling sites in the Murray Estuary (Table 3-4). Despite detecting no YOY black bream, a range of other fish species were caught in the fyke nets during 2019 (Appendix C).

Table 3-3. Relative abundance (CPUE) of young-of-year black bream at different by single-wing fyke nets and small seine net in January 2018, February 2019 and April 2018 and 2019 (SE = standard error). Fyke CPUE = number of fish.net night^{-1} and seine net CPUE = fish.net^{-1}. HI = Hindmarsh Island and SRP = Sir Richard Peninsula.

	Jan-18				Apr-18				Feb-19				Apr-19			
CPUE	Fyke		Small Seine		Fyke		Small Seine		Fyke		Small Seine		Fyke		Small Seine	
Sites	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Goolwa Barrage saltwater side HI	0.0	0.0	0.0	0.0	2.3	2.3	-	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Goolwa Barrage saltwater side SRP	0.0	0.0	-	-	1.8	1.1	-	-	0.0	0.0	-	-	0.0	0.0	-	-
Beacon 19	0.0	0.0	-	-	-	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Midway bw Goolwa Barrage and Mouth	0.0	0.0	0.0	0.0	-	-	-	-	-	-	-	-	0.0	0.0	-	-
Mundoo Barrage	0.0	0.0	-	-	4.3	1.3	-	-	0.0	0.0	-	-	0.0	0.0	-	-
Boundary Creek	0.0	0.0	-	-	0.0	0.0	-	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Boundary Creek Mouth	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Boundary Creek Structure	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Godfrey's landing	0.0	0.0	0.0	0.0	-	-	0.0	0.0	0.0	0.0	-	-	0.0	0.0	0.0	0.0
Ewe Island	0.0	0.0	0.0	0.0	1.3	0.8	-	-	0.0	0.0	-	-	-	-	-	-
Opposite Tauwitcherie barrage	0.0	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pelican Point	0.0	0.0	0.0	0.0	-	-	-	-	-	-	-	-	-	-	-	-
Cattle Point	0.0	0.0	-	-	1.3	1.3	-	-	0.0	0.0	-	-	0.0	0.0	-	-
Mark Point	0.0	0.0	0.0	0.0	0.5	0.5	-	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Long Point	-	-	-	-	4.0	1.4	-	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Long Point Sand Dune	-	-	-	-	2.0	1.7	-	-	0.0	0.0	-	-	0.0	0.0	-	-
Noonameena	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mt Anderson	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 3-4. Inter-annual comparison of relative abundance (CPUE, fish.net night^{-1}) of young-of-year black bream sampled at regular sampling sites in the Murray Estuary between February and June from 2009 to 2019. HI = Hindmarsh Island and SRP = Sir Richard Peninsula.

Regular sites	Goolwa Barrage HI		Goolwa Barrage SRP		Mundoo Barrage		Boundary Creek		Annual	
CPUE	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**
2009	3.5	1.3	4.3	1.3	0.3	0.3	0.1	0.1	2.1	1.1
2010	0.4	0.2	1.6	0.5	-	-	0.0	0.0	0.7	0.4
2011	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2012	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.0
2013	0.8	0.3	1.3	0.5	0.1	0.1	0.0	0.0	0.6	0.3
2014	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2015	0.0	0.0	0.0	0.0	-	-	0.0	0.0	0.0	0.0
2016	0.4	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
2017	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2018	2.3	2.3	1.8	1.1	4.3	1.3	0.0	0.0	2.1	0.9
2019	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Black bream size and age compositions

Black bream collected in March and April 2019 ranged from 128−390 mm TL, with ~38% between 160−179 mm TL (Figure 3-9). In contrast, fish collected during the same period in 2018 were much smaller, ranging from 32−63 mm TL with 80% measured between 40−59 mm TL. The age structure of black bream in 2019 indicated a dominant cohort of 1+ year old fish, comprising 79% of the fish collected; whereas the fish collected in 2018 were all YOY (Figure 3-10).

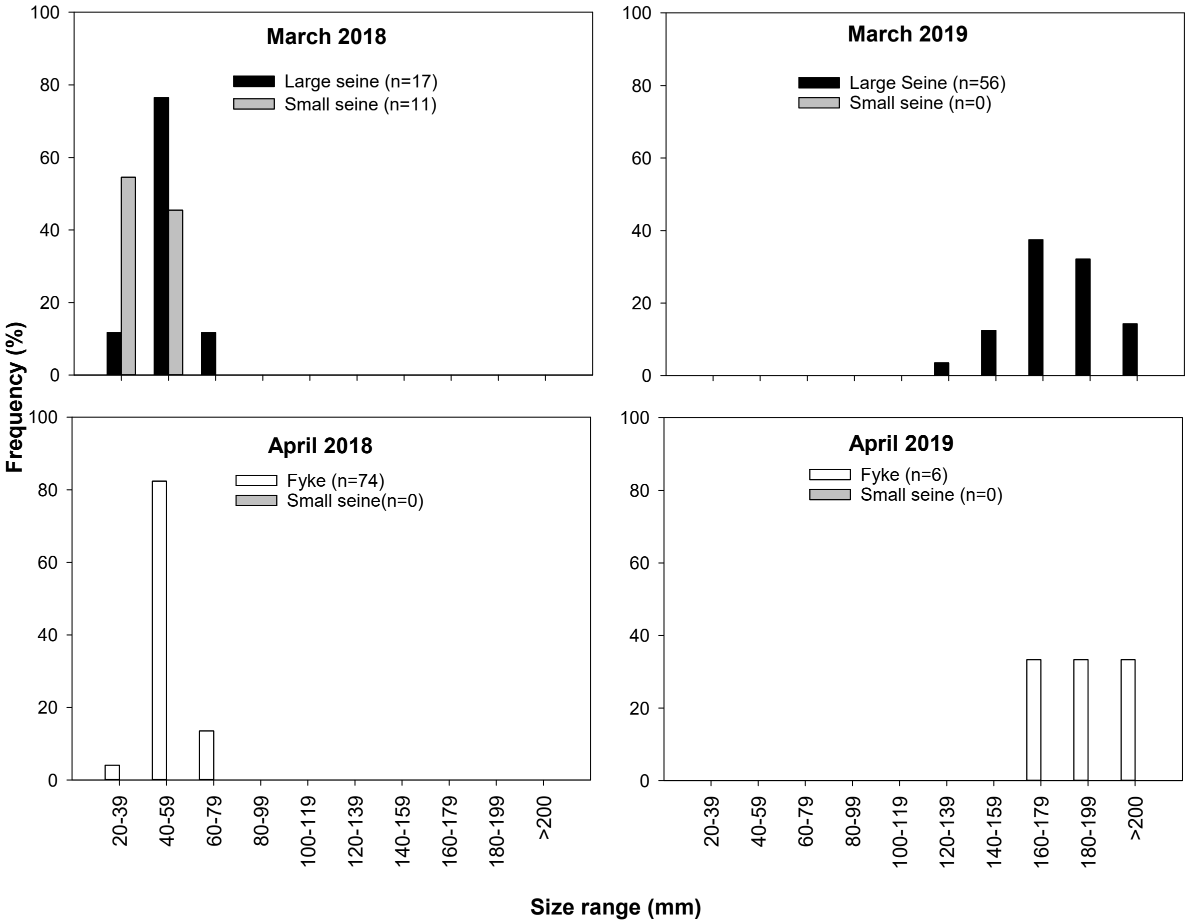

Figure 3-9. Length frequency distributions of black bream collected by different gear types in the Murray Estuary and North Lagoon of the Coorong in March and April 2018 and 2019.

