The effects of flow on silver perch population dynamics in the Murray River

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July 2017

Arthur Rylah Institute for Environmental Research Technical Report Series Number 282

Arthur Rylah Institute for environmental research

VICTORIA State Government | Environment, Land, Water and Planning

Acknowledgements

We acknowledge the Murray–Darling Basin Authority, in particular Heleena Bamford and Stuart Little, for providing funding and for their continued support of this research. We would also like to acknowledge numerous staff for field assistance, in particular Justin O'Mahoney, Andrew Pickworth, Scott Raymond and Jason Lieschke (ARI). andJamin Forbes and Glen Miller (DPI Fisheries).Thanks to Paul Moloney (ARI) and John Morrongiello (University of Melbourne) for early input into statistical analysis and to Kasey Stamation for valuable comments on drafts of this report. We appreciate help from Alan Williams, Goulburn-Murray Water, in sample collection at Torrumbarry Weir. This work was conducted under Fisheries NSW Scientific Research Permit F93/158(C) and P01/0059(A)-3.0, Victorian Fisheries Research Permit RP827, FFG Research Permit 10007273, DELWP Animal Ethics 14/04 and Fisheries NSW Animal Ethics 14/10. The collection of silver perch at sites in the mainstem of the lower River Murray and water samples throughout the southern connected MDB for Strontium isotope analysis was funded by the Commonwealth Environmental Water Office as a component of Long-term Intervention Monitoring in the lower Murray River selected area.

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Citation

Tonkin, Z., Stuart, I., Kitchingman, A., Jones, M., Thiem, J., Zampatti, B., Hackett, G., Koster, W. and Koehn, J. (2017). The effects of flow on silver perch population dynamics in the Murray River. Arthur Rylah Institute for Environmental Research. Technical Report Series No. 282. Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Photo credit

Adult silver perch from the Murray River at Yarrawonga. [Photo: Zeb Tonkin]

ISSN 1835-3827 (print)
ISSN 1835-3835 (pdf)

ISBN 978-1-76047-663-2 (Print) Disclaimer

Contents

Summary

Optimising the benefits of environmental water for fishes is contingent on restoring key aspects of the natural flow regime linked to processes governing population dynamics. Verifying and quantifying links between flows and key population processes provides an evidentiary basis to support decision making and assists waterway managers to adaptively manage environmental water for fish-related outcomes. Silver perch *Bidyanus bidyanus* are a nationally endangered fish endemic to the Murray–Darling Basin (MDB) that has declined as a result of river regulation. It is clear that flows have an important influence on key aspects of silver perch life-history (e.g. spawning), however there is still considerable uncertainty surrounding the specific role of flow as a driver of recruitment strength and subsequent population dynamics. This creates a management challenge when planning delivery actions such as environmental flows aimed to restore populations. The aims of this study were to:

- Assess the current geographic distribution and population structure of silver perch throughout the Murray River (Lower Murray to Lake Hume), with a specific focus on the mid-Murray reach located between Mildura and Yarrawonga;
- Investigate links between river flow and recruitment dynamics in the mid-Murray River;
- Explore existing data to identify links between river flow and silver perch movements;
- Provide a case study of these population processes in relation to a floodplain lake (Lake Boga);
- Use results to update conceptual models on the effect of flow on population dynamics of silver perch and provide management recommendations, particularly for optimising environmental flows.

Current distribution, population structure and recruitment dynamics of silver perch in the Murray River

We assessed the current distribution and population structure of silver perch throughout the Murray River using data collected in 2016. The results reiterate the importance of the mid-Murray River reach for silver perch in the southern MDB. The mid-Murray River had the greater density of fish with a more balanced size and age structure compared to the lower and upper Murray River regions. Recruitment has occurred in the mid-Murray region almost each year for the past 11 years, a period which encompassed extremes in discharge (drought and flood). However, a very small proportion of fish are greater than seven years of age. As such, we suggest annual recruitment should be the management objective to maintain and restore populations for this species.

Age-structure data was used to explore the role of extrinsic factors, particularly hydrological and hydraulic conditions, in influencing recruitment of silver perch in the mid-Murray River. Results indicated that silver perch occupying a river reach such as the mid-Murray with perennial flowing water extending over a broad spatial scale (> 300 km), will recruitment in most years, including under low within-channel flows and overbank floods. For all years for which year classes were present, the mid-Murray River exhibited minimum daily water velocities and mean daily water temperature during the period of November and December (peak spawning period) >0.45 m/s and 21.5 – 24°C, respectively. Years subject to broad-scale, flood-induced blackwater events are perhaps the only years which will not produce significant year classes. Nevertheless, large flow events appear to significantly improved survival of juvenile fish (which preceded the event), which, along with rising water temperatures during the core November–December spawning period, was a significant factor governing recruitment strength. As such, in the mid-Murray River, the strongest year classes of silver perch were associated with low to average river discharge (6100 – 8400 ML/d) and high water temperatures during November and December, and which preceded a year of extended high flows and widespread flooding.

Movement of PIT tagged fish in the Murray River

Movement patterns of silver perch (> 150 mm in length) in the Murray River were explored using data collected from passive integrated transponder (PIT) reader systems, installed at fishways along the Murray River. These data provided evidence that silver perch are using the Murray fishways, commonly undertaking extensive longitudinal migrations. Movements increased substantially during both within-bank river rises and during flooding, with the highest rates of detection and multi-site detections occurring during periods of high magnitude and extended flooding. This result, despite excluding data representing early juvenile movements, highlights the importance of large-scale connectivity for this species and the opportunity to provide flow-related movement cues to enhance movements and expand the range of the population. Further tagging of, and investigations of juvenile movement behaviour is therefore recommended.

Processes influencing population dynamics in an off-channel lake: Lake Boga case study

We also present a case study on the processes influencing population dynamics of silver perch in an off-channel lake, by examining the age structure and otolith microchemistry of silver perch in Lake Boga. All fish captured in the Lake during 2016 were aged from 6+ (88% of the sample) to 8+ years. This age structure, combined with information obtained from otolith microchemistry, indicated that silver perch entered the Lake primarily as juveniles aged 1+ during the 2010–11 flood event. These results provide further evidence of the importance of productivity and connectivity to enhance dispersal and survival of juvenile silver perch. Additionally, the growth rates of silver perch captured in Lake Boga were significantly greater than silver perch captured in the Murray River. This suggests off-channel floodplain habitats have the potential to act as silver perch recruitment and grow-out zones, where juvenile fish can undergo rapid growth before returning to the Murray River following reconnection events.

Key management implications

Maintaining the hydrological and hydraulic conditions within and enhancing connectivity to the mid-Murray region is vital for the long-term future of this critically endangered species.

Unlike golden perch and Murray cod, only a very low proportion of fish in the population were found to live beyond seven years of age in the Murray River. As such, it is imperative that annual recruitment is the management objective for the mid-Murray population. This objective will provide some insurance for potential recruitment failure as well as assuring the potential for strong recruitment during episodic conditions which boost juvenile survival.

Recruitment strength of silver perch is enhanced substantially by conditions which facilitate growth and survival of juvenile fish, particularly 1-year olds. As such, interventions aimed at enhancing productivity, habitat availability and dispersal opportunities of juvenile fish should be incorporated into annual environmental flow planning. Specific examples include:

- using environmental water to extend floodplain inundation events along the Murray River (e.g. icon sites);
- providing connectivity with the Murray River and permanently flowing water in key tributaries and anabranch systems.

Silver perch are highly reliant on riverine connectivity to complete migrations as adults and juveniles. There is improved connectivity in the mid-Murray from the recent Murray fishway program, but a further prioritisation of barriers in northern Victoria and southern NSW as well as coordinated flow cues is likely to be important for enhancing populations in tributaries, especially in the mid-Murray (e.g. Loddon, Goulburn, Gunbower, Murrumbidgee, lower Darling, Edward-Wakool).

Off-channel floodplain habitats have potential to act as silver perch recruitment and grow-out zones, for juvenile fish. Reconnection events to the Murray River should also be considered in flow planning to return fish to the system to complete their lifecycle (e.g. riverine spawning).

Concluding remarks

This study has provided support for existing knowledge of silver perch ecology and more importantly has provided additional insights into the role of flows in governing recruitment strength, movement and subsequent population dynamics. Our collective exploration of movement, distribution and recruitment indicates that optimising productivity and dispersal opportunities (particularly juveniles) is likely to enhance the species in the mid-Murray River. As such, restoring connectivity using infrastructure and/or managed flows (including environmental water) aimed at enhancing movement cues, productivity and habitat availability needs to be a management priority for the species.

1 Background

The construction of storages and alteration of flow regimes is a major threatening process for native freshwater fish populations worldwide (Bunn and Arthington 2002). These changes can influence native fish populations by reducing cues for spawning and migration (Lake 1967; Todd et al. 2005), survival of eggs and larvae (Ryan et al. 2003), growth and developmental rates (Ryan et al. 2003), productivity (Martinez et al. 1994) and riverine connectivity (Mallen-Cooper 1999). Furthermore, river regulation has converted many lotic (permanently flowing) riverine habitats to lentic weir pools (Walker 2006) and increased competition with 'cold water' specialist species (Koehn et al. 1995).

Environmental flows, which aim to reinstate or protect key aspects of a river's natural flow regime, are a restoration tool used to maintain or restore the ecological health of rivers with degraded flows (Poff and Zimmerman 2010; Yin et al. 2012). For many such rivers, environmental flow programs have specific objectives aimed at enhancing native fish populations because of their high social, cultural and conservation value (Bradford et al. 2011; Koehn et al. 2014a). For instance, in the Murray–Darling Basin (MDB) environmental water allocations for native fish represent a major investment in restoring river health. Native fish populations in the MDB have suffered an estimated 90% decline in abundance since European settlement, with altered flow regimes a major contributing factor (Koehn et al. 2014a). As a result, environmental water delivery is increasingly being used as a mechanism to maintain or restore native fish populations in degraded rivers throughout the MDB (Koehn et al. 2014b), with specific themes or objectives focussing on enhanced native fish populations being embedded or proposed in state and national environmental watering objectives, such as the Victorian Environmental Flow Monitoring, the Murray–Darling Basin Environmental Watering Strategy and the Commonwealth Environmental Watering Strategy.

Optimising the benefits of environmental water delivery for fishes is contingent on restoring key aspects of flow regimes, over appropriate spatial scales that link to processes governing population dynamics (e.g. King et al. 2009). Conceptually, aspects of a river's flow regime have vital links to the key processes governing fish populations (i.e. recruitment, survival, immigration and emigration). Verifying and quantifying these links assists waterway managers to adaptively manage environmental flows and provides scientific support for decisions regarding environmental water for fish outcomes. For many fish species in the MDB there is still uncertainty surrounding many of these vital links, making environmental flow recommendations and subsequent predictions of responses difficult (Humphries et al. 1999; King et al. 2009; Koehn et al. 2014b). While there is a relatively good understanding of the role of flow for spawning of some of these species (e.g. Humphries et al. 1999; Koehn and Harrington 2006; Zampatti and Leigh 2013a; King et al. 2016; Koster et al. 2017), there is still some uncertainty surrounding the role of flows as a key driver of recruitment strength (except see Mallen-Cooper and Stuart 2003; Zampatti and Leigh 2013a) and subsequent population growth, even for well-studied recreational species such as Murray cod *Maccullochella peelii.*

Recent research suggests that key drivers of population dynamics such as dispersal and recruitment for long-lived native fish species like golden perch *Macquaria ambigua* may be operating at an inter-river scale — perhaps thousands of kilometres — over extended time periods (e.g. Sharpe 2011; Zampatti et al. 2015). The spatial scale of such a life-history highlights the requirement for research to accommodate this extensive spatial and temporal variability in order to identify and quantify any such population responses to flow (Bradford et al. 2011; Zampatti and Leigh 2013a). Indeed, there is an urgent need for the latest knowledge and data to be made available to inform the processes and decisions surrounding environmental watering in the southern MDB, particularly for threatened fish species where there is a need for immediate actions.

The silver perch *Bidyanus bidyanus* is a long-lived, omnivorous, large-bodied fish species endemic to the MDB (Rowland 2009). The species is up to 500 mm in total length and 8 kg in weight (Trueman 2012), although it is usually under 450 mm long and weighs less than 1.5 kg (Lintermans 2007). It was once widespread over most of the MDB but has suffered extensive declines in abundance and range (Clunie and Koehn 2001a; Lintermans 2007; Trueman 2012). The greatest concentration of silver perch in the MDB is now centred in the mid-Murray River, between Yarrawonga and Euston, although even in this region abundances declined considerably (e.g. by 94% at Euston) over a 50-year period (Mallen-Cooper and Brand 2007). There have been concerns for the conservation of this species for some time,. A recovery plan was prepared in 2001 (Clunie and Koehn 2001b) and the species was listed as critically endangered nationally in 2013 under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (DEE 2017). Silver perch is also listed as endangered in the ACT, and vulnerable in Victoria (Lintermans, 2007), New South Wales and SA (DEE 2017).

Silver perch has been broadly referred to as a ‘flow recruitment specialist’ (Lake 1967; Gehrke 1997; Humphries et al. 1999; Baumgartner et al. 2014a) on the basis of observations linking flow with key life-history processes, particularly spawning (Mallen-Cooper and Stuart 2003; King et al. 2009; King et al. 2016) and the movement of adults (presumed to be associated with spawning; Reynolds 1983) as well as juveniles (thought to be an important dispersal mechanism; Mallen-Cooper and Stuart 2003; Baumgartner et al. 2014b). The life-history of silver perch appears to include spawning on small river rises, recruitment and dispersal of young fish over large spatial-scales (e.g. hundreds of km) and a preference for long, uninterrupted, perennial river reaches with complex hydrodynamics. Despite being categorised within the ‘flow recruitment specialist’ guild, silver perch populations in the mid-Murray seem to recruit and disperse annually and juvenile fish can be reasonably common in the lower reaches of tributaries and anabranches connected to the mid-Murray, such as the Edward–Wakool system (Mallen-Cooper and Stuart 2003). Other information linking silver perch life history to flow has been collated as part of the MDBA population modelling project (see conceptual model in Appendix 1). Nevertheless, like many other MDB fish species there is still considerable uncertainty surrounding the specific role of flow as a driver of recruitment strength (except see Mallen-Cooper and Stuart 2003; Zampatti and Leigh 2013a) and subsequent population dynamics, particularly because of the large spatial scale over which populations operate.

2 Current distribution and population structure in the Murray River

2.1 Background

Formerly widespread over most of the MDB, silver perch have suffered substantial declines in abundance and range (Clunie and Koehn 2001a; Lintermans 2007; Trueman 2012). It is thought that the greatest concentration of silver perch in the MDB is now centred in the mid-Murray River, between Yarrawonga and Euston (Lintermans 2007; Mallen-Cooper and Brand 2007), but there is limited information on the distribution and population structure throughout this reach, with little comparison to the lower and upper reaches of the Murray River. In this chapter we assess the current distribution and population structure of silver perch throughout the Murray River, with a strong focus on the mid-Murray reach. A more detailed investigation of age structure data to investigate recruitment dynamics is presented in Chapter 3.

2.2 Methods

2.2.1 Fish surveys and sample collection

We used boat electrofishing surveys to assess the current distribution of silver perch in the lower Murray (downstream of the Darling River confluence), mid-Murray (Darling River confluence to Yarrawonga weir) and upper Murray (upstream of Yarrawonga weir) regions (Table 1). We also included previous electrofishing survey data from the upper Murray and mid Murray regions (see Lyon et al. 2014; Raymond et al. 2016) to increase the spatial and temporal coverage of distributional and fish abundance data.

In 2016, boat electrofishing was conducted at nine locations using either a 5 kW or 7.5 kW Smith Root electrofishing unit (Model GPP 5 or 7.5). All electrofishing surveys were undertaken between March and June to maximise the chance of collecting young-of-year (YOY) silver perch, spawned the previous spring–summer. For the lower Murray River region, electrofishing was conducted at eight sites in the main channel of the South Australian Murray River (as part of the Commonwealth Environmental Water Office's Long-term Intervention Monitoring Program; Ye et al. 2016) and 22 sites in the Chowilla Anabranch system and adjacent River Murray (Lock 5 to Lock 7), as well as throughout the Murray River (Lock 6 to Lock 8) and adjacent Mullaroo Creek in autumn (March–April) 2016 (Table 1; Figure 1). Sampling of the mid-Murray River was conducted at four sites located between Euston weir and Torrumbarry (both day and night shots); six sites in the Barmah-Millewa area (see Raymond et al. 2016); and 120 sites between Tocumwal and Yarrawonga. Surveys of the reach below Euston weir pool was a notable gap for this part of the river. No surveys of the upper Murray River (above Yarrawonga; Figure 1) were undertaken in 2016; information for this region is taken from surveys conducted from 2000 to 2013 (Lyon et al. 2014).

Electrofishing was conducted during daylight hours within all available habitats (e.g. littoral, weir pools, backwaters and instream wood piles). The total time electrical current was applied (seconds) was recorded for each site to enable count data to be standardised (number of fish per 1000 electrofishing seconds). All silver perch captured were measured to the nearest mm (fork length, FL) and weighed (to the nearest gram). All silver perch captured in 2016 were euthanised and retained to collect otolith samples to obtain information on age structure (see below). To supplement these data and improve our estimates of population structure in the mid-Murray region, 125 fish were collected for otolith analysis. These fish were taken from the Torrumbarry fishway using the fish monitoring cone-trap covered with 20 mm by 15 mm 'birdwire', as described in Mallen-Cooper and Stuart, (2003). Specifically, to account for any temporal variation in the demographics of fish moving through the fishway, a subsample of fish, representative of the size structure present at the time of sampling, was conducted bimonthly from December 2015 to February 2016 inclusive (six sampling occasions). The sample of fish collected from the fishway was proportionally representative of the length-frequency of silver perch present in the trap at the time. Importantly, the size and age structure of the fish from the fishway (all samples combined) was not significantly different from the independent electrofishing surveys for 2016 (Appendix 2; see also Chapter 3).

Table 1: Details of boat electrofishing sampling in the Murray River, including counts of Silver perch in 2016.

Counts in parentheses indicate total numbers of fish recorded for the entire sample period of the relevant data sets. All electrofishing sampling was conducted in Autumn (March – May).

Region	Area	Sample period	Latitude (°S)	Longitude (°E)	Effort (EF seconds)	2016 count
Lower Murray	Chowilla and adjacent Murray River	2016	34.227	140.740	21702	15
Lower Murray	Murray River (Locks 3–5)	2016	34.553	139.608	5351	9
Lower Murray	Murray River (Locks 6–8)*	2016	34.082	141.239	12000	1
Mid-Murray	Euston	2016	34.653	142.871	5028	6
Mid-Murray	Tooleybuc	2016	35.052	143.331	2081	0
Mid-Murray	Barham	2016	35.634	144.131	1530	1
Mid-Murray	Torrumbarry	2016	35.941	144.464	2681	31
Mid-Murray	Murray River at Barmah–Millewa	2007 – 2016	35.842	145.153	7200	4 (93)
Mid-Murray	Murray River, Yarrawonga–Tocumwal	1999 – 2016	35.972	145.935	13346	43 (3186)
Upper Murray	Murray River, Hume Dam – Yarrawonga	2000 – 2013	36.015	146.659	3105	(7)
TOTAL					74024	110 (3286)

* Includes adjacent anabranches (Mullaroo Creek and Lindsay River).

2.2.2 Otolith processing

Collections of silver perch were used primarily to collect otoliths, but gonads were also removed to identify sex. Sagittal otoliths were removed, cleaned using distilled water and stored in individual paper envelopes. Otoliths were prepared and interpreted as outlined in Anderson et al. (1992). Briefly, thin transverse sections of either the left or right sagittal otolith from each fish were mounted on a glass slide and examined under a stereo microscope with transmitted light. Counts of annuli, defined as a pair of translucent and opaque zones, were independently determined by three researchers with extensive experience in otolith preparation and interpretation, as has previously been conducted for silver perch (Mallen-Cooper and Stuart 2003; Tonkin et al. 2014). Otoliths were read ‘blind’ (i.e. without information on the size, sampling date and sampling location of the fish) by each researcher. As in Mallen-Cooper and Stuart (2003), if all readers agreed on an age then it was considered verified. If one reader disagreed with an age then that reader would re-read the otolith; and if all readers disagreed with an age then all readers would independently re-read the otolith. If the age was still not consistent among readers, then the otolith was not verified and was excluded from the data. Opaque zones become visible in otolith sections in November each year, so by convention 1 November was chosen as the nominal birth date for the species (Mallen-Cooper and Stuart, 2003).

2.3 Results

A total of 110 silver perch were collected during boat electrofishing fish surveys of the Murray River in 2016. These data, when collated with previous records and standardised for electrofishing effort as fish per 1000 electrofishing seconds (fish/1000 EFS), indicate that the greatest density of fish occurs in the mid-Murray River reach, being more than two times greater than the lower Murray sites and thirty times greater than previous surveys of the upper Murray reach (1.85 fish/1000 EFS compared to 0.85 and 0.05 for the lower and upper Murray respectively). In the mid-Murray section the greatest density of fish was recorded in the Torrumbarry sample (downstream of the weir; 4.02 fish/1000 EFS) followed by Yarrawonga (1.96), Barmah–Millewa (1.44), Euston (1.19), Barham (0.65) and Tooleybuc (0.00) (Figure 2).

