Fish movement in the Lindsay and Mulcra Island anabranch systems

2017 Progress Report

Arthur Rylah Institute for Environmental Research, July 2017

Arthur Rylah Institute for environmental research

VICTORIA State Government | Environment, Land, Water and Planning

Acknowledgements

This project was funded by the Mallee Catchment Management Authority through The Living Murray initiative. The Living Murray is a joint initiative funded by the New South Wales, Victorian, South Australian, Australian Capital Territory and Commonwealth governments, coordinated by the Murray-Darling Basin Authority. We would like to acknowledge Andrew Greenfield from the Mallee Catchment Management Authority, Allan Drechsler from SA Water – River Murray Operations Lock 7, the staff from Parks Victoria Werrimull office and the local landholders of the Murray Sunset National Park and surrounding region for accommodating access to study sites. Wayne Koster (Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning) is thanked for comments on a draft review of this report. This work was carried out under the Victorian Fisheries Research Permit RP827, FFG Research Permit no. 10007273 and animal ethics approval no. 14/04.

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Citation

Tonkin, Z., O'Mahony, J., McMaster, D., 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 Unpublished Client Report for the Mallee Catchment Management Authority.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.

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Summary

The Murray-Darling Basin Authority (MDBA), Victorian and South Australian state governments and the Mallee Catchment Management Authority (MCMA) have collaborated to construct regulating structures on the upper Mullaroo Creek and Lower Lindsay River to restore natural flows and flooding to the Chowilla-Lindsay-Wallpolla Icon Site. Despite major alterations to the systems flow regime, the system maintains numerous species and communities of conservation significance. Of particular note, is the importance of several anabranch systems in providing critical habitat for native fish due to their unique hydrological regimes and high density and complexity of instream habitat. Flow modifications resulting from the operation of the new regulating structures must therefore consider the habitat and migration requirements of native fish in the system. Subsequently, a 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 our understanding of migration cues and habitat use by native and exotic fish species under a range of managed and natural flow events. This progress report provides an update of the third year of the program. This includes reporting of the number of tagged fish and fish detections in the system as well as a discussion of the impact of the newly constructed regulator and fishway on fish movement. Furthermore, we investigate the impact on fish movement of the flood and hypoxic blackwater event that occurred within the study area during November / December 2016.

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 deployed throughout the study reach to connect and collaborate with a number of other fish movement programs enabling an assessment of inter-river and basin scale fish movements. Loggers were strategically positioned around the current radio-telemetry data logging stations, to provide a position and direction of movement for each acoustically tagged fish. 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 283 fish, belonging to four study species, Murray cod (*Maccullochella peelii*), golden perch (*Macquaria ambigua)*, freshwater catfish (*Tandanus tandanus*) and carp (*Cyprinus carpio*), have been tagged with radio and acoustic transmitters thus far (including 56 fish in March 2017). Of these fish, 188 are still ‘active’ (detectable) in the system although the status (alive or dead) of 43 Murray cod is unknown.

Data collected since March 2014 have high detection (98% of tagged fish) and transition rates of detected fish (78%) 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. All four study species have been recorded transitioning between the Murray River and anabranch habitats with carp having the highest probability of these moves, closely followed by golden perch, Murray cod and catfish respectively. The study period has encompassed a range of environmental conditions including periods of low flows, extreme floods and hypoxic blackwater as well as changes in infrastructure, all of which have proven to have strong influences on habitat use and survival. In particular:

- The extended floodplain inundation and hypoxic blackwater event in 2016 dramatically increased movement and transitions from the anabranch to the Murray River for all species. Only Murray cod appear to have suffered a dramatic decline in occupancy of the study region as a result, with almost 40% of fish moving out of the study reach and into the Murray River. So far we have recorded 20% mortality of all tagged Murray cod, with the status of ~63% of all active tagged fish (prior to the event) unknown. As of March 2017, 17% of tagged Murray cod are confirmed to have 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 events to allow fish to seek refuge and then return after the event has passed.
- A high proportion of Murray cod movements encompassed the upper Mullaroo Creek, with a large proportion of occupancy of this reach occurring during the spawning period. 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.

- There was a higher probability of Murray cod moving between anabranches and the Murray from mid-autumn to spring, with peak periods in mid-April and the highest in October. Murray cod movements to the anabranch (predominantly upper Mullaroo Creek) from the Murray River were influenced by anabranch discharge with an increased chance of transitioning as discharge increased to ~1400 ML day^{-1}.
- For golden perch, a greater rate of movement between anabranches and the Murray River occurred when discharge in the Mullaroo Creek was high, peaking around 60% likelihood when discharge in the Mullaroo Creek were 6000 ML day^{-1}. Like Murray cod, the likelihood of transitioning from the Murray River to anabranch systems increased dramatically with small increases in discharge within the anabranch.
- Carp movement between the Murray River and the anabranches was most effected by day-of-year with a greater likelihood of movement between August and mid-November (most likely spawning). Carp movements to the Murray River (from the anabranches) were also influenced by discharge with fish more likely to move out of the anabranch system in April and August to mid-December and when discharge in Mullaroo Creek is low. We found no significant influence of anabranch discharge increasing carp transitions to the anabranch. This suggests low level changes in anabranch discharge targeted at enhancing native fish transitions are unlikely to increase adult carp movement into these habitats.
- Fish movement from the Upper Mullaroo Creek to the Murray River appears to be negatively impacted by the old ford structure and the Mullaroo Creek regulator (newly constructed fishway). Murray cod, golden perch and carp all successfully traversed the Mullaroo Creek regulator pre- and post-construction, however, prior to the flood of 2016, the percentage of approaching fish that ascended the structure declined. During the flood, the regulator gates were laid flat, and percentages of all four species which successfully passed upstream through the regulator greatly increased.

The information gathered on fish movement and habitat use (and associated drivers) during the program has generated important information to help guide management of environmental flows and infrastructure operations aimed at maximising benefits for native fish in the Lindsay and Mulcra Island anabranch system. As such, the program is well placed to assess fish outcomes resulting from future interventions. Nevertheless, continuing the annual fish tagging and maintenance routine as has been undertaken thus far is still required to do so. Specific study areas and recommendations for the program include:

- A final assessment of blackwater impacts on the survival and return movements of Murray cod.
- Continued assessment of fish transitions between the Murray River and upper Mullaroo Creek under a range operational scenarios including:
  - simulated flooding,
  - increased spring discharge in Mullaroo Creek (specifically, a gradual increase to 1200 ML day^{-1} from October – December),
  - increased autumn discharge in Mullaroo Creek (specifically, a gradual increase to 1200 ML day^{-1} during April), and
  - different regulator operational scenarios, particularly under different gate and weir pool height scenarios.

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 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. In an effort 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 (Mullaroo 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 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). 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 will be 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 over the coming years. The study specifically aims to add to understanding of habitat use and migration 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 fish detections following the third year of the study, and incorporates fish movement dynamics pre-and post-construction/operation of instream structures within the system. Furthermore, we investigate the impact on fish movement of the flood and hypoxic blackwater event that occurred within the study area in November/December 2016.

2 Methodology

2.1 Study site and logging towers

With the *Upper Lindsay Watercourse Enhancement Project* well underway, 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 March 2017, the study area was complemented with the deployment of 23 acoustic loggers. Acoustic loggers were secured underwater with steel cable to a buoy or large log within the river. Three loggers were strategically 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 of acoustic tagged fish (Figure 2). A further four acoustic loggers maintained by South Australian Research and Development Institute (SARDI) are positioned within our study area adding to the acoustic array. An additional three acoustic loggers, at the top and middle of Potterwalkagee Creek and on the Little Mullaroo Creek downstream of the Murray River junction (sites were dry in March 2017), will be deployed in August 2017 to complete the 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 three times per year, and given routine maintenance to ensure they are operating correctly. Radio tagged fish are also manually tracked twice a year to verify positon 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.

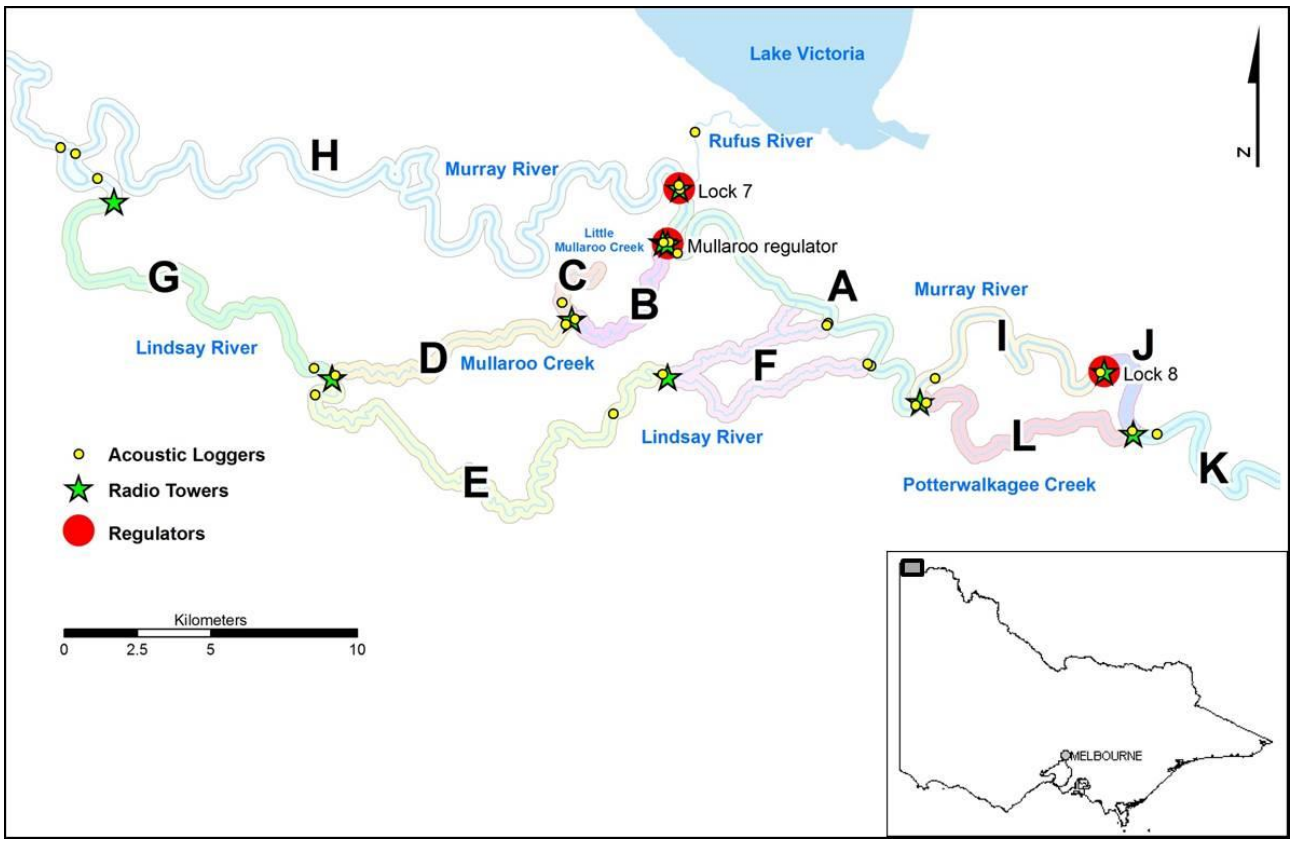

Figure 1: The Lindsay Island anabranch study site. Red circles represent regulator infrastructure, green stars represent radio logging towers, yellow circles represent acoustic loggers and letters represent fish tagging and movement zones.

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

2.2 Fish collecting and 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 during September 2014, August 2015, December 2015, September 2016 and December 2016 to obtain detailed information on site location as well as checking for mortality signals.

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

Figure 3: The size range of radio transmitters used in the study.

Figure 4: Golden perch with external identification tag.

2.2 Data analysis

Catchment rainfall data were obtained from the Bureau of Meteorology (BOM) (2017). Hydrology and water temperature data within the study area was obtained from gauges operated by WaterConnect South Australia (2016) and the MDBA (2017). Dissolved oxygen data during November/December 2016 was provided by Al Drechsler from the River Murray Operations team.

For the purpose of activity and progress reporting, we first generated descriptive statistics relating to fish occupancy, detection and movement patterns near and through the Mullaroo Creek fishway (using signal strengths). We then conducted a more formal investigation of Murray cod transitions between the Murray River and anabranch habitats (Mullaroo Creek; Lindsay River and Potterwalkagee Creek) given the aims of the program. For the latter, we used data collected during this study (2014 – 2017), as well as historical data collected during 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 analyses the probability of fish movement between the Murray River and the anabranch. A fish was given a score of one (1) if it moved either from the anabranch to the Murray River or vice versa and a zero (0) otherwise. Separate models were constructed for each species (carp, golden perch and Murray cod). The length of the fish at capture and tagging was used as a potential explanatory variable for all species, while the monitoring period (either 2004 to 2006 or 2014 to 2016) was also used to explain variation between Murray Cod (given this was the only species tagged in the earlier study). The full model and each nested model was estimated for each species and Akaike information criteria corrected for small samples (AICc) was used to determine the model with the most evidence (Burnham and Anderson 2010).