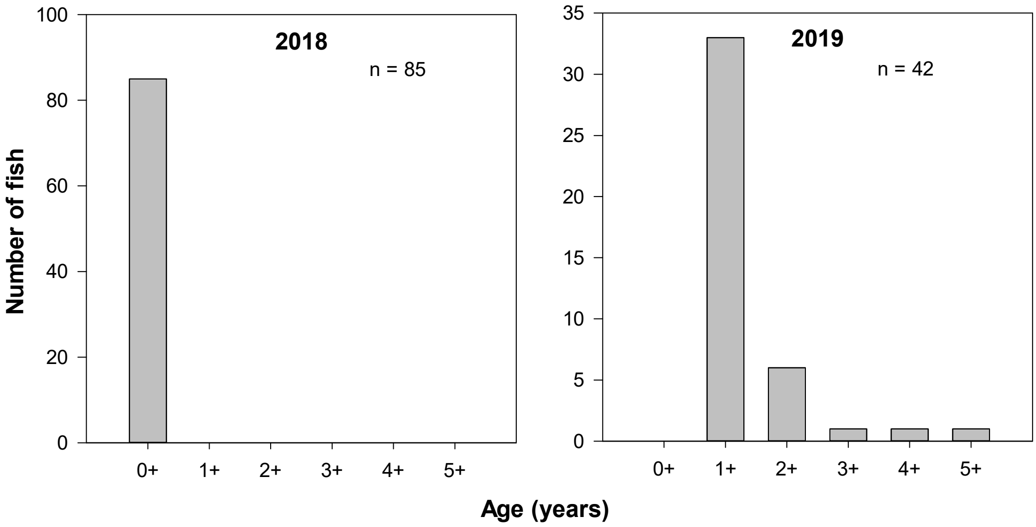

Figure 3-10. Age structure of black bream using samples from different gear types (fyke net, as well as large and small seine nets) in the Murray Estuary and North Lagoon of the Coorong in March and April 2018 and 2019.

4. DISCUSSION

Barrage releases and salt wedge dynamics

Freshwater flow is critical in maintaining estuarine habitats to support fish recruitment, including providing salt wedge conditions with high salinity stratification (halocline) in estuaries (Jenkins *et al.* 2010). During 2018-19, a climatically and hydrologically dry year, barrage releases were maintained using Commonwealth environmental water (377 GL), aiming to maintain end-of-system connectivity and estuarine habitats in the MDB. Nevertheless, the volume of releases was less than half of that during 2017-18 (850 GL), and was well below the minimum target of the environmental water requirement for the Coorong (650 GL) (DEWNR 2015).

Aligning with the protracted spawning season of black bream in the Coorong (Cheshire *et al.* 2013; Ye *et al.* 2019), salt wedge dynamics were monitored between mid-October 2018 and mid-February 2019. During this period, mean barrage discharge rates were 360 (± 22), 375 (± 16), and 380 (± 16) ML.day^{-1} for Goolwa Barrage, Tauwitcherie Barrage and Ewe Island and Tauwitcherie combined, respectively; the total barrage discharge ranged 3–1,478 ML.day^{-1}, which was an order of magnitude lower than the discharge (140–12,597 ML.day^{-1}) during the same period in 2017-18 (Figure 4-1).

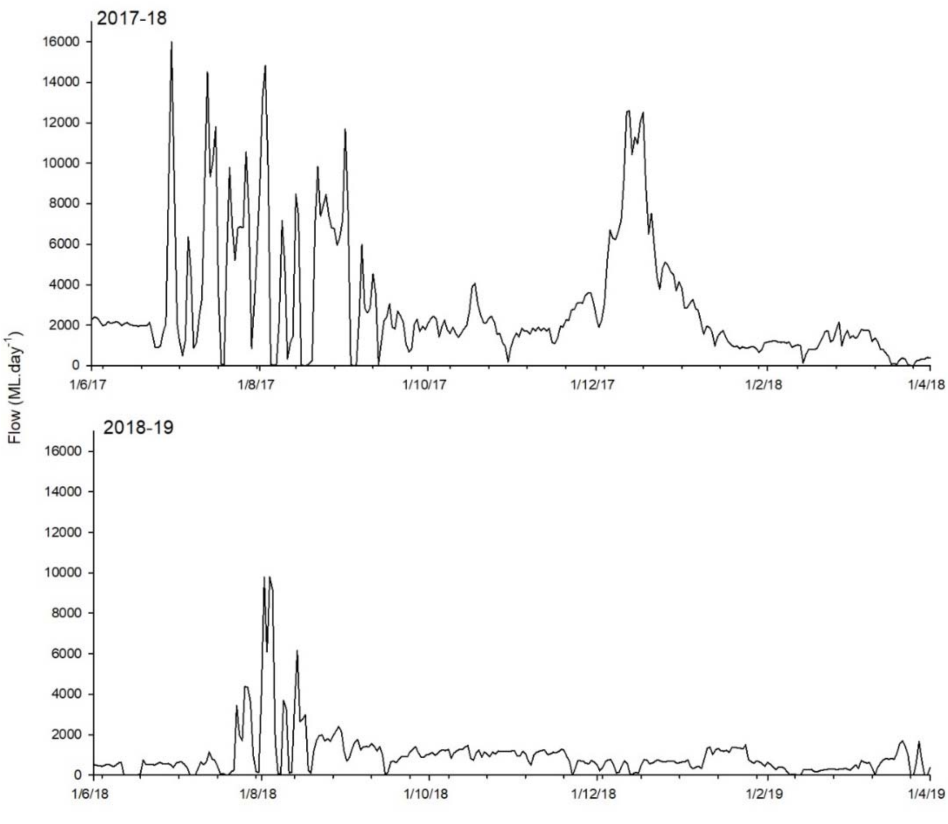

Figure 4-1. Daily combined (all barrages) flow discharge (ML.day^{-1}) for the study period in 2017-18 and 2018-19. Data source: DEW.