Silver perch ranged in length from 84 ─ 404 mm with weights of 7 ─ 1172 g. Fish were aged between 0+ (young-of-year) and 11 years, with very few fish older than 7 years. Adult fish longer than 300 mm were the dominant size class of fish captured in both the lower Murray and mid-Murray. This size class consisted mainly of 6-year-old fish, equating to fish spawned in the 2009–10 season (Figure 2). A comparison between size-structure and age-structure of fish between the lower Murray and mid-Murray sites highlighted a more even distribution of both size and ages in the mid-Murray, where there was a much greater proportion of smaller (≤ 200 mm long) and younger (≤ 2 years) fish. Five-year-old fish (spawned in 2010–11) were a notable absence from the mid-Murray sites but were present in the lower Murray. There was a relatively even distribution of ages and sizes of males and females across all sites (Figure 3). The Torrumbarry and Yarrawonga sites had relatively similar age and size structures, albeit a slightly greater proportion of juvenile fish ≤ 2 years and fewer fish ≥ 7 years of age at the Torrumbarry site (Figure 4).

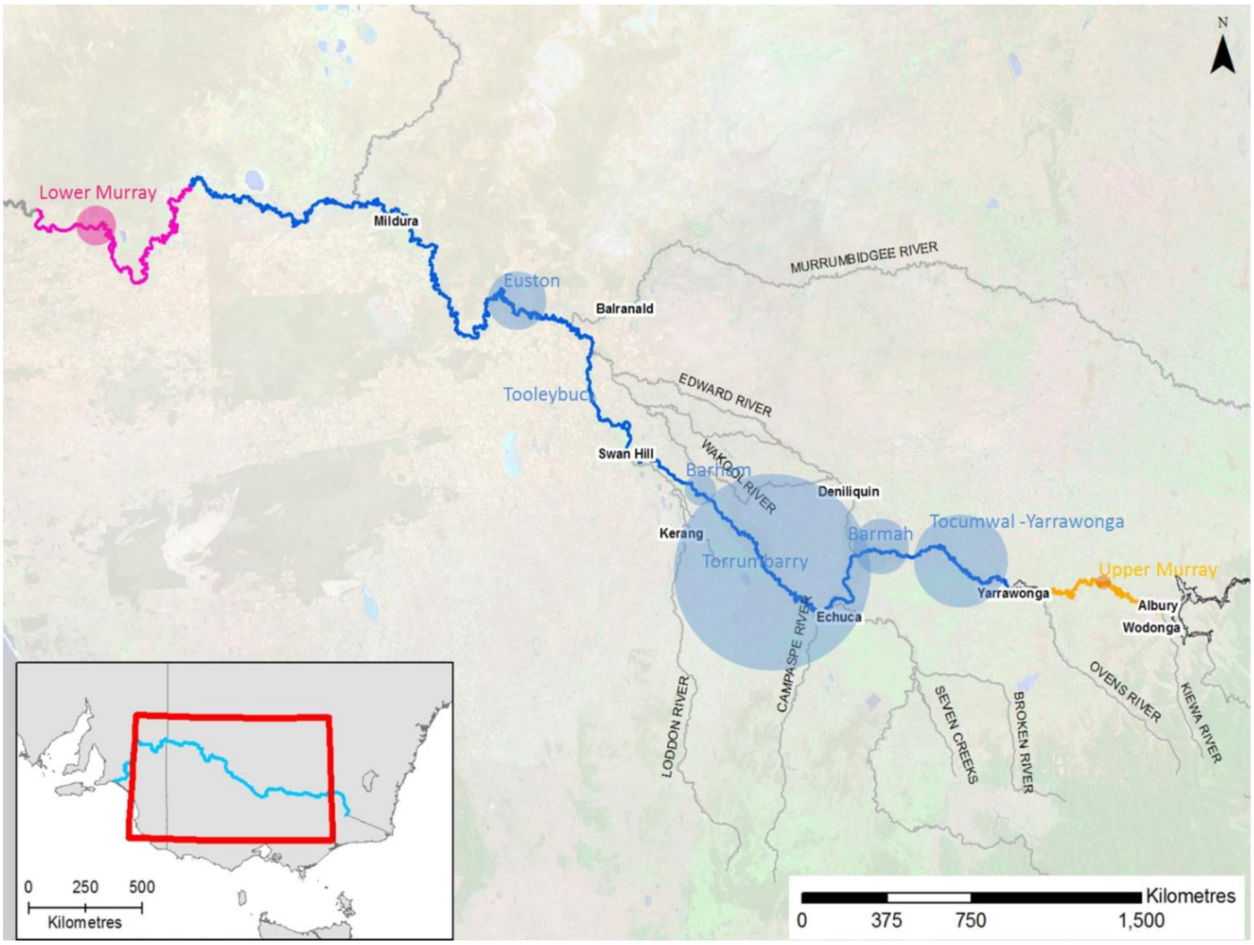

Figure 1: Map of the study area, showing approximate locations of sample areas in the lower Murray (pink), mid-Murray (blue), and upper Murray (yellow) regions.

Site locations represented by bubble points and coloured text, with size of the points scaled to represent catch per unit effort (fish per 1000 electrofishing seconds) for silver perch.

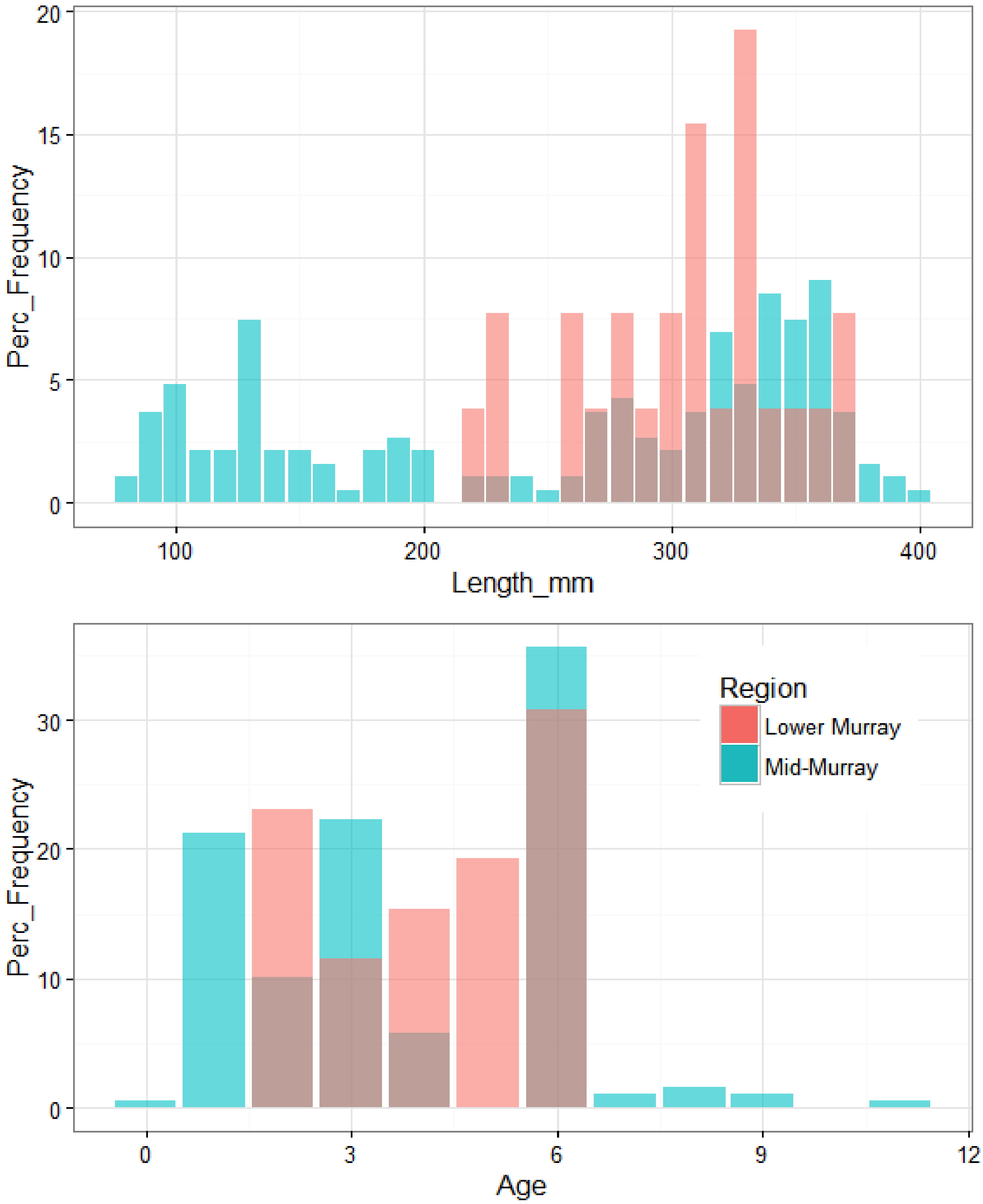

Figure 2: Length (fork length; top) and age (years; bottom) frequency histogram of silver perch collected in the lower (pink, *n* = 26) and mid (blue, *n* = 188) Murray in 2015–16 using both electrofishing and Torrumbarry fishway trapping.

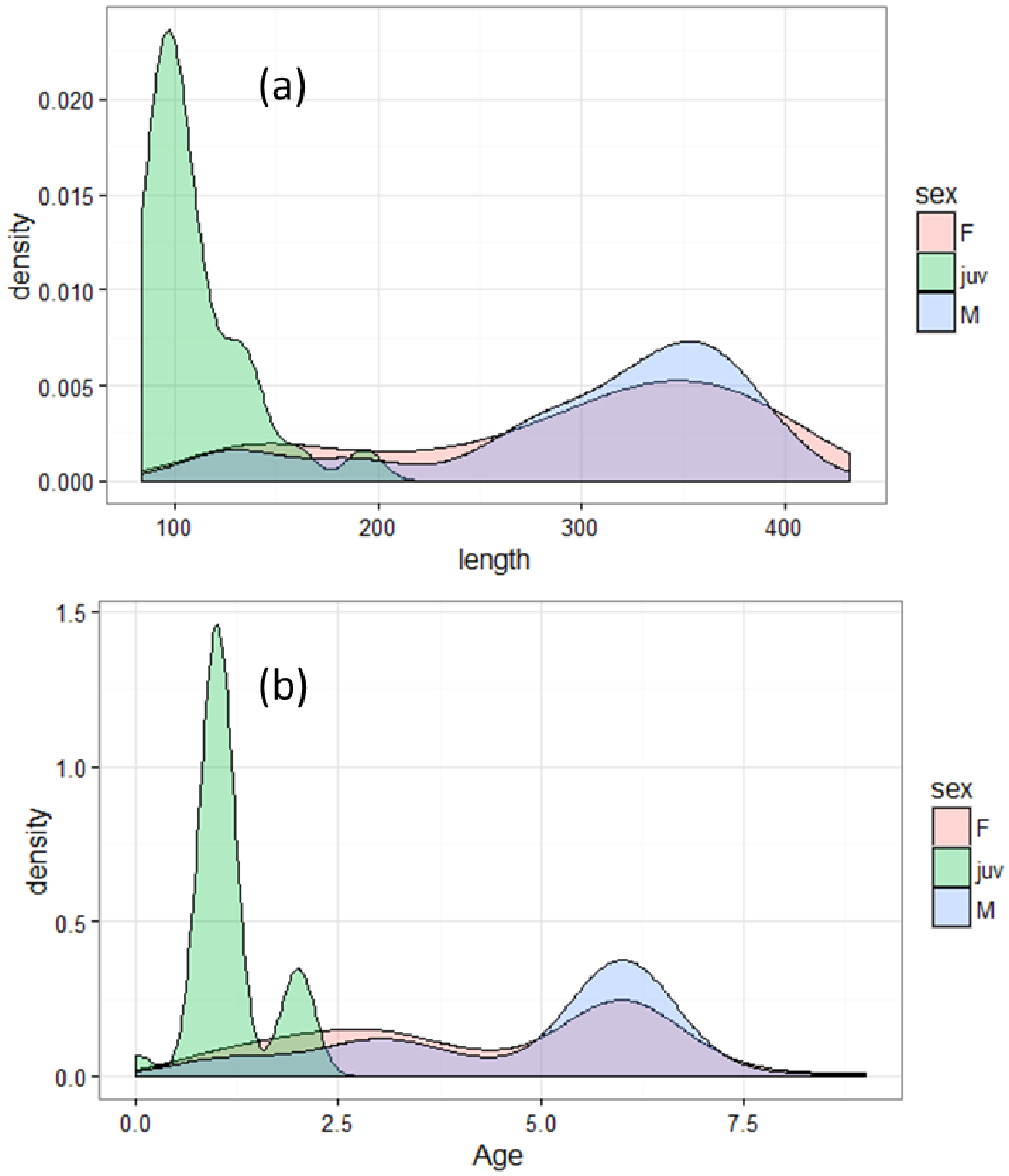

Figure 3: Length (fork length) and age (years) density plots specific to sex for all silver perch collected in the Murray River in 2015–16 using both electrofishing and trapping at the Torrumbarry fishway (*n* = 235).

Note: a number of fish were grouped as 'juveniles' because sex could not be determined for a large proportion of young fish.

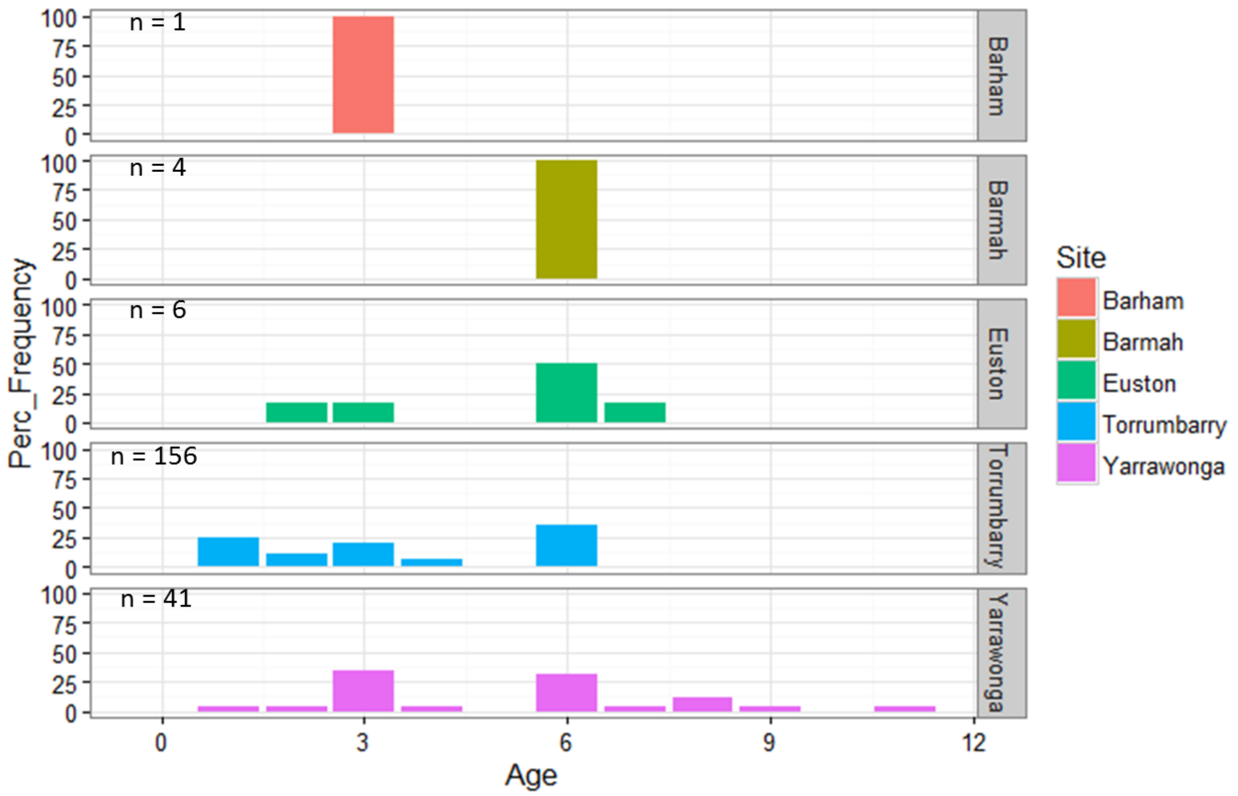

Figure 4: Age (years) frequency histogram of silver perch captured at five mid-Murray sites in 2016.

2.4 Discussion

The population assessment of silver perch across the Murray River in 2016 reiterates the importance of the mid-Murray for this species in the southern connected MDB. Specifically, the mid-Murray had the greater density of fish, and the broadest size and age structures, including more young fish, compared to the lower and upper Murray. The mid-Murray has previously been highlighted as the stronghold for the species within the MDB (Lintermans 2007; Mallen-Cooper and Brand 2007), most likely because of the spatial scale of perennial lotic habitat that exists in this region (about 290 km in the Yarrawonga–Torrumbarry section and about 550 km in the Torrumbarry–Euston section).

The age structure of fish confirmed to have been spawned in the mid-Murray (see Zampatti et al. 2017) revealed recruitment has occurred in this region almost each year for the past 11 years, a period which encompassed extremes in discharge (drought and flood). These results indicate that silver perch occupying a river reach such as the mid-Murray (with perennial flowing water extending over a broad spatial scale) will recruit in most years. This is a strategy more akin to that described for species such as Macquarie perch *Macquaria australasica* or Murray cod rather than a ‘flow dependent specialist’ such as golden perch *Macquaria ambigua*. If a reproductive guild approach were utilised (e.g. Humphries et al. 1999), silver perch would be considered a circa-annual spawner. We also note that these reproductive guilds often do not account for other life-history processes likely to be influenced by flow, including juvenile survival and dispersal, despite perhaps being a key driver of recruitment dynamics.

Considering that very few fish appear to live beyond seven years of age (unlike Murray cod or golden perch), regular recruitment would appear to be a strong requirement for the life-history strategy of the species. This information (age structure, distribution and recruitment regularity) will be particularly important in the development of a silver perch population model and for the future management of this threatened species. Practically, the management need here is maintaining the current hydrological and hydraulic conditions within the mid-Murray River reach, a pattern of flow that has supported annual silver perch recruitment; and enhancing connectivity of anabranches and tributaries to the mid-Murray region for long-term sustainability of this critically endangered species.

A notable absence within the current age structure in the mid-Murray was the 2010–11 year class. It is noteworthy that there were negative impacts from high flows and a hypoxic blackwater event in this reach in late 2010 and early 2011, including the well-documented death of fish (particularly Murray cod) and crustaceans (e.g. King et al. 2012). During this project, the 2010–11 season was the only year that silver perch eggs were not detected as part of annual larval drift surveys of the Murray River at Barmah–Millewa Forest, which have been conducted since 2003 (Raymond et al. 2016). Nevertheless, the presence of a large proportion of fish aged ≥ six years indicates that these events, although appearing to have impacted spawning (and the subsequent 2010–11 year class), did not have a negative impact on the survival of juvenile and adult fish, and in fact may have strengthened the 2009–10 year class. Despite the absence of a 2010–11 year class in the mid-Murray, this year class was present in 2016 in the lower Murray River, and otolith microchemistry indicated that fish from this cohort were spawned in the lower Murray in 2010–11 (Zampatti et al. 2017). Further details on year class strength, habitat attributes of the mid-Murray and recruitment dynamics of silver perch was discussed by Zampatti et al. (2017) and is explored further in Chapters 3, 5 and 6.

Very few young-of-year silver perch were captured in this study. While this might suggest a relatively poor recruitment from the 2015–16 year class, the rarity of young-of-year fish in annual population samples in previous years (e.g. see Raymond et al. 2016) and the current (autumn 2017) abundance of 1+ fish detected at a number of sites across the southern MDB, in the Goulbourn, Loddon, Campaspe and Wakool rivers (unpublished data) suggests this age class of fish were simply not detected. This size class might be underrepresented because of the sampling strategy (boat eletrofishing), or because they were only present at specific locations (nursery habitat) in areas not surveyed during the study. For example, no surveys were conducted in the reach below Euston weir. A more intensive survey of this reach in early summer (following a non-blackwater season) using a range of sampling methods may be required to determine whether this hypothesis is correct.

Although comparisons between sample areas within each river reach were difficult because of the low sample size and small number of locations sampled, the Torrumbarry and Yarrawonga areas had proportionately similar age structures; albeit a slightly greater proportion of juvenile fish (≤ 2 years) and relatively fewer old fish (≥ 7 years) at the Torrumbarry area. This pattern in juvenile distribution suggests that recruitment is occurring throughout the entire mid-Murray reach, or that a large proportion of the upstream migration following egg and larval drift (which is assumed to reposition early life stages in the mid to lower areas of the reach), occurs in the first one or two years of life. Retrospective investigation of the movement history of individual silver perch using otolith microchemistry has shown that the migration of juvenile silver perch to alternative river reaches commonly occurs in the spring–summer of the fish's second year of life (i.e. age 1+) (Zampatti et al. 2017). The partial reliance of the Yarrawonga reach in the upstream migration of juvenile silver perch at Torrumbarry is supported by fishway catch records and the gradual improvement of silver perch populations in the Yarrawonga reach after the construction of the Torrumbarry fishway in the early 1990s (Mallen-Cooper 1999; John Koehn, pers. obs.).

2.5 Management implications

Maintaining the hydrological and hydraulic conditions in the mid-Murray region and enhancing its connectivity to other parts of the river system is vital for the long-term future of this critically endangered species.

Unlike golden perch and Murray cod, only a very low proportion of fish in the population were found to live beyond seven years of age in the Murray River. It is therefore imperative that annual recruitment is the management objective for the mid-Murray population, to provide some insurance against potential recruitment failure as well as assuring the potential for strong recruitment during episodic conditions which boost juvenile survival.