Due to the large number of fish that never moved between the Murray River and the anabranch a zero-inflated model was considered suitable. Zero-inflated models account for extra (structural) zeros in the data that affect the overall average. The model has two parts, one accounting for the extra zeros, the other accounting for the mean number of fish moving between systems on the day. Julian day of the year, discharge in the Mullaroo Creek, temperature in the Mullaroo Creak as well spawning season were considered as explanatory variables. When Julian day of the year was included, it was included as a smoothed term. Hence the overall model was a general additive model (GAM) using zero-inflated Poisson (ZIP) distribution (S. N. Wood, Pya, and Säfken 2016). All the analyses were conducted using the statistical program R version 3.4.0 (R Core Team 2017). The zero-inflated Poisson GAMs were estimated using the package mgcv (S. Wood 2011).

Logistic Markov transition matrix 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 tomorrow, and the probability fish currently in the Murray River stays in the Murray River tomorrow. 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.

All the analyses were conducted using the statistical program R version 3.4.0 (R Core Team 2017), with GAM fitted using the package "mgcv" (S. Wood 2011).

3 Results

3.1 Hydrology

Seasonal flow variability throughout the study area is generally low as can be seen in the hydrograph during the first two years of the study (Figure 5). During this period, stream flow in the Murray River at lock 8 ranged between 1,000 – 10,000 ML day^{-1} except for a small flow event in August 2014 where flow peaked at 17,241 ML day^{-1}. Flows diverted down Mullaroo Creek are smaller in volume and ranged between 400-1,350 ML day^{-1} during the same period. During the third year of the study however, a major rainfall event in September 2016 across Australia and much of the Murray-Darling Basin, led to significant flooding across the catchment and a large flood event within our study area (see section 3.1.1 below).

Seasonal variation in stream water temperature was observed within the Murray River (at lock 8) and Mullaroo Creek with minimum temperatures around 10C° during winter and maximum temperatures up to 30C° during the summer months (Figure 5). During the flood event, daily water temperatures were highly variable depending on where flood waters were coming from (i.e. cold waters received from up in the Victorian Alps or warm water received from low lying floodplains).

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 5; WaterConnect South Australia 2016; MDBA 2017).

Peak flows inundated parts of the Murray River floodplain that had not been flooded for more than 20 years. Leaf litter and organic matter that had accumulated over two decades subsequently leached high amounts of dissolved organic carbon into floodwaters which in turn increased bacterial activity and stripped the water of oxygen. This process, which is often more pronounced during summer flooding, 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 (Figure 5). Dissolved oxygen concentrations upstream and downstream of Lock 7 were below 4 mg L^{-1} (the level documented to cause stress in many native fish species) for over a month and below 2mg L^{-1} (the level which can be lethal) for over three weeks (Figure 6). Dissolved oxygen concentrations were only slightly higher on the Rufus River during this period and were generally below 4 mg L^{-1} (Figure 6).

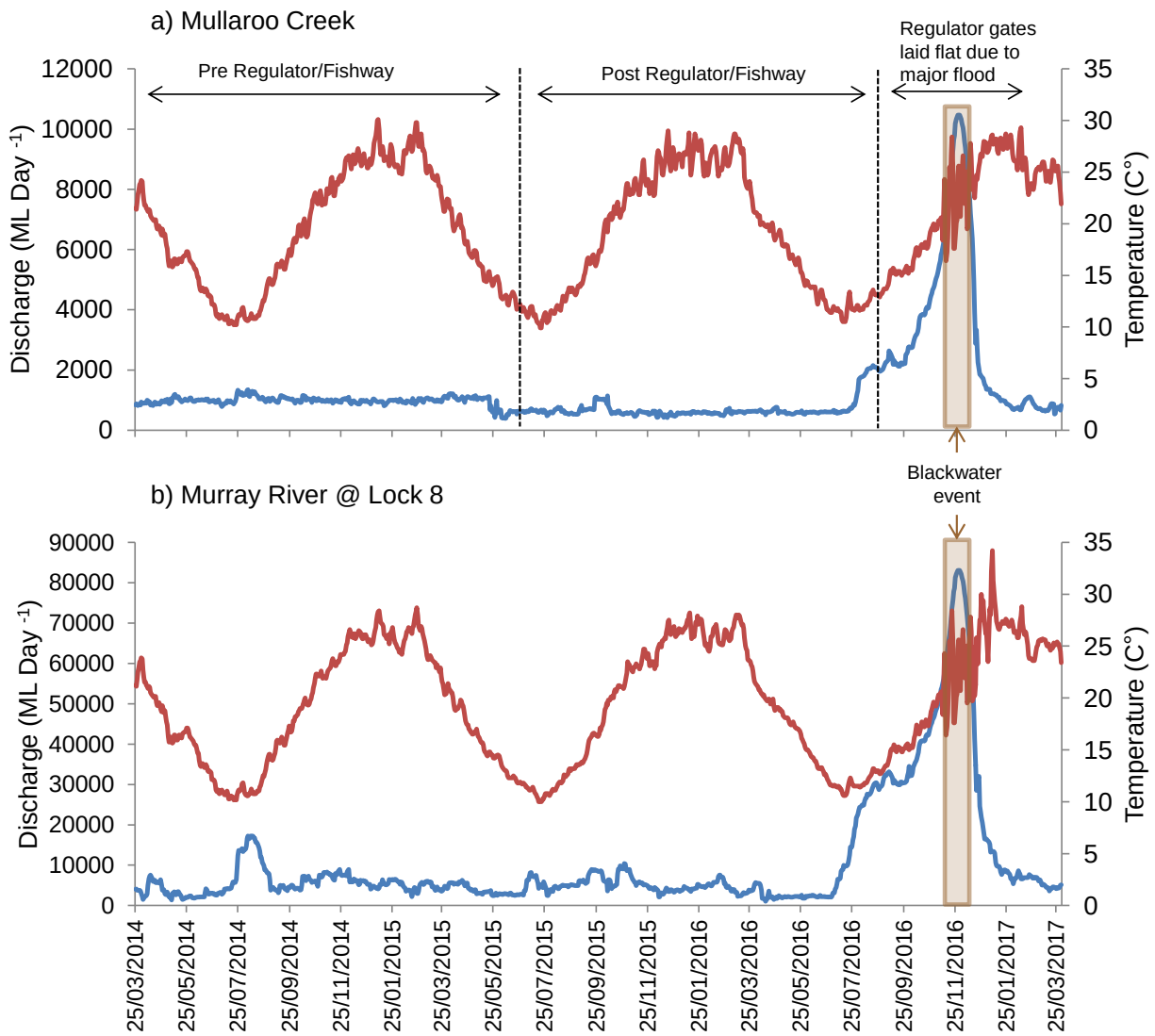

Figure 5: Average daily discharge (blue) and water temperature (red) in a) Mullaroo Creek and; b) the Murray River at Lock 8. Dotted vertical lines illustrate approximate commencement of the Mullaroo Creek regulator and when the regulator gates were laid flat to avoid infrastructure damage during the flood event. Brown boxes show the duration of the blackwater event that occurred within the study area where dissolved oxygen concentrations were below 4 mg/L.

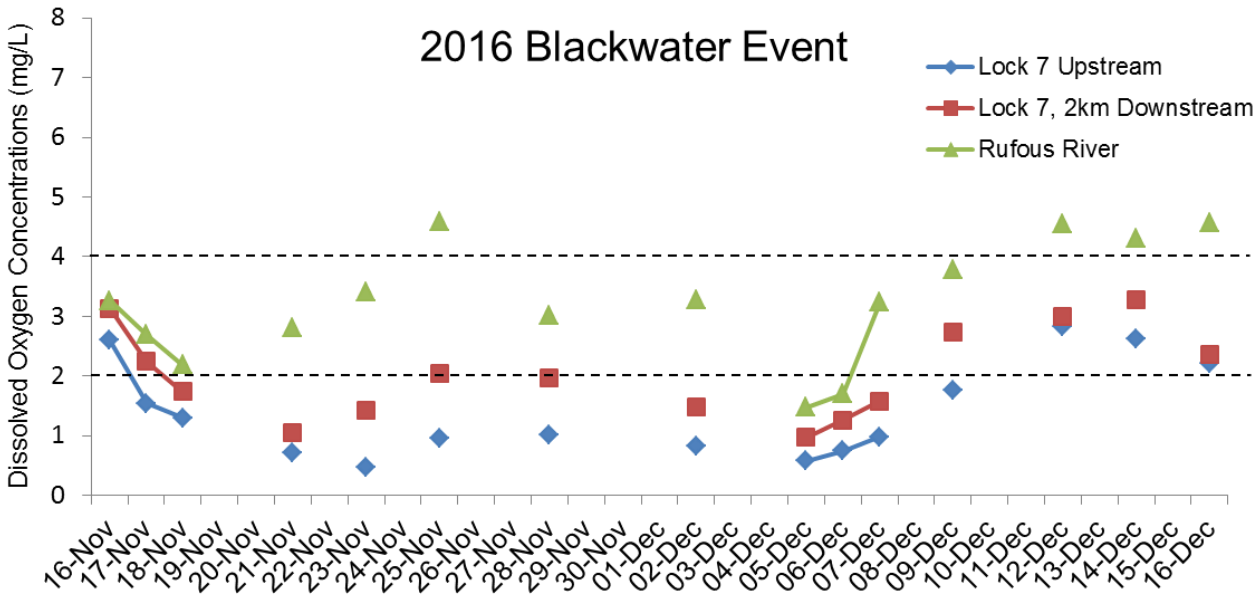

Figure 6: Dissolved oxygen concentrations recorded upstream of Lock 7 (blue), 2km downstream of Lock 7 (red) and in the Rufous River (green) during the 2016 hypoxic blackwater event. Dotted lines represent concentrations at which native fish species may become stressed (4 mg/L) and when fish deaths may occur (2 mg/L) (Gehrke 1988; Small et al. 2014).

3.2 Fish tagging and logger array update

In March 2017, all radio logging towers were checked, downloaded and subject to routine maintenance. At the same time, the study area was complemented with an acoustic array with the deployment of 23 acoustic receivers. The incorporation of acoustic technology will connect this project to a number of other telemetry programs operating across the southern Murray-Darling Basin, allowing for the detection of fish movements between river systems and the investigation of fish migration at a basin scale.

A total of 283 fish have now been implanted with radio and acoustic transmitters since 2014, with 188 of these fish still possessing an active transmitter (Table 2 and Table 3; 95 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, including 4 golden perch during the third year of the study (Appendix 1, Table A1).

An additional 56 transmitters were implanted into fish during March 2017 to supplement numbers of tagged fish in the system (Table 3). Specifically, two Murray cod, two catfish and 37 golden perch were tagged in Mullaroo Creek and Lindsay River; and one catfish and 14 golden perch were tagged in the Murray River between Lock 6 and 8. Initially our aim was to tag over 80 fish; however these numbers could not be captured via boat electrofishing. In particular, the abundance of Murray cod and catfish was low due to one or a combination of migrating out of and high mortality rates within the study area in response to the blackwater event (and associated prolonged hypoxic conditions; see section 3.3.1 below for further details). In contrast, golden perch were caught in high abundances throughout the study area and 30 of the 51 tagged individuals were implanted with acoustic tags (Table 3). No existing transmitter fish were recaptured during the March 2017 fish sampling.

Table 2: Details of fish implanted with radio transmitters in (a) Mullaroo Creek and Lindsay River in March/April 2014, May/August 2015 and April 2016, and (b) the Murray River below Lock 8 in May/August 2015 and April 2016. *numbers do not include fish tagged in March 2017.

