Fish movement in the Lindsay and Mulcra Island anabranch systems

2018 Progress Report

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Front cover photo: Mullaroo Creek (Scott Raymond).

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Contents

Tables

Figures

Summary

The Murray-Darling Basin Authority (MDBA), Victorian and South Australian state governments and the Mallee Catchment Management Authority (MCMA) have collaborated to construct a regulating structure on the upper Mullaroo Creek with the aims of managing flow in the Mullaroo Creek independently of weir pool levels, and to replace a historical rock structure that had significant risk of failure. Despite major historical alterations to the flow regime in the lower Murray River, the Lindsay/Mullaroo anabranch system maintains a native fish community of high conservation significance. Of particular note, is the importance of the anabranch system in providing critical habitat for native fish due to its unique hydrological regimes and high density and complexity of instream habitat.

While the regulating structure was an essential component on the river management network, the MCMA have recognised that associated changes to flow regime and connectivity of the Lindsay/Mullaroo anabranch could impact on the native fish community, so that along with the construction of the regulator, there was an associated need to consider how best to manage the structure to maximise outcomes for native fish in the system. As such, a research program was established in 2014 to monitor the movements of fish between the Murray River and the anabranch system in response to flows and the operation of the new regulating structure. The specific aim of this program was to add to the understanding of migration cues and habitat use by native and exotic fish species under a range of managed and natural flow events, particularly in relation to the operation of the new regulating structure. In addition to this, the MCMA are committed to enhancing operation of the new structure, by utilising data results from this study to inform their adaptive management loop to ensure continual improvement of conditions for native fish in the Mullaroo Creek.

This progress report provides an update of the research program; in particular reporting on tagged fish, reach occupancy and movements between reaches over the four years of the study (2014 – 2018). We explore the role of flows in governing fish transitions between reaches, particularly the Murray River and anabranch system; how these transitions have changed pre-and post-construction and operation of the Mullaroo inlet regulator (and fishway); and the impact on fish movement and survival of the flood and hypoxic blackwater event that occurred within the study area in late 2016. The results described here will be used by the MCMA to both inform the next round of research questions and associated operational plans.

In March 2014, five radio-telemetry data logging stations were installed along the Mullaroo Creek and Lindsay River study site. An additional two logging stations were installed on the upper and lower Potterwalkagee Creek in May 2015; with an eighth logging station installed at Lock 7 in April 2016. In March 2017, 23 acoustic logging devices were positioned around the current radio-telemetry data logging stations, to provide a position and direction of movement for each acoustically tagged fish throughout the study reach. This shift towards an acoustic system will allow the project to connect and collaborate with a number of other fish movement programs enabling an assessment of inter-river and basin scale fish movements. These two arrays record individual fish movement and occupancy in 12 distinct zones, with the study area containing a variety of both river and anabranch habitats with a range of hydraulic conditions.

A total of 331 fish, including Murray Cod (*Maccullochella peelii*), Golden Perch (*Macquaria ambigua*), freshwater Catfish (*Tandanus tandanus*) and Carp (*Cyprinus carpio*), were tagged with radio and acoustic transmitters thus far (including 52 fish in March 2018). Of these fish, 201 are still ‘active’ (detectable) in the system although the status (alive or dead) of 30 Murray Cod, most of which have moved downstream of the study area, is unknown. Data collected since March 2014 have shown high detection (87% of tagged fish) and transition rates of detected fish (86%) between zones throughout the lower Murray River and Lindsay and Mulcra Island anabranch systems for all four species. In addition to the movement data collected since 2014, we also used movement data from 71 Murray Cod tagged in an earlier program (2004 – 2006) for our analysis. This significantly increased the amount of movement data representative of the pre-regulator conditions.

Patterns of fish movements displayed a high degree of spatio-temporal variability, both among and within species, with the fish experiencing a range of environmental conditions including low flows, floods and hypoxic blackwater as well as construction/operation of new infrastructure. Our analysis revealed fish movement between the Murray River and anabranches (specifically the upper Mullaroo Creek or lower Lindsay River) changed significantly for all species since the new inlet regulator was constructed. Specific results from this analysis include:

- Since the construction/operation of the Mullaroo inlet regulator, the probability of a Murray Cod moving into the Murray River from the anabranch system (upper Mullaroo Creek or lower Lindsay River) slightly reduced during autumn, although the probability was low throughout the entire study (generally <1% likelihood of moving on any given day). The greatest change however, was the

likelihood of Murray Cod moving from the Murray River into the anabranch system (upper Mullaroo Creek or lower Lindsay River), which significantly reduced compared to pre-regulator period. Whilst the overall timing of movements has not changed (highest likelihood in spring), Murray Cod were 18.8 times more likely to move into the upper Mullaroo Creek or lower Lindsay River from the Murray River prior to the installation and operation of the new inlet regulator. Given the strong positive relationship previously identified between fish transition rates and discharge in the anabranch, it is likely that the reduction in fish moving into the anabranch from the Murray River is at least partly driven by the changes in overall reduction in discharge and construction of the regulating structure. Other changes in flow patterns (particularly variability) should also be explored in future analyses. While we recognise that these data may be impacted by the after-effects of the 2016 blackwater event, we believe that these data will be essential to inform regulator gate configurations (and associated weir pool heights) to be tested in the next stage of the program (in particular to enhance fish movement from the Murray river into the upper Mullaroo Creek).

- Catfish movement between the lower Lindsay River and Murray River has increased (both directions) since the operation of the Mullaroo Creek inlet regulator, increasing from <1% likelihood of moving on any given day, to 15% movement between the lower Lindsay and Murray River in spring. The exact cause for this increased movement between habitats is unclear, however we propose that this is perhaps due to a return to a more variable hydrograph in the anabranch system and subsequent provision of movement cues whereby there has been a shift towards a peak in discharge in late winter and spring followed by a reduction to lower baseflows in Summer and Autumn (rather than the previous more stable flow regime). This result is important because it suggests that the hydrograph can be further optimised for multi-species outcomes and further analysis will investigate this aspect.
- For Golden Perch, there was no change in the overall likelihood of movement between different periods of the Mullaroo inlet regulator status, however there was a significant shift in temporal movement patterns. Prior to the construction of the inlet regulator, Golden Perch were more likely to move into the upper Mullaroo Creek or lower Lindsay River from the Murray River in autumn. However, since the construction and operation of the regulator, the temporal patterns in movement of Golden Perch have reversed, being more likely to move into the Mullaroo Creek or lower Lindsay from the Murray River in spring. Like the patterns observed for Catfish, this is perhaps due to a shift in the shape of the hydrograph in the anabranch system although, further exploration of other changes in flow patterns should be explored in future analyses.
- Carp movement from the Murray River to the Lindsay/Mullaroo anabranch changed dramatically, decreasing from a peak movement rate of around 13% likelihood of moving on a given day pre-regulator, to under 5% per day since the regulator installation and subsequent changes to the flow regime in the anabranch. This may also be related to one or a combination of changes in discharge and flow variability in the anabranch system.

We also used transmitter signal strength recorded at the Mullaroo Regulator logger tower to specifically explore patterns in fish transition from the Upper Mullaroo Creek to the Murray River. Our data suggests the movement of our tagged fish from the Upper Mullaroo Creek to the Murray River is, like the previous structure, negatively impacted by the Mullaroo Creek regulator (and newly constructed fishway). Whilst Murray Cod, Golden Perch and Carp have all successfully traversed the Mullaroo Creek regulator pre- and post-construction, the proportion of fish that approach the structure and successfully moved through the regulator declined from 61% to 38%. Catfish have still not been recorded to successfully ascend the fishway. These results suggest changes to fish passage between the upper Mullaroo Creek and the Murray River is also likely to be contributing transition rates of all study species. As such, there is opportunity to improve fish passage between the Murray River and upper Mullaroo Creek by optimising gate configurations and discharge levels.

The extended floodplain inundation and hypoxic blackwater event in 2016 dramatically increased movement and transitions from the lower Lindsay or upper Mullaroo Creek anabranch system to the Murray River for all species. Only Murray Cod appear to have suffered a dramatic decline in occupancy, with almost 40% of fish moving out of the study reach and into the Murray River. As of March 2018, there is 38% mortality of all tagged Murray Cod, with the status of ~29% of all active tagged fish (prior to the event) unknown. As of March 2018, 33% of tagged Murray Cod survived the blackwater event with nine of these fish returning from the Murray River downstream of the lower Lindsay River junction. The size of surviving fish ranged from 50 – 119 cm. The results of Murray Cod movement and survival in response to the hypoxic conditions has provided strong evidence for the importance of providing connectivity between the Murray River and anabranch systems prior to, during and after these hypoxic blackwater events, emphasising the need for fish to quickly move to refuges and then return over extended timescales after the blackwater event has passed.

The information gathered on fish movement and habitat use (and associated drivers) during the program has generated important information to help guide management of flows and infrastructure operations aimed at maximising benefits for native fish in the Lindsay and Mulcra Island anabranch system. As such, the program will continue to assess fish outcomes resulting from future interventions and inform a program of continual improvement. Nevertheless, we recommend the program can now, in addition to monitoring overall reach occupancy and transition rates, shift to monitor specific flow events (including weir pool and regulator gate operations) which will require close collaboration between waterway managers, operators (MDBA and SA Water) and researchers. This approach should encompass both telemetry data (as per that being used in this program) and event-based netting or fish trapping with the former requiring a continuation of the annual fish tagging and maintenance routine to ensure that native fish outcomes for the Mullaroo Creek continue to be maximised

Management recommendations

- To maximise Murray Cod use of lower Lindasy and Mullaroo Creek during the spawning period, implement a spring/summer (September-December) steady flow hydrograph (1000-1200 ML day^{-1}) into the upper Mullaroo Creek.
- To increase Murray cod movement into the anabranch system outside of the spawning period, implement fresh events in summer/autumn and winter in Mullaroo Creek (1000 ML day^{-1}).
- To continue the positive outcomes for Catfish and Golden Perch, continue to deliver spring high flows as extended fresh type events by maintaining suitable rates of rise and fall (back to lower baseflows) to maintain the increased flow variability present in the reach post-regulator operation.
- Continue the tagging program and expand the analysis to improve knowledge of fish transition rates under a variety of hydrological conditions and determine the influence of infrastructure on upstream and downstream passage.
- Expand the intervention monitoring to include further targeted monitoring of upstream and downstream passage of both large and small-bodied fish species between the upper Mullaroo Creek and the Murray River (via the regulator and fishway). This should be conducted under a range of hydrological conditions; different gate arrangements and Lock 7 weir pool heights.

1 Introduction

The decline in connectivity of lowland rivers and their floodplain habitats has contributed substantially to the decline of their native fish populations (Natarajan 1989; Saddlier et al. 2007). Regulation of flows has negatively impacted the natural variability of hydrological regimes within the lower Murray River floodplain through alterations to the frequency, duration and size of floodplain inundation and dramatic changes to riverine hydraulics (Maheshwari et al. 1995; DSE 2010). The continued regulation of the Murray River main stem poses a threat to the ecological integrity of the region including native fish populations. The Chowilla-Lindsay-Wallpolla Icon Site is one of six icon sites identified under the Murray-Darling Basin Ministerial Council's 'The Living Murray' initiative. The area is situated within Murray Sunset National Park, which covers an area of 15,000 ha of floodplain to the south of the Murray River, between Lock 8 and Lock 6. The waterways, wetlands and floodplain provide refuge and resources for a range of flora and fauna, including threatened fish species. The area also has high social and cultural significance.

River regulation is the key threatening process to the values of the Chowilla-Lindsay-Wallpolla Icon Site, causing a reduction in the frequency, duration and size of floods, reduction in the variability of natural hydrological regimes and, severely altered hydraulic characteristics (such as velocity) of the system. To mitigate this threat, The Living Murray initiative developed the Upper Lindsay Watercourse Enhancement Project with the purpose of restoring aspects of the natural flow regime to the Icon Site (DSE 2010). This project includes lowering the sill in the southern Lindsay River, constructing regulators on the northern and southern Lindsay River inlets and replacing the degraded causeway in the Mullaroo Creek with a new regulator and fishway. A proposed regulator (Lindsay Stage 2) on the lower Lindsay River outlet (upstream of the Lindsay and Murray Rivers confluence) will further regulate hydrological regimes in the Lindsay River and Mullaroo Creek.

The Mullaroo Creek regulator and fishway, together with the Lindsay River regulators are reported to increase the area and diversity of available aquatic habitat and contribute to the overall viability, abundance and extent of existing fish communities (Mallen-Cooper et al. 2010). However, there is also the potential for these (and future) regulators to restrict fish movement (particularly downstream) and alter the hydrological and hydraulic characteristics of several key reaches, that have historically provided critical habitat to native fish (Saddlier and O'Mahony 2009). The upper Mullaroo Creek in particular is an important refuge and breeding ground for a number of native fish species. These species are dependent on the systems unique hydraulic characteristics and high density of instream woody habitat compared with sites within the lower Mullaroo Creek, Lindsay River and Murray River (Saddlier and O'Mahony 2009; Henderson et al. 2013). In particular, Murray Cod from the Murray and Lindsay rivers showed a preference for the upper Mullaroo Creek during the spawning period (September-November; Saddlier et al. 2007).

The influence of the new regulating structures on fish movement, positive or negative, will be dependent on regulator and fishway operational procedures, movement dynamics and key life-history requirements of individual fish species. Therefore, incorporating ecological data to improve operational procedures is an important component to facilitate future watering regimes within and through the icon site. This research program was established in 2014 to monitor the movements of fish between the Murray River and anabranch systems in response to flows and the operation of floodplain structures. The study specifically aims to add to understanding of habitat use and movement cues by native species including Murray Cod (*Maccullochella peelii*), Golden Perch (*Macquaria ambigua*), and Freshwater Catfish (*Tandanus tandanus*), as well as the exotic Carp (*Cyprinus carpio*), and how these are influenced by changes in water management, particularly infrastructure construction and operation (fishways and regulators).

This progress report provides an update of tagged fish, reach occupancy and movements between reaches over the four years of the study (2014 – 2018). We explore the role of flows in governing fish transitions between reaches, particularly the Murray River and anabranch system; how these transitions have changed pre-and post-construction and operation of the Mullaroo regulator (and fishway); and the impact on fish movement of the flood and hypoxic blackwater event that occurred within the study area in November/December 2016.

2 Methods

2.1 Study site and telemetry array

This study is focussed on the Lindsay Island anabranch network of the Chowilla-Lindsay-Wallpolla Icon Site, in north-western Victoria. The primary waterways investigated were the Mullaroo Creek, Lindsay River, Potterwalkagee Creek and Murray River (Lock 6 – Lock 8 reach; Figure 1). The study region was separated into twelve reaches, giving a variety of both river and anabranch habitats and a range of hydraulic conditions, including the moderate water velocities of the upper Mullaroo Creek and semi-lotic weir pools of the Murray River.

In March 2014, five radio logging towers were installed at strategic locations along the Mullaroo Creek and Lindsay River (Figure 2). This repeated the array of Saddlier and O'Mahony (2009), with additional logging towers erected at a fork in the Upper Lindsay River, one each on the upper and lower Potterwalkagee Creek (May 2015) and another at Lock 7 on the Murray River (April 2016). Data logging towers receive radio signals (via antennae) from transmitters up to 300 metres away. As the antennas are directional (i.e. an antenna picks up its strongest signal when pointed directly at the transmitter), each antenna receives and records a signal of different strength. The antennas are positioned in either an upstream or downstream direction on the river/creek, and if a tributary exists, a third antenna is directed towards the inflowing tributary. Because signal strength and detection time is recorded for each antenna, the position and direction of movement for each fish within the range of the logger can be determined, thus enabling the exact reach a fish is occupying at any point in time. As radio loggers are subject to theft and vandalism, recording equipment was housed in 8 mm thick steel plate boxes set on 4 m poles secured into the ground with concrete. Ventilation holes and shade cloth were provided to protect the equipment from high summer temperatures. An articulated pole was hinged off the back plate of the logger box for ease of installing and maintaining antennae. Each four-element Yagi antenna was attached by a 1.5 m coaxial cable to a three-way switch box. A 40 W solar panel was attached to the roof or the antenna pole and connected to a 12 volt, 100-amp hour lead-acid battery via a regulator. The radio logger was connected to the battery to allow continuous, uninterrupted power to the unit.