During 2018-19, the overall area in the Coorong with suitable salinities (15−30 PSU) and stratifications (≥10 PSU) to support black bream spawning and larval development (William *et al.* 2013) was much smaller than in 2017-18, and mostly confined below Goolwa Barrage (Appendix D). Haloclines only occurred occasionally along Tauwitcherie and Coorong transects despite the presence of brackish conditions (15−30 PSU) at different times. These conditions resulted in a much smaller larval nursery habitat in 2018-19 compared to 2017-18 (Appendix E), despite that water temperature and DO generally met the criteria during the sampling period.

Using combined data from two relatively low flow years (2017-18 and 2018-19), the relationship between barrage discharge and the extent of suitable larval nursery areas for black bream in the Coorong was explored. The dome shape pattern for the Tauwitchere, Coorong and all transects combined suggests that larval nursery area could be enhanced with barrage releases of 4,500 ML.day $^{-1}$ (from the Tauwitchere and Ewe Island Barrages), 3,000 ML.day $^{-1}$ (from the Tauwitchere Barrage) and 6,000 ML.day $^{-1}$ (from all barrages combined), respectively. However, the results must be treated with caution given the relatively small sample size over two years of monitoring (seven sampling trips each year), and that a multiple but limited set of parameters (i.e. salinity range, salinity gradient, water temperature and DO) were included in assessing habitat suitability. The Coorong is a highly dynamic system where salinity profiles are not only strongly influenced by barrage flows but also other factors (e.g. tidal and wind conditions). The combination of these factors may have confounded the flow-habitat relationships, which may explain the complex pattern for Goolwa transect. Additional potential factors could be considered in future analyses, and further monitoring should continue to collect data under a range scenarios of barrage releases and environmental conditions so that quantitative relationships could be developed/improved to guide flow management.

Food availability for black bream larvae

Overall, the productivity benefits delivered to the Coorong in 2018-19 were likely to have been lower than during 2017-18. Between June and August 2017, Lake Alexandrina levels went up to approximately 0.8 m AHD and remained there for three months throughout spring (Figure 4-2). The inundation of the upper banks of lakes (here Lake Alexandrina and the adjoined Lake Albert) is likely to have resulted in nutrients from the sediments entering the water column, the breakdown of organic material and hatching of zooplankton from the egg bank (Boulton *et al.* 1992; Ning *et al.* 2010). These nutrient increases are likely to have fueled high primary production throughout spring, which in turn would have provided food for the zooplankton community. In early-December 2017, water levels increased further to approximately 0.9 m AHD, before they were drawn down. Nutrients, phytoplankton and zooplankton would have become concentrated with the drawdown and a portion of this concentrated productivity transferred to the Coorong as the freshwater pulse was delivered in mid-December. In comparison, with reduced flow in 2018-19, lake levels were not surcharged to the same extent as previous year, and also the levels peaked earlier in August/September. Unlike the barrage flow pulse in December 2017, discharge rate was substantially lower and relatively steady during 2018-19 (Figure 4-1). Therefore the productivity benefits delivered to the Coorong in 2018-19 were likely to be smaller than in 2017-18. The transfer of nutrients, phytoplankton and zooplankton from freshwater environments is an important driver for the productivity within the lower trophic levels of the food web within estuaries (Bice *et al.* 2015; Giatas *et al.* 2019). In 2018-19, the timing of lake level changes and low volumes of freshwater discharge may have been a significant contributor to the lower abundances of pelagic copepods throughout the study period.

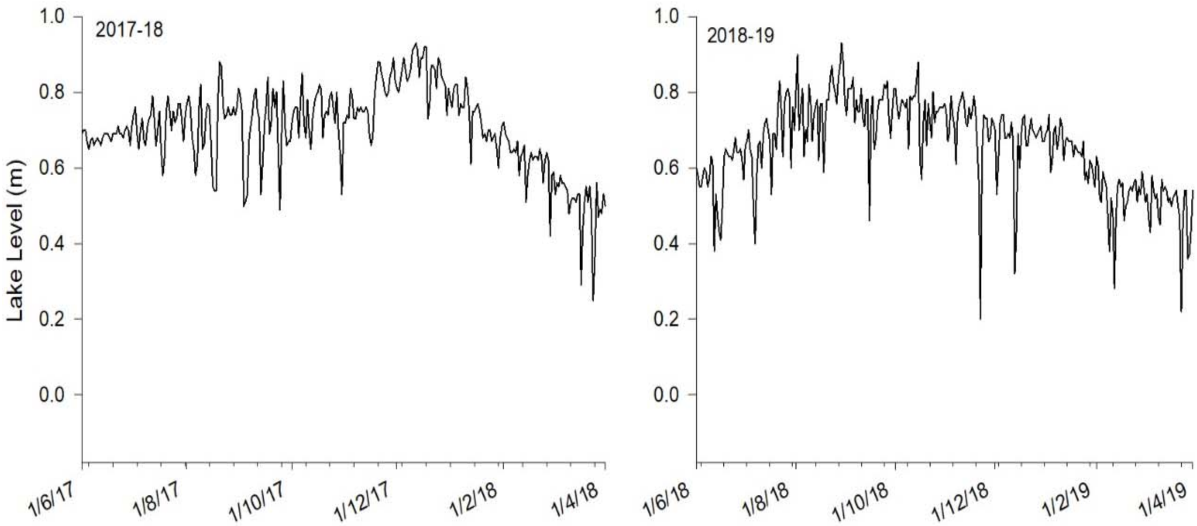

Figure 4-2. Daily average water level in Lake Alexandrina (mAHD) for the study period in 2017-18 and 2018-19 Data source: DEW.