Silver perch population (and perhaps metapopulation) dynamics appear to presently operate as 'source' and 'sink', with the Yarrawonga reach partially reliant on upstream migration of adults and juveniles from the river reach downstream of Torrumbarry. Management actions should be considered on a large spatial scale (e.g. hundreds of km) to enhance connectivity among reaches and tributaries by providing appropriate passage and environmental flows.

Flood events that create hypoxic blackwater are likely to have a detrimental impact on silver perch spawning success, but such events may still benefit juvenile fish spawned in previous years (see Chapter 3).

3 Recruitment dynamics of silver perch in the mid-Murray River

3.1 Background

Recruitment is a highly variable and complex process that is fundamental to the dynamics of fish populations. Recruitment is generally defined as the number of fish in a year class as it enters a specific segment of the population, ranging from early juvenile through to maturation (Wootton 1998; Milner et al. 2003; King et al. 2013; Harris et al. 2013). The variable life-stages for which recruitment is considered is therefore governed by the processes that affect survival during each of the critical life-history stages between spawning and the defined recruitment life-stage (e.g. fish that recruit to reproductive maturity). Whilst much attention is given to the success or failure of spawning in governing population trajectories, knowledge of total lifespan mortality and associated survival, is fundamental to understanding recruitment and subsequent population dynamics (Harris et al. 2013).

In general, mortality rates in fish populations are size related, with the highest rates of mortality associated with egg, larval and juvenile periods (Wootton 1998). For some species, there may also be additional critical periods of mortality, ranging from yolk sac absorption in larvae (e.g. Heath 1992), over-wintering of juveniles (e.g. Shuter and Post 1990) and reproduction (e.g. Pitcher and Hart 1982). As such, survival is governed largely by biotic (competition, predation, parasitism and infectious disease) and abiotic factors (temperature, salinity and flows; Wootton 1998). Thus, identifying the factors influencing age, growth and survival has long been regarded as important in understanding population dynamics (Hastings 1990; Tyler and Rose 1994) and how management interventions such as environmental flow delivery, can be used to enhance populations.

For silver perch, much of the conceptual thinking that links recruitment dynamics with river flows is derived from studies investigating spawning ecology and, to a lesser degree, observations on migratory behaviour of the species. For the latter, movement of both adults (presumed to be associated with spawning; Reynolds 1983) and juveniles (thought to be an important dispersal mechanism; Mallen-Cooper and Stuart 2003; Baumgartner et al. 2014a) has been linked with river flows. Specifically, high spring flows and flow pulses in spring have been linked to adult movement (Reynolds 1983; Mallen-Cooper 1996); whilst small rises in river height from spring through to early autumn have been linked to upstream movements of juveniles (Mallen-Cooper and Stuart 2003; Baumgartner et al. 2014a).

Spawning is temperature cued, commencing in spring when water temperatures exceed 18°C (Gilligan and Schiller 2003; Koehn and Harrington 2005; Tonkin et al. 2007; King et al. 2009), with > 20% of predicted maximum spawning occurring between 20 and 25°C (King et al. 2016). King et al. (2016) also found the occurrence and abundance of silver perch eggs in the Murray River was positively associated with river discharge and weekly water temperature change, and was negatively associated with the number of flood days in the three months preceding spawning.

Collectively, this information linking both spawning and movement with flows has resulted in the species being classified as a ‘flow recruitment specialist’ (Lake 1967; Gehrke 1997; Humphries et al. 1999; Baumgartner et al. 2014a) despite little work specifically investigating the recruitment dynamics for the species. Whilst recruitment has been associated with high flows in spring or summer (Lake 1967; Reynolds 1983; Gehrke 1992; Harris and Gehrke 1994), an assessment of year class strength in the mid-Murray River reported the strongest cohorts to be those which were spawned during relatively stable in-channel flows (Mallen-Cooper and Stuart 2003). This work would appear at odds with what would be expected if silver perch populations were being driven primarily by the factors governing spawning and movement.

Since the publication of Mallen-Cooper and Stuart (2003), there have been considerable advances in both the conceptual thinking and analytical techniques that can be undertaken for these types of data which may provide new insights and alternative results from these data (for example, the use of catch-curve regression which account for age-based mortality when interpreting year class strength). Here we combine the data of Mallen-Cooper and Stuart (2003), supplemented with additional age structure data collected in 2013/14 and 2015/16 to explore the role of extrinsic factors, particularly hydrology and hydraulics, in governing year class strength of silver perch in the mid-Murray River. Importantly, these additional sample periods integrate information on recruitment dynamics across a broad range of environmental conditions, including the Millennium drought (Djik et al. 2013) and following major flooding in 2010/11.

3.2 Methods

3.2.1 Silver perch collection and age structure assessment

Silver perch were sampled from the mid-Murray River over three broad time periods, to gather information on the age structure of the population over a range of environmental conditions. The first sample period was that described by Mallen-Cooper and Stuart (2003), specifically, silver perch were collected monthly from three sites in the mid-Murray River (35 km upstream, immediately below (<1 km), and 6 km downstream, of Torrumbarry Weir) from January 1990 to June 1992. At each site, fish were collected on separate contiguous days using six gill nets (two each of 38, 62, and 100 mm stretched mesh) and two fyke nets (20 mm square mesh) set for 14–17 h, from 2 h before dusk to at least 2 h after dawn. The Torrumbarry Weir fishway was also sampled as described in chapter 2.2 for two periods of 22 h that were concurrent with the monthly netting.

All fish from the nets and fishway were identified and measured for fork length (mm). Subsamples of silver perch were collected each month for the removal of sagittal otoliths; if available, four fish from each 100 mm size class were collected yielding a total of 167 otoliths for the time period. Whilst this approach to subsampling suited the development of growth models for the species, this sample was not derived from a true representation of the population structure at the time of sampling (e.g. in a given sampling event a catch of 4 fish from the 100-200 mm FL range would have had equal representation as 400 fish captured from the 200-300 mm FL range). As such, for our recruitment analysis (see below), we incorporated a reduced data set so as to better reflect the true age structure of the population at the time of sampling. This was achieved by using the length frequency histogram data presented in Mallen-Cooper (1999) which was generated using all fish (n = 1522) captured during the fishway sampling. The percentage of each size class of fish 100 mm size classes was then used to adjust the otolith data set, whereby samples belonging to size groups of fish which were over represented in the data (for fish in the 200-300 mm and 300-400 mm size bins) were removed randomly so as to best represent the size frequency of fish present in the system during sampling. This exercise reduced the sample from 167 otoliths to 60.

The second sample of fish was from standardised electrofishing surveys and opportunistic captures from the Edward – Wakool River system from December 2013 – May 2014 (Watts et al. 2014). A total of 53 silver perch were captured, all of which after being measured for fork length (mm) were retained for otolith removal and subsequent ageing. Whist this sampling was not specifically from the Murray River main channel, otolith microchemistry undertaken on a subset of these fish has identified that they originated from the Murray River (Jason Thiem, Unpublished data). Given the spatial scale over which the species life-history occurs, we consider the sample to be representative of the population for the mid-Murray region (and subsequent year class strength also aligns with samples from the Murray River in later years).

The most recent sample of fish from the mid-Murray River was collected from December 2015 - June 2016 as described in Chapter 2.2. This included boat electrofishing conducted at four sites located between Euston weir and Torrumbarry (both day and night shots); six sites in the Barmah-Millewa area (see Raymond et al. 2016); and 120 sites between Tocumwal and Yarrawonga; as well as fishway sampling at the Torrumbarry weir (see Chapter 2.2). We also included seven silver perch collected during surveys of ten sites sampled on the lower Goulburn River in April 2016. A total of 211 fish were retained for otolith samples and subsequent ageing. Importantly, otolith microchemistry conducted on samples representing each age class revealed all fish from the sample originated in the mid-Murray River reach (see Zampatti et al. 2017). All silver perch retained were measured for fork length (mm), weighed (g) and subject to otolith removal, sectioning and ageing as per the methods described in Chapter 2.2. Counts of opaque annual increments were converted into fish age, taking into account the validated assessment of marginal increment and date-of-capture with year of birth (year class) assigned on the basis of spawning year with an allocated 'birthday' of 1st November (see Mallen-Cooper and Stuart 2003).

3.2.2 Recruitment analysis

Fish counts belonging to each year class, were used to estimate year class strength (YCS) and subsequent measures of recruitment success (as it is a measure of the relative contribution of a year class to the overall population structure). We applied a catch curve regression approach, which estimates YCS by accounting for annual mortality of fish to our raw year class counts for each sample period (e.g. Maceina 1997; Morrongiello et al. 2014). This approach uses deviations from the catch curve as a reflection of variable recruitment (Maceina 1997) with positive and negative residuals indicative of strong and weak year classes respectively. We then investigated the relationship between YCS and predictor variables using zero-inflated negative binomial (ZINB) generalised mixed effects modelling (GLMM).

Our data consisted of five estimates of population age structure collected between 1990 and 2016 (1989/90; 1990/91; 1991/92; 2013/14; 2015/16) with the sample size for each period used as an offset in the models. The oldest fish collected across all samples was 17 years old, however all other fish were <11 years. Therefore 11 years was used as an upper age-class ceiling for each year (i.e. annual spawning cycle). Inspection of the catch curves indicated that fish younger than 1 year of age (young-of-year), despite being present in the catch, were not fully vulnerable to sampling. Our analyses were therefore restricted to fish aged 1–11 years. Missing or few fish in an age class in each sample were assumed to be indicative of weak year classes, assigned zero abundance and retained in the analysis. Due to the large number of age classes with zero occurrences in the data set, a fit to standard distributions (Poisson, Gaussian and negative binomial) was tested with none showing a ready fit due to the zero-inflated nature of the data. Zero-inflated models were then compared using Akaike's information criterion corrected for small sample sizes (AICc), with the best-performing model found to be a ZINB. The zero-inflated model takes into account, and models, the probability of true and false zeros in association with the chosen model distribution - in this case negative binomial. An age and sample period identifier random effect was used to account for any different mortality rates over sample sets.

We ran our analysis on the entire data set and on the 2013 – 2016 data sets only, due to the gap between sampling and difference in sample collection before the 2013 sample season. Catch-curve regression models (the first stage) were fitted using the pscl package (Zeileis et al. 2008), and GLMM were fitted using the package glmmADMB (Skaug et al. 2006), in R 3.2.2 (R Core Team 2016). Model comparisons were undertaken using Akaike’s Information Criterion corrected for small sample sizes (AICc; Burnham and Anderson 2010).

3.2.3 Environmental covariates

We compiled a complementary time-series of environmental data considered as likely candidates to explain recruitment variability (Table 2). Of particular interest was the hypothesis of a positive association between silver perch recruitment strength and flow magnitude and/or variability during the core period of spawning (November – December; Harris and Gehrke 1994; King et al. 2016); pre-spawning spring flows and/or variability (due to its links with adult spawning migration; Reynolds 1983; Mallen-Cooper 1996); spawning season water temperature (King et al. 2016); and river flows in the year following spawning due to observations linking juvenile dispersal (e.g. Mallen-Cooper and Stuart 2003; Baumgartner et al. 2014b) to survival (Table 2).

In recognition of the uncertainty surrounding the hydrologic drivers of ecological responses, we included three measures for each flow covariate, specifically, river discharge (ML/day); water velocity (m/s); and river gauge height (m). All discharge and height data were obtained from relevant gauging stations in the mid-Murray region. Velocity data was generated using cross sectional profiles generated for each gauge site, with mean daily water velocities obtained from the relationships between river height and water velocity (see Appendix 3). Pairwise Pearson’s correlation coefficients revealed discharge, velocity and gauge height were highly correlated for each of these flow metrics (as well as many other flow covariates; Appendix 4), and as such, separate suites of models were run so as not to include these correlated covariates.

Water temperature data was also extracted from the gauging site data sets, however, the temperature time series for all sites had a number of gaps in the early 1990s and was absent prior to 1990. To complete the temperature time series back to 1974 we modelled air surface temperature at Echuca Airport (sourced from the Australia Bureau of Meteorology) with Torrumbarry Weir water temperature along with day-of-year using a generalised additive model. The water temperature data was then extrapolated to fill gaps and extend the dataset back to 1974. Given the importance of the Torrumbarry region within the mid-Murray reach (see Chapter 2), we chose to use the flow and temperature data from this site for all of our analysis. Nevertheless, pairwise correlation coefficients revealed trends in discharge, velocity and gauge height were highly correlated between each of the sites within the mid-Murray reach for each of these flow metrics (Appendix 4). Even if other flow and temperature attributes for other sites were (unknowingly) more relevant for assessing year class strength, any such patterns would be captured using the covariates recorded at Torrumbarry.

Table 2: Environmental covariates used to predict silver perch recruitment strength. Description and associated hypotheses of each also provided.

Covariates in italics represent detailed spawning season flow dynamics added to the best fitting model.

Variable	Description	Hypothesis
mn_flow_annual	Average daily discharge / velocity / height (October – September)	High flows throughout year will increase productivity, growth and survival age 0 –1 year and therefore recruitment strength.
cv_flow_annual	Coefficient of variation in flow discharge / velocity / height (October – September)	High flow variability throughout year will increase productivity, growth and survival age 0–1 year and therefore recruitment strength.
mn_flow_spawning	Average daily discharge / velocity / height during core spawning period (November – December)	High flows throughout core spawning period will increase spawning magnitude and therefore recruitment strength (e.g. King et al. 2016).
cv_flow_spawning	Coefficient of variation in flow discharge / velocity / height during core spawning period November – December)	High flow variability during core spawning period will increase spawning magnitude and therefore recruitment strength.
mn_temp_spawning	Average daily water temperature during core spawning period (November – December)	High temperatures during core spawning period will increase spawning magnitude and therefore recruitment strength (e.g. King et al. 2016).
cv_temp_spawning	Coefficient of variation in water temperature during core spawning period (November – December)	High variability in water temperature during core spawning period will increase spawning magnitude and therefore recruitment strength.
pos_mn_flow_annual	Maximum daily discharge / velocity / height (October – September) the year following the first year of life.	High flows throughout year will increase habitat availability, productivity, growth and survival age 1–2 year and therefore recruitment strength.
pos_max_flow_annual	Average daily discharge / velocity / height (October – September) the year following the first year of life.	High magnitude flow event throughout year will increase habitat availability productivity, growth and survival age 1–2 and therefore recruitment strength.
ant_mn_flow_annual	Average daily discharge / velocity / height (October – September) the year prior to spawning.	High flows throughout year before spawning will increase productivity, growth and fecundity of adults, reproductive output and therefore recruitment strength.
count_rising_flow_spawning	Count of rising days in discharge during core spawning period (November – December)	Increased number of days of rising water will increase spawning magnitude and therefore recruitment strength
mean_rising_flow_spawning	Mean rising discharge in discharge during core spawning period (November – December)	Higher magnitude rises will increase spawning magnitude and therefore recruitment strength
rising_flow_maxrun_spawning	Maximum consecutive days of rising discharge during core spawning period (November – December)	Increased number of days of rising water in a single event will increase spawning magnitude and therefore recruitment strength

3.3 Results

3.3.1 Hydrology and hydraulics

The period over which our samples were collected, along with the ages of fish captured in each of the samples, encompassed extremes in environmental conditions. At a broad level, the ages of fish recorded encompassed years of large unregulated floods and for the two most recent sample periods of regulation-induced drought. Specifically, for the first sample period, fish ages (0 – 11 years) encompassed relatively average flow conditions with low flows in 1987, and 1988, prior to a prolonged period of above average to high flow years from 1989 – 1994 (Figure 5). For the six-year period from 2007 to 2012 there was a period of highly variable annual discharges, with four years of extreme low and two years of very high spring flows respectively. The following three years consisted of relatively average to low flows (2013–2015; Figure 5). Minimum daily velocity and mean daily water temperature during the peak spawning period of November and December at the Torrumbarry gauge site (and indeed most of the other gauge sites on the mid Murray River) was always more than 0.45 m/s and 21.5–24°C, respectively (Figure 6).

3.3.2 Year class strength (YCS) and recruitment dynamics

In general, each sample period was characterised by few missing year classes from the previous seven years of sampling. Furthermore (as discussed in Chapter 2), on each sampling occasion fish more than 7 years of age were rarely collected (Figure 7). In any case, there was high variability in YCS. For the first sample period of 1989–94 (n = 167, with n = 60 for the analysis), the strongest year class belonged to the 1988–89 cohort (fish collected primarily at 2 and 3 years of age in 1990–91 and 1991–92, respectively). For the latter sample periods (2013–14 and 2015–16) the dominant cohort were spawned in 2009–2010 (collected at 4 and 6-years of age in 2013–14 and 2015–16 respectively). Both of these year classes were spawned in relatively average to low flow seasons, but each of these years preceded a year of extended high flows and widespread flooding. Conversely, YCS for the 2010–11 season, which exhibited the aforementioned extended high flows with widespread flooding and a prolonged blackwater event, was one of the lowest for our data set (excluding fish over 7 years of age).

Our analysis of 24 ZINB mixed models run on the entire dataset revealed all models which included additional flow and/or temperature predictor variables performed better than the null model which included just age-at-capture (first stage catch-curve regression output) in explaining variation in YCS (Table 3). Of this suite of models, there was substantial support for two models (model 17 and model 18) that best explanation YCS of silver perch (Table 3). Both of these models contained (along with age-at-capture) the covariates mean discharge during November–December, mean water temperature during the November and December and mean annual discharge the year following the first year of life. Model 17 had the additional variable antecedent mean annual discharge, although this was not a significant predictor in the model ($p >$ 0.05) and as such, model 18 was selected to best explain silver perch year-class strength (i.e. the most parsimonious supported model). Further attempts to improve the model fit by replacing discharge covariates with both height and velocity attributes, as well as including the additional spawning flow dynamic attributes showed considerable less, or essentially no, support from the data in comparison to model 18 (all ∆AICc values ≥ 2).

The parameter estimates and subsequent predictions of model 18 indicated a significant positive relationship between YCS and mean annual discharge (Figure 8; $p < 0.001$; GLMM coefficient estimates of 0.566) and mean water temperature during November and December (Figure 8; $p < 0.001$; GLMM coefficient estimates of 0.623); and a significant negative relationship with mean discharge during November and December ($p <$ 0.05; GLMM coefficient estimates of –0.702). While model 18 was a better fit to the data than 22 of the other models (including just age-at-capture), the 95% confidence intervals indicate there is still a large amount of uncertainty in the model predictions (Figure 7). Using the same variables from the best-fitting model, but excluding the first period of monitoring (1989–1992), yielded a significant positive relationship between YCS and mean annual discharge ($p < 0.05$; GLMM coefficient estimates of 0.8024).

Table 3: Results of the model selection procedure for 24 additive models, comparing the effects of different attributes of discharge and temperature on silver perch year class strength across the monitoring period.

No.	Model structure	AICc*	∆AICc*	Rank
1	catch ~ age + cv_flow_annual + offset(log(samplesize)) + (age | code)	223.29	17.30	21
2	catch ~ age + cv_flow_annual + pos_mn_flow_annual + ant_mn_flow_annual + offset(log(samplesize)) + (age | code)	222.28	16.29	19
3	catch ~ age + cv_flow_annual + pos_mn_flow_annual + offset(log(samplesize)) + (age | code)	220.41	14.42	17
4	catch ~ age + cv_flow_annual + pos_max_flow_annual + offset(log(samplesize)) + (age | code)	219.35	13.36	16
5	catch ~ age + mn_flow_annual + offset(log(samplesize)) + (age | code)	221.90	15.91	18
6	catch ~ age + mn_flow_annual + pos_mn_flow_annual + ant_mn_flow_annual + offset(log(samplesize)) + (age | code)	217.75	11.76	15
7	catch ~ age + mn_flow_annual + pos_mn_flow_annual + offset(log(samplesize)) + (age | code)	216.17	10.18	12
8	catch ~ age + mn_flow_annual + pos_max_flow_annual + offset(log(samplesize)) + (age | code)	214.34	8.35	7
9	catch ~ age + mn_flow_spawning + offset(log(samplesize)) + (age | code)	226.66	20.67	23
10	catch ~ age + mn_flow_spawning + pos_mn_flow_annual + ant_mn_flow_annual + offset(log(samplesize)) + (age | code)	214.97	8.98	10
11	catch ~ age + mn_flow_spawning + pos_mn_flow_annual + offset(log(samplesize)) + (age | code)	217.44	11.45	14
12	catch ~ age + mn_flow_spawning + pos_max_flow_annual + offset(log(samplesize)) + (age | code)	213.75	7.76	5
13	catch ~ age + cv_flow_spawning + offset(log(samplesize)) + (age | code)	222.71	16.72	20
14	catch ~ age + cv_flow_spawning + pos_mn_flow_annual + ant_mn_flow_annual + offset(log(samplesize)) + (age | code)	214.71	8.72	8
15	catch ~ age + cv_flow_spawning + pos_mn_flow_annual + offset(log(samplesize)) + (age | code)	213.91	7.92	6
16	catch ~ age + mn_flow_spawning + mn_temp_spawning + offset(log(samplesize)) + (age | code)	214.88	8.89	9
17	catch ~ age + mn_flow_spawning + mn_temp_spawning + pos_mn_flow_annual + ant_mn_flow_annual + offset(log(samplesize)) + (age | code)	205.99	0	1
18	catch ~ age + mn_flow_spawning + mn_temp_spawning + pos_mn_flow_annual + offset(log(samplesize)) + (age | code)	206.63	0.64	2
19	catch ~ age + mn_flow_spawning + mn_temp_spawning + pos_max_flow_annual + offset(log(samplesize)) + (age | code)	209.35	3.36	3
20	catch ~ age + cv_flow_spawning + cv_temp_spawning + offset(log(samplesize)) + (age | code)	224.33	18.34	22
21	catch ~ age + cv_flow_spawning + cv_temp_spawning + pos_mn_flow_annual + ant_mn_flow_annual + offset(log(samplesize)) + (age | code)	216.62	10.63	13
22	catch ~ age + cv_flow_spawning + cv_temp_spawning + pos_mn_flow_annual + offset(log(samplesize)) + (age | code)	215.51	9.53	11
23	catch ~ age + cv_flow_spawning + cv_temp_spawning + pos_max_flow_annual + offset(log(samplesize)) + (age | code)	211.67	5.68	4
24	catch ~ age + offset(log(samplesize)) + (age | code)	231.30	25.31	24

* AIC Akaike's Information Criterion (c = corrected for small sample size). ∆AICc is the difference in AICc between this model and the model with the lowest AICc. The two best supported models (with ∆AICc ≤2) are highlighted in bold. Additional model structures that replaced discharge covariates with corresponding height and velocity values, as well as the addition of spawning season flow dynamics, made no significant improvement to the best supported models and are not included in the table.