In 2017, the study area was complemented with the deployment of 26 acoustic receivers (loggers). Acoustic receivers were secured underwater with steel cable to a buoy or large log within the river. Three receivers were positioned upstream, downstream and on an inflowing tributary surrounding an existing radio tower to provide the same coverage and allow for the position and directional movement as per radio tagged fish (Figure 2). A further four acoustic receivers maintained by South Australian Research and Development Institute (SARDI) are positioned within our study area adding to the acoustic array. The incorporation of acoustic technology will help to connect this project with a number of other acoustic telemetry programs currently operating across the southern connected basin as part of The Living Murray initiative and Commonwealth's Long-Term Intervention Monitoring project. An acoustic array currently spans from the Murray River mouth up to Yarrawonga as well as more intensive arrays within the Goulburn and Edward-Wakool system. Connecting and collaborating with these other programs will allow for the detection of fish migrating between different river systems and ultimately help investigations of basin scale fish movements.

All data loggers are downloaded two or three times per year and given routine maintenance (e.g. battery change) to ensure they are operating correctly. Radio tagged fish are also manually tracked twice a year to verify position and to check if the transmitter is emitting a mortality signal (triggered if the fish has not moved for 168 hours), therefore indicating if fish had either died or rejected the transmitter. We also note that transmitters can also be reactivated if disturbed.

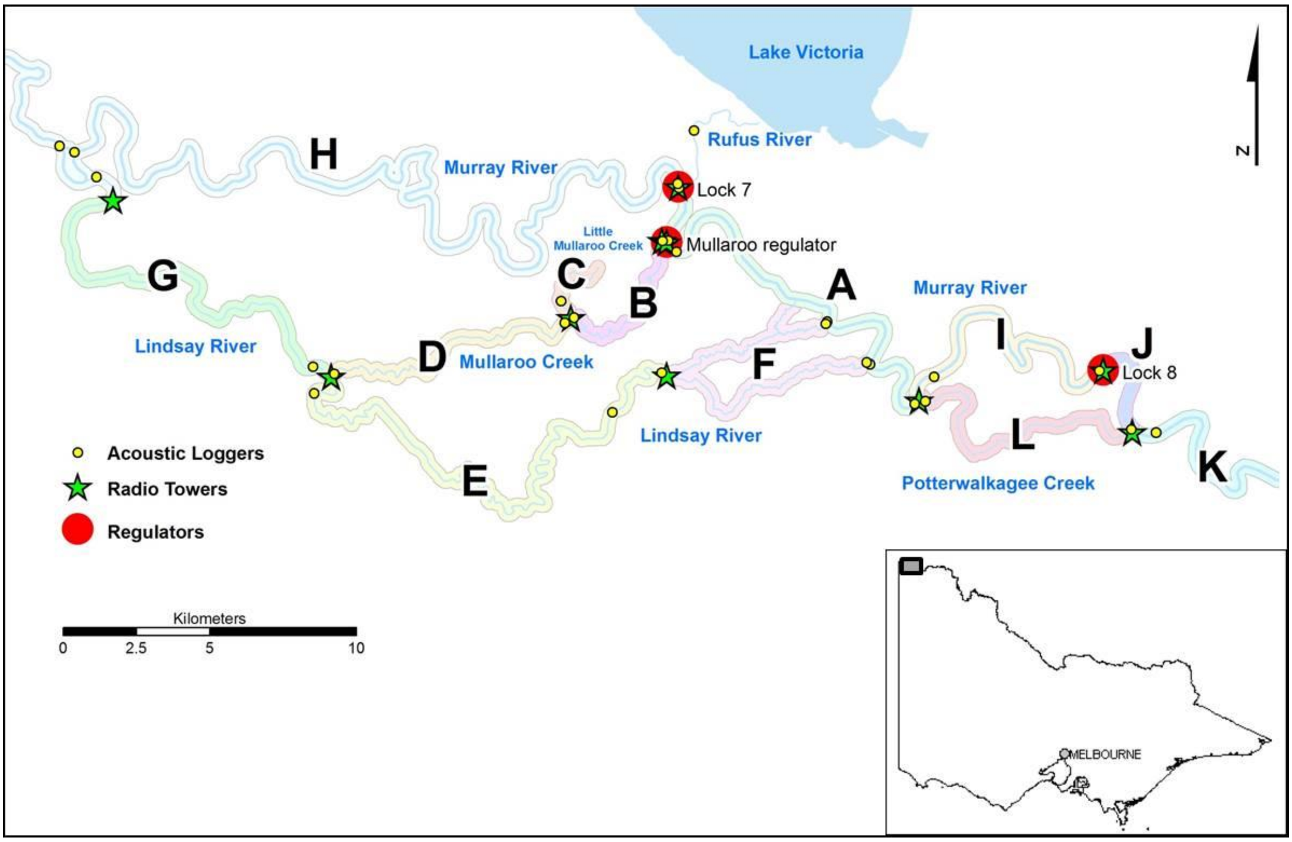

Figure 1. The Lindsay Island anabranch study site. Red circles represent regulator infrastructure, green stars represent radio logging towers, yellow circles represent acoustic loggers and letters represent fish tagging and movement zones.

Figure 2. Upper Mullaroo data logger, showing logger box, solar panel and antennae.

2.2 Fish tagging

This program focuses on movement patterns of the native species, Murray Cod, Golden Perch and Freshwater Catfish; and exotic Carp. A Smith-Root 7.5 GPP boat-mounted electrofisher (settings: 500-1000 volts, 38 Hz, pulse DC) was used to capture fish for radio and acoustic transmitter implantation. Angling and fyke nets were also used to capture target fish species.

Surgical procedures used to implant fish with radio and acoustic transmitters followed those outlined in O'Connor et al. (2009). Fish were sedated by immersion in an anaesthetic solution of Aqui-S at a concentration of 1.5 ml per 50 litres of water. After fish were sedated (lack of observed movement) they were placed upside-down on an operating bench. The aforementioned anaesthetic solution was poured directly over the gills to ensure fish remained sedated during surgery. Prior to incision, the underside of the fish was bathed with diluted (0.9% saline solution) Betadine® solution to ensure the area was adequately sterile. A small incision (approximately 2 – 3 cm long) was made through the body wall on the lower left ventral side (parallel with the digestive tract) and the transmitter inserted into the body cavity of the fish. Radio transmitter size (7, 14, 23 or 56 g; Figure 3) and acoustic transmitter size (11g) was determined as a proportion (<2%) of total fish body weight (Table 1). Once inserted, radio transmitters were positioned so that the external aerial could be passed through the body wall approximately 3 – 7 cm posterior of the incision, depending upon the size of the fish. Once the transmitter was positioned, the incision was again bathed in Betadine® solution before internal sutures were used to close the body wall. External sutures were used to close the outer incision and the entire area bathed with Betadine® solution before the fish was returned to an aerated recovery tank containing a 10 g/L salt solution to limit the possibility of infection. Careful observation of each fish was made to ensure it was able to maintain an upright swimming position prior to release into the same area from which it was captured. Radio transmitters operated on 150 MHz (manufactured by Advanced Telemetry Systems), while acoustic transmitters operated at 69kHz (manufactured by VEMCO).

Each fish was weighed (nearest gram) and measured for total length (mm). Fish were also marked with an external identification tag (T-bar or Dart; Figure 4) adjacent to the dorsal fin, and passive integrated transponder (PIT) tag. External tags display a telephone number for the reporting of fish capture data, which was incorporated into a fish database (Victorian fish tagging database; Arthur Rylah Institute). PIT tags have an individual code which is read as fish pass PIT reading stations. PIT tag readers have been installed on most Locks along the Murray River to record fish movement data.

Whilst not a direct objective of the project, manual tracking of the Mullaroo Creek, Lindsay River and the Murray River was also conducted to obtain detailed information on site location as well as checking for mortality signals. Manual tracking of radio tagged Murray Cod was conducted during September 2014; August and December 2015; September and December 2016; and December 2017.

Table 1. Radio and acoustic transmitter weight, minimum weight of fish and battery life of transmitters.

Tag type	Transmitter weight (g)	Minimum fish weight-2% (g)	Radio Battery life (days)
Radio tag	7	350	245
	14	700	528
	23	1150	1142
	56	2800	1460
Acoustic tag	11	550	1316

2.3 Data analysis

Hydrology and water temperature data within the study area was obtained from gauges operated by WaterConnect South Australia (2018) and the MDBA (2018). Dissolved oxygen data during November/December 2016 was provided by Al Drechsler from the River Murray Operations team. We conducted an investigation of fish transitions between the Murray River and anabranch habitats (Mullaroo Creek and Lindsay River. We used fish movement and hydrological data collected during this study (2014 – 2018), and for Murray Cod, movement data of 71 fish from 2004 – 2006 (Saddlier et al. 2007), which used the same logger locations and tagging protocols, and preceded any regulator interventions.

Logistic regressions were used to analyse the probability of fish movement between the Murray River and the anabranch. Specifically, Logistic Markov transition matrices were used to examine relationships between the probabilities of fish moving between main-stem and tributary locations and environmental factors (Koster et al. 2014). Transition matrices can be used to look at the probability of individuals in one location either staying in that location or moving to a new location. Given we are looking at movement from the Murray River to the anabranch and vice versa, the transition matrix only needs two models, the probability a fish currently in the anabranch stays in the anabranch the following day, and the probability fish currently in the Murray River stays in the Murray River the following day. As each of these models are binary (stay or move) the result is four probabilities for any day, the probability that:

- a fish is in the anabranch and stays in the anabranch;
- a fish is in the anabranch and moves to the main-stem;
- a fish is in the main-stem and stays in the main-stem;
- a fish is in the main-stem and moves to the anabranch.

Separate models were constructed for each species (Murray Cod, Golden Perch, Catfish and Carp). Explanatory variables used in the models were the day-of-Year (Julian day); temperature in the Murray River (strong correlation with temperature in the Mullaroo Creek); discharge in the Mullaroo Creek; and the status of the Mullaroo regulator operation, specifically pre- construction (September 2004 – December 2006; March 2014 – April 2015), post-construction and operation (July 2015 – December 18; exc. flood period); and the period during flood when gates were laid flat (August 2016 – March 17). The period subject to Blackwater in late 2016 (November – December) was excluded from the analysis. Discharge in the Mullaroo Creek and regulator operation period were included as explanatory variables for Murray – anabranch transitions given all transitions for native species outside of the major flood period, and majority of carp transitions (85%) encompassed the Murray River and either the upper Mullaroo Creek or lower Lindsay River. Indeed, both of these areas are influenced by the operation of the regulator (via discharge down the anabranch system and/or the new fishway at the structure). When Julian day was included, it was included as a smoothed term. Hence the overall model was a general additive model (GAM) using a binomial distribution. Residual plots were used to assess model fit and assumptions (binomially distributed and independent). All the analyses were conducted using the statistical program R version 3.4.4 (R Core Team 2018), with GAM fitted using the package "mgcv" (S. Wood 2011).

3 Results

3.1 Hydrology

Seasonal flow variability throughout the study area during the first two years of the study was generally low (Figure 3). During this period, stream flow in the Murray River at Lock 8 ranged between 1,000 – 10,000 ML day^{-1} except for a medium flow event in August 2014 where flow peaked at 17,241 ML day^{-1}. Despite similar flow conditions in the Murray River during the first two years, flows in the Mullaroo Creek reduced substantially in the second year from an average of ~1000 ML day^{-1} to ~600 ML day^{-1}. This coincided with the construction and commencement of operation of the Mullaroo Creek inlet regulator on July 2015 (post-regulator period).

During the third year of the study there was a major rainfall event in September 2016 across Australia and much of the Murray-Darling Basin, leading to significant flooding across the catchment and a large flood event within our study area. Rainfall for the winter and spring period of 2016 was 'very much above average' across most of the Murray-Darling Basin, with highest on record totals across large parts of central New South Wales and in a small area of the Victorian Alps (BOM, 2016). September 2016 was the Basin's wettest September on record. Heavy September rainfall, combined with already abnormally wet catchments, resulted in substantial flooding in many regions. Minor, moderate and major flooding was recorded across large parts of New South Wales, Victoria, southern Queensland and parts of South Australia from September to December 2016 (BOM, 2016).

Due to its downstream position in the catchment minor to moderate flooding of the Murray River was experienced between Mildura and Wentworth from November (NSW SES 2016), with peak flows of over 80,000 ML day^{-1} experienced through the Chowilla-Lindsay-Wallpolla Icon Site (Murray River at Lock 8) between 25 November and 4 December (Figure 3; WaterConnect South Australia 2018; MDBA 2018).This event resulted in a widespread 'hypoxic blackwater event' throughout large parts of the Murray River system as well as the Lachlan and Murrumbidgee systems (MDBA 2016). The hypoxic blackwater event extended for over a month within the Chowilla-Lindsay-Wallpolla Icon Site corresponding with the peak flows between early November and December 2016 (see Tonkin et al. 2017).

Flow conditions in the fourth year of the study (Jan 2017 – February 2018) were similar to the low flows experienced in the first years of the study (Figure 3). In the Murray River, discharges whilst low, were more variable than the first years of the study ranging from 675 ML day^{-1} to ~1600 ML day^{-1}. The Mullaroo Creek was also variable; however, flows were generally low (< 700 ML day^{-1}), falling as low as 340 ML day^{-1}. Only during a period between October and December did flows exceed the recommended discharge to maximise Murray Cod transitions between the anabranch and Murray River (1000 ML day^{-1}; Tonkin et al. 2017).

In summary, discharge in the Mullaroo Creek pre- and post- operation of the Mullaroo Creek inlet regulator therefore varied considerably during the period that fish movement was being monitored. Discharge in the Mullaroo Creek was on average higher (mean = 823 ML day^{-1}) and less variable (Coefficient of Variation = 19.9) prior to inlet regulator operation period than the post-regulator period (mean = 670 ML day^{-1}; Coefficient of Variation = 29.3).