Calanoid copepods were present sparsely in the Coorong during the 2018-19 sampling period with mean abundance of 300 ind.m^{-3} (± 165). The abundance was very low in contrast to those (e.g. ~100,000 ind.m^{-3}) from other studies in Victorian rivers (Newton 1996; Willis *et al*. 1999, Williams *et al.*, 2013). Low larval food availability was likely a contributing factor to the lack of recruitment of black bream in 2018-19. Whilst black bream is considered a generalist feeder, the diet shift only occurs after settlement (at fish size >40 mm TL) (Willis *et al.* 1999), and larval fish prefer specific prey such as the two calanoid copepod species: *Gladioferens* species and *Sulcanus conflictus* (Norriss *et al.* 2002; Wiliams 2013). These species were found in the Coorong estuary on a number of occasions in previous years (e.g. Shiel and Aldridge 2011;

Shiel and Tan 2013; Geddes *et al.* 2016). In this study, however, no *S. conflictus* was detected and adult *Gladioferens* species were absent for most of the sampling period during 2018-19 (except for Trip 3 in late November 2018, with low abundances below Goolwa Barrage). One reason for this may be related to the fact that *Gladioferens* are pioneer herbivores, reaching peak abundance following disturbance (e.g. Rippingale and Hodgkin 1974; 1975). In estuaries, this is primarily driven by freshwater discharge, which was low to the Coorong (maximum of 1,487 ML.day^{-1}) during the 2018-19 study and resulted in the development of persistent, close to marine conditions. Additionally, *S. conflictus* predate upon *Gladioferens* nauplii and therefore their population development possibly relies upon that of *Gladioferens* (e.g. Ough and Bayly 1989). Consequently, the competition exerted by the established copepod community may have limited opportunity for the successional development of populations of *Gladioferens* and *S. conflictus*. In comparison, the salinity profiles from 2017-18 (Appendix D) clearly demonstrate a much greater freshening of the system in December as the freshwater pulse (Figure 4-1) was delivered to the Coorong (Ye *et al.* 2019). This disturbance, combined with the greater productivity benefits likely to have been delivered with the barrage flow releases, may have resulted in greater availability of these preferred food resources for black bream. The contrasting results in black bream recruitment between 2017-18 and 2018-19 may have been influenced by differences in the availability of food resources.

Freshwater flow are critical for key life history processes of *Gladioferens*, for example, their egg production requires low salinities (≤1 PSU) (Hall and Burns 2002). In the Brisbane River, *Gladioferens* was consistently present at the freshwater end of the gradient zone and only extended down into higher salinity water (>16 PSU) during colder months (water temperature ~15–18°C) (Bayly 1965). In the Coorong, low freshwater inflow and persistent exposure to higher salinities (>30 PSU) during spring–summer (temperature generally >15°C) 2018-19 may have negatively affected the survival and abundance of *Gladioferens*, and thus limited their availability as a food resource. In this study, the only occasion when *Gladioferens* were present (Trip 3) coincided with the largest area of salt wedge conditions along the Goolwa Barrage transect. *Gladioferens* are one of the genera of zooplankton commonly found to benefit from productivity increases associated with salt wedges (Jenkins *et al.* 2010; Williams *et al.*, 2013). Despite of their rare occurrence in this study, harpacticoid copepods were found to be most abundant below Goolwa Barrage area with the presence of salt wedge conditions (Furst *et al.* 2019). Hapacticoid copepods are an important food source for sandy sprat which is an important prey species to support the food web in the Murray Estuary (Bice *et al.* 2015). This finding suggests some productivity benefits even with a low barrage discharge during 2018-19.

Black bream recruitment

The relative abundance of YOY black bream in 2017-18 was the highest since monitoring commenced in 2008-09, suggesting that the level of recruitment in the Coorong was highest in that year. This strong cohort continued to dominate the research samples of black bream as 1-year-old fish during 2018-19, which reinforced the successful outcome of environmental water management during 2017-18. Nevertheless, no YOY black bream were collected during 2018-19. Much reduced area of suitable nursery habitat due to lower barrage releases and low availability of preferred food resources, as explained in previous sections, were likely to have been contributing factors to the lack of recruitment in this year.

The population of black bream in the Coorong is currently depleted, with a substantially reduced abundance and spawning biomass (Earl *et al.* 2016; Ye *et al.* 2018; Earl 2019). Temporary management arrangements were introduced in 2018 to protect the remnant spawning biomass and support recovery of the stock, but have not yet resulted in measurable improvements (Earl 2019). Any benefit from these arrangements within the population would likely take at least several years to develop. This is because black bream is a long-lived species and the Coorong population has historically been characterised by irregular recruitment events, the magnitude of which has depended on levels of egg production and appropriate environmental conditions relating to freshwater inflows to support the survival and growth of eggs and larvae (Earl *et al.* 2016).

Promoting more frequent recruitment will help increase abundance over time and improve population resilience. In this regard, environmental water and barrage management is critical, as it could be tailored to provide suitable flow and habitat conditions and increased food availability to support more frequent black bream recruitment. Fishery management should continue to protect the remnant spawning biomass in the Coorong. In addition, it’s important to maximise the survival of new recruits (e.g. by minimising fishing mortality of undersized black bream), so that they can continue to grow and contribute to adult population and spawning biomass in future years. The survival and growth of new recruits could also be enhanced by barrage flows to improve estuarine habitat and food resources in the Coorong.

Future research and monitoring needs

Monitoring salt wedge dynamics in the Coorong over the last two years has provided initial quantitative data, to enable an investigation into the hypothesised link between barrage discharge and larval nursery habitat availability for black bream in the Coorong. In 2018-19, additional zooplankton assessment was undertaken to evaluate the productivity effects in the Coorong by environmental flow releases through barrages, with a focus on food availability for black bream larvae. Due to the dynamic nature of the Coorong estuary, further monitoring of these parameters and black bream recruitment will provide a larger dataset and ecological insight under a range of flow scenarios and environmental conditions and enable development of quantitative relationships to inform adaptive management. Such information will guide the barrage operation for optimal releases to maximise quality estuarine habitat that facilitates the recruitment of black bream and other fish species.

Further studies are also required to better understand flow and other environmental effects on the key life history processes that underpin the recruitment success of black bream in the Coorong. A key knowledge gap is the spawning of black bream in the Coorong, i.e. does spawning occur annually, irrespective of environmental conditions, and is recruitment more driven by the survival of early life stages with the presence of favourable nursery habitats (salt wedge and food resources)? Investigation of spawning could be conducted by sampling adult fish during peak spawning season to assess reproductive conditions. Egg and larval fish sampling could also be undertaken for black bream, in conjunction with the monitoring of salt wedge dynamics and zooplankton assemblages to explore the mechanism driving recruitment of this species. The criteria of habitat suitability (i.e. salinity, stratification level, temperature and DO) used in this study for black bream reproduction and larval nursery were based on research findings from other geographical regions; therefore, Coorong specific knowledge is required to improve the evaluation of habitat quality and availability for this region.