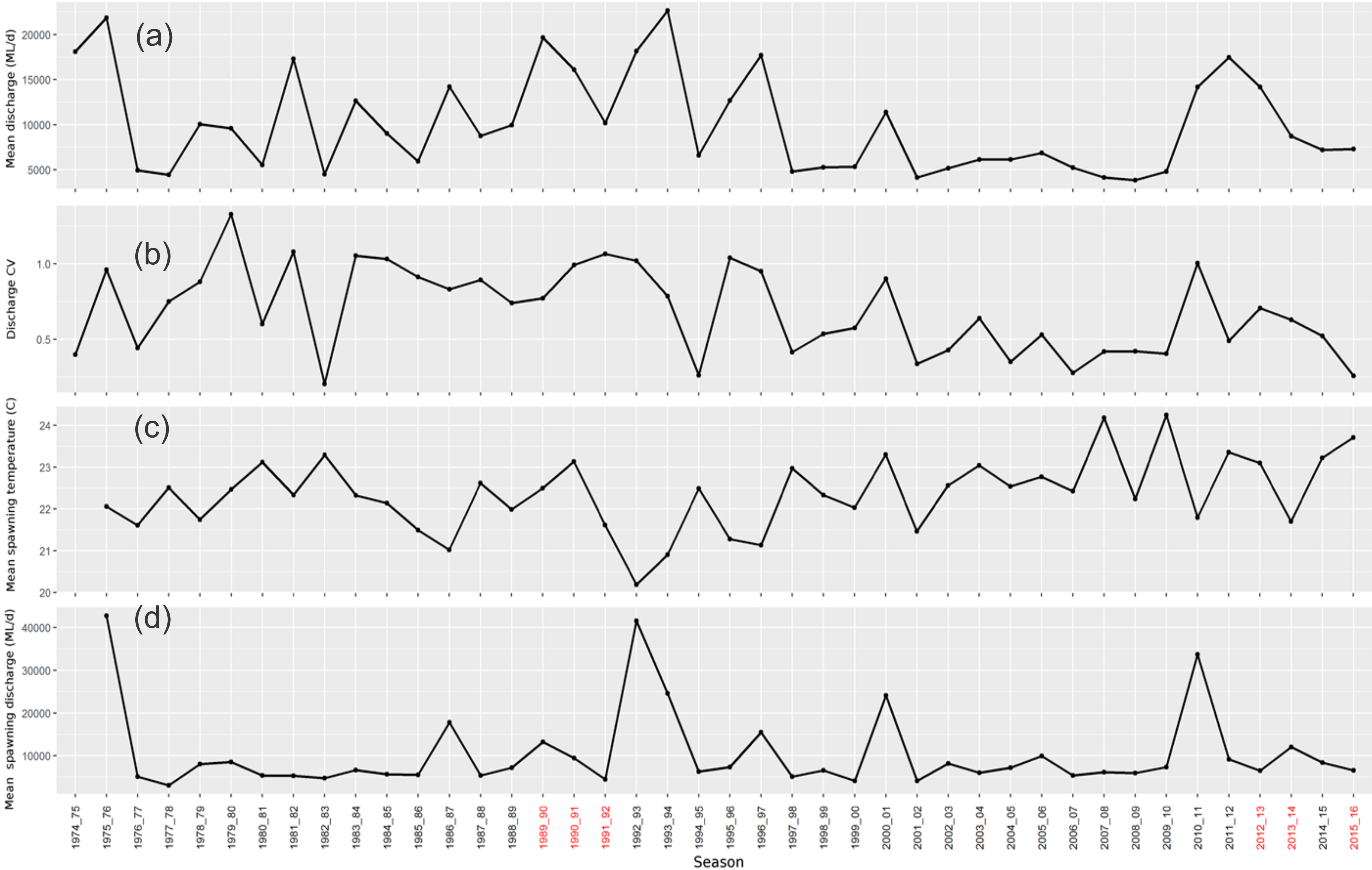

Figure 5: (a) Mean daily discharge, (b) coefficient of variation of daily discharge, (c) maximum daily discharge, and (d) mean daily discharge downstream of Torrumbarry weir during the core silver perch spawning season (November – December), 1972–73 to 2015–16. (Fish collection seasons are shown in red.)

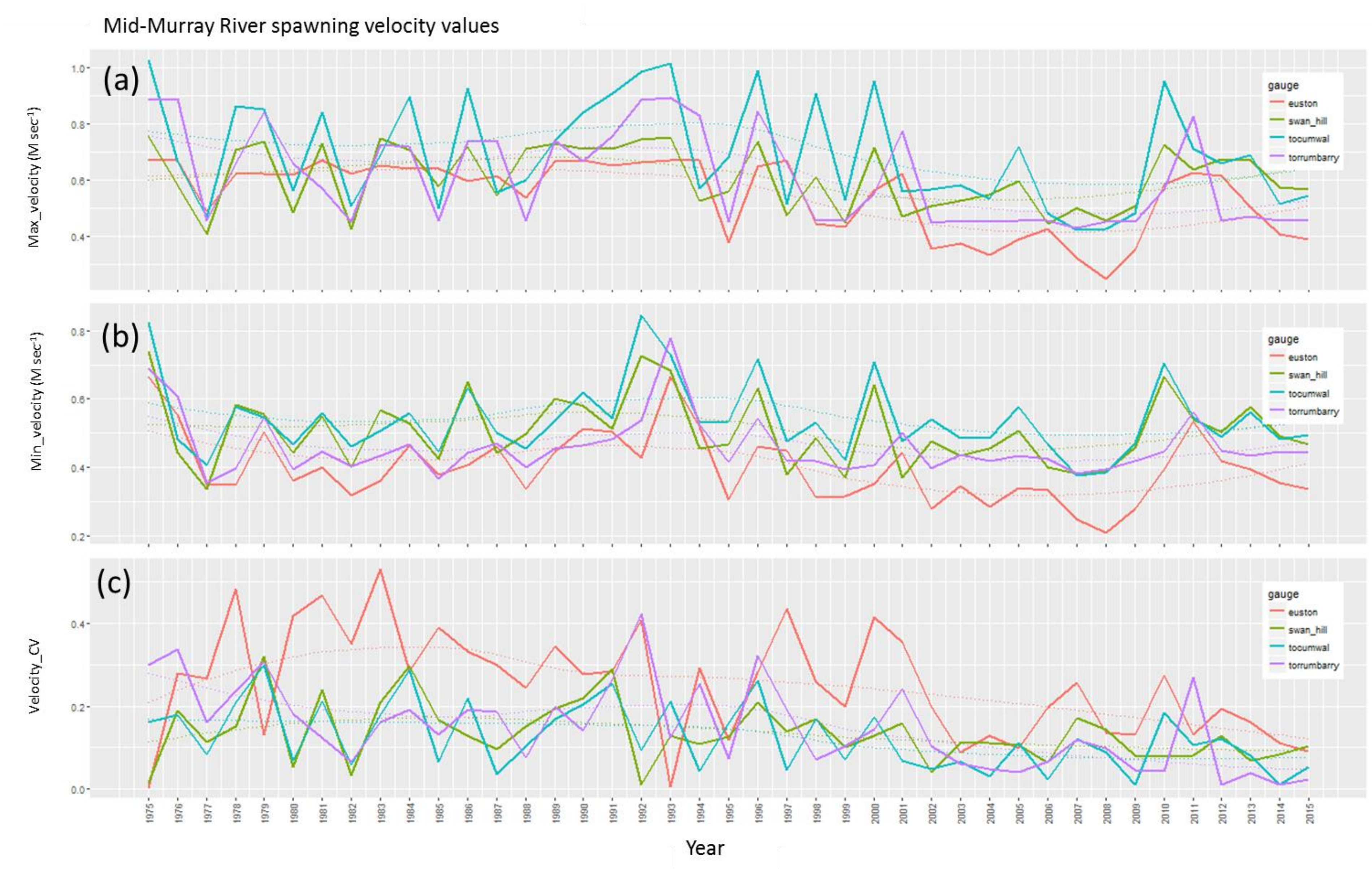

Figure 6. (a) Maximum daily water velocity, (b) minimum daily water velocity, and (c) coefficient of variation of daily water velocity at five gauges along the mid-Murray River during core silver perch spawning season (November–December), 1975–2015.

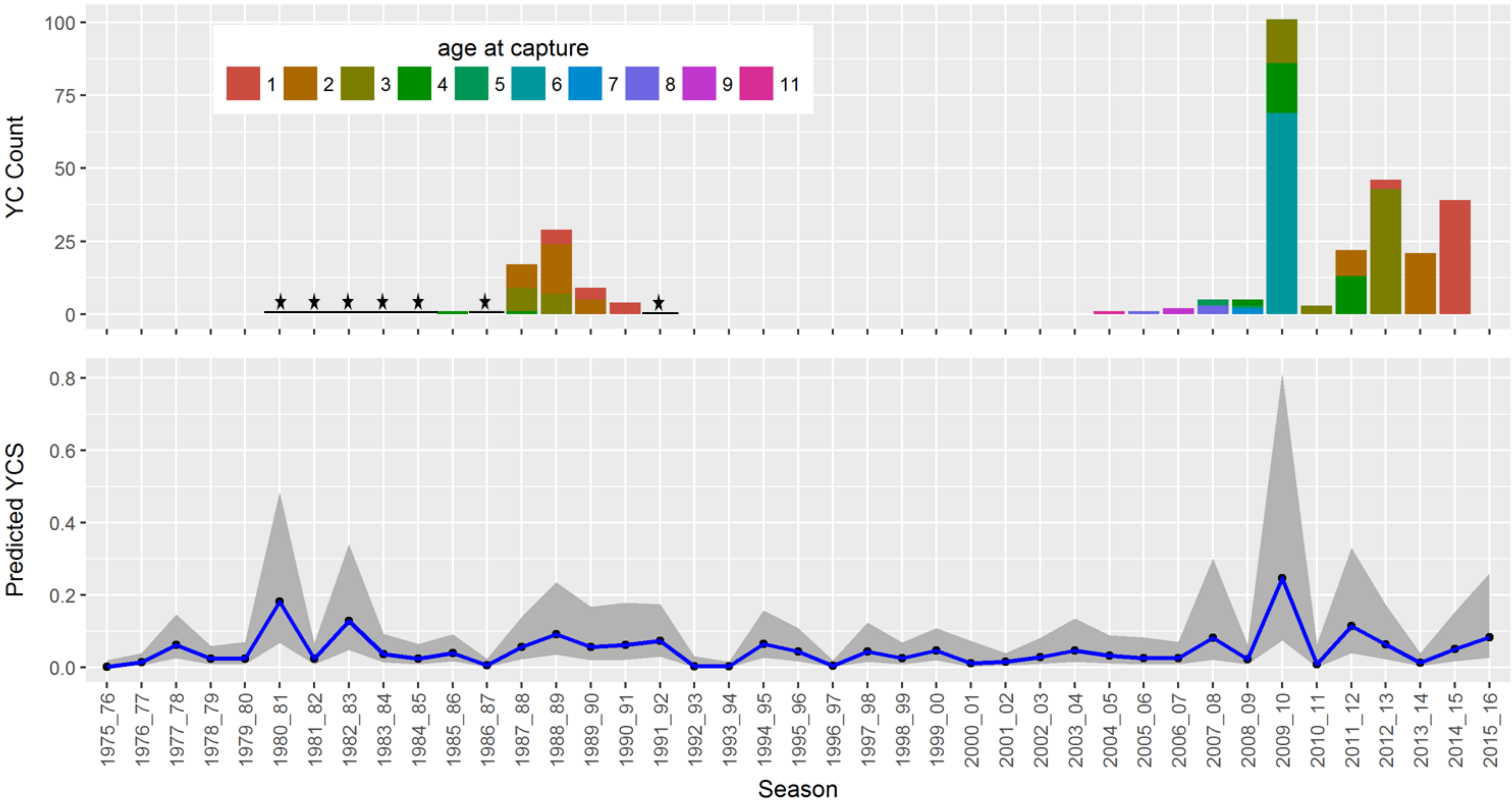

Figure 7: Raw count data of year class strength (YCS; top) and predicted YCS (bottom; ±95% CI) of silver perch in the mid-Murray River for the 75/76 to 2015–16 seasons.

Predicted YCS proxied by catch per unit effort and conditional on age-five at capture and environmental covariates (average daily discharge during core spawning period; and average daily discharge the year following the first year of life). Black stars indicate year classes present but not used in the recruitment analysis due to over representation in the sample set. 2015–16 sample period omitted from the figure due to underrepresentation of 0+ fish.

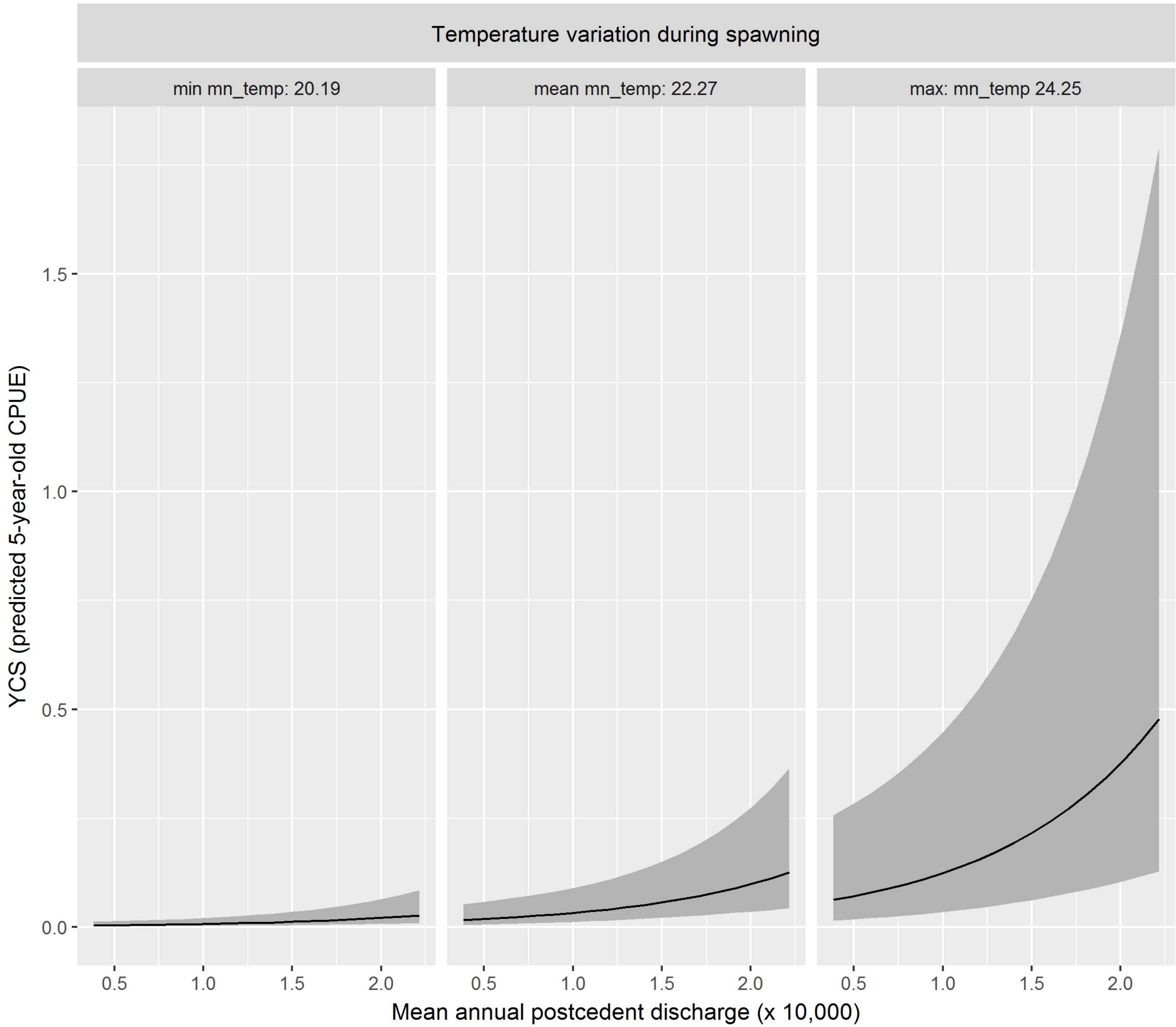

Figure 8: Predicted YCS (bottom; ±95 % CI) conditional on CPUE for five year old fish, average daily temperature during core spawning period (November and December) and average daily discharge the year following the first year of life (x-axis) over the ranges present during the study.

3.4 Discussion

Knowledge of the factors influencing age, growth and subsequent survival is fundamental to understanding recruitment and subsequent population dynamics of a species (Hastings 1990; Tyler and Rose 1994; Harris et al. 2013). This information is critical to help plan and implement river restoration programs such as environmental water delivery that have fish population outcomes as a key objective, especially those that target recovery of fish that operate over broad spatial scales (Stuart and Sharpe 2017). This study has provided important information on the recruitment dynamics of silver perch, a species which is nationally endangered, whose populations are in need of restoration, and which is currently targeted as a beneficiary of environmental water delivery.

Our assessment of age structure data, collated over a number of years and a broad range of environmental conditions, provides further evidence that silver perch, when occupying a river reach such as the mid-Murray (with perennial flowing water extending over a broad spatial scale), will recruit in most years, irrespective of the magnitude of flow. In our data from the mid-Murray, year classes were present in years subject to both extreme drought and a range of flood events. This builds on the findings of Mallen-Cooper and Stuart (2003), who reported year classes associated with both overbank flooding and average within channel flow years, reflecting substantial flexibility in the recruitment strategy of this species.

In addition to our findings of silver perch recruitment frequency, this study has provided an insight into the conditions associated with variability in recruitment strength. Our analysis highlighted that YCS was highly variable and likely to be associated with covariates associated with river flow and temperature. Specifically, variation in YCS was best explained by the addition (to age-at-capture) of mean discharge (negative association) and temperature (positive association) during the core spawning period (November–December), as well as mean annual discharge the year following the first year of life (positive association). The strongest year classes of silver perch, which was more than ten times greater than average YCS, were therefore associated with low to average discharge and high water temperatures during November–December that preceded a year of extended high flows and widespread flooding. Conversely, one of the weakest year classes (2010–11) was associated with extended high flows (and widespread flooding) and low water temperatures during the core spawning period.

The positive association between YCS and water temperature during the core spawning period is, as hypothesised, likely to be linked to the positive association between spawning intensity and temperature reported in previous spawning studies. Spawning of silver perch in the Murray River is largely temperature cued, commencing in spring when water temperatures exceed 18°C (Gilligan and Schiller 2003; Koehn and Harrington 2005; Tonkin et al. 2007; King et al. 2009), with more than 20% of predicted maximum spawning occurring between 20°C and 25°C (King et al. 2016). Conversely, King et al. (2016) also found that the occurrence and abundance of silver perch eggs in the Murray River was positively associated with river discharge, which does not support our finding of a negative association of discharge during the core spawning season with YCS. We propose that this is likely to be a result of the 2010–11 year class, for which high flows and a hypoxic backwater event occurred in the reach during the spawning period of 2010, with well-documented negative impacts including the death of fish (particularly Murray cod) and crustaceans (e.g. King et al. 2012). More specifically to these results, the 2010–11 season has been the only year that silver perch eggs have not been detected as part of annual larval drift surveys of the Murray River at Barmah–Millewa Forest which have been conducted since 2003 (see Raymond et al. 2016). Further investigation of YCS from years with high discharge during the spawning season without associated blackwater is required to test this.

While the 2010–11 high flows and associated blackwater event appear to have negatively impacted both spawning and subsequent YCS, the presence of a large proportion of fish six or more years old indicates that these flows did not negatively impact juvenile and adult fish, but rather strengthened the 2009–10 year class. Although it is generally acknowledged that the highest rates of mortality are associated with egg and larval stages (Wootton 1998), for some species there may also be additional critical periods, including the juvenile (e.g. Shuter and Post 1990). Indeed, our results would suggest that the juvenile stage is one such critical period for silver perch. Specifically, we propose that increased survival of juvenile silver perch occurs during prolonged periods of high discharge and floodplain inundation, when there is an increase in both habitat and food resources. This conforms to predictions of several river productivity paradigms such as the flood-pulse concept (FPC) and its extensions (Junk et al. 1989; Bayley 1991; Junk and Wantzen, 2006; Tockner et al. 2000) which stress the importance of floods and flow pulses in which the rise and fall of water across the land–water boundary (‘shifting littoral’ zone) and increases organic carbon availability, increases the rate of decomposition and lower trophic order production, which in turn increases higher trophic level productivity, including fish (Junk et al. 1989; Bayley 1991; Tockner et al. 2000; Robinson et al. 2001). This was recently demonstrated for fish in the Murray River, where significant increases in the growth of Murray cod, trout cod *Maccullochella macquariensis* and golden perch in the 2010–11 season were documented (Tonkin et al. 2014). Indeed, the results of this study suggest that such growth responses by fish to this event were followed by increases in survival and subsequent year class strength. Like silver perch, a cohort of golden perch spawned in 2009–10, prior to the 2010–11 floods, significantly increasing the abundance of golden perch in the lower Murray River over subsequent years and continuing to dominate the population structure of golden perch in the lower and Mid-Murray River (Zampatti and Leigh 2013a, 2013b; Zampatti et al. 2017).