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	54	53	49	36
Catfish	348 – 520	366 – 1234	22	22	8	1
Golden perch	310 – 493	402 – 1508	51	51	39	20
Carp	437 – 680	1320 – 5250	22	22	17	17
Total			***149***	***148***	**113**	***74***
(b) Murray R.						
Murray cod	712 – 1190	5200 – 32000	21	20	16	20
Catfish	401 – 485	535 – 960	3	3	0	0
Golden perch	320 – 536	570 – 2170	25	25	21	12
Carp	380 – 715	930 – 6050	29	27	24	26
Total			***78***	***75***	**61**	**58**
SYSTEM TOTAL			**227**	**223**	**174**	**132**

Table 3: Details of fish implanted with transmitters in March 2017 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	435 – 574	1008 – 3072	2
Catfish	382 – 495	470 – 1232	3
Golden perch	326 – 436	508 – 1588	21
Carp	n/a	n/a	0
(b) Acoustic tags			
Golden perch	350-457	616-1668	30
Total			**56**

3.3 Fish movements 2014- 2017

The first three years of the study detected 223 individual fish which represents 98% of all fish tagged prior to 2017 (Table 2). Of these detected fish, 174 (78%) have undertaken movements outside of the zone in which they were released (Table 2). 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 past three years movements have generally comprised those that appear to be associated with reproductive activity, range shifts and transitions between anabranches and the Murray River main channel. However, the large flood and hypoxic blackwater event in November/December 2016 led to a peak period of fish movement with frequent transitions between anabranch habitats and the Murray River main channel and out of the study area completely.

3.3.1 Fish movement and survival in response to 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 (Figures 6). Forty-four fish (i.e. 33% of fish with active transmitters) left the system, with approximately half heading upstream on the Murray River past the Potterwalkagee Creek junction (into zone K), and the other half heading downstream out of the Mullaroo Creek and Lindsay River systems and turning left at the Murray River junction (past zone G and H; Table 4). Subsequently, the current status and location of many tagged fish remains unknown. Murray cod showed a preference for downstream movement, while golden perch moved predominantly upstream (Table 4). Carp showed no preference for upstream or downstream movement (Table 4). Only one catfish had an active transmitter during this period (transmitters had expiring on other catfish) and this fish moved out of the study area in an upstream direction into zone K (Table 4).

Table 4: Total number of fish (for each species) which moved out of the study area during the high flows and blackwater event from September – December 2016.

Species	Upstream of the Potterwalkagee Creek junction (Zone K)	Downstream of the lower Lindsay River junction (Downstream of Zone G and H)	Total
Murray cod	4	16	20
Catfish	1	0	1
Golden perch	10	2	12
Carp	6	5	11
Total	***21***	***23***	***44***

Following the logger download and manual tracking of the study reach in March 2017, it was clear that Murray cod occupancy of the study area underwent a dramatic decline during the peak flooding and blackwater event either through emigration out of the anabranch system or mortality. Prior to November 2016, 63 tagged Murray cod were active in the system (Table 5). Just prior to and during the event, Murray cod activity increased dramatically, with 56 fish (~90%) actively moving zones. As of March 2017 the aftermath of the blackwater event and status of Murray cod in the study reach was:

- Eleven tagged Murray cod (17% of fish), are confirmed to have survived the blackwater event. Nine of these fish migrated downstream during the blackwater event before returning from the Murray River downstream of the lower Lindsay River junction; one returned to the Murray River from the upper Lindsay River, and one remained in the Murray River between Locks 7 and 8. All of these fish were > 500 mm in length with 61% of fish between 83 – 119 cm.
- Thirteen tagged Murray cod (20%) which were alive prior to the blackwater event were confirmed dead (five of which were found washed up on the floodplain during the December 2016 manual tracking). Four were found dead in both the Mullaroo Creek and Lindsay Rivers, three in the Little Mullaroo, one in the Rufus River and one in the Murray River downstream of the lower Potterwalkagee Creek junction.
- The location and status of 43 of these fish (~68% of tagged fish) remain unknown, despite efforts to manually track fish in March 2017 (Table 5). Thirty seven (37) of these fish were all active in the study area prior to the blackwater event (the remaining six fish having already left the region or not been detected in the reach).
    - Twenty one (21) of these fish were last detected in the study reach; whether or not these fish are still alive is unclear as mortality switches in transmitters had insufficient time to be activated when fish were manually tracked in December 2016.
    - The remaining 16 fish (of unknown status) moved out of the study reach down the Murray River (below the Lindsay River junction). Whilst it is unknown how far these fish travelled downstream, nine surviving fish returned to the study reach from the Murray River downstream (of the Lindsay River), There is therefore some hope that the 16 fish which moved downstream, equating to ~25% of all active Murray cod in the system prior to the event, may still return to the system.
- Unlike Murray cod the other species did not appear to suffer the mortality rates like Murray cod. 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 5: The status and number of Murray cod in the study area prior to, and following the 2016 flood and blackwater event. Numbers exclude the two Murray cod tagged in March 2017.

Tagged Murray cod status	Prior to November 2016	November - March 2017
Alive (detected in the study area)	63	11
Dead (mortality signal triggered)	6	19
Unknown (left the study area or not detected on loggers)	6	43

3.3.2 Patterns of species movements

We investigate the influence of timing, temperature and river flows in a formal analysis below, however, the general patterns of species movements are provided here with specific examples to show the variety of movements recorded for each species (Figure 7 and 8).

Murray cod

Murray cod movement peaked between September - December 2016 in response to the flood and blackwater event. Twenty cod left the study area with 25 fish travelling downstream in the Murray River past zone G and H, while 4 headed upstream past the Potterwalkagee Creek junction and into zone K. Nine of these fish returned to the study area in the months following the event with the fate of the fish remaining fish unknown. Thirteen cod made several zone transitions during this period before a mortality signal was transmitted. Dead fish were detected within several zones, indicating that poor water quality conditions were experienced across the study area. Individual fish movements include:

- In the first two years, Murray cod Fish ID 153.34 (980mm, 15500g, tagged in the lower Mullaroo Creek on 29/03/2014) moved downstream during the spawning season into the Murray River via the Lindsay River, and returned back to the same zone in Mullaroo Creek via the same route the following March. In November 2016 during the blackwater event, it again moved downstream into the Murray River, however it is currently downstream of zone G and H and its status remains unknown (Figure 7).
- Murray cod Fish ID 153.18 (1140mm, 24000g, 01/04/2014, upper Mullaroo Creek) was not detected changing zones until 14/10/2016, when it moved into the Little Mullaroo Creek for one day, then returned to the upper Mullaroo Creek. In November 2016 when dissolved oxygen concentrations dropped below 2mg/L in the study area (Figure 6), it migrated downstream into the Murray River via the Lindsay River. The fish was then detected moving upstream past the lower Lindsay River logger on 21/12/2016, and returned to the upper Mullaroo Creek, where it was detected below the Mullaroo Creek regulator logger on the 24/12/2016, hence survived the blackwater event (Figure 7).

Golden perch

Prior to spring 2016, 18 golden perch were present in the Mullaroo Creek. During the flood period, 15 transitioned into the Murray River. The three fish that remained in Mullaroo Creek were manually tracked within small anabranches during the flood period, with two fish changing zones and one individual remaining in the same zone. Prior to spring 2016, 13 golden perch were located in the Murray River. All of these fish made multiple zone changes during the flood, with six of these using the anabranch systems (either the Mullaroo Creek, Lindsay River or Potterwalkagee Creek).

- Golden perch Fish ID 132.45 (415mm, 1035g, tagged in upper Mullaroo Creek 05/05/2015) 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 dropping 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) (Figure 7). 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).
- Golden perch Fish ID 173.04 (451mm, 1450g, tagged in Murray River downstream of Lock 8 on 09/05/2015) moved downstream in to the Mullaroo Creek on the 20/10/2016, and returned back to the Murray River and upstream into the Potterwalkagee Creek on the 23/10/2016. The fish remained in the Potterwalkagee Creek until the 16/11/2016 (when dissolved oxygen levels decreased), and then migrated downstream to the upper and mid Lindsay River, where it is currently located (Figure 7).

Catfish

The majority of catfish tagged within the study area have displayed very little movement between zones indicating strong site fidelity (Table 2). Only two catfish (Fish ID 173.29 and Fish ID 234.23) transitioned zones on more than two occasions which represents 19 of the 29 total zone transitions.

- Catfish Fish ID 173.29 (497mm, 1100g, tagged in the upper Mullaroo Creek on 13/04/2016) 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 (Figure 8).

Carp

Prior to spring 2016, 12 carp with active transmitters were located in the Mullaroo Creek. All 12 individuals changed zones during the flood, with nine moving into the Murray River and transitioned into at least four different zones. Prior to spring 2016, 17 carp with active transmitters were located in the Murray River. Twelve changed zones during the flood, with seven moving into the anabranch system of Potterwalkagee Creek, Lindsay River and Mullaroo Creek. The five carp that stayed in the Murray River during this period remained in the same zone that they were tagged.

- Carp Fish ID 132.29 (600mm, 3398g, 13/04/2016, tagged in upper Mullaroo Creek) transitioned into the Murray River on 31/10/2016 and moved upstream out of the study reach within four days. It migrated back downstream on the 16/12/2016 and returned to the upper Mullaroo Creek within three days (Figure 8).
- Carp Fish ID 132.36 (610mm, 4367g, 13/04/2016, tagged in upper Mullaroo Creek) moved to the Little Mullaroo Creek on 12/08/2016 for 60 days. On 11/10/2016 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) (Figure 8).
- Carp Fish ID 132.31 (618mm, 3750g, 12/04/2016, tagged in the Murray River upstream of Mullaroo Creek) started moving up and downstream of Lock 7 from 03/08/2016. On 6/10/2016 the fish migrated downstream via the Little Mullaroo Creek, lower Mullaroo Creek, Lindsay River and into the Murray River within five days. It swam back upstream in the Murray River and returned to the Little Mullaroo Creek on the 29/10/2016, where it repeated its downstream path via the lower Mullaroo Creek, Lindsay River and back in to the Murray River within four days. Was not detected again until 08/01/2017, where it migrated back upstream to the Murray River, via the Lindsay River and Mullaroo Creek (Figure 8).

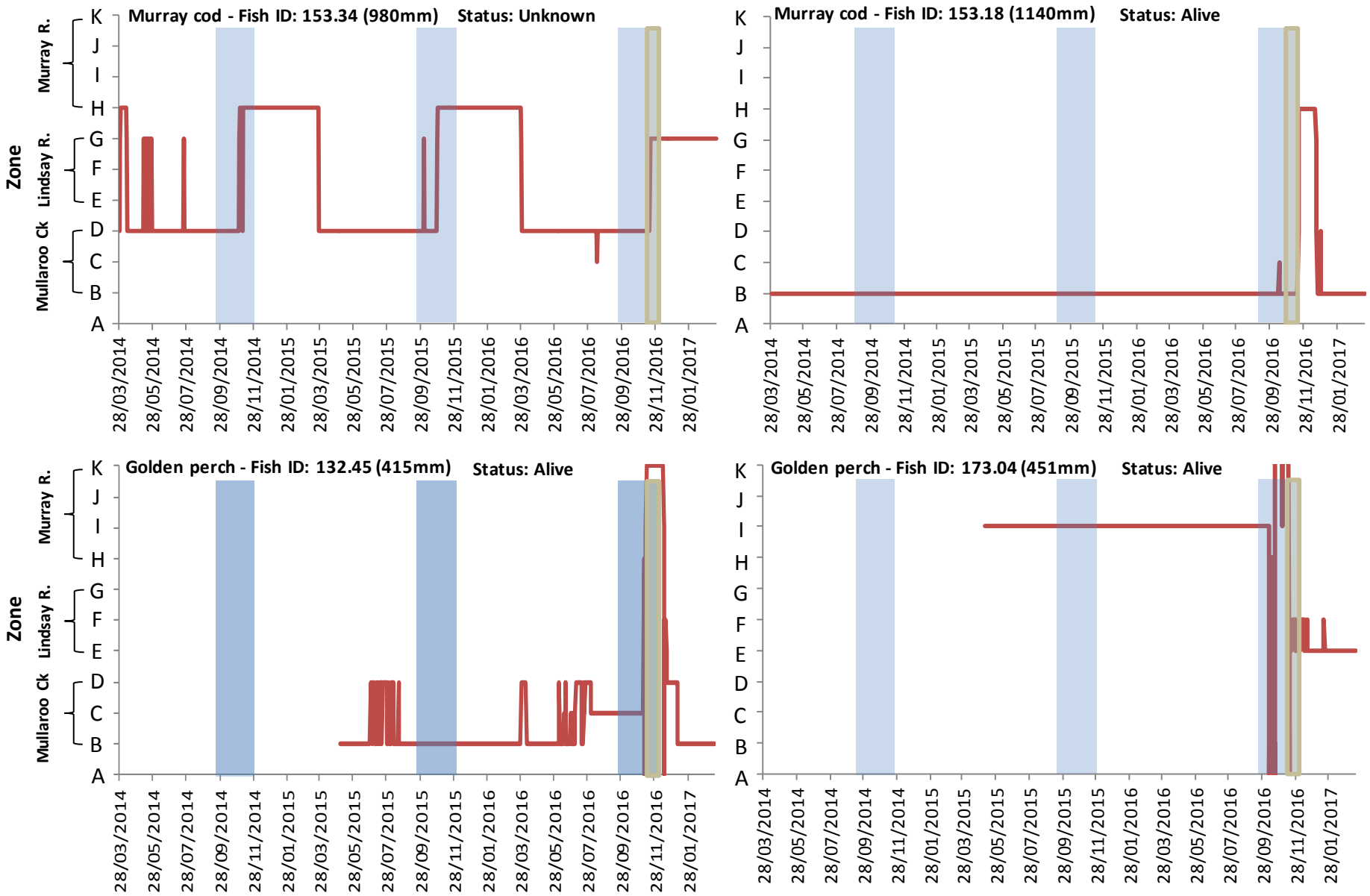

Figure 7: The movement patterns of two individual Murray cod and two individual golden perch between March 2014 and April 2017. Core reproductive period highlighted in blue shading. Blackwater event highlighted in brown. Letters denote specific zones of the study area (see Figure 1).