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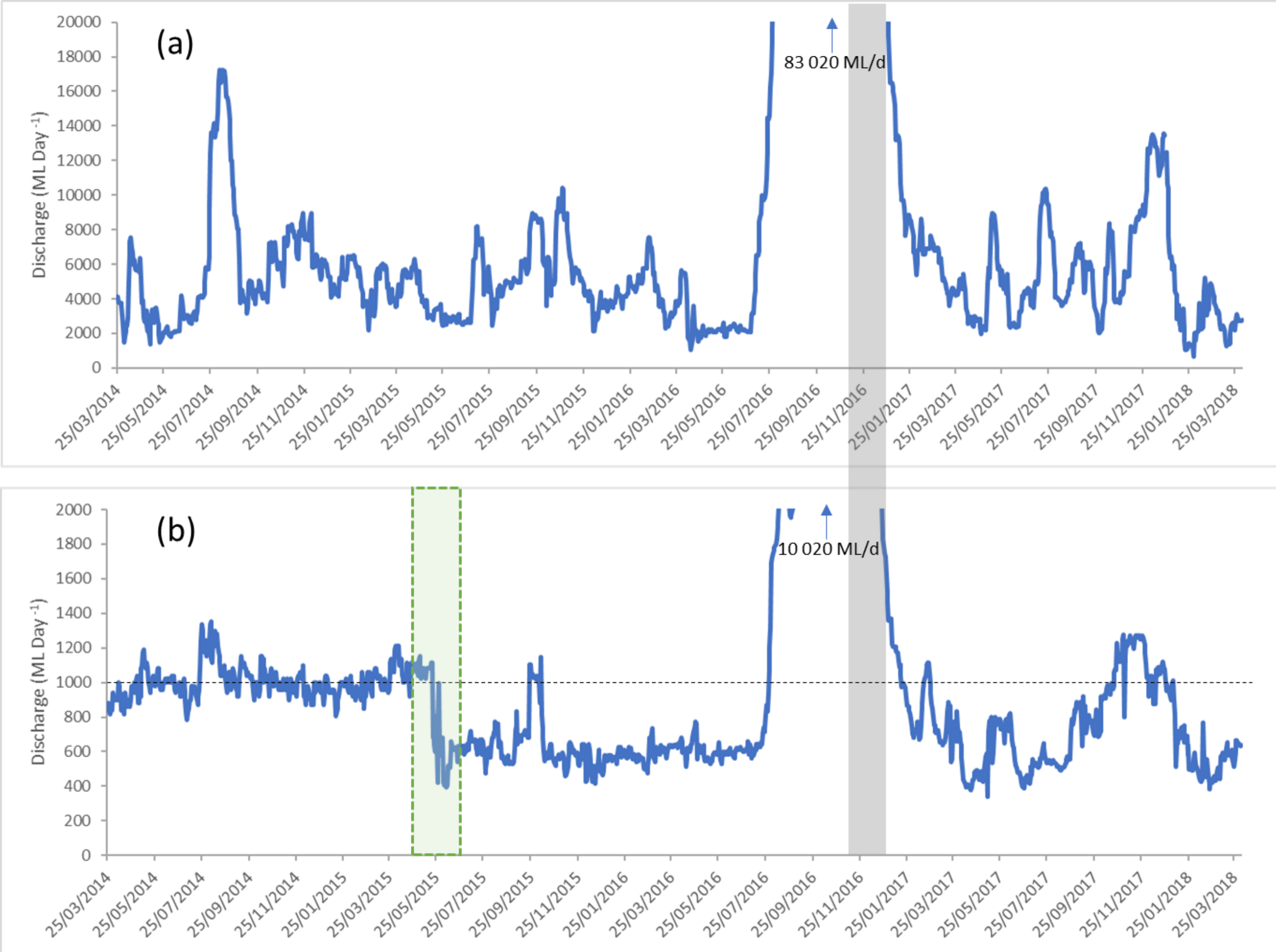

Figure 3. Average daily discharge (blue) in a) the Murray River at Lock 8; and b) Mullaroo Creek. Dotted horizontal line illustrate recommended minimum discharge in Mullaroo Creek to maximise fish transitions with the Murray River. Grey shaded bar represents the blackwater event that occurred within the study area. The vertical green block indicates period of construction preceding operation of the Mullaroo Creek Regulator (period excluded from the analysis).

3.2 Fish tagging and logger array update

All radio logging towers and acoustic receivers were checked, downloaded and subject to routine maintenance in December 2017 and March 2018. Fifty-two (52) transmitters were implanted into fish during March 2018 to supplement numbers of tagged fish in the system (Table 2). Like 2017, the abundance of Murray Cod was low (but higher than 2017) with just eight fish. Electrofishing did however detect a number of young-of-year Murray Cod in the upper Mullaroo Creek (DELWP unpublished data), indicating conditions were favourable for spawning and juvenile survival the previous Spring – Summer. Golden Perch were caught in high abundances throughout the study area, with 40 fish implanted with acoustic tags (Table 2).

A total of 331 fish have now been implanted with radio and acoustic transmitters since 2014, with 203 of these fish still possessing an active transmitter (Table 2 and Table 3; 128 tagged fish have either died, been kept by anglers or the transmitter battery life has elapsed). Since 2014, 14 fish (2 Murray Cod, 9 Golden Perch and 3 Carp) have been caught, kept and reported by recreational anglers (Appendix 1).

Table 2. Details of fish implanted with transmitters in March 2018 in Mullaroo Creek, Lindsay River and Murray River with (a) radio tags, and (b) acoustic tags. TL = total length.

Species	Length Range (TL: mm)	Weight Range (g)	Total
(a) Radio tags			
Murray Cod	610 – 1110	3450 – 22000	8
Catfish	437 – 501	760 – 1418	4
Golden Perch	n/a	n/a	0
Carp	n/a	n/a	0
(b) Acoustic tags			
Golden Perch	301-458	362-1446	40
Total			**52**

Table 3. Details of fish implanted with transmitters in (a) Mullaroo Creek and Lindsay River and (b) the Murray River below Lock 8 from March 2014 - 2017. Numbers do not include fish tagged in March 2018.

Species	Length Range (TL: mm)	Weight Range (g)	Total	No. detected	No. Changed zone	No. Active Transmitters
(a) Mullaroo Ck. / Lindsay R.						
Murray Cod	299 – 1210	356 – 35000	57	55	50	13
Catfish	348 – 520	366 – 1418	26	15	9	6
Golden Perch	301 – 493	362 – 1508	87	73	63	55
Carp	437 – 680	1320 – 5250	22	20	17	14
Total			**192**	**163**	**139**	**88**
(b) Murray R.						
Murray Cod	712 – 1190	5200 – 32000	26	19	19	26
Catfish	401 – 485	535 – 960	3	3	1	0
Golden Perch	320 – 536	570 – 2170	29	33	28	15
Carp	380 – 715	930 – 6050	29	24	21	22
Total			**87**	**79**	**69**	**63**
SYSTEM TOTAL			**279**	**242**	**208**	**151**

3.3 Fish movements

Since 2014, 242 individual tagged fish have been detected which represents 87% of all fish tagged prior to 2018 (Table 3). Of these detected fish, 208 (86%) have undertaken movements outside of the zone in which they were released (Table 3). Many of the movements between zones encompassed transitions between anabranch and the Murray River main channel, highlighting the importance of these habitats for fish in the region. The patterns of fish movements displayed a high degree of spatiotemporal variability, both across and within species. Over the study period, movements have generally comprised those that appear to be associated with reproductive activity (spring), range shifts and transitions between anabranches and the Murray River main channel. Murray Cod, Golden Perch and Carp were detected to have occupied all reaches in the study area (including Potterwalkagee Creek during high flow periods). What is also becoming evident as the amount of data increases is that the patterns in movements appear to have shifted in the three years following the construction and operation of the Mullaroo inlet regulator (see below).

Murray Cod

The movement of Murray Cod in the study reach was highly seasonal, with the detection of fish most likely during the period preceding, and during the spawning season for the species (September – December). It is becoming clear that Murray Cod movement between the Murray River and anabranches (specifically the upper Mullaroo Creek and lower Lindsay River) has changed since the installation and operation of the Mullaroo regulator in mid-2015. Our analysis of transitions between the Murray River and anabranch habitats showed these movements were most influenced by day-of-year and regulator status according to the models (Appendix 2.1). The probability of Murray Cod in the anabranch staying in the anabranch was generally high (≥ 99% on any given day) with the probability of moving peaking during spring during the entire study period (Figure 4). Since the operation of the regulator, the probability of a Murray Cod moving to the Murray River during autumn decreased (~1% per day; Figure 4).

Similarly (although more pronounced), Murray Cod movements from the Murray River to the anabranch (lower Lindsay or upper Mullaroo Creek) were also influenced by day-of-year and regulator status according to the models (Appendix 2.2). Murray Cod in the Murray River had an increased probability of movement to the anabranch in early spring and a smaller peak in winter (Figure 5). In general, there was a greater likelihood of movement to the anabranch pre-regulator and when the regulator was down compared to the regulator operation period. The odds of a Murray Cod moving to the anabranch pre-regulator (which included the 2004 – 2006 data) was 18.8 (95% CI from 12.5 to 28.2) times greater than post-regulator. The odds of a Murray Cod moving to the anabranch during the high flow event (excluding the blackwater period) was 2.3 (95% CI from 1.3 to 4) times greater than the post-regulator.

Movement data of individual fish which typify these patterns include:

- Fish ID 153.11 (760 mm TL) transitioned between the upper and lower Mullaroo Creek, with a general trend of moving to the upper reaches during the core spawning period (between September and December), however the amount of time spent in the upper reaches reduced substantially the year following the regulator construction and subsequent lower discharges in the creek (Figure 6). The fish moved out of the anabranch system via the lower Lindsay River and of the study reach (Murray River downstream) during the blackwater event and returned in early November 2017. The fish has remained in the Murray River since this time (not returning to the Mullaroo Creek).
- Fish ID 153.27b (1060 mm TL) was tagged in the upper Mullaroo Creek, with the fish moving to the Murray River a few days after flows declined from 1100 to 550 ML day^{-1} (Figure 6). The fish returned to the upper Mullaroo Creek during increased flows during the spawning period, before leaving the study reach during the blackwater event. The fish returned to the study reach however, it has primarily occupied the Murray River and only returned to the Mullaroo Creek during increased flows (during the spawning period).

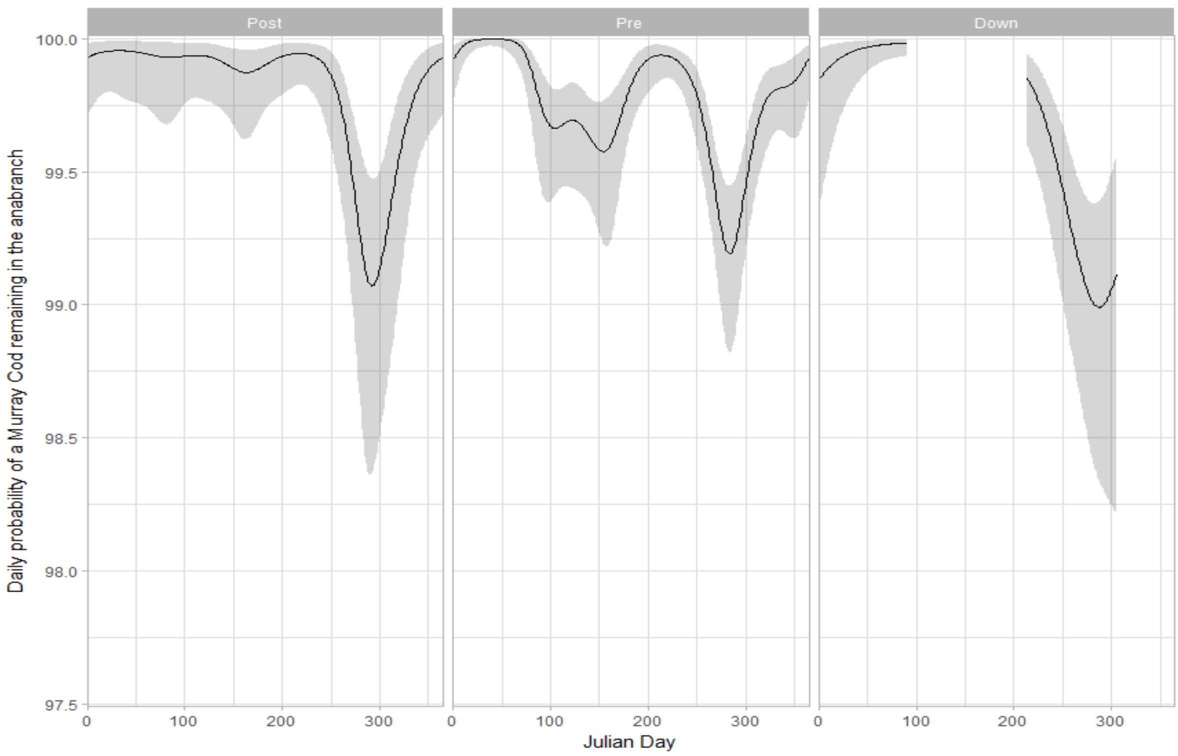

Figure 4. The probability that a Murray Cod in the anabranch stays in the anabranch dependent on day-of-year and regulator status (pre-, post- and during the flood event when the gate configuration was laid flat).

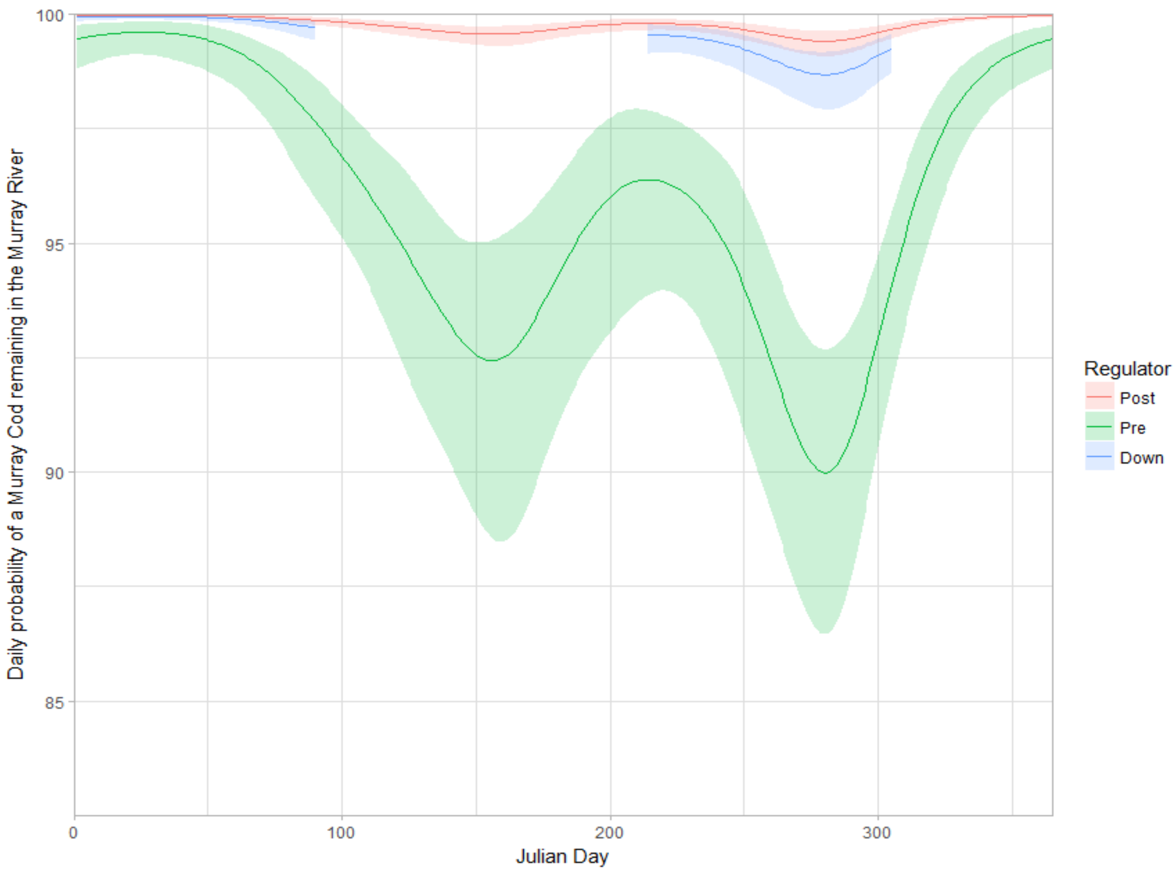

Figure 5. The probability that a Murray Cod in the Murray River stays in the Murray River dependent on day-of-year and regulator status (pre-, post- and during the flood event when the gate configuration was laid flat).