5. CONCLUSION AND MANAGEMENT IMPLICATIONS

During 2018-19, a climatically and hydrologically dry year, barrage releases were sustained using Commonwealth environmental water (377 GL) to maintain end-of-system connectivity and estuarine habitat in the Coorong. This project conducted monitoring to characterise salt wedge conditions below the Murray barrages (objective 1) and to assess food (zooplankton) availability for black bream larvae (objective 2). Suitable salt wedge habitat was present below Goolwa Barrage with low discharge (mean ~400 ML.day^{-1}) during spring–summer 2018-19; whereas almost no haloclines were present along the Tauwitcherie and Coorong transect at similarly low discharge rates. Overall, the suitable larval nursery area was much smaller during 2018-19 than 2017-18, when barrage discharge was substantially higher. Furthermore, the general productivity benefits delivered to the Coorong were likely to have been lower in 2018-19 than previous water year (2017-18), and important food resources for black bream larvae, calanoid copepods (i.e. *Gladioferens* species and *Sulcanus conflictus*) were rarely present during this water year. Sampling in the Coorong during summer/autumn 2018-19 did not detect any YOY black bream (objective 3), and it was likely that the aforementioned factors contributed to the lack of recruitment success in the Coorong in this season.

Nevertheless, our sampling during 2018-19 demonstrated the persistence of the 2017-18 strong cohort of black bream in the population. This is encouraging and reassures that barrage flow management, supported by water for the environment, can generate favourable habitat conditions (likely including food resources) to facilitate successful recruitment of black bream, which over time should support the population recovery in the Coorong. In dry years such as 2017-18 and 2018-19, without environmental water, barrage flows would not have been maintained throughout spring−summer, which is the primary reproductive season of black bream and many other estuarine species. This project evaluated the outcomes of the Commonwealth environmental water delivery through barrage releases during 2018-19, and provides management recommendations below (objective 4).

Recruitment of black bream is highly variable in the substantially modified estuary of the Coorong. Our recent studies suggest that strong cohorts are associated with low to moderate river flows (Ye *et al.* 2018; Ye *et al.* 2019). Under certain climatic and hydrological conditions, environmental water plays a critical role in maintaining barrage releases, which can be managed to provide optimal flow regimes to increase favourable salt wedge habitat and potentially enhance productivity to promote black bream recruitment. For example, the successful recruits (YOY) in 2017-18 were from the spawning period from late December to early February, which corresponded with barrage releases of 600−5,000 ML day^{-1} and temperature of 18−25°C, and commenced about 1−2 weeks after a ~10,000−12,000 ML day^{-1}

flow pulse. Similar flow regimes could be applied, with outcomes monitored to improve our learnings to inform management. In addition, the water level regime in the Lower Lakes should be considered to increase productivity benefits for the inter-connected Coorong ecosystem. Furthermore, given the depleted population of black bream in the Coorong, fishery management should continue to seek to protect the remnant spawning biomass and maximise the survival of new recruits to rebuild population abundance and resilience in this region.

The monitoring during 2017-18 and 2018-19 characterised larval nursery habitat for black bream in the Coorong, and collected quantitative data to investigate potential relationships between barrage flows and suitable habitat area. Future research and monitoring will be required, particularly to obtain information on environmental and habitat requirements (including food resources), and how they influence key life history processes (including spawning) and recruitment dynamics for the population of black bream in the Coorong. Such information will support adaptive management of environmental water and inform optimal barrage flow regimes to improve estuarine habitat and enhance the recruitment of black bream and many other estuarine fish in the Coorong.

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APPENDIX

Appendix A. Sampling sites of salt wedge monitoring in November and December 2017 along four transects below Goolwa, Mundoo and Tauwitcherie barrages in the Coorong.

Transect	Site Code	Distance from barrage release point (~km)	Latitude	Longitute
Goolwa	G1	0.2	-35.5264	138.8103
Goolwa	G2	1.2	-35.5279	138.8210
Goolwa	G3	2.2	-35.5311	138.8313
Goolwa	G4	3.2	-35.5346	138.8414
Goolwa	G5	4.2	-35.5398	138.8504
Goolwa	G6	5.2	-35.5466	138.8583
Goolwa	G7	6.2	-35.5477	138.8695
Goolwa	G8	7.2	-35.5516	138.8782
Tauwitcherie	T1	0.4	-35.5959	139.0185
Tauwitcherie	T2	0.7	-35.5933	139.0140
Tauwitcherie	T3	1.2	-35.5910	139.0093
Tauwitcherie	T4	2.2	-35.5872	138.9992
Tauwitcherie	T5	3.2	-35.5817	138.9901
Tauwitcherie	T6	4.2	-35.5765	138.9810
Tauwitcherie	T7	5.2	-35.5720	138.9713
Tauwitcherie	T8	6.2	-35.5683	138.9612
Tauwitcherie	T9	7.3	-35.5632	138.9522
Tauwitcherie	T10	8.2	-35.5623	138.9415
Tauwitcherie	T11	9.2	-35.5670	138.9322
Tauwitcherie	T12	10.2	-35.5702	138.9222
Tauwitcherie	T13	11.2	-35.5677	138.9117
Tauwitcherie	T14	12.2	-35.5612	138.9042
Tauwitcherie	T15	13.2	-35.5598	138.8935
Coorong	C1	0.5	-35.5981	139.0230
Coorong	C2	1.0	-35.6007	139.0275
Coorong	C3	2.0	-35.6056	139.0369
Coorong	C4	3.0	-35.6103	139.0463
Coorong	C5	4.0	-35.6156	139.0554
Coorong	C6	5.0	-35.6218	139.0635
Coorong	C7	6.0	-35.6290	139.0704
Coorong	C8	7.0	-35.6355	139.0782
Mundoo	M1a	1.1	-35.5386	138.8941
Mundoo	M2	1.4	-35.5376	138.8913
Mundoo	M3	2.4	-35.5429	138.8823
Mundoo	M4	3.5	-35.5460	138.8927
Mundoo	M5	4.8	-35.5524	138.9001

Appendix B. Summary of the species identified and species abundance (E+3) (ind.m^3) at each site from Trip 1 to Trip 7 and their preferred environment where F = fresh, M = marine and B = brackish. Grey shading indicates that the species was only found in the bulk sample, not within the quantitative counts. All abundances have been rounded to two significant figures.