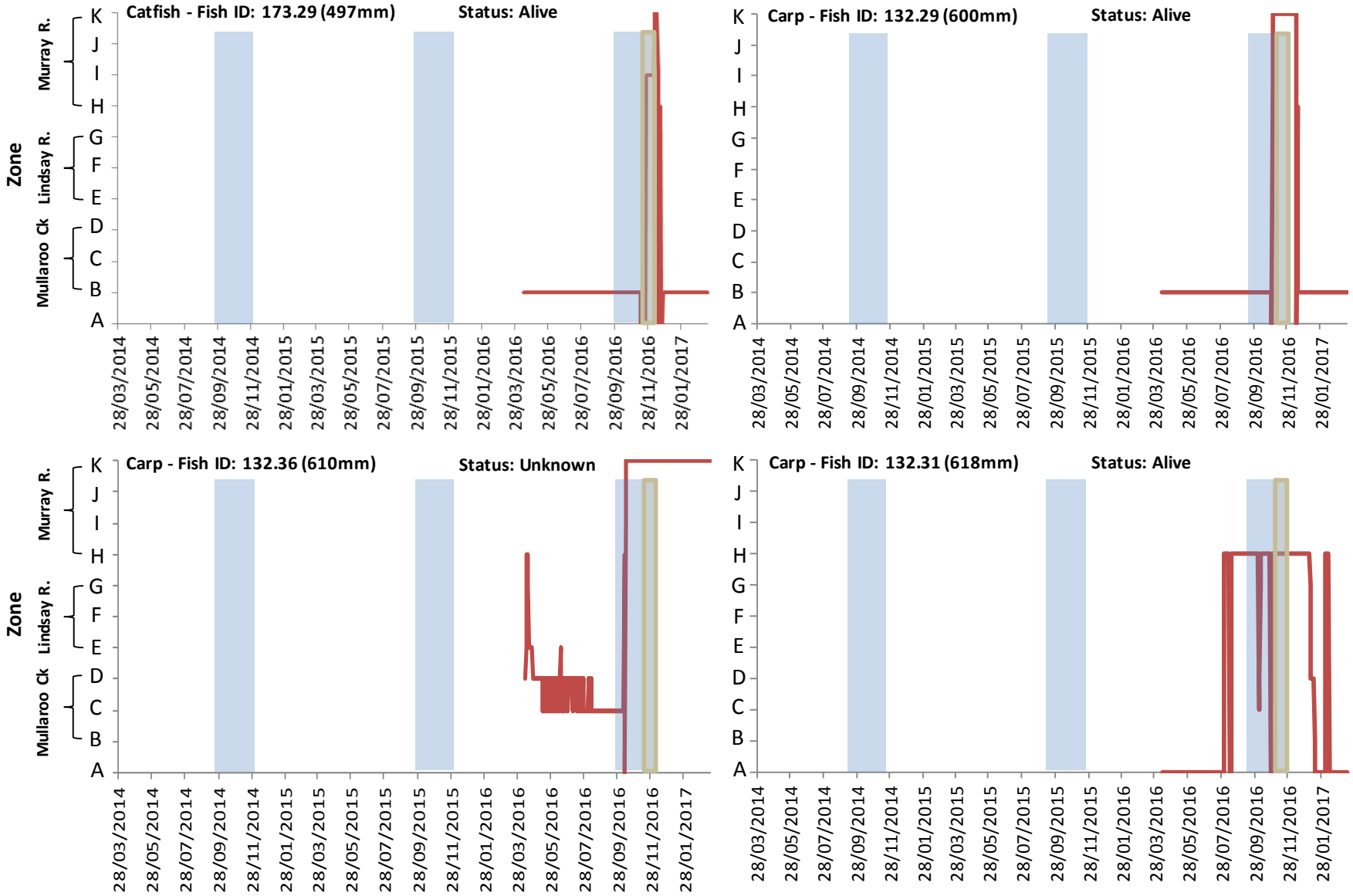

Figure 8: The movement patterns of one individual catfish and three individual carp between March 2014 and April 2017. Core reproductive period highlighted in blue shading. Blackwater event highlighted in brown. Letters denote specific zones of the study area (see Figure 1).

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

An exploration of transmitter signal strength recorded at the Mullaroo Regulator logger tower enabled further exploration of 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), a 12 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 indicate 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%) and the total percentage of individual fish transitions (61%) 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 6).

Following the construction of the regulator/ fishway the total percentage of transitions was slightly lower (26%) and the total percentage of individual fish transitions (34%) was much lower (Table 6). Carp in particular had much lower transition rates. Although catfish did not ascend the fishway only one individual approach was recorded (Table 6).

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

Table 6: 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 – July 16) and post construction with the gates laid flat during flood event (August 2016 – March 17). *numbers do not include fish which approached or ascended during regulator construction between April 2015 and July 2015.

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 – July 16			
Murray cod	120	25	26	31
Golden perch	20	37	7	57
Catfish	1	0	1	0
Carp	12	17	7	29
TOTAL	***153***	***26***	***41***	***34***
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***

3.3.4 Transitions between the Murray River and anabranch habitats

Likelihood a fish ever moves between Murray River and anabranch systems

The likelihood that a monitored fish moved from the Murray River and the anabranch system (Mullaroo Creek or Lindsey River) or vice versa was different for the four species. The likelihood of Murray cod moving was dependent on the length of the fish and the period of monitoring (i.e. 2004 to 2006 or, 2014 to 2017). The model with that parameterisation had the smallest AICc (see Appendix 2). The greater the length of the Murray Cod, the greater the likelihood it moved between the Murray and the anabranch (Figure 10). For instance, a 400mm Murray cod (in 2014) has an expected probability of moving between systems of 31.7% (with 95% confidence interval from 17.8% to 49.8%), while a 1200mm Murray cod (in 2014) has a 76.9% (59.6% to 88.2%) chance. In the earlier (2004 to 2006) monitoring period the odds of a Murray cod moving was 3.5 (1.7 to 7.4) times smaller than the same sized Murray cod in the later (2014 to 2016) monitoring period (Appendix 2).

The likelihood of a golden perch moving was dependent on the length of the fish (Appendix 2). The greater the length of the golden perch, the greater the likelihood it moved between the Murray and the anabranch (Figure 11). For instance, a 300mm golden perch (in 2014) has an expected probability of moving between systems of 16.3% (3.8% to 48.6%), while a 500mm golden perch (in 2014) has a 97.6% (86.2% to 97.6%) chance.

The probability of Carp and Catfish moving between systems was independent of length. The null model had the smallest AICc for each species (Appendix 2, Table A8 and A9). The fraction of Carp that moved between the Murray River and the anabranch was the highest amongst the four species monitored at 82% (69% to 90%, Figure 12). The fraction of Catfish that moved between the Murray River and the anabranch was 24% (11% to 45%, Figure 11).

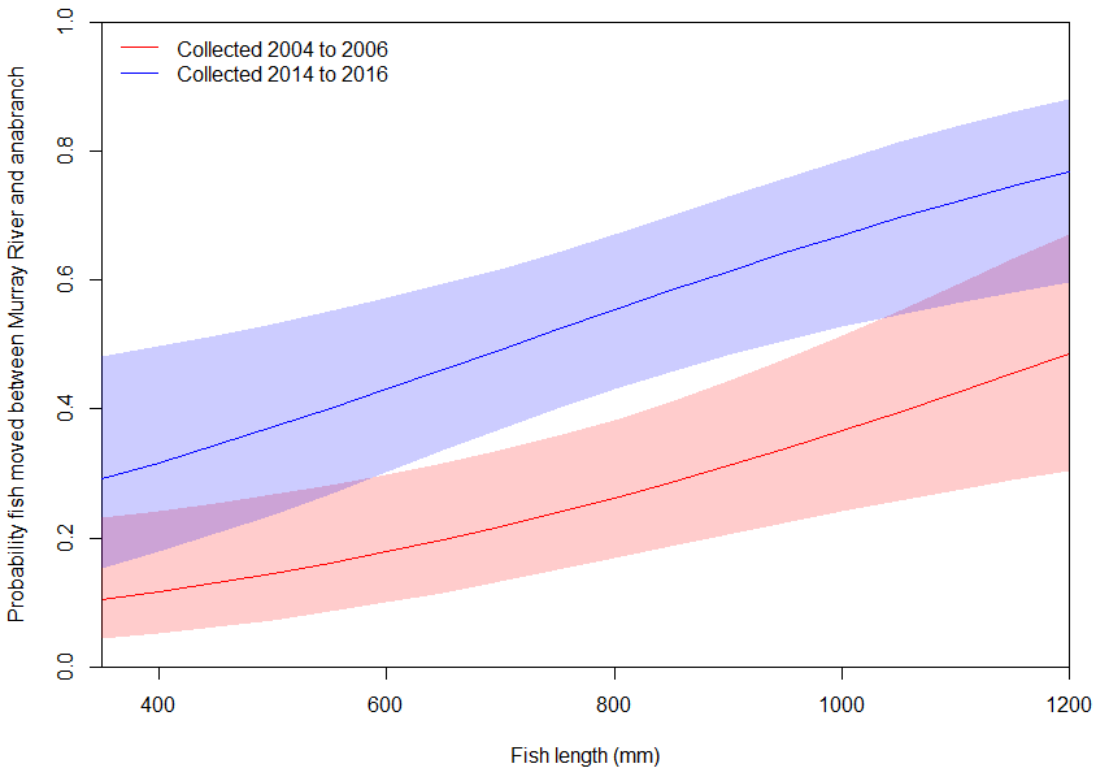

Figure 10: The probability (±95% confidence intervals) that a Murray cod ever moves between the Murray River and the anabranch, or vice versa during each of the study time periods and fish size (total length, mm).

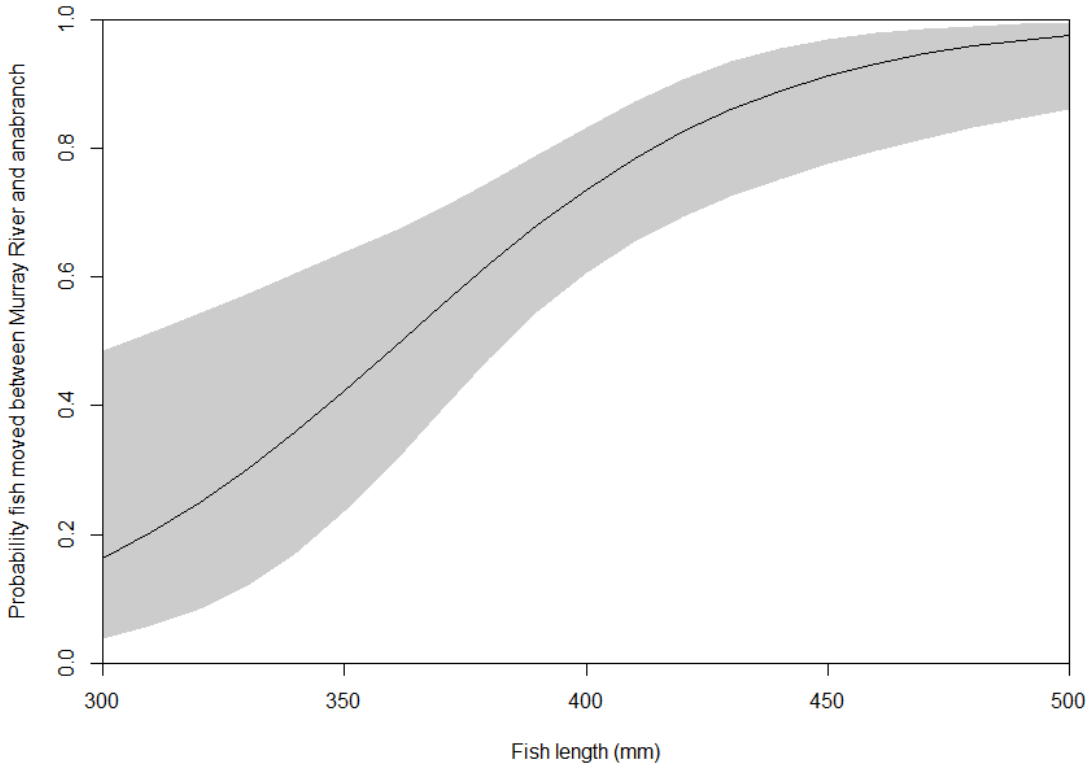

Figure 11: The probability (±95% confidence intervals) that golden perch move between the Murray River and the anabranch, or vice versa in relation to fish size (total length, mm).