There is still some uncertainty in our model predictions, owing to low sample size and the restricted temporal scale represented by our sample set, which unfortunately frequently hinder investigations of recruitment dynamics for species that are both long-lived and rare (Tonkin et al. 2017a). Even with such uncertainty in our models, patterns in raw data for year classes still highlight our finding of frequent recruitment and strong year classes for years that precede major flooding events. Unfortunately, with much focus on spawning conditions and outcomes as a key indicator of ‘recruitment’ success, the processes associated with post-spawning survival are frequently dismissed or included as an afterthought when it comes to investigating and planning management actions to enhance the process of recruitment. The whole recruitment strategy of silver perch would therefore appear more akin to that described for species such as Macquarie perch or Murray cod, whereby recruitment can occur on an annual basis in regions with suitable hydraulic characteristics, variability in YCS is often associated with survival of juvenile cohorts, and non-recruitment is rare and associated with major disturbance events (such as high flows and resultant blackwater). Attention should therefore be given to post-spawning conditions associated with survival, recruitment and subsequent population dynamics in the mid-Murray.

The results of this study highlight the need to consider multiple processes when assigning species to recruitment guilds. Previous classifications of silver perch as a ‘flow recruitment specialist’ (Lake 1967; Gehrke 1997) or ‘flow-dependent specialist’ (Baumgartner et al. 2014a) due to observations linking flow with spawning (Mallen-Cooper and Stuart 2003; King et al. 2009) and (assumed) spawning related movement of adults (Reynolds 1983). We agree that increased recruitment is partly a result of increased flows, but in the mid-Murray the mechanism does not appear to be purely related to spawning, but rather linked to the survival of early life stage cohorts, just as it is for species such as Macquarie perch that are classified as ‘foraging generalists’ (Baumgartner et al. 2014a). Nevertheless, silver perch (like Macquarie perch) still require flowing water for spawning, and given the spatial scale over which this appears necessary (i.e. the mid-Murray river reach) do differ from most of the other species in this classification. In light of these findings there is a need to further investigate the recruitment dynamics of silver perch at sites with more variable flows conditions in the northern MDB.

3.5 Management implications

- Juvenile survival is a critical period silver perch. Recruitment strength is enhanced substantially by increased growth and survival of juvenile fish, particularly one-year-olds, during a subsequent flood.
- Conditions that promote growth and survival of juvenile fish include optimising productivity, habitat availability and dispersal opportunities for these fish are likely to enhance populations.
- Conditions which favoured silver perch spawning success in the mid-Murray River included a minimum daily water velocity above 0.45 m/s and a mean daily water temperature of 21.5–24°C during November–December.
- In addition to silver perch spawning metrics, there is a strong need to include annual recruitment objectives into environmental flow planning in the mid-Murray region. Therefore interventions aimed at enhancing productivity, habitat availability and dispersal opportunities of juvenile fish should be incorporated into annual environmental flow planning. Specific examples include:

- using environmental water to extend floodplain inundation events along the Murray River (e.g. at icon sites);
- providing connectivity with the Murray River and permanently flowing water in key tributaries and anabranch systems.

4 Movements of PIT-tagged silver perch in the Murray River

4.1 Background

Riverine fish can be highly mobile and undertake specific movements during their development through various life stages as a response to numerous intrinsic and extrinsic stimuli (Lucas and Baras 2008). Fish stocks in freshwater systems have undergone substantial declines as a result of the fragmentation and regulation of many of the world's rivers (Dudgeon et al. 2006). River regulation can have direct negative effects because the infrastructure disrupts the movement pathways essential for breeding and dispersal. Indirectly, reduced natural cues or poor water quality associated with river regulation can limit key movements through the absence of appropriate extrinsic stimuli (providing movement cues) or suitable habitats. Remediation tools commonly used to redress some of these issues include the installation of fishways, fish lifts and other engineered structures that facilitate both upstream and downstream movement of fish past barriers (Katopodis 2005). Water delivery through the provision of environmental flows can also reinstate natural cues for movement, because river discharge exerts a strong influence on the frequency and magnitude of riverine fish movements (Taylor and Cooke 2012).

Native fish abundances in the Murray–Darling Basin (MDB) are estimated to be at 10% of pre-European levels (Koehn et al. 2014a). Instream barriers and the loss of instream connectivity are major factors in these declines (Murray–Darling Basin Commission 2004; Koehn and Lintermans 2012). In the MDB alone, Arthington and Pusey (2003) reported 3600 weirs with up to 41% of individual river catchments being obstructed by instream barriers (Harris et al. 2016). This is particularly relevant because movement, not just migration, requires connectivity and is an essential component for spawning, feeding, survival of individuals, gene flow and recruitment of populations (Lucas and Baras 2008). Recognising this impact, a fish passage restoration program was instigated that aimed to restore fish passage to over 2300 km of the Murray River, through the construction of 14 new fishways at lock and weir structures (Barrett and Mallen-Cooper 2006; Baumgartner et al. 2014b).

Numerous large native fish species within the MDB exhibit some form of migration, although potamodromy (migrations that occur wholly within freshwater) is the most common (Baumgartner et al. 2010; Harris et al. 2016). Of the potamodromous species, golden perch, silver perch and spangled perch *Leiopotherapon unicolor* are often the most prevalent large-bodied species moving large distances, as both adults and juveniles (Reynolds 1983; White et al. 2011; Ellis et al. 2015). Often these large-scale movements are associated anecdotally with high-flow events (e.g. Reynolds 1983), although only more recently have these associations been quantitatively confirmed for some (golden perch), but not all, species (Koster et al. 2014; Koster et al. 2017). Silver perch are known to undertake movements during rising discharge in spring and early summer as adults and in late summer and early autumn as juveniles (Mallen-Cooper and Stuart 2003). Spring–summer movements are presumed to be associated with spawning (Reynolds 1983), while the summer–autumn movements of juveniles are presumed to be more associated with dispersal, particularly for fish 1–2 years of age (Mallen-Cooper and Stuart 2003; Baumgartner et al. 2014b). Nevertheless, beyond fishway trapping (Mallen-Cooper and Stuart 2003; Baumgartner et al. 2014b), and mark–recapture (Reynolds 1983), published evidence of movement and scale of behaviour in silver perch is rare.

In this study we utilised an extensive passive integrated transponder (PIT) data logger/antenna network located on the Murray River at fishway sites (including all locks), and the corresponding existing tagged fish (Baumgartner et al. 2014b) to examine associations between movements of silver perch and abiotic conditions (stream discharge and water temperature). We hypothesised that movement rates both through and between fishways (representing persistent and directional movements), would be associated with a specific set of environmental conditions (e.g. increasing discharge and water temperature) that provide the necessary extrinsic stimuli for movements in this species.

4.2 Methods

This investigation explored movement data for silver perch collected from PIT reader systems, located at 14 fishways along the Murray River and five PIT reader systems installed in Victorian tributaries including the Loddon River and Broken Creek (Figure 9). PIT reader systems consist of a PIT tag (typically 23 mm long, implanted into the fish), which is an inert transmitting device with a unique number, a PIT reader/antenna that is used to read the PIT tag in situ, and a database (FishNet by KarlTech) that collates data from the PIT tag reader and is used to interrogated the PIT tag data. The PIT tag database also retains capture data such as species, length (FL, mm), weight (g), capture location and capture date, so that biological details can be monitored through time and the movement behaviours documented.

PIT tagging of fish was undertaken by a range of agencies but mostly by the Arthur Rylah Institute for Environmental Research (Department of Environment, Land, Water and Planning, Victoria), the South Australian Research Institute (SARDI) and the New South Wales Department of Primary Industries. Most tagged fish were captured by boat electrofishing or fishway trapping. Only fish longer than 150 mm FL were tagged, as they were considered not to be adversely affected by implanted PIT tags. Unfortunately this excludes fish which were 0 – 1+ (and some 2 year old fish) from the data. Most fish were tagged in the Murray River between Lock 1 in South Australia and Yarrawonga in Victoria, but fish were also tagged in tributaries and Murray River anabranches in New South Wales and Victoria.

It is important to note that there has been inconsistent operation of some of the PIT reader systems as a result of flooding, equipment failure, power faults, equipment upgrades and decommissioning of sites in the short-medium term for upgrades. However, most PIT reader systems along the Murray River have been operating consistently since June 2014; the exceptions are Lock 7 (June 2015), Lock 10 and Lock 15 (September 2014) and Lock 26 (Karl Pomorin, pers. comm.). During widespread flooding in the Murray River in 2010–11, several readers were inundated and failed, so there is a high chance that some movement data was missed from 2011 to 2014. Further, during flooding, weirs were often removed from the Murray River and during these periods fish had unhindered movement (i.e. not through the fishway) along the mainstem of the Murray and therefore were not likely to be recorded as fish movements in the data. Fish can also pass through the lock chamber (rather than through the fishway) as boats pass through. The tagged fish population will also have a natural mortality and emigration out of the study area, so the percentage of fish recorded (as a proportion of the tagged population) on the FishNet database is likely to be unclear.

PIT tag data were extracted from the FishNet database (http://fishnet.karltek.com.au/FishNet/login.php) on 19 January 2017. Capture and detection data was extracted using the predefined queries on FishNet. Water temperature and stream discharge were supplied by the Murray–Darling Basin Authority. Data was explored using basic descriptive statistics generated in Microsoft Excel. Movement detection data was summarised into monthly intervals for ease of interpretation and because of low detection rates (note that detection data was assumed to be independent between months which resulted in the same fish being detected between months). Movement distances were derived from fish that undertook multi-lock journeys, or movement between two or more Locks separated by a known distance. Movement distances were cumulative and regardless of directionality.

Capture data locations (latitude/longitude) were plotted on ArcGIS, and a near neighbour analysis was completed to determine the number of fish tagged within a 5 km radius of every 100 m grid point along the river. The resulting raster data output was then classified into 10 quantile classes for ease of graphic interpretation and for displaying tagging effort across the study area.

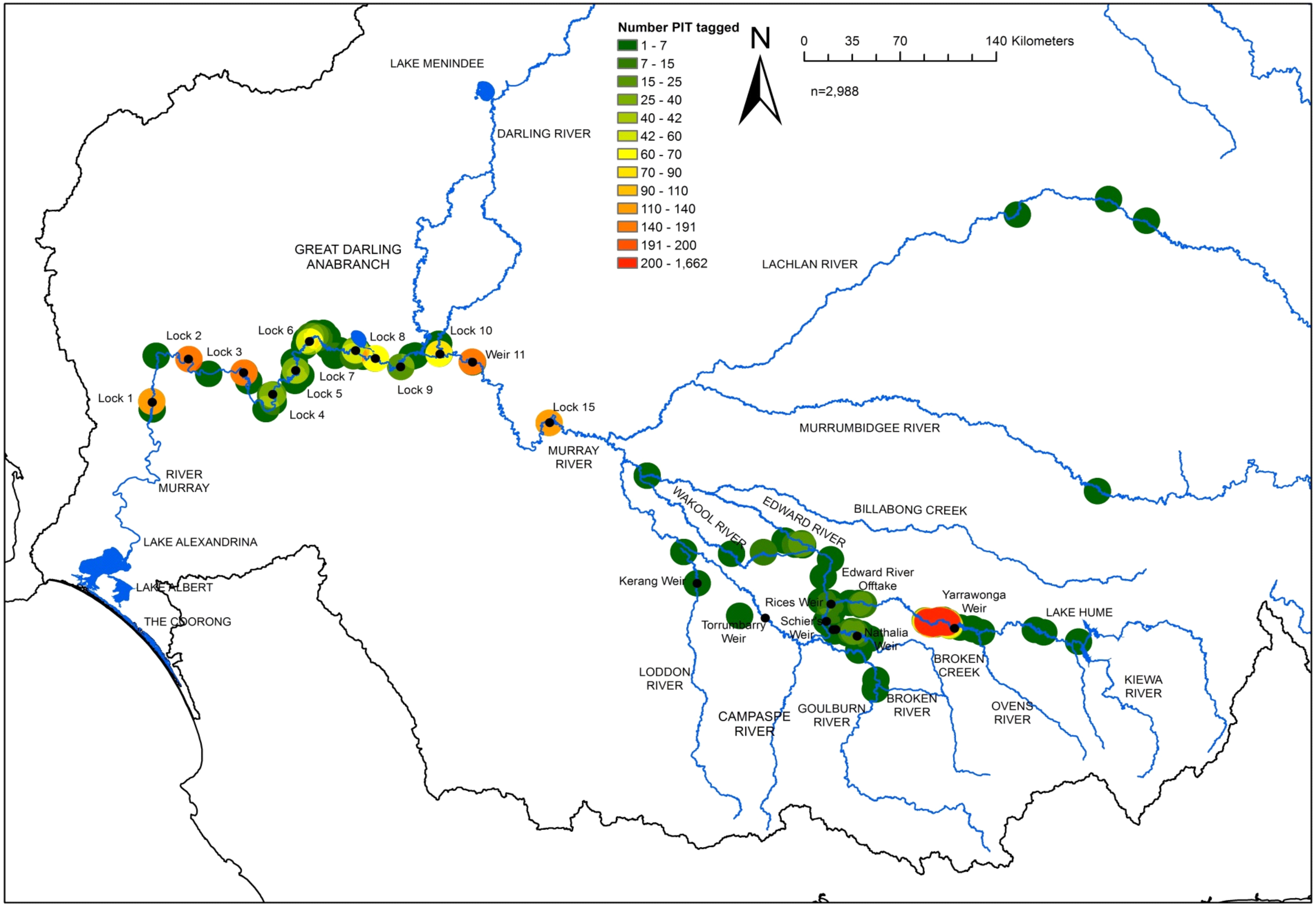

Figure 9: Number of silver perch PIT tagged in the southern Murray–Darling Basin, with the location of locks indicated.

4.3 Results

A total of 2987 silver perch were PIT tagged in the Murray River and its tributaries between 2002 and 2016 (Figure 10). Fish ranged in size from 150-533 mm (mean 345 mm, median 353 mm). A total of 1691 silver perch were weighed, with weights ranging from 48–1772 g (mean 571 g, median 561 g).

Silver perch were tagged in the Murray River between Lock 1 at Blanchetown and Lake Hume at Albury-Wodonga, a 1713 km length of river (Figure 9). The majority of fish (55.8%) were PIT tagged downstream of Yarrawonga. Fish have also been tagged in the Edwards–Wakool systems, Goulburn-Broken system, Loddon, Lachlan Rivers and Murrumbidgee Rivers. A total of 471 (15.8% of 2987) silver perch were recorded on at least one PIT reader system over the study period. The length-frequency distribution of fish recorded on a PIT tag reader was similar to the PIT tagged population (Figure 10), however the majority of movements were by fish > 300 mm long (noting that fish under 150 mm long were not tagged). The maximum recorded movement of a PIT tagged silver perch was 1198 km between Lock 3 and Lock 26 (Torrumbarry weir), however the majority of multi-lock movements were less than 600 km (mean 301.2 km, minimum 29 km) (Figure 11). No noticeable patterns were present in the raw data linking movement distance with fork length for PIT tagged fish (Figure 10). Mean monthly detections generally increased at Locks 8, 9, 10 and Yarrawonga during the warmer months (spring-summer) (Figure 12 and Figure 13). The number of detections at Yarrawonga increased substantially during the flood of 2010/11. This same pattern was not detected at Locks 8 and 10, during the same period, primarily due to weir removal. Lock 9 did show an increase in the detection rate before/during weir removal. The movements of four fish that made long distance multi-lock journeys were plotted (Figure 14). Fish mostly moved upstream from spring–autumn, potentially in association with increasing discharge.

4.4 Discussion

The data presented here provides some preliminary observations on the relationships between silver perch movements through fishways, long distance (multi-site) movements, flows and temperatures. Silver perch exhibited large-scale movements of up to 1,200 km during the period of investigation. These movements were often in conjunction with large flow events, including over-bank flooding, a result consistent with previous observations (Reynolds 1983). Additionally, this data provides evidence that newly constructed fishways are providing movement opportunities for silver perch resulting from increased riverine connectivity in the Murray River. Given that barriers to movement and altered timing and frequency of flows are implicated in the declines of this threatened species (Lintermans 2007) movements of this scale demonstrate the importance of landscape scale river connectivity, which by necessity requires inter-jurisdictional (and agency) management. This is particularly so for a system like the Murray River which, with complex river-floodplain systems covering >1,000,000 km2, has highly variable river flows (Walker 1985), a high water demand (Walker and Thoms 1993), and abundant instream barriers restricting movement (Arthington and Pusey 2003).

Prior to the construction of fishways on the locks and weirs of the River Murray, Reynolds (1983) documented movements of golden perch, Murray cod and silver perch past weirs along the Murray suggesting that movement was largely via boat lockage’s and during weir drown-out from flooding flows. Data presented in this investigation provides direct evidence that fish are using the newly constructed fishways along the Murray River, undertaking longitudinal migrations. This evidence is important for justifying the expenditure in this highly successful restoration action (Baumgartner et al. 2014b). Restoring movement between resource patches and fragmented populations is vital to improve population viability and recovery for silver perch (Clunie and Koehn 2001).

The movement data presented here are largely for sexually mature silver perch (i.e. 3+ years of age). Additional evidence presented by others suggests that large-scale movements in the Murray River, including and fishway passage, is not limited to adults of this species. For example, Mallen-Cooper (1999) and Mallen-Cooper and Stuart (2003) identified regular dispersal/colonisation movements of 1+ and 2+ cohorts through Torrumbarry weir fishway. Collectively, these results indicate that movement and dispersal are important components at various stages of this species’ lifecycle, and that unhindered movement of immature fish may be essential for successful recruitment into tributaries of the Murray River, and for overall population expansion.

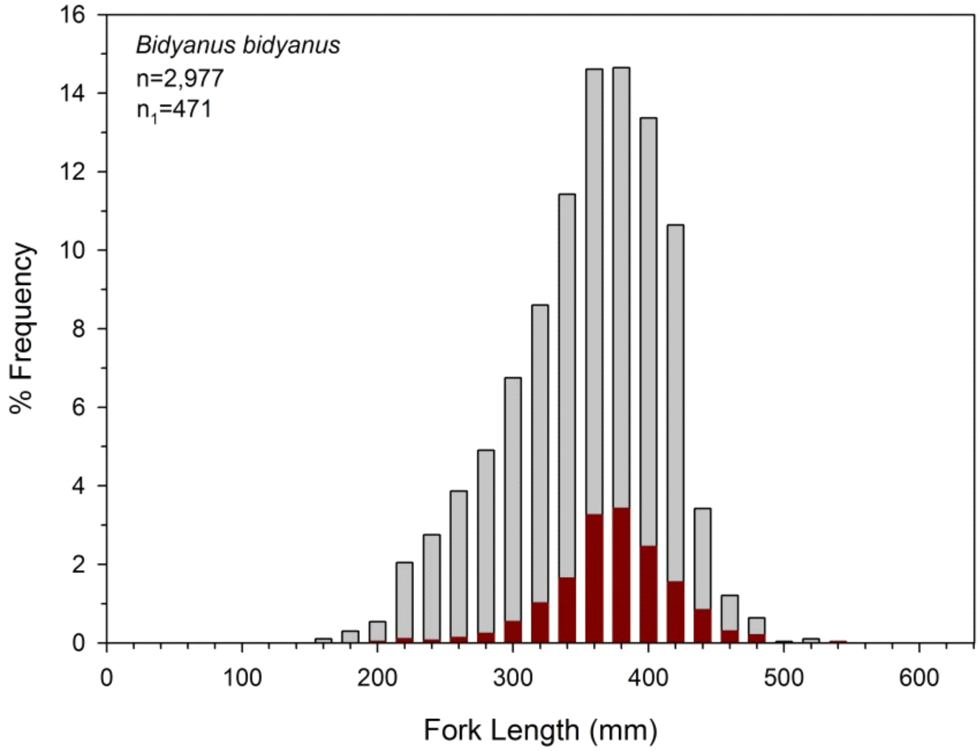

Figure 10: Length-frequency of PIT tagged silver perch (grey) and those that have been recorded on a PIT reader system (dark red).

n = number of PIT tagged fish. n_1 = number of PIT tagged fish recorded on a PIT reader system.