		Trip 1						Trip 2					
	Habitat	G3	G6	T1	T6	T12	C6	G3	G6	T1	T6	T12	C6
HARPACTICOIDS													
Mesochra parva	B	0.3/0.22	0.07/0.37		0.07/0	0.37/0.15	0.22	0.3/1.3	0/2.6			0/1.3	
Euterpina acutifrons	M/B									0.15	0.3/0.44	0.74/2	
cf. Quinquelaophonte sp.	M												
cf. Robertsonia sp	M											0.66	
Species a	-											0.66	
Species b	-												
Species c	-												
CYCLAPOIDS													
Oithona cf. plumifera	M		0.15					0.67	0/4.1		0.07/0.15	0.81	
Oithona cf. atlantica	M												
Oithona cf. simplex	M												
Oithona cf. rigida	M												
cf. Cyclopetta orientalis	M/B												
Unidentified	-												
CALANOIDS													
Gladioferens pectinatus	M/B												
Acartia cf. *fancetti*	M/B												
Unidentified juveniles	-	0.07	0.15			0.15		0/4.4	0.59	0.22	0.22/0	0.74	
Copepod nauplii	-												
Nauplii	-	2.7/12	5.7/55	0.15	0.15/0.89	7.9/7.3	18/0.96	12/149	24/81	1.1/34	36/41	23/239	6/5.9
Total abundance		3/12	5.8/55	0/0.15	0.22/0.89	8.3/7.6	18/1.2	13/155	24/89	1.1/34	37/41	24/245	6/5.9
Total taxa identified		3	3	1	1	3	2	3	5	2	3	6	1

Appendix B (continued). Summary of the species identified and species abundance (E+3) (ind.m^3) at each site from Trip 1 to Trip 7 and their preferred environment where F = fresh, M = marine and B = brackish. Grey shading indicates that the species was only found in the bulk sample, not within the quantitative counts. All abundances have been rounded to two significant figures.

		Trip 3						Trip 4					
	Habitat	**G3**	**G6**	**T1**	**T6**	**T12**	**C6**	**G3**	**G6**	**T1**	**T6**	**T12**	**C6**
HARPACTICOIDS													
Mesochra parva	B			0.070	0.15/0.30	0.15/1.5				0.15/0.22	0.070		
Euterpina acutifrons	M/B							0/3.4	0.22/0.15				
cf. Quinquelaophonte sp.	M												
cf. Robertsonia sp	M			0.07/0.07									
Species a	-												
Species b	-												
Species c	-		0.07/0.3										
CYCLAPOIDS													
Oithona cf. plumifera	M					0.67	0.070		0.96				
Oithona cf. atlantica	M												
Oithona cf. simplex	M												
Oithona cf. rigida	M												
cf. Cyclopetta orientalis	M/B	0.15/0	0.070										
Unidentified	-												
CALANOIDS													
Gladioferens pectinatus	M/B	0.070											
Acartia cf. *fancetti*	M/B												
Unidentified juveniles	-		0.74	0.07/0.07	0.07/0.07	0.44/1.0				0.15/0	0.070/0		
Copepod nauplii	-												
Nauplii	-	8.9/22	12/71	1.2/9.7	0.22/1.9	0.81/26	0.15/2.2	0.37/3.3	6.8/65	1.4/0.96	0.15/0.3	0.15	1.3/2.6
Total abundance		9.1/22	12/72	1.3/9.9	0.44/2.3	1.4/29	0.15/2.2	0.37/6.7	7.0/66	1.7/1.2	0.22/0.37	0/0.15	1.3/2.6
Total taxa identified		2	4	5	3	4	1	1	2	3	2	1	1

Appendix B (continued). Summary of the species identified and species abundance (E+3) (ind.m^3) at each site from Trip 1 to Trip 7 and Trip 6 and their preferred environment where F = fresh, M = marine and B = brackish. Grey shading indicates that the species was only found in the bulk sample, not within the quantitative counts. All abundances have been rounded to two significant figures.

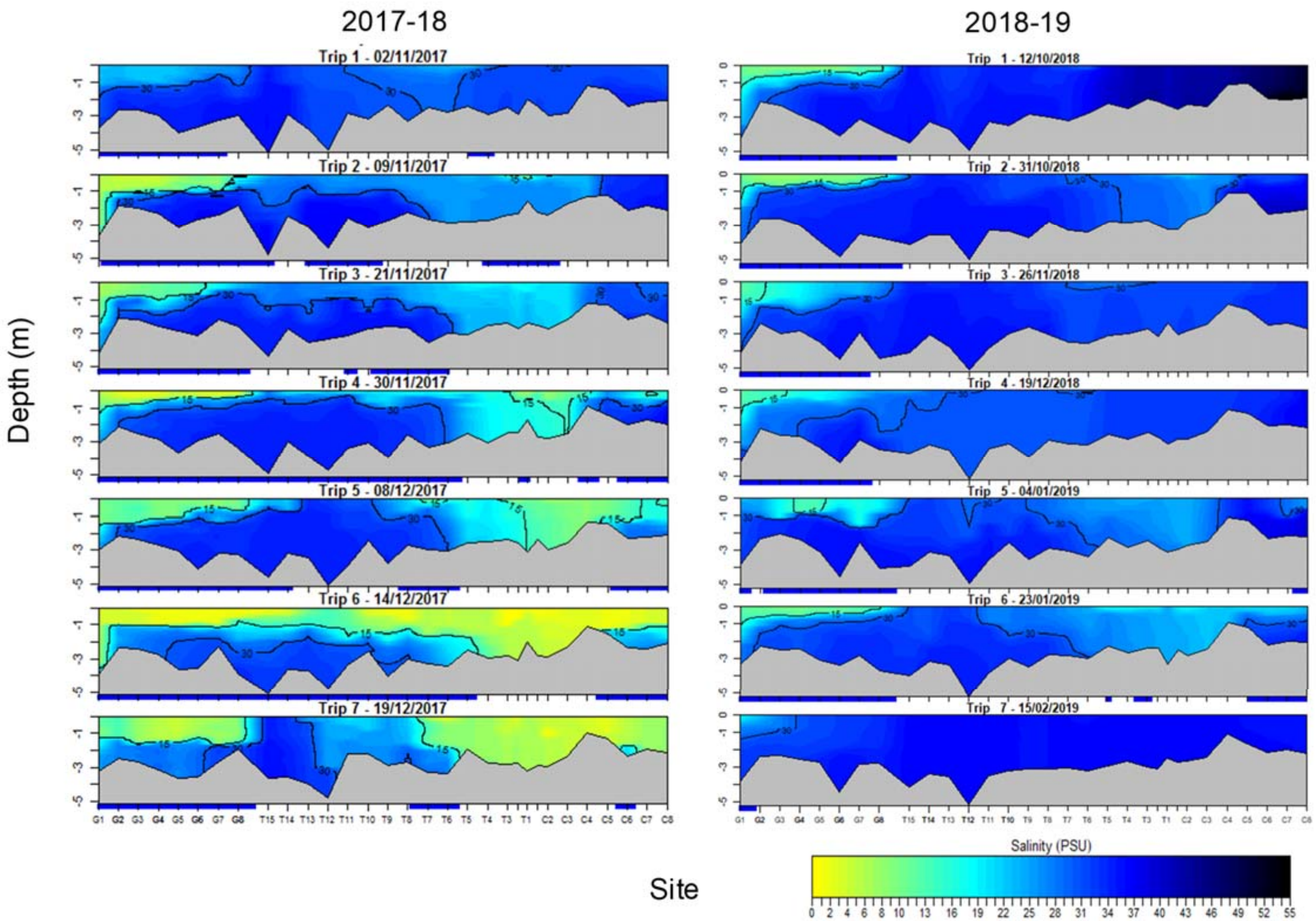
		Trip 5						Trip 6					
	Habitat	**G3**	**G6**	**T1**	**T6**	**T12**	**C6**	**G3**	**G6**	**T1**	**T6**	**T12**	**C6**
HARPACTICOIDS													
Mesochra parva	B												
Euterpina acutifrons	M/B		0.44/5.6	0.070/0	0.15	0.22/2.5		0.070	0.30	0.15/0.07	0.15/0.07	0.52/0.15	
cf. Quinquelaophonte sp.	M												
cf. Robertsonia sp	M												
Species a	-												
Species b	-												
Species c	-												
CYCLAPOIDS													
Oithona cf. plumifera	M								0.30	0.07	0.07/6.6		
Oithona cf. atlantica	M												
Oithona cf. simplex	M				0.07/0.15							1.6/11	
Oithona cf. rigida	M		0/1.0			0.59/2.1							
cf. Cyclopetta orientalis	M/B												
Unidentified	-												
CALANOIDS													
Gladioferens pectinatus	M/B												
Acartia cf. *fancetti*	M/B												
Unidentified juveniles	-	0.37	0.81/7.3	0.070/0.15	0.15/1.0	1.3/8.4	0.070/0	0.81	0.070/4.4	0.59/0.59	0.15/8.3	1.6/20	0.3
Copepod nauplii	-												
Nauplii	-	41/101	24/87	6.2/1.3	49/82	13/73	3.04/21	18/18	37/120	26/20	22/53	41/63	5.1/6.7
Total abundance		41/102	25/101	6.4/1.5	50/83	15/86	3.1/21	18/19	37/125	27/20.51	23/68	44/95	5.1/7.0
Total taxa identified		1	3	2	3	3	1	2	3	4	3	4	1