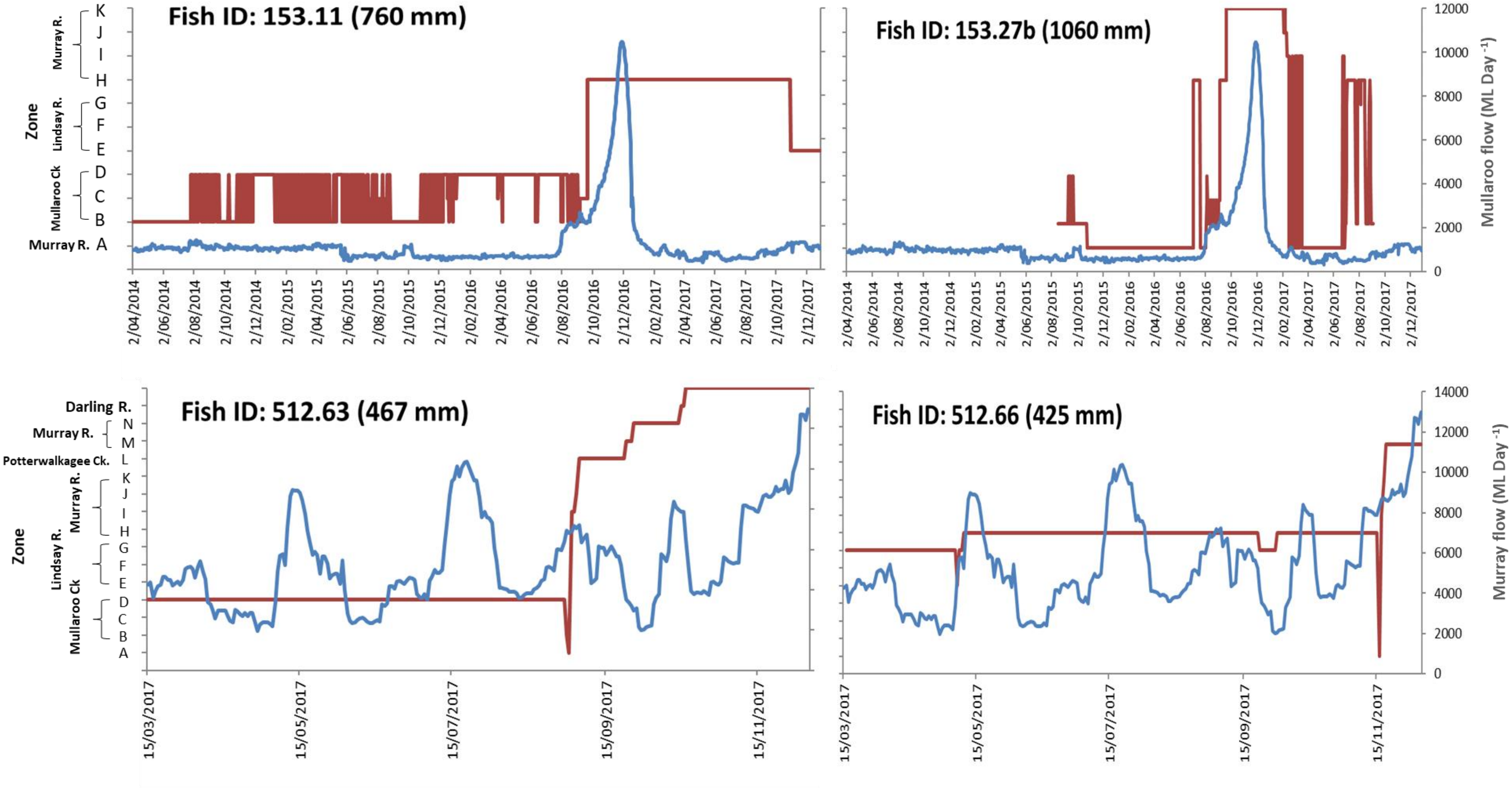

Figure 6. The movement patterns of two individual Murray Cod and two individual Golden Perch during the study. Mean daily discharge in the Mullaroo Creek (for Murray Cod) and the Murray River (below Lock 8) also presented for reference. Letters denote specific zones of the study area (see Figure 1).

Golden Perch

Golden Perch displayed highly variable movement, both spatially and temporally. A number of Golden Perch tagged with acoustic transmitters have undertaken large upstream movements, including three fish that were detected moving out of the study reach and into the Darling River. Whilst our pre-regulator data is does not span as great a temporal scale as our Murray Cod data, Golden Perch transitions between the Murray River and anabranch habitats (lower Lindsay River and upper Mullaroo Creek) were influenced by day-of-year and regulator status according to the models (Appendix 2.3). Prior to the construction of the Mullaroo inlet regulator Golden Perch were more likely to move to the Murray River in autumn. However, since the construction and operation of the regulator, the probability of movement to the Murray River changed substantially, being slightly more likely to move in spring, although a there is no clear pattern to when Golden Perch are likely to move to the Murray River. Golden Perch movements to the anabranch were influenced by day-of-year and regulator status according to the models (Figure 7; Appendix 2.4). Prior to the construction of the regulator Golden Perch were more likely to move into the anabranch in autumn. However, since the construction and operation of the regulator, the temporal patterns in movement of Golden Perch have reversed, being more likely to move into the anabranch in spring.

Movement data of individual fish which typify these patterns include:

- Golden Perch Fish ID 512.63 (467mm TL), tagged in lower Mullaroo Creek, transitioned to the Murray River (via the Mullaroo Creek regulator) in early September 2017 during a small flow event (Figure 6). The fish moved up the Murray and into the Potterwalkagee Creek for almost a week before returning to the Murray River on the receding limb of the flow event. The fish then migrated up the Murray River on another flow event, moving into the Darling River in early November (where it has since remained).
- Golden Perch Fish ID 512.66 (425mm TL), tagged in lower Lindsay River, transitioned to the Murray River (via the Mullaroo Creek regulator) in mid-November 2017 during elevated flows in the Mullaroo Creek and Murray River (Figure 6). The fish migrated to the Murray River upstream of Lock 8 (where it has remained).
- Golden Perch Fish ID 132.45 (415mm TL), tagged in upper Mullaroo Creek, continually moved between the Little, upper and lower Mullaroo Creek from June 2015 to August 2016. In November 2016 when dissolved oxygen concentrations began to drop, it transitioned into the Murray River moving upstream above the upper Potterwalkagee Creek junction (via zone A, I and J) and out of the study area (zone K). On the 15/12/2016 when dissolved oxygen concentrations started increasing, the fish returned to the upper Mullaroo Creek via the upper Lindsay River and lower Mullaroo Creek.

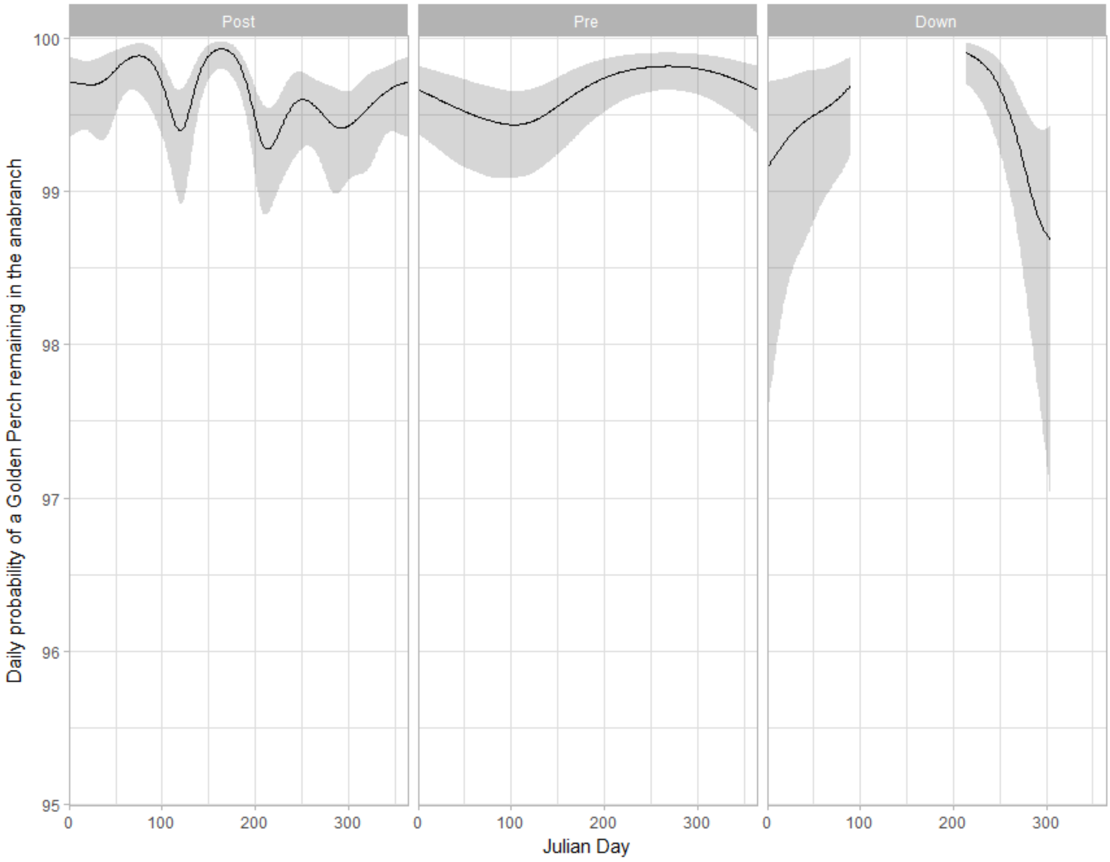

Figure 7. The probability that a Golden Perch in the anabranch stays in the anabranch dependent on day-of-year and regulator status (pre-, post- and during the flood event when the gate configuration was laid flat).

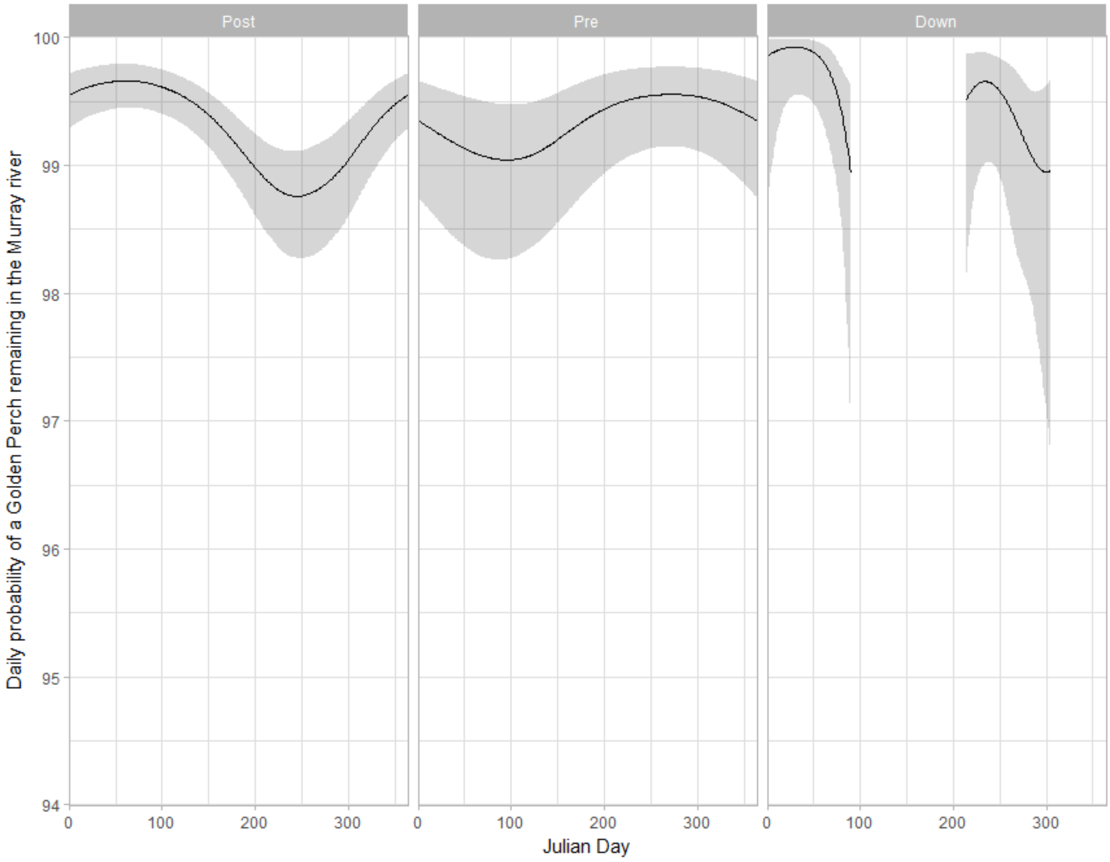

Figure 8. The probability that a Golden Perch in the Murray River stays in the Murray River dependent on day-of-year and regulator status (pre-, post- and during the flood event when the gate configuration was laid flat).

Catfish

Catfish showed the lowest rate of movement between zones indicating strong site fidelity (Table 3), however 10 of the 18 fish detected on our receivers (55 %) were found to shift zones at least once. Like the other species, Catfish movements to the Murray River were influenced by day-of-year and Mullaroo inlet regulator status according to the models (Appendix 2.5). Since the regulator was installed there is a clear signal of increased movement of Catfish from the anabranch (the lower Lindsay River) to the Murray River in spring with a peak of around 8% (5 – 13% CI) during spring (Figure 9). At all other times, movement to the Murray River was very low (<1% per day), including all times of year pre-regulator and when the regulator was down.

Similarly, Catfish movement to the anabranch were also influenced by day-of-year and regulator status according to the models (Appendix 2.6) with a clear signal of increased Catfish movement from the Murray River to the anabranch (lower Lindsay River), peaking at 15% per day (10 – 23% CI) during spring since the regulator was installed (Figure 10). At all other times, movement to the Murray River was very low (<1% per day), including all times of year pre-regulator and when the regulator was down.

Movement data of individual fish which typify these patterns include:

- Catfish Fish ID 173.29 (497 mm TL, tagged in the upper Mullaroo Creek in April 2016) was the only Catfish with an active transmitter during the flood and blackwater event (transmitters had expired on all other Catfish). Over a 32-day period from 25 November to 26 December this fish transitioned 11 times between zones (Figure 9). This fish initially transitioned from the upper Mullaroo Creek (zone B) into the Murray River moving upstream above the upper Potterwalkagee Creek junction (via zone A, I and J) and out of the study area (zone K). This fish returned back into the study area on 16 December moving downstream past Lock 8 and 7 on the Murray River (via zone J, I, A, and H) before heading up into the lower Lindsay River (zone G). The fish then travelled back to the Murray River on 21 December, headed upstream (via zone H) through lock 7 and transitioned back into the upper Mullaroo Creek on 26 December where it was first captured.
- Fish 173.73 (382 mm TL, tagged in the Murray River below Lock 7 in March 2017) moved constantly between the Murray River and lower Lindsay River between August and October 2017, a period of increased discharge in the upper Mullaroo Creek and lower Lindsay River. This individual has since shifted into the lower Lindsay River Figure 11).
- Fish 132.57 (464 mm TL) tagged in the upper Mullaroo Creek (March 2017) remained in this reach until February 2018, at which time it moved downstream during a flow pulse into the lower Lindsay River (Figure 11).

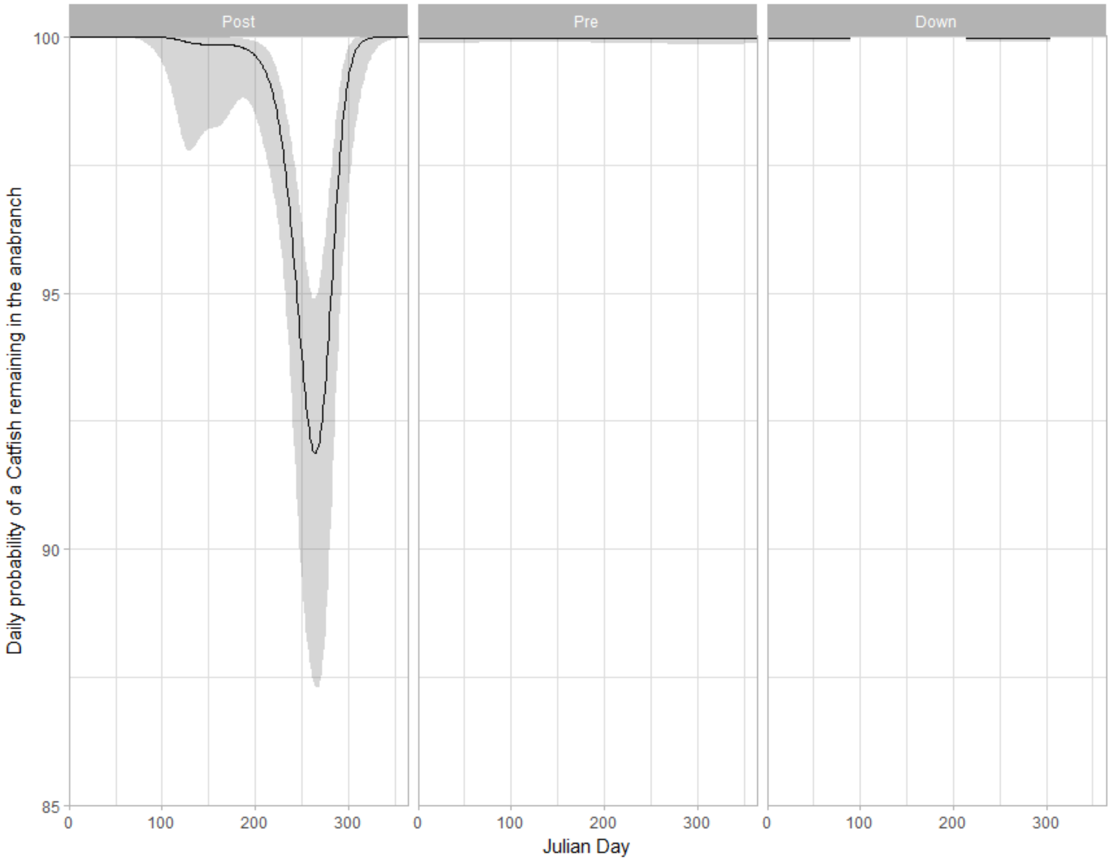

Figure 9. The probability that a Catfish in the anabranch stays in the anabranch dependent on day-of-year and regulator status (pre-, post- and during the flood event when the gate configuration was laid flat).