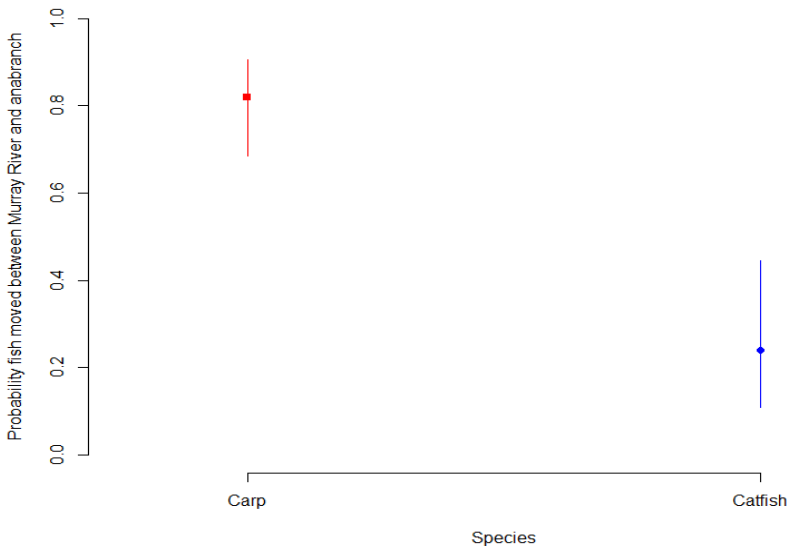

Figure 12: The probability (±95% confidence intervals) that a Carp or Catfish moves between the Murray River and the anabranch, or vice versa.

Amount and direction of movement between Murray River and Anabranches

The model with the most evidence for affecting Murray cod movement between the Murray River and the anabranches included the factors time-of-year and anabranch discharge (see Appendix 2). There was a higher rate of movement during the middle of the year, with the probability that some fish move on a day being greater than 15% from mid-autumn to spring, with a peak in October (Figure 13). Murray cod movements to the Murray River (from the anabranch) were influenced by day-of-year and anabranch water temperature (Appendix 2). Given average temperature, Murray cod in the anabranch were more likely to move (>5%) to the Murray River in early to mid-December and when temperatures were low (relative to the time of year; Figure 14). Murray cod movements to the anabranch (predominantly Mullaroo Creek) from the Murray River were influenced by anabranch discharge (Appendix 2). Murray cod occupying the Murray River had an increased chance of transitioning to the anabranch as discharges increased to approximately 1400 ML day^{-1}; then decreased as flows increased to 2000 ML day^{-1}; before increasing again (Figure 15).

The model with the most evidence for affecting golden perch movement between the Murray River and the anabranches included the factor discharge (in the anabranch) (Appendix 2). A greater rate of movement occurred when discharge in the Mullaroo Creek was larger, peaking around 60% likelihood when discharge in the Mullaroo Creek were extremely high (6000 ML day^{-1}; Figure 16). Golden perch movements to the Murray River (from the anabranch system) were influenced by day-of-year and anabranch temperature (Appendix 2). Golden perch in the anabranch were most likely to move to the Murray River in March and mid-November to mid-January (Figure 17) with these movements more likely when temperatures in the Mullaroo Creek were low (relative for the time of year). Golden perch movements to the anabranch were influenced by anabranch discharge (Appendix 2). This movement displayed a very similar pattern to that of Murray cod with an increased chance of transitioning to the anabranch as discharges increased to approximately 1400 ML day^{-1}; then decreased as flows increased to 2000 ML day^{-1}; before increasing again (Figure 18).

The model with the most evidence for affecting carp movement between the Murray River and the anabranches included the factor day-of-year only (Appendix 2) with a greater likelihood of movement occurring between August and mid-November (Figure 19). Carp movements to the Murray River from the anabranches were influenced by day-of-year and anabranch discharge (Appendix 2, Table A12). Carp were more likely to move out of the anabranch system in April and August to mid-December (Figure 20) and when discharge in the Mullaroo Creek is low. Carp movements to the anabranch were influenced by day-of-year (Appendix 2, Table A13) with an increased chance of movement to the anabranch in August to mid-November (Figure 21). No analysis of catfish transitions was conducted given less than 1.2% of days detected any catfish movement.

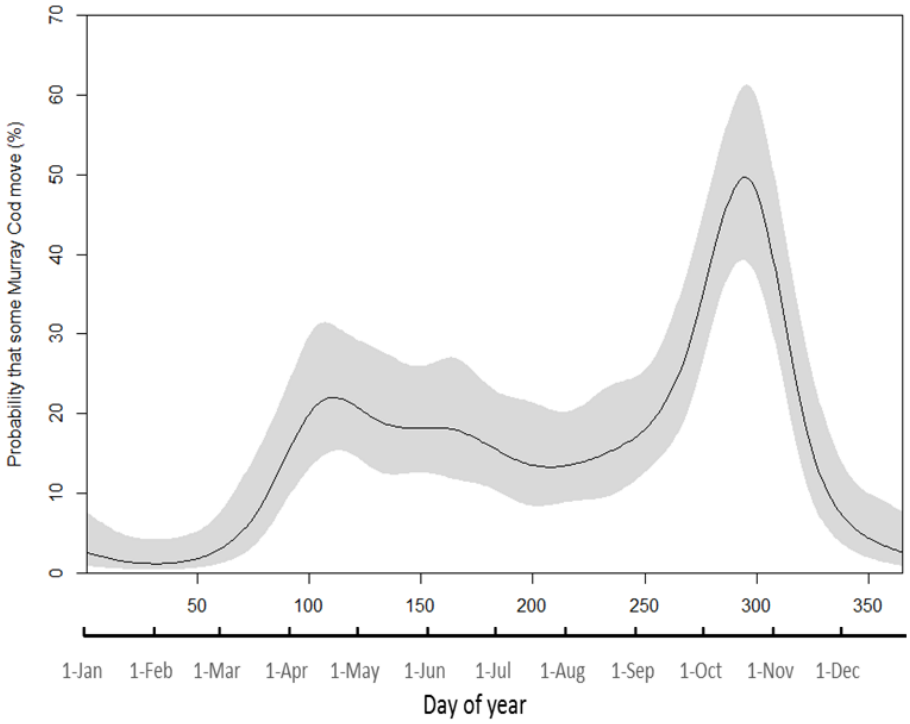

Figure 13: The proportion (±95% confidence intervals) of Murray cod expected to move between the Murray River and the anabranch, or vice versa dependent on day-of-year, given average discharge.

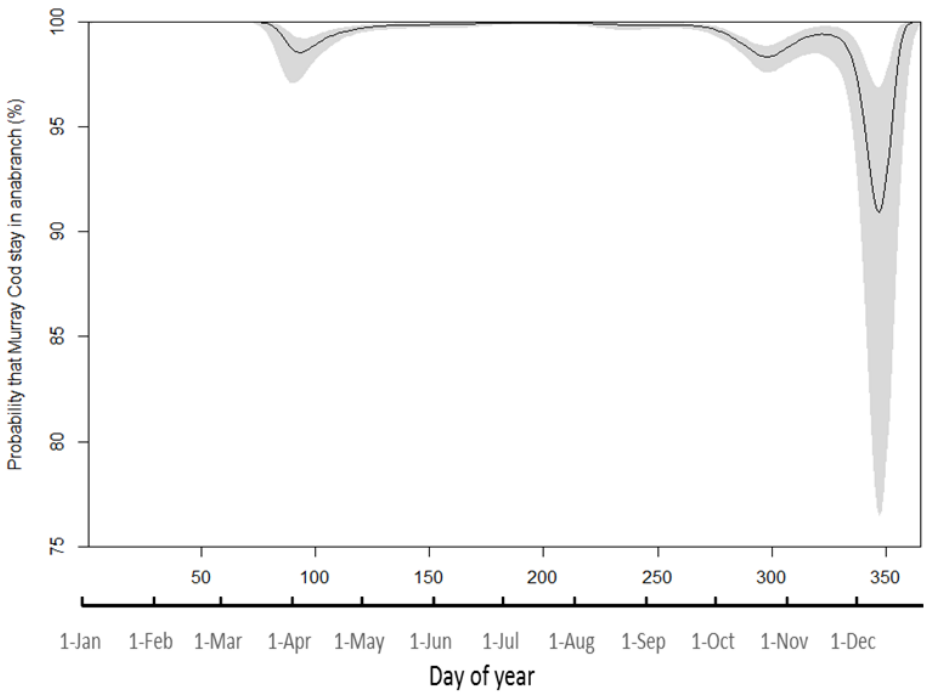

Figure 14: The probability (±95% confidence intervals) that a Murray cod in the anabranch stays in the anabranch dependent on day-of-year, given average temperature.

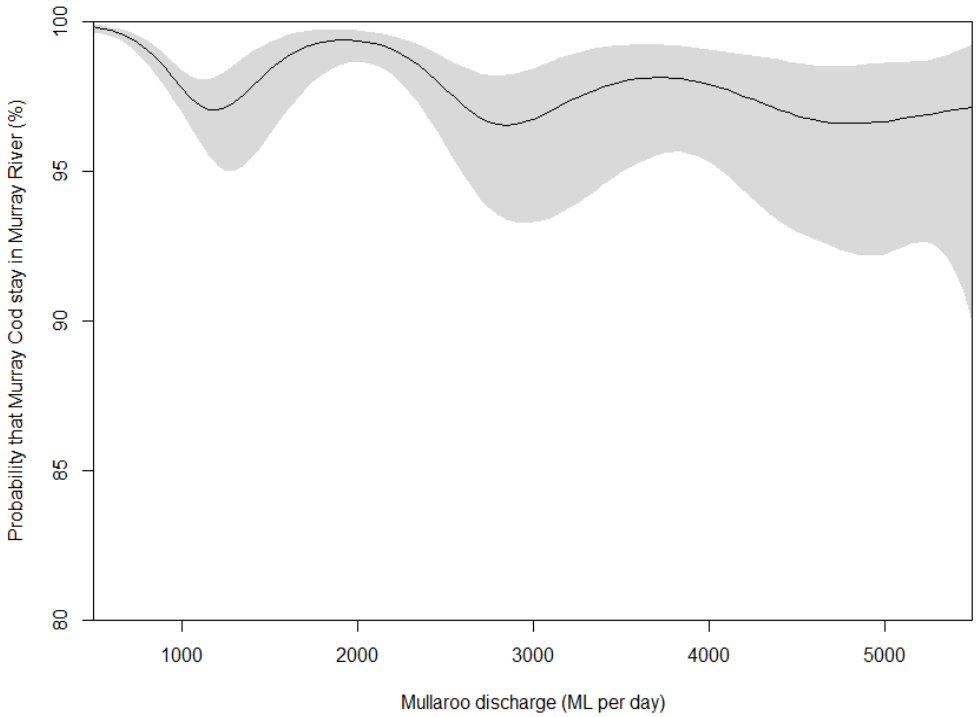

Figure 15: The probability (±95% confidence intervals) that a Murray cod in the Murray stays in the Murray on any given day dependent on discharge in Mullaroo Creek.