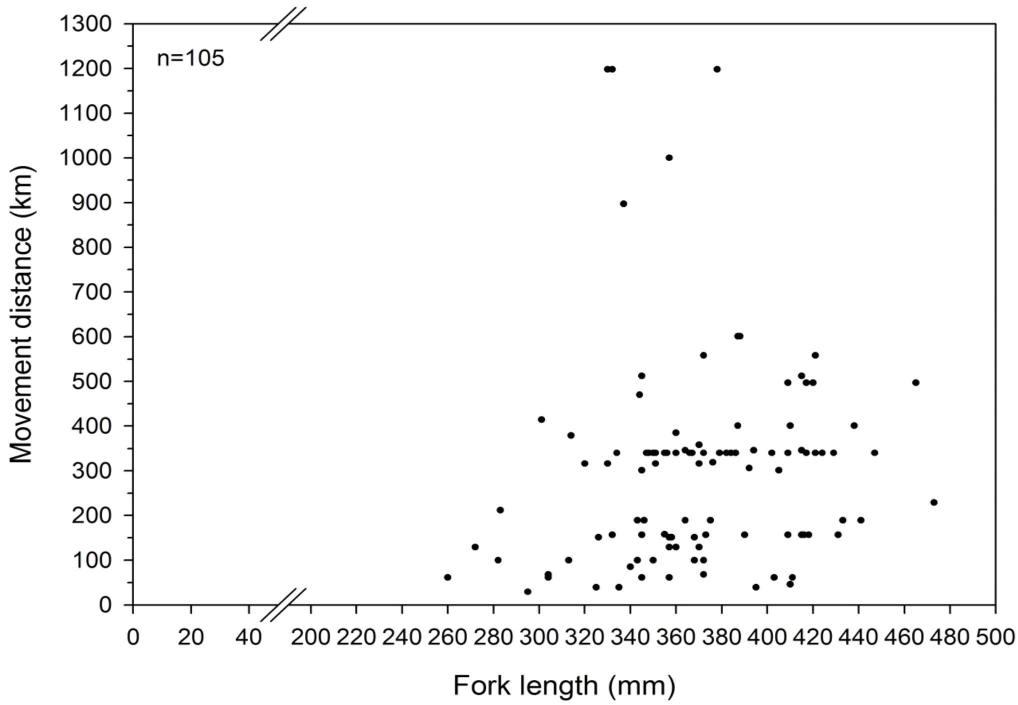

Figure 11: Distance moved by silver perch that moved through multiple fishways plotted against fish fork length.

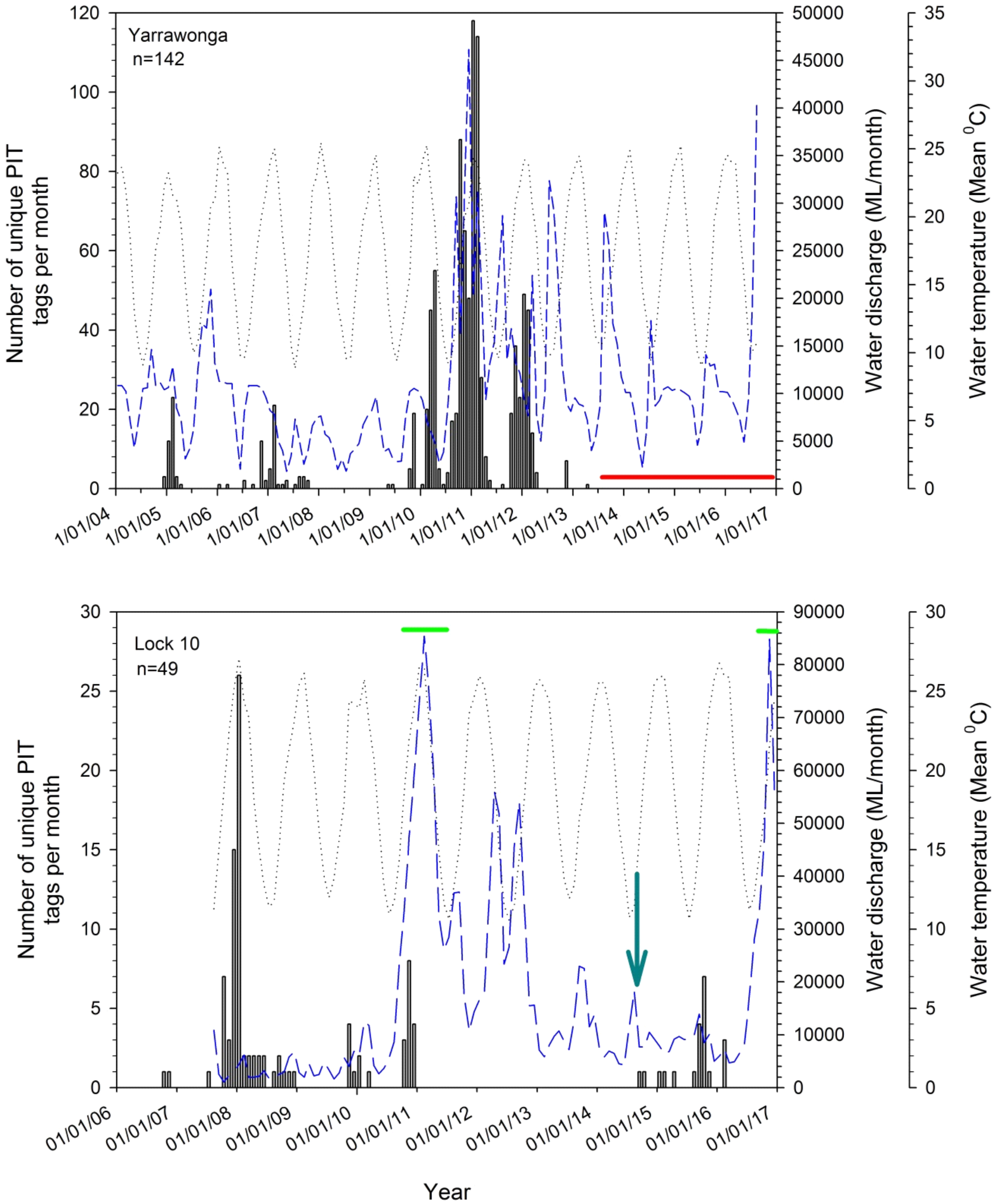

Figure 12: Number of unique PIT tags per month with mean monthly water discharge (blue dashed line) and water temperature (grey dotted line) at Yarrawonga (top) and Lock 10 (bottom).

Light green line indicates when weir was removed. Dark green arrow indicates consistent PIT system reads. Red bar indicates when the PIT system was not working.

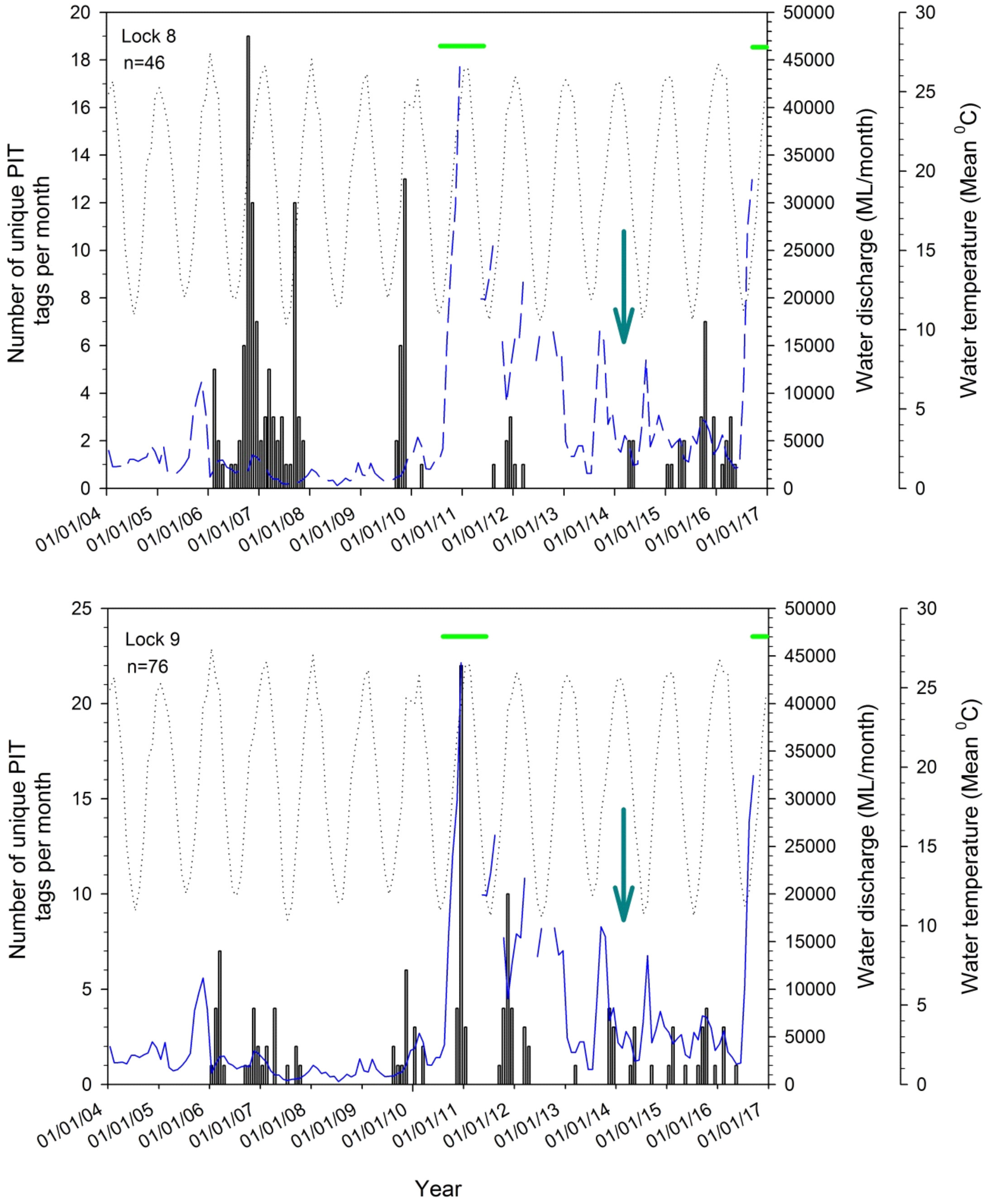

Figure 13: Number of unique PIT tags per month with mean monthly water discharge and temperature at Lock 8 (top) and Lock 9 (bottom).

Light green line indicates when weir was removed. Dark green arrow indicates consistent PIT system reads.

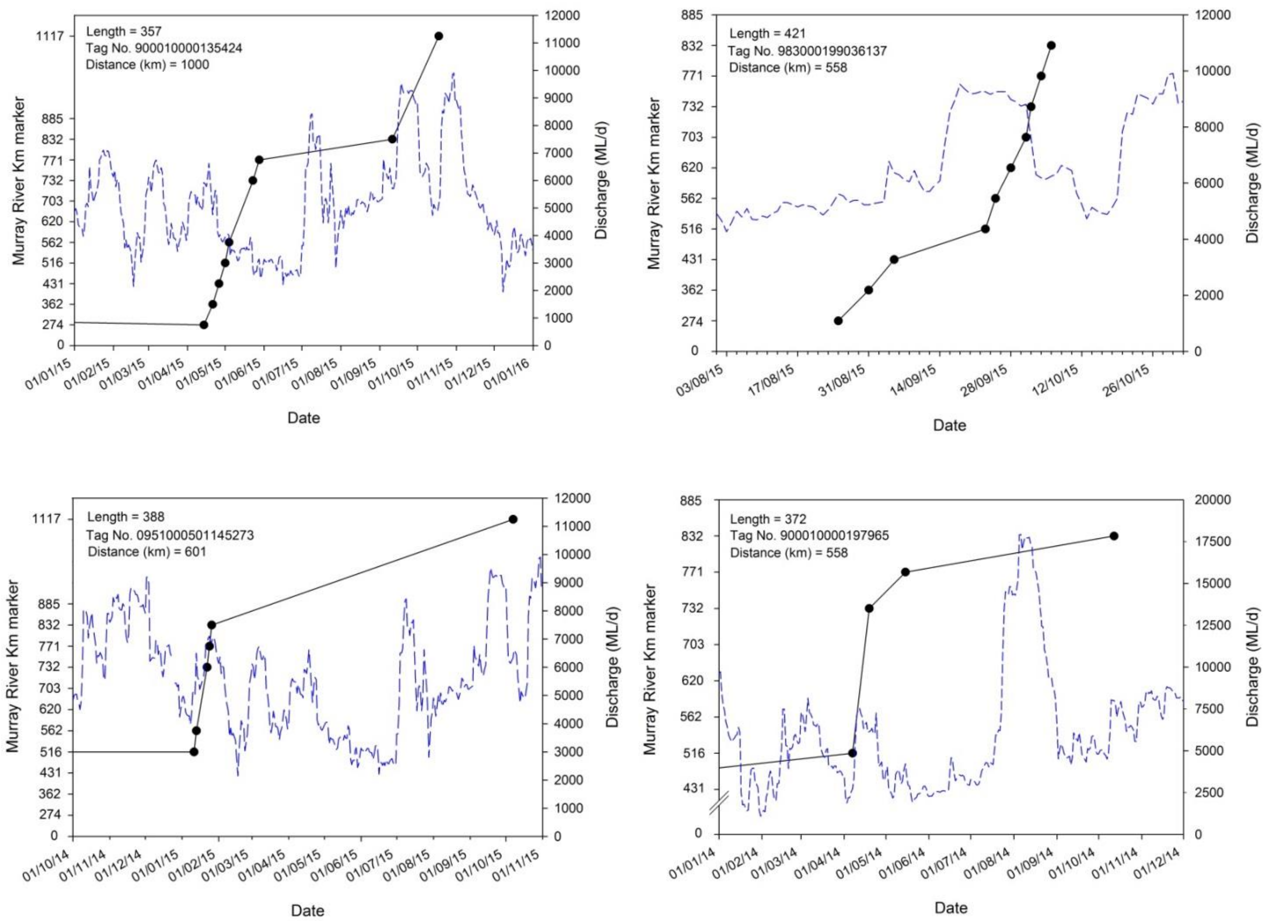

Figure 14: Examples of long distance movements of four silver perch in the Murray River.

Note: not all fish were recorded moved through each fishway, some may have passed through the Lock chamber.

Future PIT tagging programs should therefore try to target immature fish to help clarify the extent of migratory behaviour and motivation for doing so. Movement of ectothermic animals often reflects cyclic seasonal patterns (Helfman 2007), and the fishway detection rates documented during this investigation generally followed a pattern of increasing movement during warmer water temperatures and decreasing during cooler temperatures. These movements of predominantly sexually mature fish coincide with the known spawning window of the species (typically October-January with a December peak; King et al. 2013). Further, King et al. (2016) identified that the probability of spawning in the species increases with increasing discharge. We also documented elevated detection rates during within-bank river rises and during flooding for the Yarrawonga fishway. Specifically, the highest rates of detection at Yarrawonga Weir and to a lesser degree, Lock 9, occurred during the 2010/11 high flows, with this movement lasting from spring through to late autumn. These detection rates over this period generally tracked the magnitude of discharge. Such movement behaviour during the spring and early summer period could be associated with spawning (King et al. 2016). Despite a lack of direct evidence in this investigation, it has been proposed such upstream movement would be advantageous for spawning fish to move upstream to allow for downstream drift of eggs and larvae (Koehn et al. 2009). Moving upstream could also be resource-based, as riverine systems, like most natural systems, have patchy resources and finding resource rich patches can only be achieved through exploratory movements.

Whilst our exploration of fish movement data has indicated a general trend in the number and magnitude of silver perch movements being associated with large flooding events, we also documented a number of individual fish movements that were initiated by small river level rises. Substantial flexibility in the flow-ecology relationships has previously been documented for golden perch, and to a lesser extent silver perch (e.g. Mallen-Cooper and Stuart 2003; Balcombe and Arthington 2009). It is unlikely that overbank flooding alone is required to stimulate essential movements, reproductive activity and subsequent population recruitment. Rather, it may be that low-levels of spawning and/or recruitment occur in moderate flow years and high levels of recruitment are associated with flood events (see Chapter 3). As such, silver perch represents an excellent candidate species for water delivery options and the use of small river rises to stimulate fish movement should be investigated further. We also suggest that the current data should be collated and more formally analysed to account for periods when PIT reader systems were not effectively logging fish movements (i.e. equipment failure, power faults, weir removal during flooding) to increase predictive power of the findings. The data presented here demonstrates that silver perch undergo long-distance migrations using fishways to pass weirs along the Murray River. Completion of the fishways at all weirs along the Murray River (and elsewhere in the MDB) will improve connectivity for silver perch (both adults and juveniles), thereby improving population viability and reducing fragmentation. Movement appears to be associated with warmer water temperatures and a rising river levels, but not necessarily requiring river flooding. Further research and modelling of movement data is required to formally quantify the role external stimuli have on the scale, timing and extent of movement responses exhibited by this species, to inform rehabilitative management options such as environmental flow delivery.

4.5 Management implications

Silver perch are highly reliant on riverine connectivity to complete migrations as adults and juveniles. There is improved connectivity in the mid-Murray from the recent Murray fishway program, but a further prioritisation of barriers in northern Victoria and southern NSW is likely to be important for enhancing populations in tributaries, especially in the mid-Murray (e.g. Loddon, Goulburn, Gunbower, Murrumbidgee, lower Darling, Edward-Wakool).

Silver perch occupancy in tributaries is likely to be reliant on flows (including environmental flows) that include: perennial flows over large spatial scales, and within-channel tributary inflows to the Murray to attract dispersing juveniles in late spring and summer/autumn.

A further analysis of existing data and research which quantifies links between juvenile movement and flows is required to help inform flow delivery planning.

5 Processes influencing population dynamics of silver perch in an off-channel lake: A case study for Lake Boga

5.1 Background

The use of off-stream habitats by large-bodied native fishes in the MDB is not well documented (Humphries et al. 2009). While the floodplains and off-channel waterbodies have been considered to be highly productive and conducive to high levels of survival and growth rates of young fish (e.g. Bayley 1991; Tonkin et al. 2017b), evidence for this in silver perch is scant (see Appendix 1). Juvenile life-stages of golden perch use such habitats as 'nursery' areas in the Darling system (Sharpe 2011; Ebner et al. 2014; Koehn et al. in prep.) but there is no similar evidence for silver perch. The use of such habitats is a key knowledge gap in the lifecycle of silver perch (see Appendix 1 from Koehn et al. in prep.).

Lake Boga is the most northern of the Kerang Lakes, situated approximately 40 km north west of Kerang in Northern Victoria (Figure 15). Until the mid-1960s Lake Boga was part of the Torrumbarry Irrigation System, relying on floodwaters from the Avoca River and surplus flows from the Murray River during high flow periods. Lake Boga now forms part of the Victorian Mid-Murray Storages which includes Kow Swamp, Kangaroo Lake, Lake Charm and Lake Boga, with a combined active capacity of nearly 58 000 ML (Goulburn-Murray Water 2017). Despite a relatively high likelihood of drying during prolonged drought periods, the lake has been stocked annually since 2012 with golden perch and Murray cod as part of Victorian Fisheries 'Building Northern Native Fisheries' program.

An independent fishery survey was conducted in April 2016 to assess the outcomes of the Native Fisheries program. Results from this survey included the unusual recording of 74 adult silver perch, more than nine times the abundance of stocked golden perch and Murray cod combined (ARI, unpublished data). Unlike the target stocked species, there were no records of silver perch having ever been stocked in the system. Fish could have entered the lake as drifting eggs or larvae, or as juveniles or adults. Conversations with water operators (Goulburn-Murray Water), waterway managers (North Central Catchment Management Authority) and ecologists concluded that it was unlikely that larvae or eggs drifted in from the Kerang Lakes, and immigration by juveniles or adults from the Little Murray River was more likely. Furthermore, the latter would only have been possible during the 2010–11 flood period. This study examines the age structure and otolith microchemistry of silver perch in Lake Boga in 2016, which provide additional insight into the timing of occupancy and origin of silver perch in the system.

5.2 Methods

Lake Boga connects to the surrounding waterways via a series of inlet channels from the Kerang Lakes (predominantly the no. 7 main channel from Kangaroo Lake); the Lake Boga outfall channel into the Little Murray River downstream of Fish Point (Figure 16); and the No. 1/9 channel also connecting with the Little Murray River. Following on from the initial survey which identified the presence of silver perch in the Lake, additional surveys were conducted in June 2016 to collect fish for further investigation of age structure and natal origin. Boat-mounted electrofishing was undertaken across all available habitats in the Lake. All fish were measured for fork length (mm) and weight (g) and otoliths removed for age determination (as per the methods described in Chapter 2.2) and microchemistry analysis to investigate natal origin and movement history (See Zampatti et al. 2017 for full description of methods). Briefly, laser ablation – inductively coupled plasma mass spectrometry (LA-ICPMS) was used to measure $^{87}Sr/^{86}Sr$ in the otoliths of fish. We analysed $^{87}Sr/^{86}Sr$ from the core to edge of otoliths from a subsample of age 6+ (n = 6) and 7+ (n = 5) fish. We compared these transects to water $^{87}Sr/^{86}Sr$ measured at sites throughout the Murray River and its tributaries from 2011–2016 (see Zampatti et al. 2017). To elucidate the timing of movement between regions with distinct water $^{87}Sr/^{86}Sr$ (or alternatively, temporal variability in the water fish are inhabiting) we compared otolith chemistry to age, as determined by counts of otolith annuli.

Overall differences in length and weight of similar aged fish between Lake Boga and fish collected in the Murray River (where sample sizes were adequate) was also explored using the Kruskal–Wallis test, then if significant, Mann–Whitney U-tests were used to identify pair-wise differences.