Appendix B (continued). Summary of the species identified and species abundance (E+3) (ind.m^3) at each site from Trip 1 to Trip 7 and their preferred environment where F = fresh, M = marine and B = brackish. Grey shading indicates that the species was only found in the bulk sample, not within the quantitative counts.

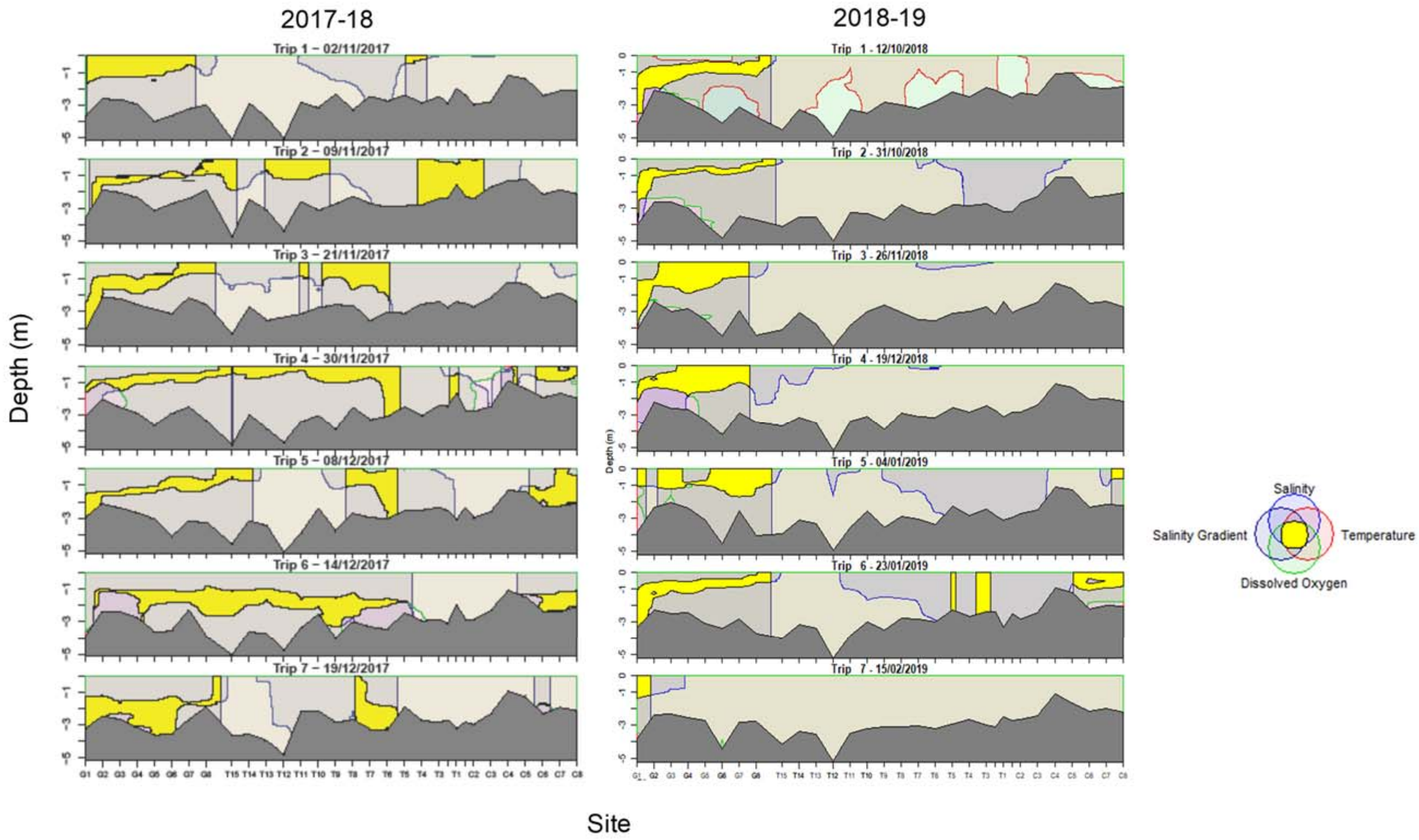
		7					
	Habitat	G3	G6	T1	T6	T12	C6
HARPACTICOIDS							
Mesochra parva	B					0.07/0	
Euterpina acutifrons	M/B						
cf. Quinquelaophonte sp.	M			0.15			
cf. Robertsonia sp	M		0.22/0.15				
Species a	-						
Species b	-						
Species c	-						
CYCLAPOIDS							
Oithona cf. plumifera	M						
Oithona cf. atlantica	M						
Oithona cf. simplex	M						
Oithona cf. rigida	M						
cf. Cyclopetta orientalis	M/B						
Unidentified	-					0.07/0	
CALANOIDS							
Gladioferens pectinatus	M/B						
Acartia cf. *fancetti*	M/B					0.070/0	
Unidentified juveniles	-		0.30/1.9	0.22/0.30			
Copepod nauplii	-						
Nauplii	-	6.3/7.0	55/94	2.1/4.3	20/39	1.8/2.7	0.89/17
Total abundance		6.3/7.0	55/96	2.3/4.8	20/39	2.0/2.7	0.89/17
Total taxa identified		1	3	3	1	3	1

Appendix C. Fish species and numbers collected using fyke nets during 2017-18 and 2018-19 in the Murray Estuary and Northern Lagoon as part of the monitoring of recruitment of key fish species of the Coorong.