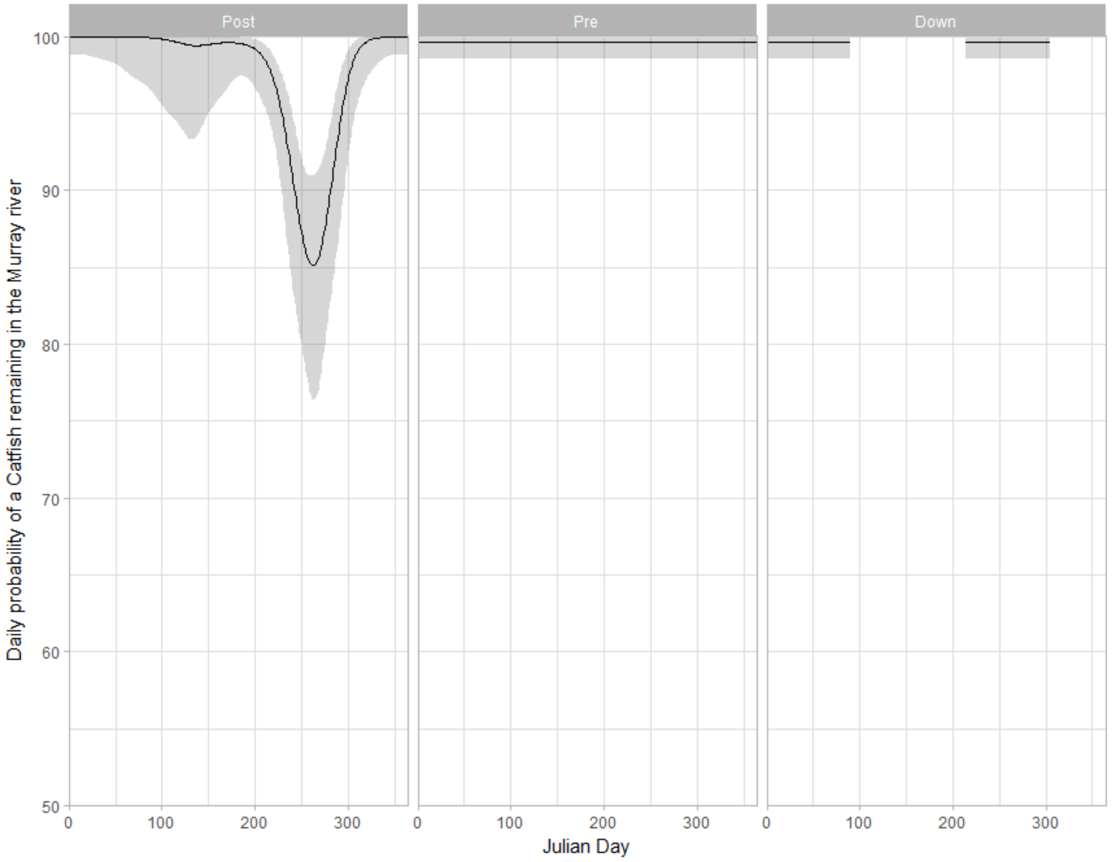

Figure 10. The probability that a Catfish in the Murray River stays in the Murray River dependent on day-of-year and regulator status (pre-, post- and during the flood event when the gate configuration was laid flat).

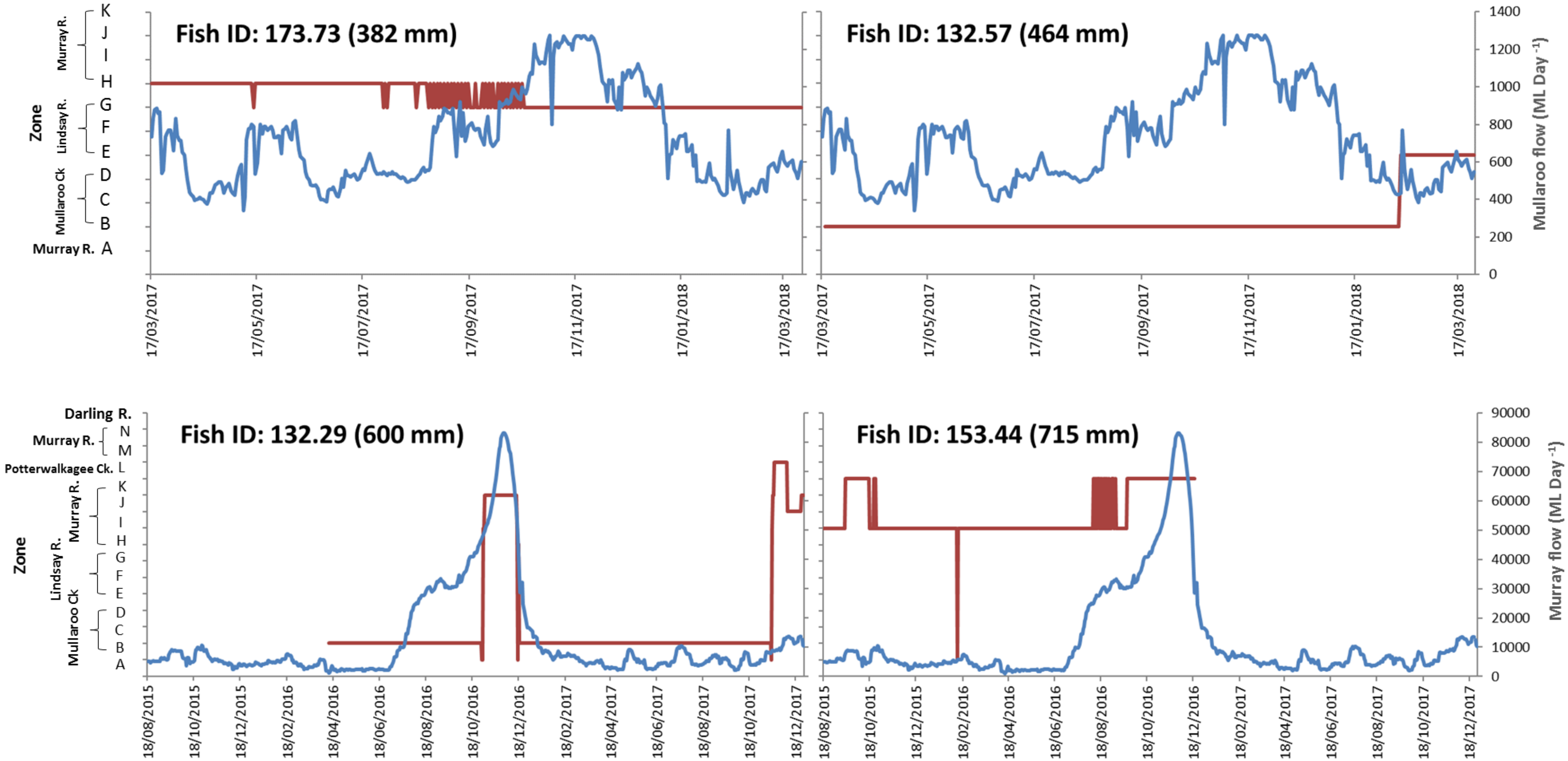

Figure 11. The movement patterns of two individual Catfish (top); and two individual Carp (bottom) during the study. Letters denote specific zones of the study area (see Figure 1).

Carp

Carp showed the highest rate of movement, with 86 % of detected fish changing zones during the study (Table 3). Carp movements to the Murray River from the anabranches (predominantly lower Lindsay River and upper Mullaroo Creek) were influenced by day-of-year and regulator status according to the models (Appendix 2.7). There is a clear signal of increased Carp movement from the anabranch to the Murray River in spring both pre- and post-regulator (Figure 12). When the regulator was flooded, the movement rate increased. Carp movements to the anabranch from the Murray River were influenced by day-of-year and regulator status according to the models (Appendix 2.8).

Carp in the Murray River stayed in the Murray River, with the increased chance of movement to the anabranch in August to mid-November (Figure 8). However, since the regulator has been installed the amount of movement from the Murray River to the anabranch has decreased dramatically, from a peak movement rate of around 13% per day pre-regulator to under 5% per day since the regulator was installed.

Movement data of individual fish which typify these patterns include:

- Carp Fish ID 132.29 (600mm FL, tagged in upper Mullaroo Creek) transitioned into the Murray River on 31/10/2016 and moved upstream out of the study reach. It migrated back downstream on the 16/12/2016 and returned to the upper Mullaroo Creek within three days (Figure 11). The fish then repeated this movement the following year at a similar time of year (early November).
- Carp Fish ID 153.44 (715mm FL, tagged in Murray River) moved to the Potterwalkagee Creek mid-September 2015 for 30 days before returning. The fish repeated this movement in 2016 (Figure 11). These seasonal movements to the anabranch reach coincide with the spawning period of the species.

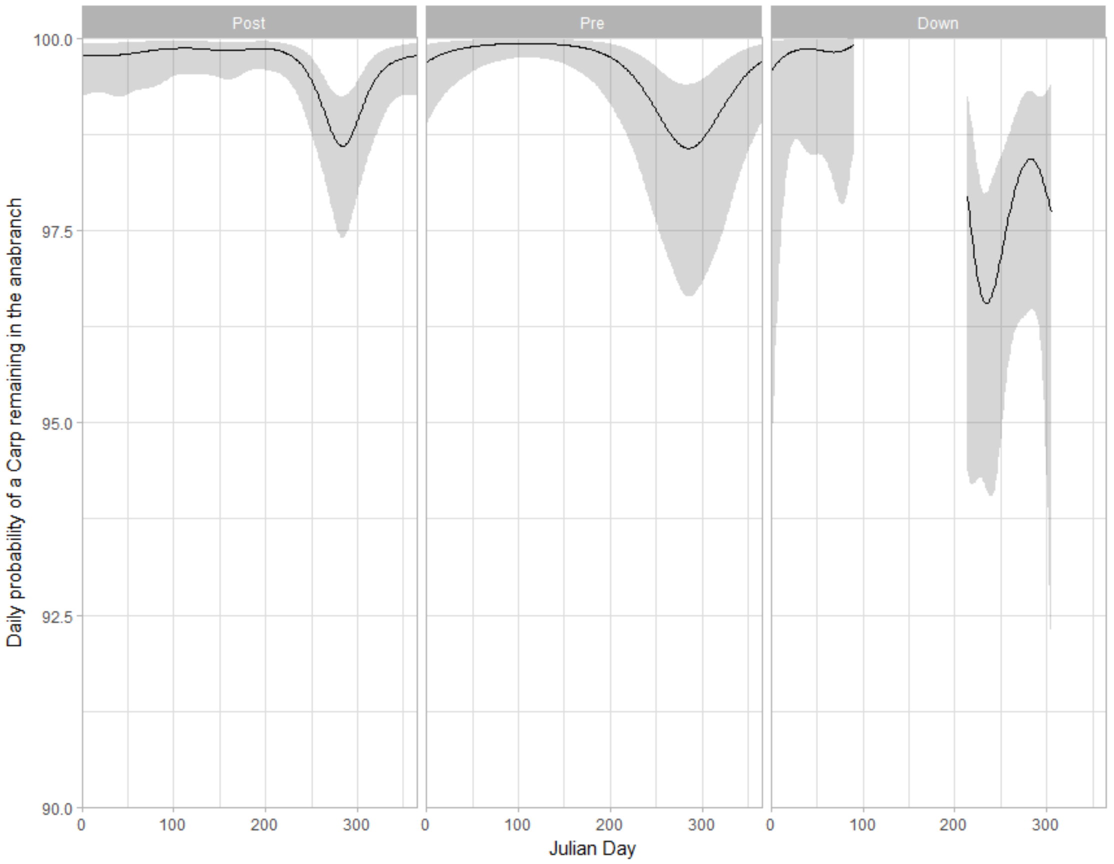

Figure 12. The probability that a Carp in the anabranch stays in the anabranch dependent on day-of-year and regulator status (pre-, post- and during the flood event when the gate configuration was laid flat).

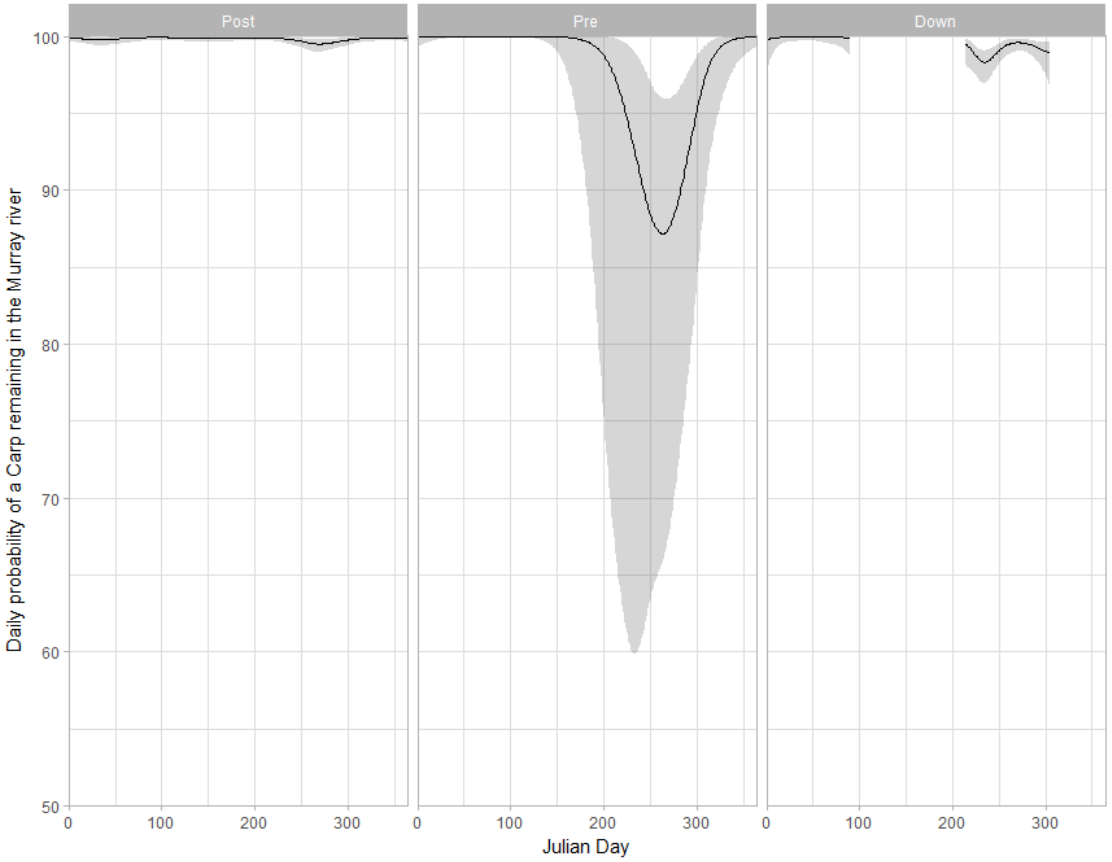

Figure 13. The probability that a Carp in the Murray River stays in the Murray River dependent on day-of-year and regulator status (pre-, post- and during the flood event when the gate configuration was laid flat).