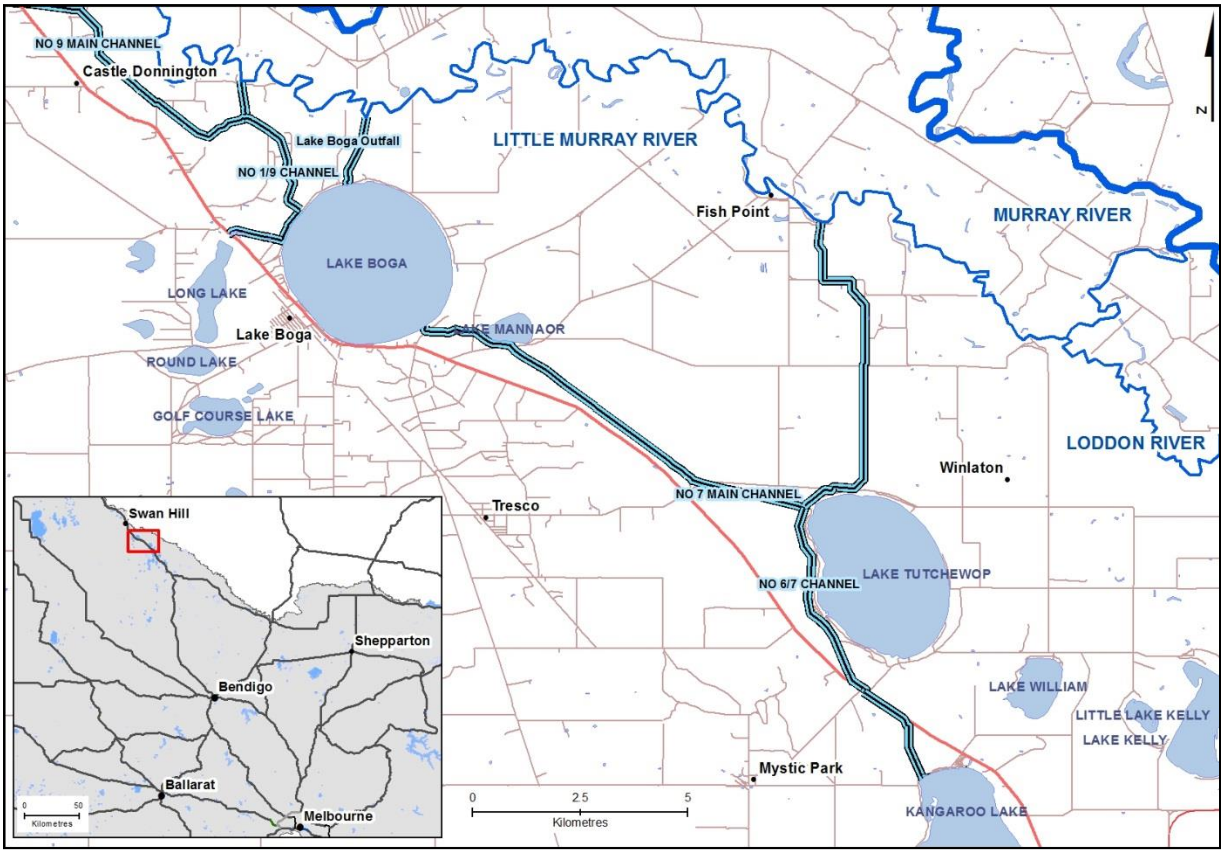

Figure 15: Location of Lake Boga in Victoria, showing relevant tributaries and channels.

Figure 16: Lake Boga outfall channel during a flood event in December 2016.

5.3 Results and discussion

A total of 42 silver perch were collected from Lake Boga in June 2016. All fish were large: 352–432 mm in length (FL) and 760–1390 g in weight (Figure 17a). They were aged between 6+ (88% of the sample) and 8+ years (Figure 17b). This dominant year class was from the 2009–2010 spawning season (the same year class that dominated the samples from the Murray River; see Chapter 3). This age structure, when considered with the hydrological history of Lake Boga (where the Lake and associated channels were only connected during the 2010–11 season) supports our hypothesis of fish entering the Lake via immigration, rather than drifting in as eggs and/or larvae. Specifically, colonisation occurred primarily when fish were juveniles aged 1+ with a small number of fish aged 2+ and 3+ also immigrating into the Lake during the flood event.

The michrochemistry results support these data. The sub-sample of silver perch collected in Lake Boga which were analysed for otolith $^{87}Sr/^{86}Sr$ demonstrated a natal (otolith core) $^{87}Sr/^{86}Sr$ ratio characteristic of water 87Sr/86Sr in the mid-Murray River. This signature was retained for the first year of life (Figure 18). In the 2nd year of life (age 1+), otolith $^{87}Sr/^{86}Sr$ gradually changes to ratios uncharacteristic of the mid-Murray, and this ratio is retained until the otolith edge (point of capture; Figure 18). Data is unavailable for water $^{87}Sr/^{86}Sr$ in Lake Boga; nevertheless, $^{87}Sr/^{86}Sr$ at the otolith edge represents the water $^{87}Sr/^{86}Sr$ at a fish's capture location (i.e. Lake Boga), and stability in this ratio following transition from the mid-Murray in the second year of life likely indicates residence in this habitat from age 1+ to 6+. Age-related profiles of otolith $^{87}Sr/^{86}Sr$ indicate that silver perch collected in Lake Boga in 2016 transitioned from the mid Murray to Lake Boga in spring–summer 2010–11, in association with widespread flooding throughout the southern MDB.

A comparison of length and weight data for 6 year old fish captured in the Murray River and Lake Boga revealed fish in Lake Boga were significantly longer and heavy than fish of the same age collected from both the lower and mid-Murray (Figure 19; $p < 0.001$). This suggests that fish that are able to access off-channel habitats like Lake Boga can benefit from increased growth rates, probably through processes linked to increased productivity or, reduced intraspecific competition for resources. This pattern, as suggested in Chapter 3, also conforms to predictions of several river productivity paradigms such as the flood-pulse concept (FPC) and its extensions (Junk et al. 1989; Bayley 1991; Tockner et al. 2000; Junk and Wantzen, 2006). Indeed, this link between growth rates, recruitment and productivity has also been demonstrated for lacustrine populations of Macquarie perch *Macquaria australasica* during times of filling and refilling and is thought to reflect trophic upsurge (e.g. Cadwallader and Douglas 1986; Tonkin et al. 2014). Such rapid increases in resource availability are likely to result in immediate reductions in intraspecific competition, a common factor governing density dependence and the regulation of fish populations (Jonsson et al. 1998; Tonkin et al. 2014).

While the source–sink nature of silver perch occupancy in Lake Boga make their occupancy of this site uncertain (as it will be governed by cycles of extreme flooding and drying), the timing of occupancy and age structure of fish in the Lake has provided a rare case study which demonstrate the range of processes that interact to influence the population demographics of the species. Specifically, the occupancy of silver perch in Lake Boga is largely a result of juvenile (predominantly 1+ aged fish) immigration from the mid-Murray (primary source population for the southern MDB) during a large, prolonged period of floodplain inundation. Once in the lake, fish encountered conditions which facilitated growth rates that exceeded those of fish occupying their natal source (the Murray River).

5.4 Management implications

- Off-channel floodplain habitats could act as silver perch recruitment and grow-out zones, where juvenile fish can undergo rapid growth, before returning to the Murray River.
- There is potential to enhance connectivity to these habitats, particularly during the spawning period (November–December) to refine knowledge and operational aspects of integrating river and lake flow management.
- Reconnection events (return flows) should also be considered in flow planning to return juveniles and / or sub-adults to the system to complete their lifecycle (e.g. riverine spawning).

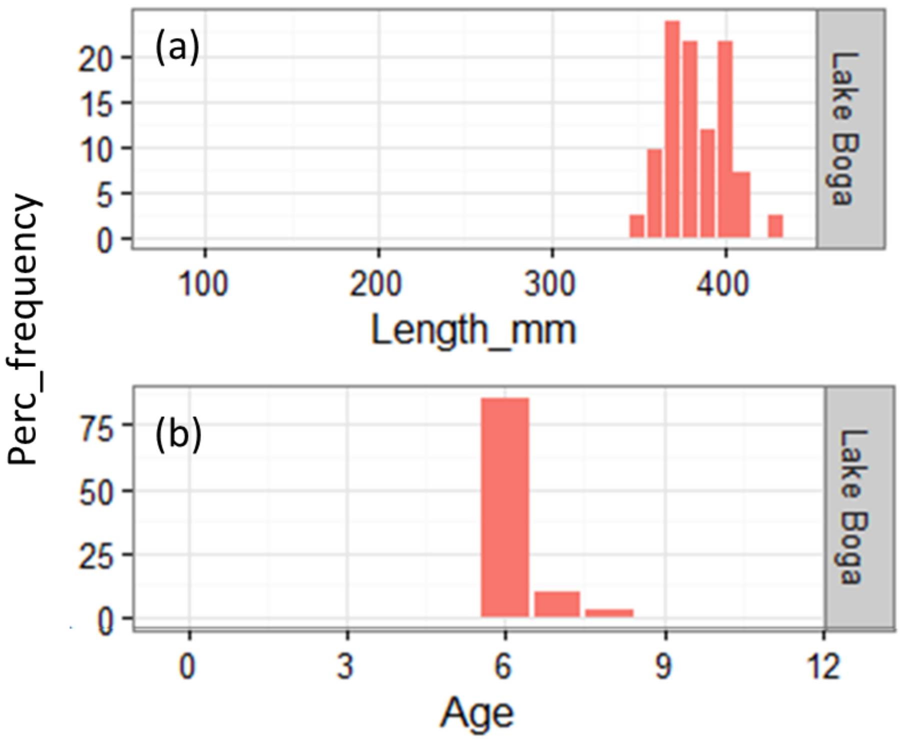

Figure 17: (a) Length (fork length) and (b) age (years) frequency histogram of silver perch collected from Lake Boga in June 2016 (*n* = 42).

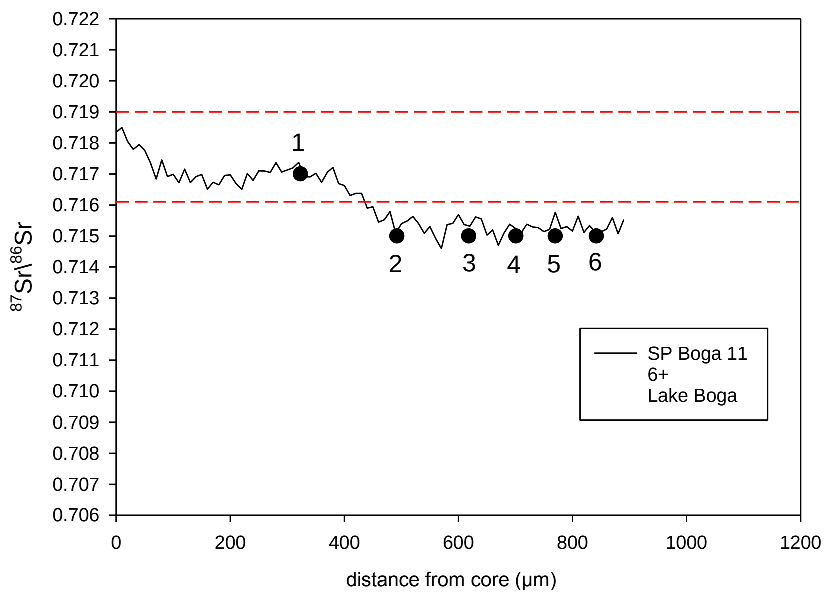

Figure 18: An individual age-related life history profile of $^{87}Sr/^{86}Sr$ from the core to edge of an otolith from an age 6+ silver perch collected from Lake Boga in 2016.

Red dashed lines represent the range of water $^{87}Sr/^{86}Sr$ in the mid-Murray River (Lock 11–Torrumbarry, c. 0.7160–0.7190). Closed black circles represent age as estimated by otolith increments.

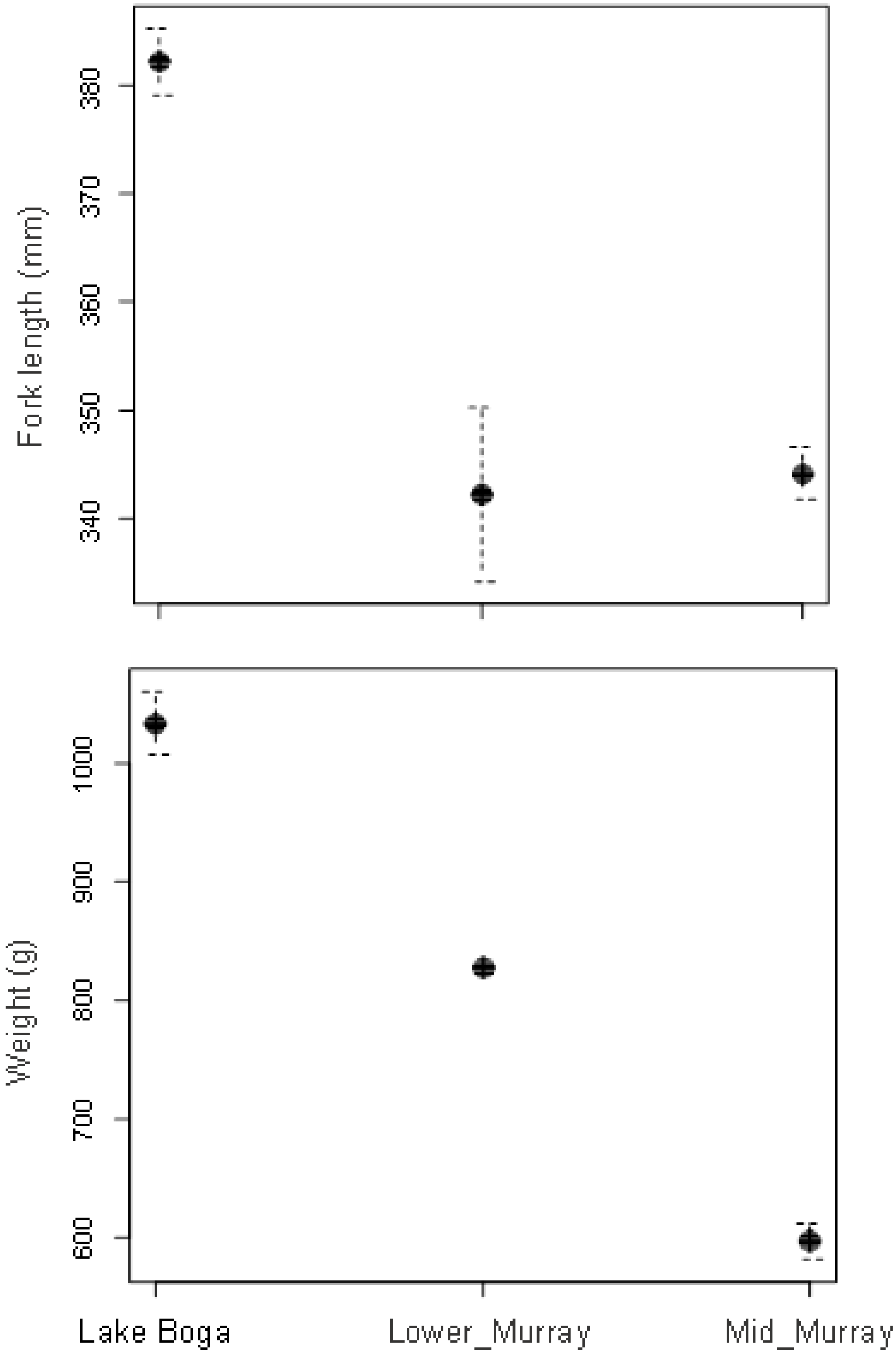

Figure 19: Mean (±SE) length and weight of 6-year-old silver perch collected from Lake Boga (*n* = 36), lower Murray (*n* = 8) and mid-Murray (*n* = 69) in 2016.

6 Conclusion and management recommendations

Like many fish species from the MDB, whilst flow clearly plays an important role in governing specific processes such as spawning and movement behaviour for silver perch, but there remains uncertainty around the role of flows as a driver of population dynamics. This makes the planning and delivery of some river restoration actions, particularly environmental flows aimed at enhancing native fish populations challenging.

This study has provided support for some of the existing knowledge on silver perch ecology and importantly, provided additional insight into the role of flows in governing recruitment strength, movement and subsequent population dynamics of silver perch in the mid-Murray River. Specifically:

- Our exploration of silver perch distribution and population structure reiterates the importance of the mid-Murray River reach for the species in the southern connected MDB. Specifically, the mid-Murray River had the greater density of fish, and most balanced size- and age structure as compared to the lower- and upper Murray River.
- In comparison with Murray cod or golden perch, very few fish appear to live beyond seven years of age, making annual recruitment a strong requirement for the conservation and rehabilitation of silver perch populations.
- Recruitment of silver perch, if occupying a river reach such as the mid-Murray (with perennial flowing water extending over a broad spatial scale), will occur in most years (under both extreme drought and flood). Years subject to broad scale blackwater events are perhaps the only years which will not yield recruits. High flow events do however appear to have significantly improved survival, movement and dispersal of juvenile and adult fish.
- Recruitment of silver perch in the mid-Murray was highly variable, with mean discharge (negative association) and temperature (positive association) during the core spawning period (November and December); as well as mean annual discharge the year following the first year of life (positive association) the best predictors of year class strength. As such, the strongest year classes of silver perch were associated with low to average discharge and high water temperatures during November and December, which were preceding a year of extended high flows and widespread flooding.
- Silver perch, as previously described, move over a large spatial scale (up to 1,200 km for an individual fish), with the latest data increasing the scale of movement by an order of magnitude. This finding highlights the fact that fish populations do not necessarily conform to artificially constrained management units and demonstrates the importance of inter-jurisdictional management.
- Silver perch are using the fishways along the Murray River, undertaking extensive longitudinal migrations. Movement increased substantially during river rises both within-bank and during flooding, with the highest rates of detection and multi-site detections occurring during periods of high magnitude and extended flooding.
- Silver perch appear to benefit from access to productive off-channel habitats such as Lake Boga through higher growth rates.
- For large-bodied native fish, despite much focus on spawning as a key indicator of population 'success', it is also the processes associated with subsequent survival and dispersal after this stage that can lead to recruitment into populations. As such, these factors need to be a major consideration for sustaining and expanding the silver perch population in the southern MDB. As per the specific recommendations presented in each chapter, our collective exploration of movement, distribution and recruitment indicate optimising productivity and dispersal opportunities for silver perch (particularly juveniles) is likely to enhance the population.
- A combination of restoring connectivity using managed flows to enhance movement cues (including environmental water) and expand habitat availability; as well as infrastructure to increase site access needs to be the focus for the southern connected MDB (Stuart and Sharpe 2017). For example, using environmental water to extend floodplain inundation events along the Murray River (e.g. icon sites) and provide coordinated flow pulses (between river systems) which extend over broad longitudinal spatial scales will allow fish to access tributaries and anabranch habitats in connection with flows in the mid-Murray River reach, thus enhancing survival and recruitment. Such planned flows, together with new fish passage facilities (e.g. on the lower Murrumbidgee River) could assist the expansion of fish from the Murray River more broadly across the southern MDB.

- The new information presented in this study could be further supplemented by additional research. In particular:
- Research that consider extensive spatial and temporal variability to quantify population responses to flow.
- A more intensive survey of the mid-Murray reach, especially below Euston Weir, in early summer (following a non-blackwater season) to determine why there were few young of year in this reach – e.g. poor recruitment or a detectability issue.
- Repeat sampling to increase sample size and temporal scale to fill in gaps and address the uncertainty in our model predictions.
- Publish evidence of movement and scale of behaviour in silver perch as there is a lack of scientific literature on this subject.
- Future PIT tagging or telemetry programs that target immature fish to help clarify the extent of migratory behaviour and associated environmental covariates.
- Formally analyse the current PIT tag data so as to account for periods when PIT reader systems were not effectively logging fish movements (i.e. equipment failure, power faults, weir removal during flooding) to increase predictive power of the findings.
- Further research and modelling of movement data is required to formally quantify the role of external stimuli have on the scale, timing and extent of movement responses to inform rehabilitative management options such as environmental flow delivery.
- The outcomes of this study in addition to the learnings of work currently underway will be of particular importance for the refinement of the silver perch population model and increase the science and knowledge base for environmental flow management and the rehabilitation of populations of this species into the future.

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Appendix 1: Silver perch conceptual model*

Silver perch *Bidyanus bidyanus* (Mitchell, 1838)

General description

A large bodied, long-lived, omnivorous, schooling, river channel specialist that has drifting eggs and larvae stages (Rowland 2009). Silver perch continues to be a popular angling species and is also regarded as a good table fish. As such the species is widely cultured in hatcheries (Rowland 1994, 2004, 2009), both for the restaurant trade and conservation/recreational purposes. The latter has resulted fish stocked throughout the MDB as well as outside it's natural range. Categorised as having a mode 2 life history (Humphries et al. 1999) and is classified as a flow dependant specialist (Baumgartner et al. 2014).

Distribution and status

Once widespread over most lowland reaches of the MDB, it has suffered serious declines in abundance and range (Lintermans 2007: Trueman 2012). The greatest concentration of fish in the MDB is centred in the mid-Murray River (Yarrawonga to Euston), with lower numbers of fish occupying the Edward-Wakool, Lower Darling, Murrumbidgee, Warrago/Condamine, Victorian tributaries (Loddon, Campaspe, Goulburn, Ovens) with low numbers present in SA. Catches in the mid-Murray have declined considerably (by 94% at Euston) over a 50 year period (Mallen-Cooper and Brand 2007) and the species is now rare in the NMDB. Listed as critically endangered nationally, endangered in the ACT, vulnerable in Victoria (DSE 2013), New South Wales and SA (DEE 2017). Concern has been expressed over the status of this species for several decades with a recovery plan and supporting document written in 2001 (Clunie and Koehn 2001).