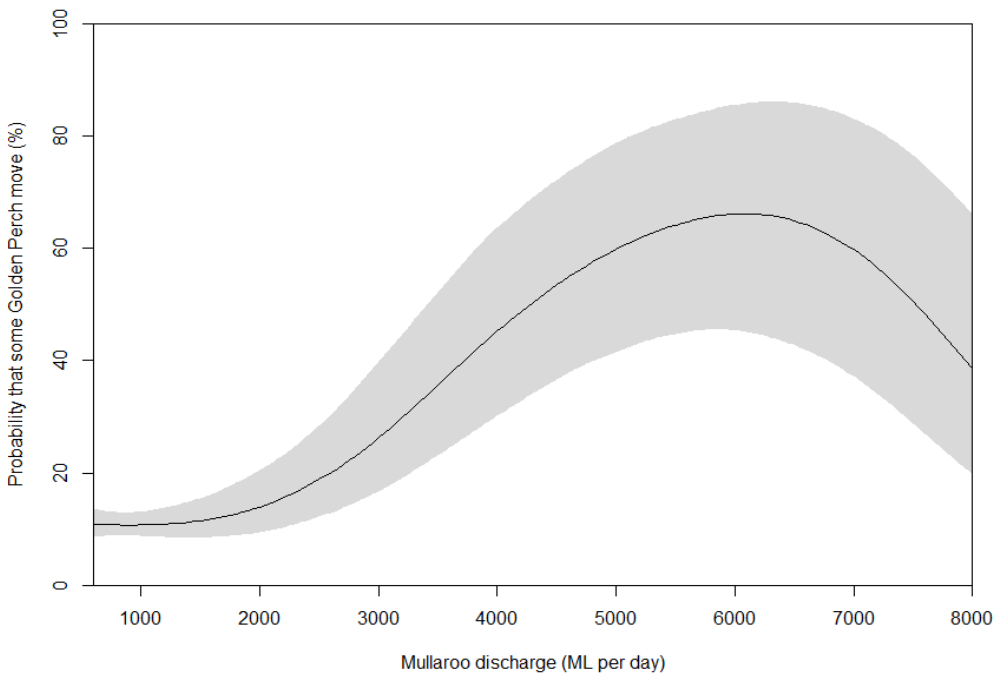

Figure 16: The probability (±95% confidence intervals) that golden perch move between the Murray River and the anabranch, or vice versa on any given day dependent on discharge in Mullaroo Creek.

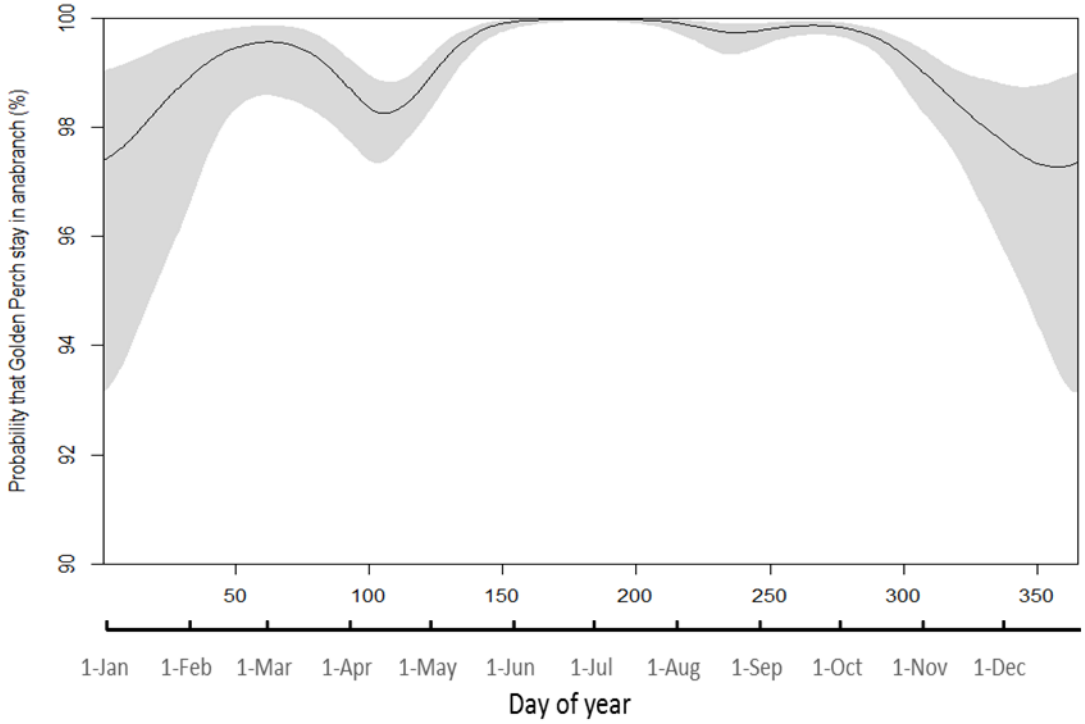

Figure 17: The probability (±95% confidence intervals) that a golden perch in the anabranch stays in the anabranch dependent on day-of-year, given average temperature.

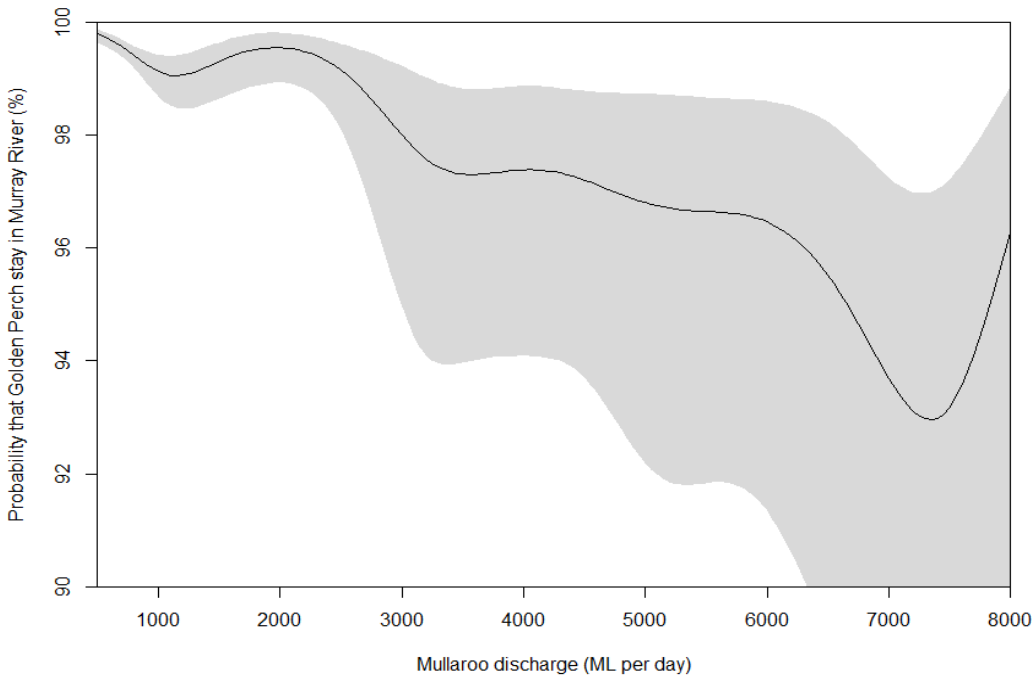

Figure 18: The probability (±95% confidence intervals) that a golden perch in the Murray River stays in the Murray River and any given day dependent on discharge in the Mullaroo Creek.

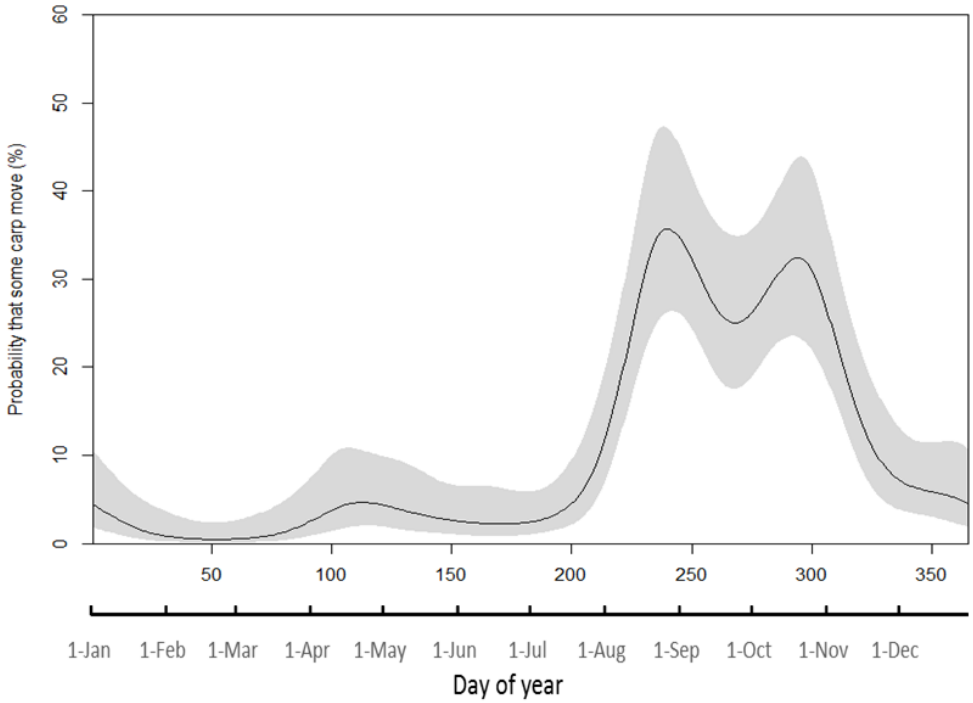

Figure 19: The probability (±95% confidence intervals) carp move between the Murray River and the anabranch, or vice versa dependent on day-of-year, given average discharge in Mullaroo Creek.

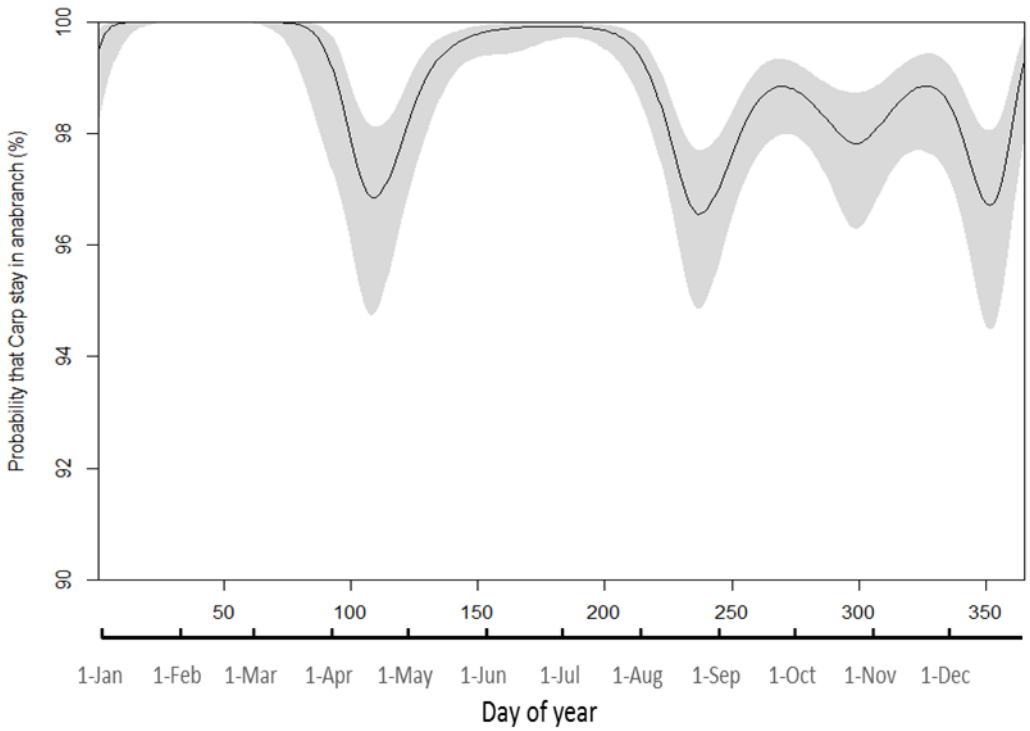

Figure 20: The probability (±95% confidence intervals) that a carp in the anabranch stays in the anabranch dependent on day-of-year, given average discharge in Mullaroo Creek.

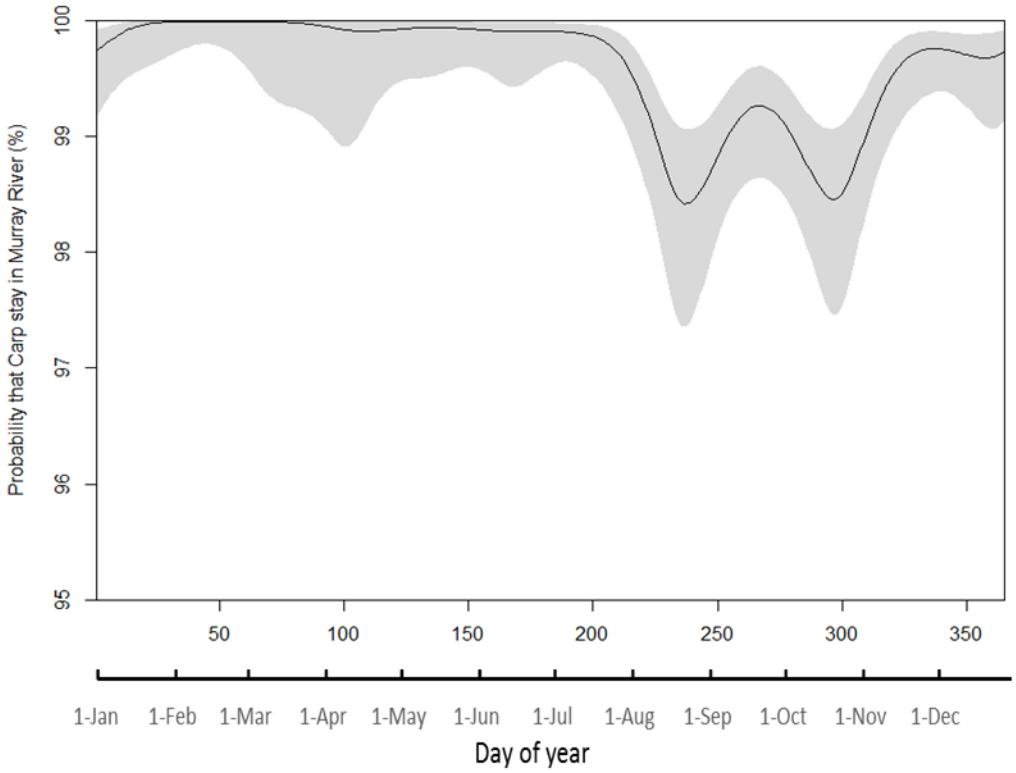

Figure 21: The probability (±95% confidence intervals) that a carp in the Murray River stays in the Murray River on a given day day-of-year, given average discharge in Mullaroo Creek.