3.3.2 Fish movement and survival following the 2016 flood and blackwater event

Elevated levels of fish movement were detected from September to December 2016 in the lead up to and at the height of the flood and hypoxic blackwater that saw dissolved oxygen concentrations drop below 1mg/L across the study area (see Tonkin et al. 2016). Whilst it is now clear that Murray Cod occupancy of the study area underwent a dramatic decline during the peak flooding and blackwater event, the proportions of fish which had perished, survived and emigrated (and not returned) was still unclear (see Tonkin et al. 2017). Prior to November 2016, 63 tagged Murray Cod were active in the system (Table 5). As of March 2018, our current understanding of the aftermath of the blackwater event and status of these tagged Murray Cod is:

- Twenty-one tagged Murray Cod (33% of fish), are confirmed to have survived the blackwater event. Seventeen of these fish migrated downstream during the blackwater event before returning from the Murray River downstream of the lower Lindsay River junction (two of these fish did not return until late 2017 and 2018). One migrated upstream and remains below Lock 9, one returned to the Murray River from the upper Lindsay River, and two remained in the Murray River between Locks 7 and 8. All of these fish were > 500 mm in length with 78% of fish between 830 – 1190 mm.
- Twenty-four tagged Murray Cod (38%) which were alive prior to the blackwater event were confirmed dead (most of which were found on the floodplain).
- The location and status of 30 fish, 24 of which were present in the study area prior to the blackwater event (~39% of tagged fish) remain unknown (Table 5). Sixteen of these fish (of unknown status) moved out of the study reach down the Murray River (below the Lindsay River junction). Like most of the surviving fish, there is some hope that these fish may still return to the system.
- Unlike Murray Cod, the other species did not appear to suffer the mortality rates. As of March 2017, only two of the 33 (6%) tagged Golden Perch which were active in the system prior to the blackwater event were found dead. No tagged Carp or Catfish were found to have died during the blackwater event.

Table 4. The status and number of Murray Cod in the study area prior to and following the 2016 flood and blackwater event. Numbers exclude Murray Cod tagged after March 2016. * Excludes mortality signals from fish detected alive after the event (e.g. non-blackwater event mortality).

Tagged Murray Cod status	Prior to November 2016	Post December 2017
Alive (detected in the study area)	63	21
Dead (mortality signal triggered)	6	24
Unknown (left the study area or not detected on loggers)	6	30

3.3.3 Patterns of fish transitions from the upper Mullaroo Creek to the Murray River

In addition to our transition models, we assessed transmitter signal strength recorded at the Mullaroo Regulator logger tower to further explore patterns in fish transition from the Upper Mullaroo Creek to the Murray River. This included an 11 month period with the old ford structure in place (Figure 9a) although it did include several months when a bypass channel was around the construction site), a 24 month period under the operation of the new regulator/ fishway (Figure 9b) and an 8 month period when the gates were laid flat and the regulator/ fishway was not in operation due to the significant flood event.

Data indicated that prior to construction all four species were able to successfully transition from the Upper Mullaroo Creek to the Murray River, although both the total percentage of transitions (29% success) and the total percentage of individual fish transitions (61% success) was relatively low (Table 6). Murray Cod and Catfish had lower transition rates, while Carp successfully transitioned across the ford structure with every approach (Table 5).

Following the construction of the regulator/ fishway the total percentage of successful transitions was slightly lower (22% success) and the total percentage of individual fish transitions (38% success) was much lower (Table 5), with this result being a further reduction than that reported in 2017. Catfish were not recorded to successfully ascend the fishway, however this is based on just two individual fish (and approaches; Table 5).

From August 2016, gates on the regulator/ fishway were laid flat to protect the infrastructure from flood damage. Data indicate that transition rates for all four species during this period were much higher than both pre-and post-regulator/ fishway construction (Table 6).

Figure 14. The Upper Mullaroo Creek in a) 2014 with the old ford structure and, b) 2016 with the construction of the new regulator/fishway.

Table 5. Total number of approaches (including multiple approaches by individual fish) and number of individual fish that approached and ascended the Mullaroo Creek regulator/fishway pre-construction (June 2014 – April 15), post-construction (July 2015 – December 18) and post construction with the gates laid flat during the flood event (August 2016 – March 17). Numbers do not include fish which approached or ascended during regulator construction between April 2015 and July 2015 nor does it include any downstream movement from the Murray River.

Species	Total approaches	% Ascended	No. individual fish approached	% individual fish ascended
Pre Regulator/ Fishway No Gates	June 2014 – April 15			
Murray Cod	84	24	17	53
Golden Perch	30	47	7	86
Catfish	16	13	5	40
Carp	3	100	2	100
TOTAL	***133***	***29***	***31***	***61***
Post Regulator/Fishway Gates raised	July 2015 – December 18 (exc. High flow period Below)			
Murray Cod	129	23	28	29
Golden Perch	63	22	17	53
Catfish	2	0	2	0
Carp	17	12	9	44
TOTAL	***211***	***22***	***56***	***38***
Post Regulator/Fishway Gates laid flat during flood event	August 2016 – March 17			
Murray Cod	64	56	31	71
Golden Perch	7	100	7	100
Catfish	1	100	1	100
Carp	5	80	4	75
TOTAL	***77***	***62***	***43***	***77***

4 Discussion

Importance of connected flowing rivers and anabranches

The substantial hydrodynamic alteration and resultant habitat homogenization in the lower Murray River has had a profound effect on ecosystem function and form (Mallen-Cooper and Zampatti 2018). Following these changes, the complex anabranch systems within the Chowilla-Lindsay-Wallpolla Icon Site now provide the unique hydraulic and structural habitat characteristics which are a critical requirement to complete key life-history stages for several native fish species, including Murray Cod (Saddlier and O'Mahony 2009). The results of this study have further demonstrated the importance of anabranch and main river habitats by quantifying the use of anabranches in the Lindsay and Mulcra Island anabranch systems for four (3 native and one introduced) fish species in the region. Importantly, the time frame over which the data has been collected (fish transitions, habitat use and survival) has encompassed a range of environmental conditions including low flows, extreme floods, hypoxic blackwater and changes in infrastructure. As such, the program is now helping guide future operation of floodplain infrastructure and environmental water delivery in the region.

The degree of connection that occurs within or between spatially separated animal meta-populations drives processes that govern the fate of species (Levin 1992; Lyon et al. 2014). Data collected since March 2014 have high detection (87% of tagged fish) and transition rates of detected fish (86%) between zones throughout the lower Murray River and Lindsay and Mulcra Island anabranch systems for all four study species. Typical of fish movement studies, the patterns of fish movements displayed a high degree of spatiotemporal variability, both across and within species. Over the study period, movements have generally comprised those that appear to be associated with reproductive activity (spring), range shifts and seasonal transitions between anabranches and the Murray River main channel.

What is also becoming evident as the amount of data increases is that the patterns in movements appear to have shifted in the three years following the construction and operation of the Mullaroo inlet regulator for all four study species. For Murray Cod, our previous analysis indicated that movement of fish between anabranches (the upper Mullaroo Creek and lower Lindsay River) and the Murray River main channel was most influenced by discharge and time of year (Tonkin et al. 2017). Not surprisingly, since discharge in the Mullaroo Creek and lower Lindsay River has reduced since the construction and operation of the inlet regulator (approximately 21 % reduction in mean daily discharge over period of data collection) our most recent analysis has shown patterns in these movement behaviours has also significantly altered.

Murray Cod movement was most likely to encompass the upper Mullaroo Creek (zone B), with a greater proportion of transitions to-and-from the Murray River occurring during the spawning period (September to early December). This highlights the previously suggested importance of this reach as a spawning area for the species due to its favourable hydraulic and woody habitat characteristics (Sharpe et al. 2009; Saddlier and O'Mahony 2009; Tonkin et al. 2016). Our analysis of Murray Cod transition rates between anabranch habitats and the Murray River has shown the significant effect of time of year (as per Tonkin et al. 2017) and now, changes in operation of the inlet regulator. Since the construction/operation of the Mullaroo inlet regulator, the probability of a Murray Cod moving into the Murray River from the anabranch system (upper Mullaroo Creek or lower Lindsay River) slightly reduced during autumn, although the probability was low throughout the entire study (<1% likelihood of moving on any given day). The greatest change however, was the likelihood of Murray Cod moving from the Murray River into the anabranch system (upper Mullaroo Creek or lower Lindsay River), which significantly reduced compared to pre-regulator period. Whilst the overall timing of movements has not changed (highest likelihood in spring), Murray Cod were 18.8 times more likely to move into the upper Mullaroo Creek or lower Lindsay River from the Murray River prior to the installation and operation of the new inlet regulator. Given the strong relationship previously identified between transition rates and discharge and the overall reduction in discharge in the anabranch system in the post-regulator period, it is likely that this reduction is at least partly driven by the overall reduction in discharge. As such, we believe our previous recommendation of flows from 1000 – 1200 ML day^{-1} in the Mullaroo Creek between September and early December (which replicate the pre-regulator conditions) will greatly enhance Murray Cod transitions from the Murray River. Of course, a reduction in Murray Cod transitions into the anabranch system may also be due to a reduction in downstream movement through the new regulator (in the upper Mullaroo Creek), a result which was unanticipated.

For Mallee CMA, implementing and maintaining the recommended hydrograph (1000-1200 ML day^{-1} in spring/early summer) is particularly important to facilitate Murray Cod movement into what appears to be favourable spawning habitat in the anabranch system. It will also facilitate movement of fish back into the system following the blackwater induced emigration (see below). We also suggest further analysis and/or targeted monitoring of these managed flow events and to consider the Murray River discharge and height at lock 8 (and its interaction with the Mullaroo Creek regulator) to better inform such future management of the site.

Our analysis also revealed some unexpected patterns in Catfish movement. Early in the program, Catfish movements between the Murray River and anabranch habitats were very low which we thought were simply a result of the species very strong site fidelity as demonstrated in previous studies (e.g. Koster et al. 2015). Our most recent analysis however has shown that Catfish movement, like other species, was influenced by day-of-year and inlet regulator status. Since the inlet regulator was installed there is a clear signal of increased movement of Catfish between the anabranch and Murray River in spring. The exact cause for this increased movement between habitats is unclear, however we propose this is perhaps due to a return to a more variable hydrograph in the anabranch system, whereby there has been a shift towards a peak in discharge in late winter and Spring followed by a substantial reduction to lower baseflows (e.g. 340-700 ML day^{-1}) in Summer and Autumn, rather than the previous stable flow regime (1000 – 1200 ML Day-1) that existed prior to the inlet regulator construction and operation. The ecological implications of the change to anabranch-main channel movement rates for Catfish requires further investigation and is a priority for future research.

Like previous years, Golden Perch displayed highly variable movement, both spatially and temporally. Golden Perch transitions between the Murray River and anabranch habitats were influenced by day-of-year and inlet regulator status. Whilst the overall rate that Golden Perch movement between habitats did not change between different periods of inlet regulator status, the temporal patterns did change. In particular, prior to the construction of the inlet regulator, Golden Perch were more likely to move into the anabranch in autumn. However, since the construction and operation of the regulator, the temporal patterns in movement of Golden Perch have reversed, being more likely to move into the anabranch in spring. This pattern in movement appears to be more akin to the general pattern of increased movements during the spring spawning period, as has been reported in other studies (e.g. O'Connor et al. 2005; Koster et al. 2017). Again, like the patterns observed for Catfish, this is perhaps due to a return to a more seasonally natural hydrograph in the anabranch system, a result that should be viewed as positive.

Whilst investigating Carp movement was not initially an objective of the study, the new information may help manage this pest fish. Like previous years, Carp showed the highest rate of movement, with 86 % of detected fish changing zones during the study, and as per other species, their movements between the Murray River and anabranches were influenced by time-of-year and inlet regulator status. There was a clear signal of increased Carp movement from the anabranch to the Murray River in spring both pre- and post-inlet regulator, with this movement increasing when the regulator was flooded. Like the other species, since the inlet regulator has been installed the amount of movement from the Murray River to the anabranch changed dramatically, however unlike the native species, these movements decreased from a peak movement rate of around 13% per day pre-regulator to under 5% per day since the regulator was installed. This shift towards a more variable flow regime in the anabranch habitats has not only increased the use of anabranches by Golden Perch and Catfish, but appears to have reduced their use by Carp, with the latter perhaps preferring the stable high flows previously present in the anabranch. This result is not surprising, particularly for movements during spring whereby Carp are more likely to seek out high flows during the spawning period (e.g. Stuart and Jones 2006).

Impacts of hypoxic blackwater

Our analysis has provided further information on the impacts of the hypoxic blackwater event on fish occupancy and survival in late 2016. Whilst it is now clear that Murray Cod occupancy of the study area underwent a dramatic decline during the event (see Tonkin et al. 2017), the proportions of fish which had perished, survived and emigrated (and not returned) was still unclear. Our data has since showed that 33% of tagged Murray Cod survived the blackwater event, with the majority of these fish migrating downstream in the Murray River during the blackwater event before returning sporadically (the most recent fish returned just days before the last logger download in 2018). A slightly greater number of Murray Cod perished (38%) and the status of ~39% of tagged fish (most of which left the study area) is still unknown. Our data also showed relatively similar proportions of size-classes from 50 – 119 cm survived (or died). The work of Small et al. (2014) also demonstrated juvenile Murray Cod were susceptible to hypoxia levels around 2 mg L^{-1}. Unlike Murray Cod the other species did not appear to suffer high mortality rates like Murray Cod which is not surprising given earlier findings that the species is more sensitive than many other native fish species (Small et al. 2014). These results highlight how vital it is to provide immediate upstream and downstream connectivity prior to, during and after these hypoxic blackwater events to allow fish to seek refuge and then return over the medium and long-term after the event has passed.

Upstream fish passage through the new inlet regulator

In addition to our transition analysis, we assessed transmitter signal strength recorded at the Mullaroo Regulator logger tower to further explore patterns in fish transition from the Upper Mullaroo Creek into the Murray River. Data indicated that prior to inlet regulator construction all four species were able to successfully transition from the Upper Mullaroo Creek to the Murray River, although both the total percentage of transitions (29%) and the total percentage of individual fish transitions (61%) was relatively low. Murray Cod and Catfish had lower transition rates, while Carp successfully transitioned across the old ford structure with every approach.

Following the construction of the inlet regulator (and fishway) in June 2015, the total percentage of transitions was slightly lower (22%) and the total percentage of individual fish transitions (38%) was lower, with this result constituting a further reduction than that reported in previous analyses (see Tonkin et al. 2017). Catfish have still not been recorded successfully ascending the fishway, other than a single fish which transitioned when the gates were laid flat under high flows. Further targeted monitoring of the fishway over the coming years will be required to quantify fish transitions between the Upper Mullaroo Creek and the Murray River. This should be conducted under a range of hydrological conditions and gate arrangements aimed at optimising fish movement. We also recommend extending this assessment to include assessing downstream passage of fish from the Murray River given the major reductions of Murray River – anabranch transitions.

4.2 Future directions

The information gathered on fish movement and habitat use (and associated drivers) during the program has generated important information to help MCMA manage environmental flows and infrastructure operations to maximise benefits for native fish in the Lindsay and Mulcra Island anabranch system. As such, we recommend the program can now, in addition to monitoring overall reach occupancy and transition rates, shift to monitor specific flow events (including weir pool and regulator gate operations, similar to that being undertaken as part of the Victorian Environmental Flow Assessment Program (DELWP 2017a, 2017b).

The ongoing success of this approach will require a close collaboration among MCMA waterway managers, operators (MDBA and SA Water) and researchers, thus enabling effective planning and delivery of appropriate interventions and subsequent monitoring. This approach should encompass both telemetry data (as per that being used in this program) and event-based netting or fish trapping with the former requiring a continuation of the annual fish tagging and maintenance routine (at least at baseline levels). We recommend the continued assessment of fish transitions between the Murray River and priority anabranch reaches which extend to smaller individuals and species (assessed via trapping and netting) under a range of operational scenarios including simulated flow pulses and flooding such as increased spring discharge in Mullaroo Creek.