Taxonomy and similar species

There are low levels of genetic variation in wild populations of silver perch across the MDB (Keenan et al. 1996). Of the species considered in this paper, Silver perch is closest ecologically to golden perch.

Age, length, weight, growth, maturity

Maximum TL is 500 mm and weight around 8 kg (Trueman 2012); although more commonly up to 450 mm and 1.5 kg (Lintermans 2007). Long-lived; to 17 years in rivers (27 years in dam) and show variable growth, (Mallen-Cooper and Stuart 2003). In rivers, however, fish over age 8 are now relatively uncommon.

Habitat use

An obligate river channel specialist that occupies a range of habitats from large, faster flowing river reaches to the slow flowing, turbid waters of lower reaches and impoundments (Clunie and Koehn 2001; Rowland 1995). They appear to prefer open waters devoid of snags (Cadwallader and Backhouse 1983), although strong ordinations with river habitat occur (Raymond et al 2014). Often found in mid-channel, rather than along the banks (EO). Were once more commonly found in lakes, but this is now rarely so; exceptions include Menindee (NSW) and Lake Boga (Nthn Vic).

Fecundity and spawning

A sexually dimorphic species: males maturing at 3 years (250 mm) and females at 4-5 years (300 mm) (Mallen-Cooper et al. 1995; Mallen-Cooper and Stuart 2003; Lintermans 2007). In hatcheries, males mature at 2 years and females at 3 years (Rowland 2004). Fecundity high, up to 500 000 for a 2 kg fish (Lake 1967d) or 139 286 eggs/kg (Rowland 2004). Females remain highly fecund up to 10 years of age (Rowland 2009. Communal broad cast spawners with no parental care that seek flowing water (e.g. > 0.3 m/s) in river channel habitats in which to spawn, presumably to facilitate egg and larval drift downstream and maintain aeration (of eggs). As an aggregate spawning species, large schools form around a known spawning period, following upstream migration (Lintermans 2007; Koehn and O'Connor 1990; Clunie and Koehn 2001). Spawning occurs on multiple, separate, trigger events. These are needed for females to release all their eggs at once (CS), otherwise egg reabsorption may occur.

* From Koehn et al. in prep. (draft April 2017)

Temperature plays a significant role in the onset of gonadal development, maturation and spawning (Bye 1984). Spawning occurs over a protracted period from spring to late summer (mid-October to mid-February) in the SMDB (King et al. 2005; King et al. 2009a; Raymond et al. 2014) and October to March in the NMDB. In the mid-Murray River, spawning occurs in most years except during a severe blackwater event, even under more stable low flows (albeit in reduced numbers; Harris and Gehrke 1994; Humphries et al 1999; Gilligan and Schiller 2003; King et al 2005; King et al. 2016). Whilst spawning has previously been thought to be stimulated by changes (often small) in river levels during the aforementioned spawning period (Mallen-Cooper and Stuart 2003; King et al. 2009) In the mid Murray River, spawning is largely temperature cued, commencing in spring when water temperatures > 18°C (Gilligan and Schiller 2003; Koehn and Harrington 2005; Tonkin et al. 2007; King et al. 2009) with > 20% of predicted maximum spawning occurring between 20 and 25°C (King et al. 2016). King et al. (2016) also found the occurrence and abundance of silver perch eggs in the Murray River was positively associated with discharge and weekly temperature change and a negative association with increasing number of flood days in preceding 3 months. The species can spawn and recruit in non-flowing water such as hatchery ponds (G. Butler, NSW DEPI, pers. comm.).

Eggs are small (mean 1.2 mm diameter, range 0.7–1.3 mm; then 2.5-3.0 mm water hardened; Lake 1967b, Rowland 1984), non-adhesive, semi-pelagic (Merrick and Schmida 1984; Merrick 1996; Rowland 2009) and sink in the absence of current (Lake 1967). Specifically, Lake (1967b) reported that the fine mat-like chorion of silver perch eggs, readily collect small clay particles, causing eggs to have increased negative buoyancy and causing settling to the bottom in slow and still water. Indeed, Tonkin et al. (2007) recorded the greatest concentration of drifting eggs in the Murray River occuring close to shore and near the bottom - suggesting either increased spawning in these microhabitats, or more likely, a gradual settling of eggs in areas of lower water velocities. Eggs hatch within 30 to 36 hours, and have a two week larval stage (NSW DPI 2006). Induced fertilization rates of 84.5% and hatch rates of 76.8% have been recorded in hatcheries (Rowland 2004). Larvae commence feeding at yolk-sac absorption, 5-6 days after hatch (Rowland et al 1983). There is no evidence of direct use ephemeral floodplains for spawning or recruitment (King et al 2007; King et al. 2008).

Recruitment

Drifting egg (about 2 days) and larval phase is considered to be up to 15 days; NSW DPI 2006). Eggs and larvae deposited in weir pools and diversion channels are considered to have high mortalities (almost 100%) and no recruitment following drift into highly unproductive lakes (B. Zampatti, SARDI, pers. comm.). In the mid-Murray River, recruitment occurs in all years (Mallen-Cooper and Stuart 2003; Tonkin et al. unpublished data), presumably due to the spatial scale of lotic conditions during the spawning period whereby in most years (both dry and flood) water velocities exceed 0.4 m/s. Conversely, recruitment in the lower Murray River and Lower Darling River is episodic, and linked to high flow years which generate lotic conditions similar to those in the mid Murray River (B. Zampattii SARDI pers. comm.).

Dominant year classes have been associated with high flows in spring or summer that inundate floodplains and produce food for larvae (Lake 1967; Reynolds 1983; Gehrke 1992; Harris and Gehrke 1994), Nevertheless, a recent assessment of year class strength in the mid Murray River has highlighted that the strongest year classes within the mid Murray River are those which spawned during relatively stable in-channel flows (as per Mallen-Cooper and Stuart 2003; Clayton Sharpe pers. comm.) followed by large overbank flows (Tonkin et al. unpublished data).). There appears to be no recruitment in impoundments (LB). Recruitment of silver perch into northern Victorian rivers appear heavily reliant on connectivity with the mid Murray River to facilitate immigration of fish, particularly juveniles (B. Zampattii SARDI unpublished data). Survival rates from 40-80 mm is guestimated to be about 20%. Although widely stocked, there is little evidence of this being successful in rivers.

Movement, migration and dispersal

Regarded as a mobile species with good swimming abilities, but as there is limited information on movements; often assumed to be similar to golden perch. They do move large distances and most silver perch tagged in the lower Murray River moved upstream; one individual moved 570 km in 19 months (Reynolds 1983). Most movements for both adults and juveniles occur over a broad timeframe (October to April). Adult movements in spring are presumed to be associated with spawning (Mallen-Cooper ~1995). Juvenile movement, whereby tens of thousands of one year old fish have been recorded moving through fishways (Mallen-Cooper and Stuart 2003; Baumgartner et al. 2011; 2014), is thought to be an important dispersal mechanism. For example, a large number of silver perch recently found occupying Lake Boga in Northern Victoria were found to have colonised the Lake from the mid Murray River as one year old fish during the large flood event in 2010/2011 (Z. Tonkin and B. Zampatti unpublished data). Movements appear to be stimulated by very sensitive to small increases in flows (e.g. +0.15m/24h) (Mallen-Cooper and Stuart

2003: J. Thiem, NSW DPI pers. comm.) and movements decline as flows reduce (Baumgartner et al. 2011; 2014). Recolonization form isolated refuge water holes is critical in the NMDB, otherwise there is no evidence to suggest movement patterns would be different between SMDB and NMDB (LB).

Key threats

River regulation and associated infrastructure is thought to be the main threatening process for silver perch populations. Weirs and dams restrict juvenile and adult movement, particularly those associated with dispersal and recolonization, creating highly fragmented metapopulations (i.e. tributaries of the Murray River). High densities of regulating structures severely reduce the availability of suitable habitat required for frequent spawning and recruitment. For example, the creation of a large number of weir pools in the lower Murray River have severely depleted the hydrodynamic conditions required for regular recruitment of the species, with episodic recruitment associated with years when these structures are inundated and the hydraulics of the systems under relatively unregulated conditions is restored (B. Zampatti unpublished data).

Water diversions mean large numbers of eggs, larvae and juveniles and adults are lost into irrigation channels (Gilligan and Schiller 2003; Koehn and Harrington 2005) as eggs and larvae can be trapped- causing them to settle and die (Clunie and Koehn 2001; Baumgartner et al 2014) and undershot weirs can kill >90% of larvae (Boys et al. 2010). Floodplain regulation structures can also strand juvenile and adult fish (Jones and Stuart 2008). Current low densities and severely fragmented populations may heighten the risk from extended recruitment failure in the future. Loss of submergent macrophytes may reduce nursery areas for juveniles. Negative impacts of blackwater events on spawning (Raymond et al. 2016). This loss may be compounded by carp; although the impacts of carp are not considered to be large. Thermal pollution will limit spawning below weirs and possibly increase larval survivorship below many impoundments. There is susceptibility to several diseases including EHNV (Langdon 1989). Silver perch is considered to have low vulnerability to the impacts climate change (Chessman 2013).

Knowledge gaps and data limitations

- Recruitment dynamics and life stages survival rates.
- Causal links between silver perch life stages and flows.
- Location of YOY silver perch.
- Eggs and larval drift distances and their survivorship in weir pools.
- Downstream movements of silver perch.
- Recolonisation rates- where do all the 1+ fish that move through Torrumbarry go?
- Percentage of females breeding under specific flow and temperature triggers throughout the season.
- Specific flow links with movement, particularly juvenile fish.
- Dietary / trophic overlap with exotic species, particularly carp.
- Genetic structure.

Key directions for environmental flows and rehabilitation

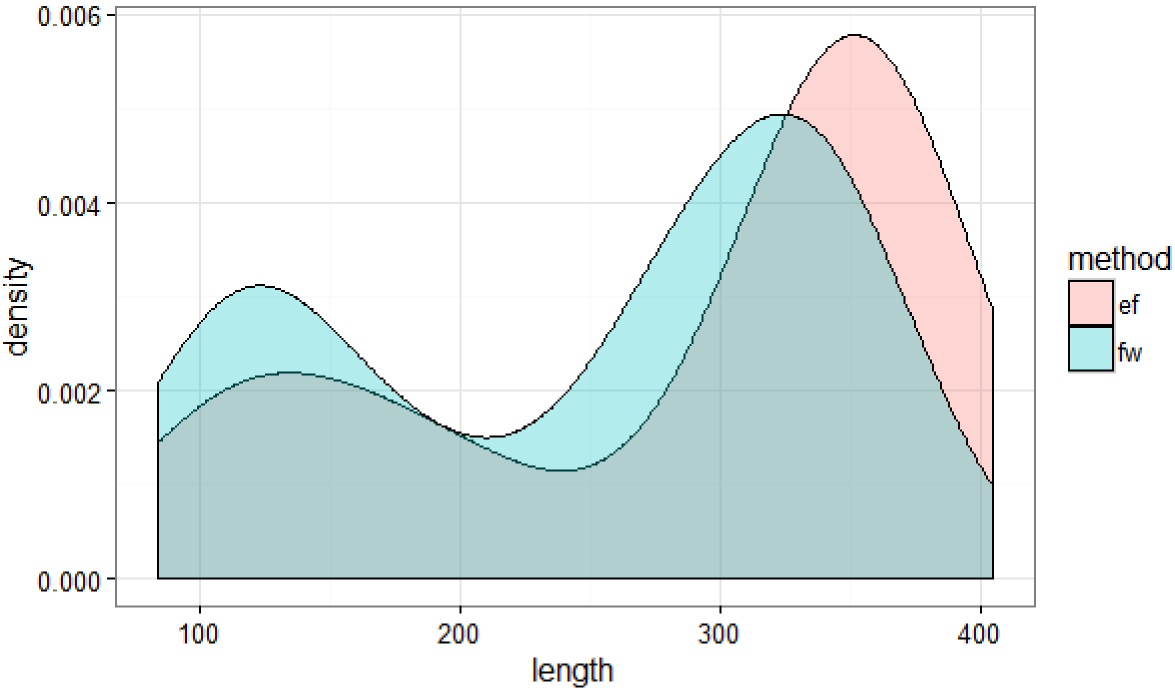
Landscape scale planning is required for management and to maximise population outcomes and providing fish passage to increase connectivity is an essential rehabilitation measure. Flow events appear critical and protecting the integrity of flows and flow components over large spatial scales (e.g. 300-500 km) through co-ordinated management is required to enhance populations dynamics (Koehn et al. 2014). Increased small short-term flow variability (1-2 days, height changes up to 0.2m) to 50% of those flows occurring naturally to stimulate juvenile movements in late summer and early autumn. Dispersal flows implemented in Murray tributaries in early summer (e.g. January-March) can attract upstream migrating juvenile fish into the in the Echuca-Yarrawonga reach, especially if synchronised with rising flows in the Murray river (Sharpe 2011; Stuart and Sharpe 2015). Spawning flows can be implemented as annual in-channel events with strong variability, and should be based on the natural hydrograph in spring/early summer. Delivery of a flood or high within-channel flow pulse a minimum of 2 in every 5 years will assist recruitment. Habitat improvements can be made by increasing hydrodynamic diversity, through weir pool lowering used in conjunction with environmental flows (Ye et al. 2008). For example, an increase in flow rate through weir pools to > 0.3m/s, can be achieved via increased flow delivery (20,000 ML/d) or through physical lowering of weir (flows of 10,000 ML/d) to achieve same ecological output. Low winter flows increase risk of fish through predation, competition, habitat loss, drying, poor water quality and lower egg and larval survival rates and mitigating low winter flows (to more natural winter flows) could improve fish condition and have flow on benefits for recruitment (Koehn et al. 2014).

Appendix 2: Population structure comparison between electrofishing and fishway samples

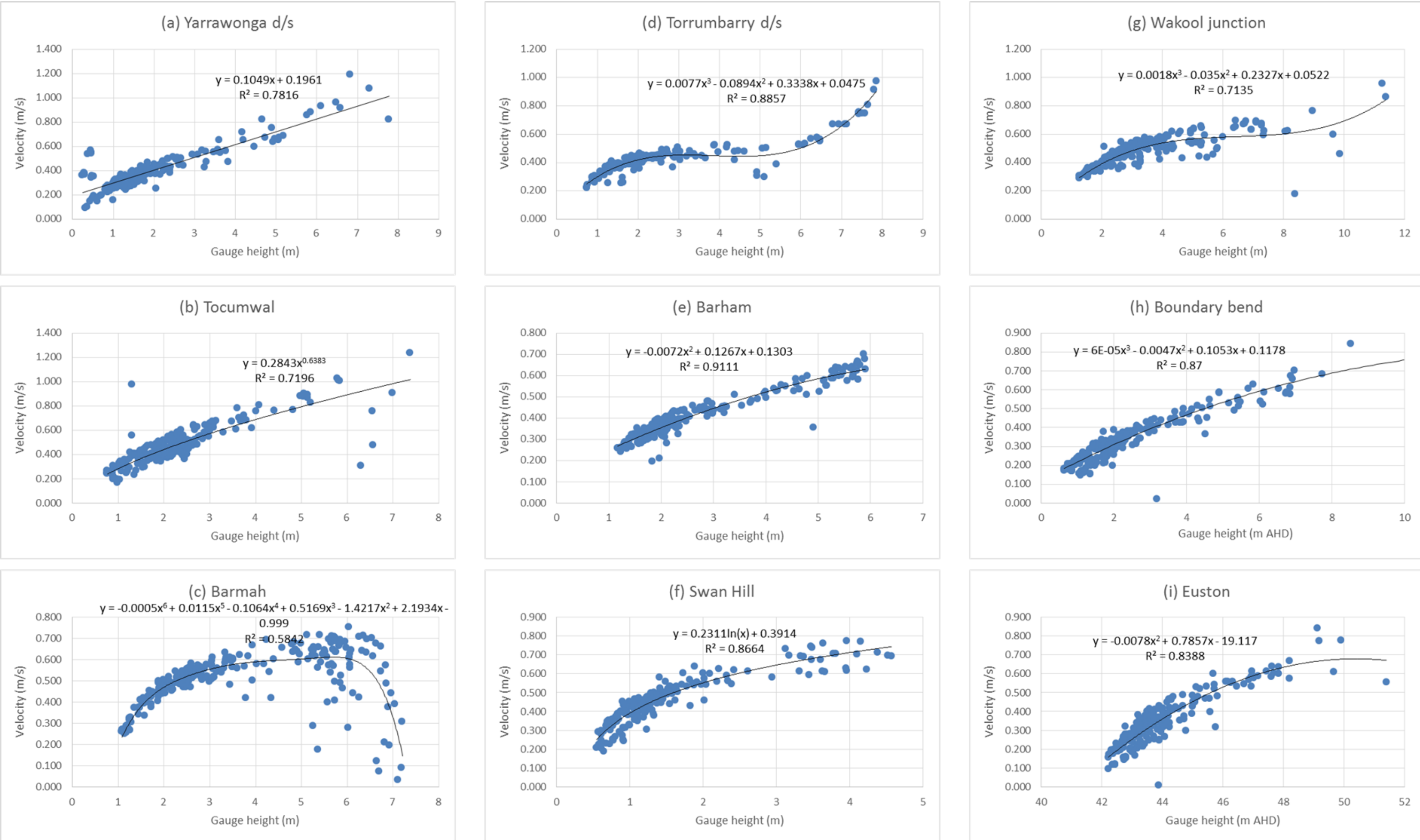
Wilcoxon rank sum test with continuity correction

Data: fish fork length by method

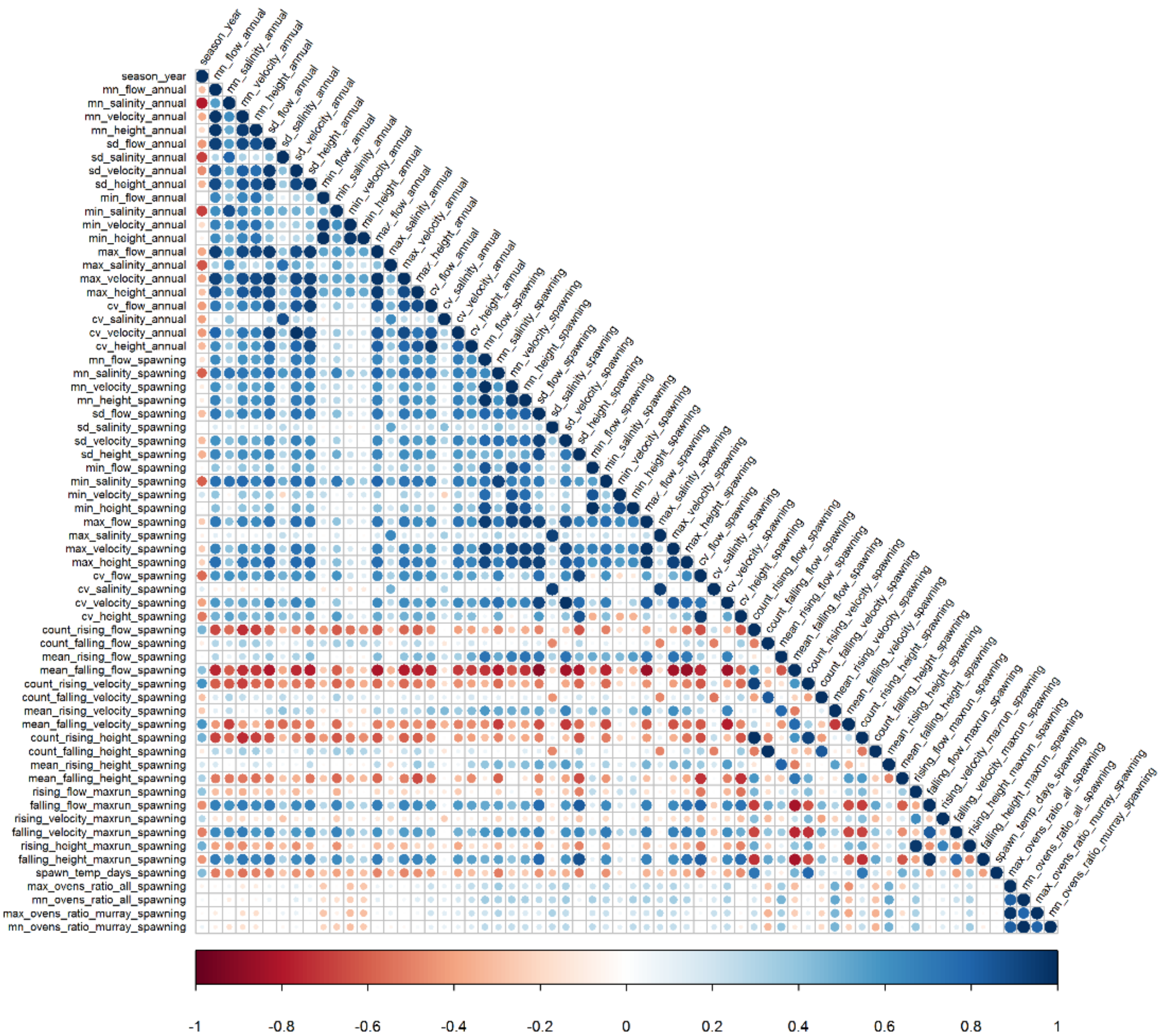
***W* = 1815, *p*-value = 0.6818**



Appendix 3: Water velocity vs gauge height relationships used to generate velocity metrics



Appendix 4: Correlation coefficients for all environmental covariates considered in the analysis of recruitment dynamics



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