4 Discussion

The complex anabranch systems within the Chowilla-Lindsay-Wallpolla Icon Site have long been recognised as critical habitat to support a diverse array of flora and fauna. In particular, the ability for fish to access the unique hydraulic and structural habitat characteristics of specific anabranches is thought to be 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 such 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 has generated a series of 'sentinel behaviours' and is therefore well placed to help guide future operation of floodplain infrastructure and environmental water delivery in the region.

The degree of connection that occurs within or between animal populations drives processes that govern, in essence, the fate of species (Levin 1992; Lyon et al. 2014). Data collected since March 2014 have high detection (98% of tagged fish) and transition rates of detected fish (78%) 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, with our analysis showing patterns of fish movement in response to fish size, timing and river discharge. All four study species have been recorded transitioning between the Murray River and anabranch habitats. Our analysis demonstrated these transitions vary between species, with carp having the highest probability of these moves, closely followed by golden perch, Murray cod and catfish respectively. Indeed, previous studies have demonstrated catfish to show extremely strong site fidelity (Koster et al. 2015). For golden perch and Murray cod the likelihood of transition increased with increasing fish length, a pattern previously recognised for Murray cod in the Mullaroo Creek (Saddlier et al. 2007).

In addition to different study species and fish size, the study period has, since 2014, encompassed a range of environmental conditions including periods of low flows, extreme floods and hypoxic blackwater as well as changes in infrastructure, all of which have proven to have strong influences on habitat use and survival. The most obvious of these drivers, given its direct effect on survival and subsequent public interest, was the extended floodplain inundation and hypoxic blackwater event which impacted the study region in late 2016. Flows through the Chowilla-Lindsay-Wallpolla Icon Site in from October − December 2016 inundated parts of the floodplain that had not been flooded for more than 20 years, resulting 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. Dissolved oxygen concentrations in the Murray River upstream and downstream of Lock 7 were below 4mg L^{-1} for over a month and below 2mg L^{-1} for over three weeks. Despite their usual preference for the anabranch system at this time of year (particularly Murray cod), 33% of all tagged fish completely left the study region, either emigrating downstream or upstream in the Murray River presumably to seek refuge from the hypoxic conditions. Whilst movement and transitions from the anabranch to the Murray River increased for all species during this event, only Murray cod appear to have suffered a dramatic decline in occupancy of the study region which is not surprising given earlier findings that the species is more sensitive than the other native fish species used in the study (Small et al. 2014).

In the lead up and during the blackwater event, approximately 90% of Murray cod moved zones, with almost 40% of fish moving out of the study reach and down the Murray River (below the Lindsay River junction). Many of the fish that remained in the study reach (20% of all tagged fish) have been confirmed to have died with the status of ~68% of all active tagged fish (prior to the event) unknown. As of March 2017, 17% of tagged Murray cod are confirmed to have survived the blackwater event with nine of these fish returning from the Murray River downstream of the lower Lindsay River junction. This level of mortality is comparable to that reported by Leigh and Zampatti (2013), who reported 25% mortality of tagged Murray cod in response to the 2010/11 blackwater event in the nearby Chowilla anabranch system. Contrary to public belief that large Murray cod are most impacted by hypoxic conditions (and that only juvenile Murray cod are likely to have survived the event); our data showed relatively even proportions of fish 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}.

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.

Specifically, it is vital that connectivity is maintained prior to, during and after these events to allow fish to seek refuge and then return after the event has passed. With a large proportion of fish that are of 'unknown' status having moved out of the study reach, down the Murray River, and the return of many of these fish via this route in recent months, there remains hope that further fish will return to the system. A logger download and manual tracking planned for August 2017 will shed further light on this and the status of many of the other fish whose status are still currently unknown.

Excluding the period of blackwater, data collected for Murray cod continues to show a high proportion of movements encompassed the upper Mullaroo Creek (zone B), with a greater proportion of transitions from the Murray River occurring during the spawning period. 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 (Saddlier and O'Mahony 2009; Tonkin et al. 2016). Our analysis of Murray cod transition rates between anabranch habitats and the Murray River also highlights the significant effects of both discharge in the Mullaroo Creek and time of year. The probability that some Murray cod move on a day was highest during the middle of the year (i.e. >15% from mid-autumn to spring), with a small peak period in mid-April (>20%) and a major peak in October (~50%). Murray cod movements to the anabranch (predominantly upper Mullaroo Creek) from the Murray River were influenced by anabranch discharge with an increased chance of transitioning as discharge increased to approximately 1400 ML day^{-1}; then decreased as flows increased to 2000 ML day^{-1}; before increasing again. The transition probabilities are of particular relevance at the lower ranges of discharge (Figure 22) given that these ranges are within the operating limits of the upper Mullaroo Creek regulator. Therefore the provision of flows from 1000 – 1200 ML day^{-1} in the Mullaroo Creek will greatly enhance Murray cod transitions from the Murray River, particularly if delivered in April or October. These results are particularly important given the aforementioned urgency to facilitate Murray cod movements back into the anabranch system following the blackwater induced emigration. Whilst the increased likelihood of transition rates to the anabranch with increasing anabranch discharge is likely a result of more favourable hydraulics (especially velocity) and habitat availability, the negative association with discharge from 1400 ML day^{-1} to 2000 ML day^{-1} (a pattern also evident for golden perch) is unclear. We propose the conditions present in the Murray River during these discharges are the likely cause given anabranch discharge was not a significant factor influencing Murray cod transitions out of the anabranch (to the Murray system). Further analysis of this data considering Murray River discharge (and its interaction with the Mullaroo Creek) will better inform such patterns.

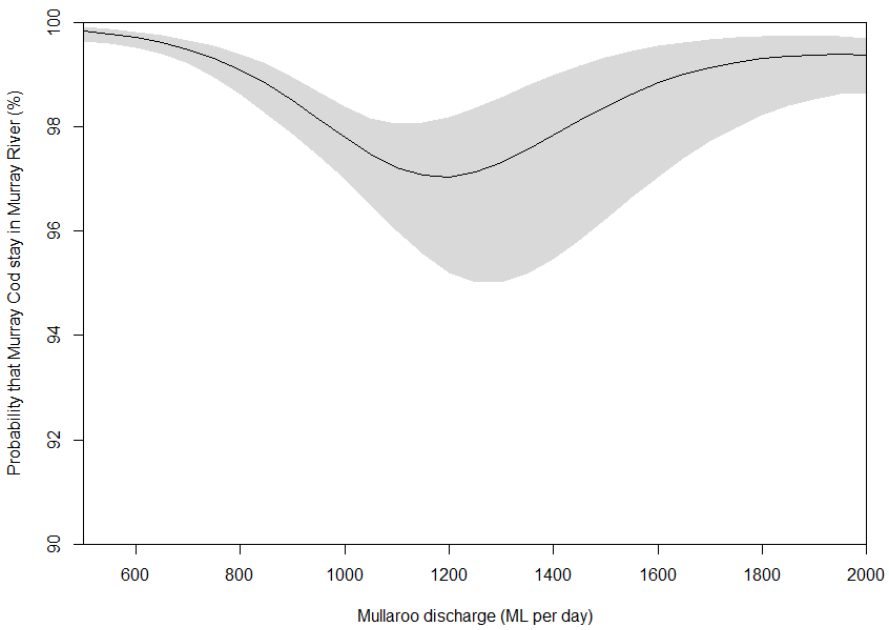

Figure 22: The probability (±95% confidence intervals) that a Murray cod in the Murray River stays in the Murray on any given day dependent on discharge in Mullaroo Creek.

For golden perch, a greater rate of movement between anabranches and the Murray River occurred when discharge in the Mullaroo Creek was high, peaking around 60% likelihood when discharge in the Mullaroo Creek was 6000 ML day^{-1}. Movements to the Murray River (from the anabranch system) were most likely in

March and mid-November to mid-January with these movements more likely when temperatures in the Mullaroo Creek were low (for this time of year). Like Murray cod, the likelihood of transitioning from the Murray River to anabranch systems changed dramatically with small changes in discharge within the anabranch. Again, these patterns provide important information to help guide waterway managers facilitate anabranch use by this species, which for golden perch is likely to be aimed at enhancing feeding and dispersal opportunities. Given the model outputs (see Figure 18) the recommended flows of 1000 – 1200 ML day^{-1} in the Mullaroo Creek during Spring will also enhance golden perch use of the anabranch system as compared to lower discharges (e.g. 400 ML day^{-1}).

Whilst investigating carp movement was not initially an objective of the study, the species has recently been included to provide information which may help manage this pest fish. In particular, movements to specific locations during the spawning period or triggers for fish to access anabranches may be useful in identifying spawning sites or target trapping (e.g. Stuart and Jones 2006; Stuart et al. 2006). Carp movement between the Murray River and the anabranches was most effected by day-of-year with a greater likelihood of movement between August and mid-November. Carp movements to the Murray River (from the anabranches) were also influenced by discharge with fish more likely to move out of the anabranch system in April and August to mid-December and when discharge in the Mullaroo Creek is low. 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). Importantly, these results also suggest that the aforementioned recommendation of discharges aimed at enhancing transitions of Murray cod and golden perch from the Murray River to the anabranch system is unlikely to increase adult carp immigration.

Further exploration (from that presented in Tonkin et al. 2016) of signal strength data recorded at the Mullaroo regulator/ fishway continued to enable an assessment of fish transition from the Upper Mullaroo Creek to the Murray River. Importantly, this could be examined during the period of the old ford structure, and during operation of the new regulator (and fishway). The data suggests that whilst all four species were recorded to have successfully transitioned into the Murray River under both new and old (except catfish for the latter) structures, in all, the total percentage of transitions was slightly lower (26%) and the total percentage of individual fish transitions (34%) was much lower. Carp in particular had much lower transition rates. Interestingly, 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 pre-and post-regulator/ fishway construction. This suggests both the old ford structure and the newly constructed fishway have some impact on fish movement. Of course higher transition rates may be related to the desire for fish to migrate during periods of flood or the need to escape the hypoxic blackwater conditions and thus it is difficult to separate the impact of the fishway. Further monitoring over the coming years will be required to accurately assess the influence of the regulator/ fishway on fish transition between the Upper Mullaroo Creek and the Murray River under a range of hydrological conditions and gate arrangements aimed at optimising fish movement.

5 Future direction

The information gathered on fish movement and habitat use (and associated drivers) during the program has generated important information to help guide management of environmental flows and infrastructure operations aimed at maximising benefits for native fish in the Lindsay and Mulcra Island anabranch system. As such, the program is well placed to assess fish outcomes resulting from future interventions. Nevertheless, continuing the annual fish tagging and maintenance routine is still required. Data collected over the next year will also enable researchers to determine the fate of many tagged Murray cod whose whereabouts and/or status (as of March 2017) was still unknown, thus giving a more accurate measure of the impact of the 2016 blackwater event. Indeed, answers to this question are a high priority for both waterway managers and the general public (particularly the recreational fishing community). Much of this information will be collected in the data collection and manual tracking trip planned for August 2017.

The transition of the program to acoustic tags (which began in March 2017), whilst limiting the ability to assess direct mortality and habitat use, will overcome previous limitations of exceeding the memory capacity of data loggers. This will also enable an assessment of larger scale migratory behaviour both to and from the study site. This will require close collaborations with other projects and agencies currently operating across the southern MDB including The Living Murray initiative and Commonwealth's Long Term Intervention Monitoring project and Victorian Environmental Flow Assessment Program (VEFMAP).