		Estuary						Northern Lagoon						
Common name	**Scientific name**	**Jan-18**	**Apr-18**	**Total-18**	**Feb-19**	**Apr-19**	**Total-19**	**Jan-18**	**Apr-18**	**Total-18**	**Feb-19**	**Apr-19**	**Total-19**	**Grand Total**
Barred toadfish	*Contusus richei*	2		**2**										**2**
Black bream	*Acanthopagrus butcheri*		43	**43**		5	**5**		31	**31**		1	**1**	**80**
Blue sprat	*Spratelloides robustus*				1	10	**11**					1	**1**	**12**
Blue weed whiting	*Haletta semifasciata*					3	**3**							**3**
Bluespot goby	*Pseudogobius olorum*	55	8	**63**	7	25	**32**	37	455	**492**	84	2	**86**	**673**
Bony herring	*Nematolosa erebi*	35	15	**50**	10	27	**37**	28		**28**	1	7	**8**	**123**
Bridled goby	*Arenigobius bifrenatus*	36	16	**52**	92	72	**164**	61	51	**112**	811	54	**865**	**1,193**
Bridled leatherjacket	*Acanthalateres spilamelanurus*	1		**1**	9	3	**12**					1	**1**	**14**
Carp	*Cyprinus carpio*	2		**2**	1		**1**							**3**
Common galaxias	*Galaxias maculatus*	3,446	155	**3,601**	322	39	**361**	206	1	**207**	42	13	**55**	**4,224**
Congolli	*Pseudaphritis urvillii*	11,966	1,038	**13,004**	1,513	820	**2,333**	12,097	1,959	**14,056**	1,003	279	**1,282**	**30,675**
Dwarf flat-headed gudgeon	*Philypnodon macrostomus*	53	1	**54**		19	**19**							**73**
Eastern gambusia	*Gambusia holbrooki*		11	**11**		34	**34**							**45**
Estuary cobbler	*Cnidoglanis macrocephalus*	1		**1**										**1**
Flat-headed gudgeon	*Philypnodon grandiceps*	1,396	1,337	**2,733**	520	820	**1,340**	3	38	**41**		26	**26**	**4,140**
Goldspot mullet	*Liza argentea*		32	**32**		8	**8**							**40**
Greenback flounder	*Rhombosolea tapirina*					2	**2**		3	**3**		1	**1**	**6**
Longsnout flounder	*Ammotretis rostratus*											1	**1**	**1**
Luderick	*Girella tricuspidata*	2		**2**		1	**1**							**3**
Mulloway	*Argyrosomus japonicus*	10	1	**11**	1		**1**							**12**
Old wife	*Enoplosus armatus*				1		**1**							**1**
Redfin perch	*Perca fluviatilis*	21	7	**28**	7	19	**26**							**54**
Sandy sprat	*Hyperlophus vittatus*	64,811	5,996	**70,807**	73,462	26,414	**99,876**				18,931	622	**19,553**	**190,236**
Scary's Tasman goby	*Tasmanogobius lasti*	20	6	**26**	25		**25**		3	**3**				**54**
Sixspine leatherjacket	*Meuschenia freycineti*					1	**1**							**1**
Smallmouth hardyhead	*Atherinosoma microstoma*	84,364	4,549	**88,913**	36,285	1,610	**37,895**	8,722	13,661	**22,383**	6,654	11,763	**18,417**	**167,608**
Smooth toadfish	*Tetractenos glaber*				10	4	**14**							**14**
Soldier fish	*Gymnapistes marmoratus*	131	7	**138**	29	7	**36**				226	12	**238**	**412**
Southern crested weedfish	*Cristiceps australis*		2	**2**	3	2	**5**							**7**
Southern pygmy leatherjacket	*Brachaluteres jacksonianus*				2		**2**							**2**
Tamar goby	*Afurcagobius tamarensis*	970	1,017	**1,987**	608	366	**974**	79	207	**286**	453	115	**568**	**3,815**
Toothbrush Leatherjacket	*Acanthaluteres vitteger*				4		**4**							**4**
Verco's pipefish	*Vanacampus poecilolaemus*					1	**1**							**1**
Western Australian salmon	*Arripis truttaceus*	1		**1**					1	**1**				**2**
Yelloweye mullet	*Aldrichetta forsteri*	68	28	**96**	560	63	**623**	2	2	**4**	3	8	**11**	**734**
Grand Total		**167,391**	**14,265**	**181,656**	**113,472**	**30,375**	**143,847**	**21,235**	**16,412**	**37,647**	**28,208**	**12,906**	**41,114**	**404,268**
Number of species		21	19	25	22	25	**31**	9	12	**13**	10	16	16	**35**



Appendix D. The longitudinal and depth profile of salinities measured at multiple sites with ~1 km interval along the Goolwa (G1−G8), Tauwitcherie (T1−T15) and Coorong (C1−C8) transects in the Murray Estuary and North Lagoon of the Coorong during seven trips between 2 November and 19 December 2017 (left) and 12 October 2018 and 15 February 2019 (right). Blue highlighting on the x-axis indicates areas with salinity stratification ≥10 PSU. G1: below Goolwa Barrage; T1: Pelican Point end of the Tauwitcherie Barrage; C8: Mark Point; and Murray Mouth: between G8 and T15. Salinity contours of 15 PSU and 30 PSU are shown.



Appendix E. Integrated values for salinity, temperature and dissolved oxygen showing longitudinal sections of suitable areas (in yellow) for black bream larval nursery habitat (using environmental criteria of salinities 15–30 PSU, salinity gradient ≥10 PSU, temperature >15°C and DO >5 mg.L^{-1}) along the Goolwa (G1–G8), Tauwitcherie (T1–T15) and Coorong (C1–C8) transects in the Coorong during seven trips between 2 November and 19 December 2017 (left) and 12 October 2018 and 15 February 2019 (right). G1: below Goolwa Barrage; T1: Pelican Point end of the Tauwitcherie Barrage; C8: Mark Point; and Murray Mouth: between G8 and T15.