The transition of the program to acoustic tags (which began in March 2017), whilst limiting the ability to assess direct mortality and habitat use, is overcoming previous limitations of exceeding the memory capacity of data loggers. Furthermore, we can also assess larger spatial and temporal scale migratory behaviour both to and from the study site, as per the data presented (e.g. the lower Darling River movements). Given such investigations are more aligned at a basin level rather than icon site scale, it will require close collaboration with other projects and agencies currently operating across the southern MDB. These include The Living Murray initiative and Commonwealth's Long Term Intervention Monitoring project, the Sustainable Diversion Limits (SDL) project, Victorian Environmental Flow Assessment Program (VEFMAP) and NSW agency weir pool manipulation programs.

Despite minimising data capacity issues, biannual maintenance of data loggers and data downloading is still necessary in late winter and summer/autumn. The late winter download will ensure that loggers are still positioned (not damaged or stolen) prior to the spawning season when large volumes of movement data is expected to be recorded. The summer/autumn download is required to change batteries and general maintenance. This biannual maintenance program also allows for radio telemetry towers to be serviced, which is still required given the large number of radio transmitters that will be active in the system for the next two years.

Knowledge of short and long-term influence of hydrological and hydraulic alterations following artificial floodplain inundation on native and exotic fish in Australian temperate floodplain ecosystems is still increasing and are vital to the long-term sustainability of the regional fish community. Collection and incorporation of ecological data and scientific representation into regulator operational procedures will be an important component in the management of future watering regimes within the Icon site.

5 Management recommendations

- To maximise Murray Cod use of lower Lindasy and Mullaroo Creek during the spawning period, implement a spring/summer (September-December) steady flow hydrograph (1000-1200 ML day^{-1}) into the upper Mullaroo Creek.
- To increase Murray Cod movement into the anabranch system outside of the spawning period, Implement fresh events in summer/autumn and winter in Mullaroo Creek (1000 ML day^{-1}).
- To continue the positive outcomes for Catfish and Golden perch, continue to deliver spring high flows as extended fresh type events by maintaining suitable rates of rise and fall (back to lower baseflows) to maintain the increased flow variability present in the reach post-regulator operation.
- Continue the tagging program and expand the analysis to improve knowledge of fish transition rates under a variety of hydrological conditions and determine the influence of infrastructure on upstream and downstream passage.
- Expand the intervention monitoring to include further targeted monitoring of upstream and downstream passage of both large and small-bodied fish species between the upper Mullaroo Creek and the Murray River (via the regulator and fishway). This should be conducted under a range of hydrological conditions; different gate arrangements and Lock 7 weir pool heights.

References

Burnham, K. P., and Anderson, D. R. (2010). Model Selection and Multi-Model Inference: A Practical Information-Theoretic Approach (Second). Springer.

DSE (2010). Murray Darling Basin, The Living Murray Environmental Works and Measures Plan Upper Lindsay Watercourse Enhancement Proposal, Lindsay Island Works Stage 1. Department of Sustainability and Environment

DELWP (2017a). VEFMAP Stage 6 Part B: Program design and monitoring methods. A report by Arthur Rylah Institute for Environmental Research and Integrated Water and Catchments Division, Department of Environment, Land, Water and Planning, Victoria

DELWP (2017). VEFMAP Stage 6: Monitoring fish response to environmental flow delivery in northern Victorian rivers, 2016/17. A client report to Water and Catchments, the Department of Environment, Land, Water and Planning.

Henderson M, Cranston G, Wood D, Freestone F, Campbell C, Vlamis T and Vilizzi L. (2013). The Living Murray Condition Monitoring at Lindsay, Mulcra and Wallpolla Islands 2012–13: Part B – Supplementary Material. Final Report prepared for the Mallee Catchment Management Authority by The Murray-Darling Freshwater Research Centre, MDFRC Publication 18/2013, November, 202pp.

Koster, W.M., Dawson, D.R., Clunie, P., Hames, F., McKenzie, J., Moloney, P.D. and Crook, D.A., (2015). Movement and habitat use of the freshwater catfish (*Tandanus tandanus*) in a remnant floodplain wetland. *Ecology of Freshwater Fish*, 24(3), 443-455.

Koster, W.M., Dawson, D.R., Liu, C., Moloney, P.D., Crook, D.A. and Thomson, J.R. (2017). Influence of streamflow on spawning-related movements of golden perch *Macquaria ambigua* in south-eastern Australia. *Journal of Fish Biology*, 90, 93-108.

Levin, S.A. (1992). The problem of pattern and scale in ecology. *Ecology* 73, 1943–1967.

Maheshwari, B. L., Walker, K. F. and McMahon, T. A. (1995). Effects of regulation on the flow regime of the river Murray, *Australia. Regulated Rivers: Research and Management*, 10, 15–38. Doi: 10.1002/rrr.3450100103

Mallen-Cooper, M., King, A., Koehn, J., Saddlier, S., Scharpe, C., Stuart, I. and Zampatti, B. (2010). Fish requirements for the proposed Upper Lindsay Watercourse Enhancement project. Report prepared for the Mallee Catchment Management Authority.

Mallen-Cooper, M. and Zampatti, B. (2018). History, hydrology and hydraulics: Rethinking the ecological management of large rivers. *Ecohydrology*. DOI: https://doi.org/10.1002/eco.1965

Murray-Darling Basin Authority (2018). River Murray Data. Accessed online on 1 April 2018 at https://riverdata.mdba.gov.au/system-view

Natarajan, A.V. (1989). Environmental impact of Ganga basin development on gene-pool and fisheries of the Ganga River system. In(Dodge, G.P. Ed), Proceedings of the International Large River Symposium (LARS). *Canadian Special Publication of Fisheries and Aquatic Science*s, 106, 545-560.

NSW SES (2016). Flood Bulletin 115. Accessed online on 10 June 2017 at http://www.murrayriver.nsw.gov.au/sites/murrayriver/files/public/Murray_River/News/NSW%20SES%20115%20Minor%20to%20Moderate%20%20Murray%20river%2020161125.pdf

O'Connor, J.P., O'Mahony, D.J. and O'Mahony, J.M. (2005). Movements of *Macquaria ambigua*, in the Murray River, south-eastern Australia. *Journal of Fish Biology*, 66,392-403.

R Core Team (2018). R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/.

Saddlier, S., O'Mahony, J. and Ramsey, D. (2007). Protection and enhancement of Murray cod populations. Arthur Rylah Institute for Environmental Research Technical Report Series No. 172. Department of Sustainability and Environment, Heidelberg, Victoria.

Saddlier, S. and O.Mahony J. (2009). Observations on the movement of Murray cod under varying flow conditions within Mullaroo Creek. A report to the Mallee Catchment Management Authority. Arthur Rylah Institute for Environmental Research. Department of Sustainability and Environment, Heidelberg, Victoria.

Sharpe, C., Wallace, T., Fraser, P. and Vilizzi, L., (2009). The Impact of Drought on the Distribution of Fish Communities in the Mullaroo-Creek – Lindsay River Complex. Murray-Darling Freshwater Research Centre, Lower Basin Laboratory, Victoria. SKM and Roberts, 2003. Assessment of water management options for Lindsay and Wallpolla Islands. Report for Mallee CMA.

Small K., Kopf R.K., Watts R.J. & Howitt J. (2014). Hypoxia, Blackwater and Fish Kills: Experimental Lethal Oxygen Thresholds in Juvenile Predatory Lowland River Fishes. *PLOS ONE*, 9(4), 1-10.

Stuart, I.G., and Jones, M. (2006) Movement of common carp, Cyprinus carpio, in a regulated lowland Australian river: implications for management. *Fisheries Management and Ecology* 13(4), 231-219.

Tonkin, Z., O'Mahony, J., Raymond, S., Moloney, P. and Lyon, J. (2017). Fish movement in the Lindsay and Mulcra Island anabranch systems: 2017 Progress report. Unpublished Client Report for the Mallee Catchment Management Authority. Arthur Rylah Institute for Environmental Research. Department of Environment, Energy, Environment and Climate Change Group, Heidelberg, Victoria.

WaterConnect South Australia (2016). Real-time data (River Murray at Lock 8, River Murray at Lock 7 Downstream, River Murray at Lock 7 2km Upstream). Accessed online on 10 June 2017 at https://www.waterconnect.sa.gov.au/

Wood, S. N. (2011). Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society* (B), 73(1), 3–36.

Wood, S. N., Pya, N., and Säfken, B. (2016). Smoothing parameter and model selection for general smooth models. *Journal of the American Statistical Association*, 1–45. http://doi.org/10.1080/01621459.2016.1180986

Appendices

Appendix 1. Size and tag details of individual fish implanted with telemetry tags in the Lindsay Island anabranch study from March 2014 – April 2018.

Species	Zone	Length (mm)	Weight (g)	Fish ID	status
Murray Cod	a	890	10500	132.01	Tag Active
Murray Cod	b	919	12600	132.02	Tag Active
Murray Cod	a	957	13500	132.03	Tag Active
Murray Cod	a	1050	22000	132.04	Mortality
Murray Cod	a	1120	24000	132.05	Mortality
Murray Cod	a	832	9239	132.06	Tag Active
Murray Cod	a	931	12300	132.08	Tag Active
Murray Cod	a	848	8650	132.09	Tag Active
Murray Cod	a	840	9000	132.27	Tag Active
Murray Cod	a	732	5200	132.28	Tag Active
Murray Cod	b	713	5191	132.32	Mortality
Murray Cod	d	574	3072	132.58	Tag Active
Murray Cod	b	435	1008	132.61	Tag Active
Murray Cod	b	760	8200	153.11	Tag Active
Murray Cod	d	720	5976	153.12	Tag Active
Murray Cod	d	815	10400	153.13	Tag Expired
Murray Cod	b	885	14000	153.14	Tag Expired
Murray Cod	d	955	16400	153.16	Tag Expired
Murray Cod	b	1140	24000	153.18	Tag Active
Murray Cod	b	579	2826	153.21	Tag Expired
Murray Cod	d	870	14200	153.23	Tag Expired
Murray Cod	b	990	18500	153.32	Tag Expired
Murray Cod	b	980	17000	153.33	Mortality
Murray Cod	d	980	15500	153.34	Tag Expired
Murray Cod	b	1210	34800	153.35	Mortality
Murray Cod	b	885	12500	153.36	Mortality
Murray Cod	i	1150	26000	153.45	Tag Active
Murray Cod	i	1190	32000	153.46	Mortality
Murray Cod	i	1010	18000	153.47	Tag Active
Murray Cod	i	1080	24000	153.48	Mortality
Murray Cod	i	712	8500	153.49	Tag Active
Murray Cod	b	360	462	153.54	Tag Expired
Murray Cod	b	379	630	153.57	Mortality
Murray Cod	b	377	606	153.58	Mortality
Murray Cod	b	395	732	153.61	Tag Expired
Murray Cod	d	303	359	153.63	Tag Expired
Murray Cod	b	384	709	153.64	Tag Expired

Murray Cod	b	1150	29000	173.05	Mortality
Murray Cod	b	588	3130	173.11	Angled
Murray Cod	d	680	5150	173.12	Mortality
Murray Cod	d	660	5190	173.13	Tag Active
Murray Cod	d	890	12900	173.14	Tag Expired
Murray Cod	b	835	11000	173.15	Tag Expired
Murray Cod	b	527	2100	173.16	Mortality
Murray Cod	b	855	9900	173.17	Tag Active
Murray Cod	b	637	3940	173.18	Tag Expired
Murray Cod	b	625	3542	173.19	Mortality
Murray Cod	d	519	1908	173.20	Tag Expired
Murray Cod	b	550	2700	173.21	Tag Expired
Murray Cod	b	640	4256	173.22	Tag Expired
Murray Cod	b	611	3408	173.23	Angled
Murray Cod	b	835	10000	173.24	Tag Expired
Murray Cod	b	900	13400	173.26	Mortality
Murray Cod	b	825	9000	173.32	Mortality
Murray Cod	b	1100	26900	173.33	Tag Expired
Murray Cod	b	1080	25400	173.34	Tag Expired
Murray Cod	b	1160	35000	173.35	Tag Expired
Murray Cod	b	640	4100	173.36	Mortality
Murray Cod	b	392	726	173.52	Mortality
Murray Cod	b	366	565	173.54	Tag Expired
Murray Cod	d	299	356	173.55	Mortality
Murray Cod	b	383	633	173.57	Tag Expired
Murray Cod	b	381	669	173.58	Tag Expired
Murray Cod	b	354	488	173.59	Mortality
Murray Cod	h	637	4560	232.53	Unknown
Murray Cod	b	610	3450	232.56	Unknown
Murray Cod	h	1020	18750	232.57	Unknown
Murray Cod	b	610	3888	232.67	Unknown
Murray Cod	i	632	3444	232.68	Unknown
Murray Cod	b	1110	22000	232.71	Unknown
Murray Cod	a	1020	18000	232.72	Unknown
Murray Cod	a	1090	20000	232.77	Unknown
Murray Cod	a	860	9700	234.30	Tag Active
Murray Cod	d	1080	21200	234.31	Mortality
Murray Cod	d	960	14000	234.33	Mortality
Murray Cod	b	712	5315	234.44	Tag Active
Murray Cod	b	740	6200	234.45	Tag Active
Murray Cod	i	920	12000	153.02b	Tag Active
Murray Cod	i	1140	25000	153.03b	Tag Active
Murray Cod	i	720	8000	153.04a	Tag Active
Murray Cod	i	718	5300	153.04b	Unknown
Murray Cod	i	965	14000	153.05b	Tag Active
Murray Cod	b	1060	21000	153.27b	Tag Active

Golden Perch	d	404	948	132.11	Tag Expired
Golden Perch	b	374	740	132.12	Tag Expired
Golden Perch	d	402	974	132.15	Mortality
Golden Perch	b	395	826	132.16	Angled
Golden Perch	b	376	802	132.17	Tag Expired
Golden Perch	d	397	894	132.18	Mortality
Golden Perch	b	493	1242	132.19	Tag Expired
Golden Perch	b	359	750	132.20	Angled
Golden Perch	b	436	1202	132.22	Tag Expired
Golden Perch	b	413	1038	132.23	Tag Expired
Golden Perch	b	376	784	132.24	Tag Expired
Golden Perch	b	402	940	132.26	Tag Expired
Golden Perch	a	536	2170	132.35	Mortality
Golden Perch	b	395	980	132.37	Tag Expired
Golden Perch	b	430	1024	132.38	Tag Expired
Golden Perch	i	402	900	132.40	Mortality
Golden Perch	d	421	985	132.41	Tag Expired
Golden Perch	i	428	1385	132.42	Tag Active
Golden Perch	d	418	970	132.43	Tag Expired
Golden Perch	b	433	1210	132.44	Mortality
Golden Perch	b	415	1035	132.45	Tag Active
Golden Perch	b	400	952	132.46	Mortality
Golden Perch	d	394	970	132.52	Tag Active
Golden Perch	d	396	970	132.53	Unknown
Golden Perch	a	435	1251	132.55	Tag Active
Golden Perch	a	436	1588	132.56	Tag Active

Golden Perch	d	388	950	132.60	Unknown
Golden Perch	d	382	923	132.62	Tag Active
Golden Perch	d	478	1508	153.20	Tag Expired
Golden Perch	i	475	1820	153.28	Mortality
Golden Perch	b	386	846	153.50	Tag Expired
Golden Perch	b	420	1130	153.51	Tag Expired
Golden Perch	b	359	635	153.52	Tag Expired
Golden Perch	b	421	1057	153.53	Tag Expired
Golden Perch	a	447	1118	153.55	Tag Expired
Golden Perch	a	405	819	153.56	Tag Expired
Golden Perch	a	359	618	153.59	Tag Expired
Golden Perch	a	438	1077	153.60	Tag Expired
Golden Perch	d	353	573	153.62	Tag Expired
Golden Perch	b	376	763	153.68	Tag Active
Golden Perch	e	362	751	153.69	Tag Active
Golden Perch	b	326	508	153.70	Mortality
Golden Perch	a	364	730	153.71	Tag Active
Golden Perch	d	355	657	153.73	Mortality
Golden Perch	i	451	1450	173.04	Mortality
Golden Perch	i	480	1690	173.06	Mortality
Golden Perch	a	435	1160	173.30	Tag Active
Golden Perch	a	443	1237	173.31	Tag Active
Golden Perch	b	425	1100	173.38	Angled
Golden Perch	i	380	940	173.39	Angled
Golden Perch	d	460	1135	173.40	Mortality
Golden Perch	i	465	1250	173.41	Mortality

Golden Perch	i	490	1860	173.42	Angled
Golden Perch	i	440	1080	173.43	Tag Expired
Golden Perch	b	360	860	173.45	Mortality
Golden Perch	a	398	983	173.47	Angled
Golden Perch	a	408	988	173.48	Tag Active
Golden Perch	d	445	1168	173.50	Tag Expired
Golden Perch	d	396	750	173.51	Tag Expired
Golden Perch	a	387	858	173.53	Angled
Golden Perch	d	412	778	173.56	Tag Expired
Golden Perch	d	398	627	173.60	Tag Expired
Golden Perch	b	402	937	173.61	Tag Expired
Golden Perch	d	423	1159	173.62	Tag Expired
Golden Perch	a	453	1055	173.63	Mortality
Golden Perch	d	404	908	173.64	Tag Expired
Golden Perch	e	335	570	173.65	Unknown
Golden Perch	e	346	716	173.66	Unknown
Golden Perch	b	368	698	173.67	Unknown
Golden Perch	a	375	730	173.68	Mortality
Golden Perch	d	346	643	173.69	Mortality
Golden Perch	b	365	693	173.70	Unknown
Golden Perch	b	368	749	173.71	Mortality
Golden Perch	b	350	623	173.74	Tag Active
Golden Perch	d	375	700	234.01	Tag Expired
Golden Perch	d	370	670	234.02	Angled
Golden Perch	i	320	570	234.03	Tag Expired
Golden Perch	i	430	1148	234.04	Tag Expired

Golden Perch	i	456	1140	234.05	Tag Expired
Golden Perch	d	405	940	234.06	Tag Expired
Golden Perch	d	386	720	234.08	Tag Expired
Golden Perch	d	353	630	234.09	Tag Expired
Golden Perch	d	340	570	234.12	Tag Expired
Golden Perch	i	374	790	234.13	Tag Expired
Golden Perch	d	423	1080	234.16	Tag Expired
Golden Perch	b	375	718	234.17	Tag Expired
Golden Perch	d	357	644	234.24	Tag Expired
Golden Perch	a	466	1695	234.29	Tag Active
Golden Perch	b	360	666	234.34	Tag Expired
Golden Perch	d	335	532	234.36	Tag Expired
Golden Perch	b	350	522	234.39	Tag Expired
Golden Perch	b	310	402	234.59	Tag Expired
Golden Perch	d	403	660	234.60	Tag Expired
Golden Perch	b	310	430	234.65	Tag Expired
Golden Perch	d	359	602	27985	Unknown
Golden Perch	b	385	800	27986	Tag Active
Golden Perch	e	390	922	27987	Unknown
Golden Perch	e	388	890	27988	Unknown
Golden Perch	b	388	952	27989	Unknown
Golden Perch	d	371	716	27990	Unknown
Golden Perch	b	369	742	27991	Unknown
Golden Perch	b	385	712	27992	Unknown
Golden Perch	b	414	1092	27993	Unknown
Golden Perch	b	385	734	27994	Unknown

Golden Perch	b	381	848	27995	Unknown
Golden Perch	d	413	894	27996	Unknown
Golden Perch	e	426	1122	27997	Unknown
Golden Perch	b	394	840	27998	Unknown
Golden Perch	b	412	958	27999	Unknown
Golden Perch	b	431	1352	28000	Unknown
Golden Perch	g	421	1362	28001	Unknown
Golden Perch	b	392	690	28003	Unknown
Golden Perch	b	417	978	28004	Unknown
Golden Perch	h	381	740	28005	Unknown
Golden Perch	d	407	960	28006	Unknown
Golden Perch	d	458	1446	28007	Unknown
Golden Perch	b	364	828	28008	Unknown
Golden Perch	b	404	950	28009	Unknown
Golden Perch	i	433	1330	28010	Unknown
Golden Perch	d	367	640	28011	Unknown
Golden Perch	g	441	1278	28012	Unknown
Golden Perch	b	381	742	28013	Unknown
Golden Perch	b	381	790	28014	Unknown
Golden Perch	g	350	616	51247	Tag Active
Golden Perch	g	376	824	51248	Tag Active
Golden Perch	h	370	785	51249	Tag Active
Golden Perch	h	400	1117	51250	Tag Active
Golden Perch	h	416	1243	51251	Tag Active
Golden Perch	g	363	662	51252	Tag Active
Golden Perch	g	412	1011	51253	Tag Active

Golden Perch	h	386	935	51254	Tag Active
Golden Perch	h	423	1190	51255	Tag Active
Golden Perch	d	415	1128	51256	Tag Active
Golden Perch	b	385	918	51257	Tag Active
Golden Perch	b	365	700	51258	Unknown
Golden Perch	b	391	902	51259	Tag Active
Golden Perch	b	411	1050	51260	Unknown
Golden Perch	b	398	1124	51261	Tag Active
Golden Perch	b	364	762	51262	Tag Active
Golden Perch	d	457	1668	51263	Tag Active
Golden Perch	d	395	875	51264	Tag Active
Golden Perch	d	371	810	51265	Unknown
Golden Perch	d	425	1317	51266	Tag Active
Golden Perch	d	417	1240	51267	Tag Active
Golden Perch	b	428	1260	51268	Tag Active
Golden Perch	b	397	1130	51269	Angled
Golden Perch	b	403	998	51270	Unknown
Golden Perch	a	441	1370	51271	Unknown
Golden Perch	d	404	1237	51272	Tag Active
Golden Perch	g	435	1410	51273	Tag Active
Golden Perch	g	425	1225	51274	Tag Active
Golden Perch	g	406	1272	51275	Tag Active
Golden Perch	g	426	1430	51276	Tag Active
Golden Perch	b	446	1340	234.02b	Tag Expired
Catfish	b	470	902	132.13	Tag Expired
Catfish	b	457	894	132.14	Tag Expired
Catfish	b	520	1234	132.21	Mortality
Catfish	b	501	1418	132.50	Unknown

Catfish	d	437	760	132.51	Unknown
Catfish	d	437	760	132.54	Unknown
Catfish	b	464	992	132.57	Tag Active
Catfish	b	495	1232	132.59	Tag Active
Catfish	b	485	1066	153.65	Unknown
Catfish	b	497	1100	173.29	Tag Active
Catfish	h	382	470	173.73	Tag Active
Catfish	b	490	1150	234.11	Tag Expired
Catfish	i	485	960	234.14	Mortality
Catfish	i	401	535	234.15	Mortality
Catfish	b	458	900	234.18	Tag Expired
Catfish	d	348	366	234.19	Tag Expired
Catfish	b	426	610	234.20	Tag Expired
Catfish	d	465	682	234.21	Tag Expired
Catfish	b	430	714	234.22	Tag Expired
Catfish	b	465	902	234.23	Tag Expired
Catfish	b	398	516	234.26	Tag Expired
Catfish	b	407	624	234.35	Tag Expired
Catfish	b	380	438	234.38	Tag Expired
Catfish	b	432	622	234.40	Tag Expired
Catfish	d	450	806	234.41	Tag Expired
Catfish	d	435	696	234.42	Tag Expired
Catfish	b	398	550	234.58	Mortality
Catfish	b	438	824	234.62	Tag Expired
Catfish	d	450	728	234.63	Tag Expired
Catfish	d	361	372	234.64	Mortality
Catfish	b	405	640	234.66	Tag Expired
Catfish	i	445	650	234.75	Tag Expired
Carp	b	600	3398	132.29	Tag Active
Carp	b	578	3468	132.30	Tag Active
Carp	a	618	3750	132.31	Mortality
Carp	b	547	2199	132.33	Mortality
Carp	a	630	4320	132.34	Tag Active
Carp	b	610	4367	132.36	Tag Active
Carp	i	380	940	132.39	Tag Active
Carp	a	575	3090	132.47	Tag Active
Carp	a	632	4310	132.48	Tag Active
Carp	b	635	4230	153.06	Tag Active
Carp	i	640	4530	153.08	Tag Active
Carp	i	550	2950	153.09	Tag Active
Carp	e	608	3680	153.15	Tag Expired
Carp	b	640	2896	153.17	Tag Active
Carp	e	640	3444	153.19	Mortality
Carp	e	603	3290	153.22	Tag Expired
Carp	e	440	1320	153.24	Tag Expired
Carp	b	502	1772	153.26	Angled
Carp	b	640	3470	153.27	Angled

Carp	i	695	5950	153.40	Unknown
Carp	i	480	1936	153.41	Mortality
Carp	i	605	3934	153.42	Tag Active
Carp	i	470	1506	153.43	Mortality
Carp	i	715	6050	153.44	Tag Active
Carp	b	590	3040	173.01	Mortality
Carp	b	680	4840	173.02	Tag Active
Carp	b	680	5250	173.03	Tag Active
Carp	b	504	1920	173.08	Tag Active
Carp	b	645	3050	173.09	Mortality
Carp	b	555	2590	173.27	Tag Active
Carp	b	565	2720	173.28	Tag Active
Carp	i	386	1180	173.37	Mortality
Carp	i	390	930	173.44	Angled
Carp	i	490	1890	173.46	Tag Expired
Carp	a	488	1935	234.27	Tag Active
Carp	a	665	5555	234.28	Tag Active
Carp	a	462	1887	234.43	Tag Active
Carp	a	594	3435	234.46	Tag Active
Carp	a	592	3328	234.47	Tag Active
Carp	a	628	3350	234.48	Tag Active
Carp	a	626	4300	234.49	Tag Active
Carp	a	616	4280	234.50	Unknown
Carp	i	520	2860	132.20b	Tag Expired
Carp	d	545	2222	153.02a	Tag Active
Carp	i	585	2830	153.03a	Mortality
Carp	i	590	3515	153.05a	Unknown
Carp	i	690	5550	153.26b	Tag Expired
Carp	i	580	3250	173.23b	Tag Expired
Carp	d	669	5138	173.38b	Mortality
Carp	d	437	1514	173.44b	Tag Expired

Appendix 2. Model selection parameters for the anabranch – Murray River transition analysis.

Table A2.1 Comparison between potential models for Murray Cod staying in the anabranch or moving to the Murray River. DoY stands for Day-of-Year, Regulator stands for regulator status, zDischarge and zTemperature stand for standardised Mullaroo discharge and temperature respectively.

Model	AICc	ΔAICc	Evidence Ratio
s(DoY)+Regulator	977.7	0.0	
s(DoY, Regulator)	978.4	0.7	1.4
s(DoY) + zDischarge	1002.9	25.2	>>1000
s(DoY)	1007.4	29.7	>>1000
s(DoY) + zTemperature	1008.5	30.8	>>1000
s(Discharge)	1063.3	85.6	>>1000
s(Temperature)	1063.5	85.8	>>1000
Null	1116.1	138.4	>>1000

Table A2.2 Comparison between potential models for Murray Cod staying in the Murray River or moving to the anabranch. DoY stands for Day-of-Year, Regulator stands for regulator status, zDischarge and zTemperature stand for standardised Mullaroo discharge and temperature respectively.

Model	AICc	ΔAICc	Evidence Ratio
s(DoY)+Regulator	1009.3	0.0	
s(DoY, Regulator)	1055.9	46.6	>>1000
s(DoY)	1278.1	268.8	>>1000
s(DoY) + zTemperature	1278.8	269.5	>>1000
s(DoY) + zDischarge	1279.9	270.6	>>1000
s(Temperature)	1285.3	276.0	>>1000
s(Discharge)	1309.0	299.7	>>1000
Null	1374.6	365.3	>>1000

Table A2.3 Comparison between potential models for Golden Perch staying in the anabranch or moving to the Murray River. DoY stands for Day-of-Year, Regulator stands for regulator status, zDischarge and zTemperature stand for standardised Mullaroo discharge and temperature respectively.

Model	AICc	dAICc	Evidence Ratio
s(DoY, Regulator)	830.7		
s(DoY)+Regulator	844.6	13.9	1043.1
s(DoY)	863.6	32.9	>>1000
s(DoY) + zDischarge	864.2	33.5	>>1000
s(DoY) + zTemperature	864.2	33.5	>>1000
s(Discharge)	867.9	37.2	>>1000
Null	873.9	43.2	>>1000
s(Temperature)	874.2	43.5	>>1000

Table A2.4 Comparison between potential models for Golden Perch staying in the Murray River or moving to the anabranch. DoY stands for Day-of-Year, Regulator stands for regulator status, zDischarge and zTemperature stand for standardised Mullaroo discharge and temperature respectively.

Model	AICc	dAICc	Evidence Ratio
s(DoY, Regulator)	803.7		
s(DoY)+Regulator	815.0	11.3	284.3
s(DoY)	843.1	39.4	>>1000
s(Discharge)	843.3	39.6	>>1000
s(DoY) + zTemperature	843.8	40.1	>>1000
s(DoY) + zDischarge	844.3	40.6	>>1000
s(Temperature)	850.0	46.3	>>1000
Null	855.7	52.0	>>1000

Table A2.5 Comparison between potential models for Catfish staying in the anabranch or moving to the Murray River. DoY stands for Day-of-Year, Regulator stands for regulator status, zDischarge and zTemperature stand for standardised Mullaroo discharge and temperature respectively.

Model	AICc	dAICc	Evidence Ratio
s(DoY, Regulator)	196.8		
s(DoY)+Regulator	204.0	7.2	36.6
s(DoY) + zDischarge	238.9	42.1	>>1000
s(DoY)	265.9	69.1	>>1000
s(DoY) + zTemperature	266.8	70.0	>>1000
s(Discharge)	296.9	100.1	>>1000
s(Temperature)	297.7	100.9	>>1000
Null	333.7	136.9	>>1000

Table A2.6 Comparison between potential models for Catfish staying in the Murray River or moving to the anabranch. DoY stands for Day-of-Year, Regulator stands for regulator status, zDischarge and zTemperature stand for standardised Mullaroo discharge and temperature respectively.

Model	AICc	dAICc	Evidence Ratio
s(DoY) + zTemperature	226.2		
s(DoY, Regulator)	228.1	1.9	2.6
s(DoY)	231.3	5.1	12.8
s(DoY)+Regulator	236.7	10.5	190.6
s(DoY) + zDischarge	238.3	12.1	424.1
s(Discharge)	246.6	20.4	2690.3
s(Temperature)	264.1	37.9	>>1000
Null	297.0	70.8	>>1000

Table A2.7 Comparison between potential models for Carp staying in the anabranch or moving to the Murray River. DoY stands for Day-of-Year, Regulator stands for regulator status, zDischarge and zTemperature stand for standardised Mullaroo discharge and temperature respectively.

Model	AICc	dAICc	Evidence Ratio
s(DoY, Regulator)	408.6		
s(DoY)+Regulator	412.4	3.8	6.7
s(DoY) + zDischarge	418.7	10.1	156.0
s(DoY)	424.8	16.2	3294.5
s(DoY) + zTemperature	426.6	18.0	>>1000
s(Discharge)	429.0	20.4	>>1000
s(Temperature)	467.6	59.0	>>1000
Null	482.5	73.9	>>1000

Table A2.8 Comparison between potential models for Carp staying in the Murray River or moving to the anabranch. DoY stands for Day-of-Year, Regulator stands for regulator status, zDischarge and zTemperature stand for standardised Mullaroo discharge and temperature respectively.

Model	AICc	dAICc	Evidence Ratio
s(DoY, Regulator)	415.5		
s(DoY)+Regulator	434.5	19.0	>>1000
s(DoY) + zDischarge	445.2	29.7	>>1000
s(DoY)	449.7	34.2	>>1000
s(DoY) + zTemperature	451.9	36.4	>>1000
s(Discharge)	452.2	36.7	>>1000
s(Temperature)	474.0	58.5	>>1000
Null	483.4	67.9	>>1000