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.

Specific topics of key interest following operation of the floodplain regulators include:

- A final assessment of blackwater impacts on the survival and return movements of Murray cod (given the fate of more than 60% of fish is still unknown).
- Continued assessment of fish transitions between the Murray River and upper Mullaroo Creek under a range operational scenarios including:
  - simulated flooding,
  - increased spring discharge in Mullaroo Creek (specifically, a gradual increase to 1200 ML day^{-1} from October – December,
  - increased Autumn discharge in Mullaroo Creek (specifically, a gradual increase to 1200 ML day^{-1} during April), and
  - different regulator operational scenarios, particularly under different gate and weir pool height scenarios.

As per 2016 recommendations, we suggest incorporating specific information on weir pool levels, regulator gate configurations and hydraulics into any future data analysis on fish movement. This will improve the analytical power and test the transferability of results across the MDB. 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 in its infancy, but 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.

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Appendix 1. Size and tag details of individual fish implanted with telemetry tags in the Lindsay Island anabranch study from March 2014 – April 2016.

Table A1: Size and tag details of individual fish implanted with telemetry tags in the Lindsay Island anabranch study from March 2014 – April 2016.

Species	Zone	Length (mm)	Weight (g)	Fish ID	Transmitter status
Murray Cod	a	890	10500	132.10	Tag active
Murray Cod	b	919	12600	132.20	Tag active
Murray Cod	a	840	9000	132.27	Tag active
Murray Cod	a	732	5200	132.28	*Unknown
Murray Cod	a	957	13500	132.30	*Unknown
Murray Cod	b	713	5191	132.32	*Unknown
Murray Cod	a	1050	22000	132.40	*Unknown
Murray Cod	a	1120	24000	132.50	*Unknown
Murray Cod	d	574	3072	132.58	Tag active
Murray Cod	a	832	9239	132.60	Tag active
Murray Cod	b	435	1008	132.61	Tag active
Murray Cod	a	931	12300	132.80	Tag active
Murray Cod	a	848	8650	132.90	*Unknown
Murray Cod	i	880	11000	153.1b	*Unknown
Murray Cod	i	920	12000	153.2b	*Unknown
Murray Cod	i	1140	25000	153.3b	*Unknown
Murray Cod	i	720	8000	153.4a	Tag active
Murray Cod	i	718	5300	153.4b	Tag active
Murray Cod	i	965	14000	153.5b	*Unknown
Murray Cod	b	760	8200	153.11	*Unknown
Murray Cod	d	720	5976	153.12	*Unknown
Murray Cod	d	815	10400	153.13	*Unknown
Murray Cod	b	885	14000	153.14	*Unknown
Murray Cod	d	955	16400	153.16	*Unknown
Murray Cod	b	1140	24000	153.18	Tag active
Murray Cod	b	579	2826	153.21	Tag active
Murray Cod	d	870	14200	153.23	*Unknown
Murray Cod	b	1060	21000	153.27	Re-used tag active
Murray Cod	b	990	18500	153.32	*Unknown
Murray Cod	b	980	17000	153.33	Mortality
Murray Cod	d	980	15500	153.34	*Unknown
Murray Cod	b	1210	34800	153.35	*Unknown
Murray Cod	b	885	12500	153.36	Mortality
Murray Cod	i	1150	26000	153.45	*Unknown

Species	Zone	Length (mm)	Weight (g)	Fish ID	Transmitter status
Murray Cod	i	1190	32000	153.46	Tag active
Murray Cod	i	1010	18000	153.47	*Unknown
Murray Cod	i	1080	24000	153.48	Mortality
Murray Cod	i	712	8500	153.49	Tag active
Murray Cod	b	360	462	153.54	*Unknown
Murray Cod	b	379	630	153.57	Mortality
Murray Cod	b	377	606	153.58	Mortality
Murray Cod	b	395	732	153.61	*Unknown
Murray Cod	d	303	359	153.63	*Unknown
Murray Cod	b	384	709	153.64	*Unknown
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	*Unknown
Murray Cod	b	835	11000	173.15	*Unknown
Murray Cod	b	527	2100	173.16	Mortality
Murray Cod	b	855	9900	173.17	*Unknown
Murray Cod	b	637	3940	173.18	*Unknown
Murray Cod	b	625	3542	173.19	Mortality
Murray Cod	d	519	1908	173.20	*Unknown
Murray Cod	b	550	2700	173.21	*Unknown
Murray Cod	b	640	4256	173.22	*Unknown
Murray Cod	b	611	3408	173.23	Angled
Murray Cod	b	835	10000	173.24	*Unknown
Murray Cod	b	900	13400	173.26	Mortality
Murray Cod	b	825	9000	173.32	Mortality
Murray Cod	b	1100	26900	173.33	*Unknown
Murray Cod	b	1080	25400	173.34	*Unknown
Murray Cod	b	1160	35000	173.35	*Unknown
Murray Cod	b	640	4100	173.36	Mortality
Murray Cod	b	1150	29000	173.50	Mortality
Murray Cod	b	392	726	173.52	Mortality
Murray Cod	b	366	565	173.54	*Unknown
Murray Cod	d	299	356	173.55	Mortality
Murray Cod	b	383	633	173.57	*Unknown
Murray Cod	b	381	669	173.58	*Unknown
Murray Cod	b	354	488	173.59	Mortality
Murray Cod	a	860	9700	234.30	*Unknown
Murray Cod	d	1080	21200	234.31	Mortality
Murray Cod	d	855	10150	234.32	*Unknown
Murray Cod	d	960	14000	234.33	Mortality
Murray Cod	b	712	5315	234.44	*Unknown
Murray Cod	b	740	6200	234.45	*Unknown
Golden Perch	d	404	948	132.11	Tag expired

Species	Zone	Length (mm)	Weight (g)	Fish ID	Transmitter status
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	132.2	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 active
Golden Perch	b	430	1024	132.38	Tag active
Golden Perch	i	402	900	132.4	Mortality
Golden Perch	d	421	985	132.41	Tag active
Golden Perch	i	428	1385	132.42	Tag active
Golden Perch	d	418	970	132.43	Tag active
Golden Perch	b	433	1210	132.44	Tag active
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	Tag active
Golden Perch	a	435	1251	132.55	Tag active
Golden Perch	d	388	950	132.60	Tag active
Golden Perch	d	382	923	132.62	Tag active
Golden Perch	a	436	1588	150.56	Tag active
Golden Perch	e	383	800	152.67	Tag active
Golden Perch	b	376	763	152.68	Tag active
Golden Perch	e	362	751	152.69	Tag active
Golden Perch	b	326	508	152.70	Tag active
Golden Perch	a	364	730	152.71	Tag active
Golden Perch	e	393	910	152.72	Tag active
Golden Perch	d	355	657	152.73	Tag active
Golden Perch	d	478	1508	153.2	Tag active
Golden Perch	i	475	1820	153.28	Mortality
Golden Perch	b	386	846	153.5	Tag active
Golden Perch	b	420	1130	153.51	Tag active
Golden Perch	b	359	635	153.52	Tag active
Golden Perch	b	421	1057	153.53	Tag active
Golden Perch	a	447	1118	153.55	Tag active
Golden Perch	a	405	819	153.56	Tag active
Golden Perch	a	359	618	153.59	Tag active
Golden Perch	a	438	1077	153.6	Tag active

Species	Zone	Length (mm)	Weight (g)	Fish ID	Transmitter status
Golden Perch	d	353	573	153.62	Tag active
Golden Perch	e	335	570	172.65	Tag active
Golden Perch	e	346	716	172.66	Tag active
Golden Perch	b	368	698	172.67	Tag active
Golden Perch	a	375	730	172.68	Tag active
Golden Perch	d	346	643	172.69	Tag active
Golden Perch	b	365	693	172.70	Tag active
Golden Perch	b	368	749	172.71	Tag active
Golden Perch	b	350	623	172.74	Tag active
Golden Perch	a	435	1160	173.3	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	173.4	Tag active
Golden Perch	i	451	1450	173.4	Tag active
Golden Perch	i	465	1250	173.41	Mortality
Golden Perch	i	490	1860	173.42	Angled
Golden Perch	i	440	1080	173.43	Tag active
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	173.5	Tag active
Golden Perch	d	396	750	173.51	Tag active
Golden Perch	a	387	858	173.53	Angled
Golden Perch	d	412	778	173.56	Tag active
Golden Perch	d	398	627	173.6	Tag active
Golden Perch	i	480	1690	173.6	Mortality
Golden Perch	b	402	937	173.61	Tag active
Golden Perch	d	423	1159	173.62	Tag active
Golden Perch	a	453	1055	173.63	Mortality
Golden Perch	d	404	908	173.64	Tag active
Golden Perch	d	375	700	234.1	Tag expired
Golden Perch	d	340	570	234.12	Angled
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	b	446	1340	234.2	Tag expired
Golden Perch	d	370	670	234.2	Angled
Golden Perch	d	357	644	234.24	Angled and released
Golden Perch	a	466	1695	234.29	Tag active
Golden Perch	i	320	570	234.3	Tag expired
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

Species	Zone	Length (mm)	Weight (g)	Fish ID	Transmitter status
Golden Perch	i	430	1148	234.4	Tag expired
Golden Perch	i	456	1140	234.5	Tag expired
Golden Perch	b	310	402	234.59	Tag expired
Golden Perch	d	403	660	234.6	Tag expired
Golden Perch	d	405	940	234.6	Tag expired
Golden Perch	b	310	430	234.65	Tag expired
Golden Perch	d	386	720	234.8	Tag expired
Golden Perch	d	353	630	234.9	Tag expired
Golden Perch*	g	350	616	1259133-51247	Tag active
Golden Perch*	g	376	824	1259134-51248	Tag active
Golden Perch*	h	370	785	1259135-51249	Tag active
Golden Perch*	h	400	1117	1259136-51250	Tag active
Golden Perch*	h	416	1243	1259137-51251	Tag active
Golden Perch*	g	363	662	1259138-51252	Tag active
Golden Perch*	g	412	1011	1259139-51253	Tag active
Golden Perch*	h	386	935	1259140-51254	Tag active
Golden Perch*	h	423	1190	1259141-51255	Tag active
Golden Perch*	d	415	1128	1259142-51256	Tag active
Golden Perch*	h	435	1410	1259159-51273	Tag active
Golden Perch*	h	425	1225	1259160-51274	Tag active
Golden Perch*	h	406	1272	1259161-51275	Tag active
Golden Perch*	h	426	1430	1259162-51276	Tag active
Golden Perch*	d	404	1237	1259758-51272	Tag active
Golden Perch*	b	385	918	51257-1259143	Tag active
Golden Perch*	b	365	700	51258-1259144	Tag active
Golden Perch*	b	391	902	51259-1259145	Tag active
Golden Perch*	b	411	1050	51260-1259146	Tag active
Golden Perch*	b	398	1124	51261-1259147	Tag active
Golden Perch*	b	364	762	51262-1259148	Tag active
Golden Perch*	d	457	1668	51263-1259149	Tag active
Golden Perch*	d	395	875	51264-1259150	Tag active
Golden Perch*	d	371	810	51265-1259151	Tag active
Golden Perch*	d	417	1240	51267-1259153	Tag active
Golden Perch*	d	425	1317	51267-1259153	Tag active
Golden Perch*	b	428	1260	51268-1259154	Tag active
Golden Perch*	b	397	1133	51269-1259155	Tag active
Golden Perch*	b	403	998	51270-1259156	Tag active
Golden Perch*	a	441	1370	51271-1259157	Tag active
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	464	992	132.57	Tag active
Catfish	b	495	1232	132.59	Tag active
Catfish	h	382	470	172.73	Tag active

Species	Zone	Length (mm)	Weight (g)	Fish ID	Transmitter status
Catfish	b	497	1100	173.29	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	234.2	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	234.4	Tag expired
Catfish	d	450	806	234.41	Tag expired
Catfish	d	435	696	234.42	Tag expired
Catfish	b	398	550	234.58	Tag expired
Catfish	b	438	824	234.62	Tag expired
Catfish	d	450	728	234.63	Tag expired
Catfish	d	361	372	234.64	Tag expired
Catfish	b	405	640	234.66	Tag expired
Catfish	i	445	650	234.75	Tag expired
Carp	i	520	2860	132.2	Tag expired
Carp	b	600	3398	132.29	Tag active
Carp	b	578	3468	132.3	Tag active
Carp	a	618	3750	132.31	Tag active
Carp	b	547	2199	132.33	Tag active
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	e	608	3680	153.15	Tag active
Carp	b	640	2896	153.17	Tag active
Carp	e	640	3444	153.19	Mortality
Carp	e	603	3290	153.22	Tag active
Carp	e	440	1320	153.24	Tag active
Carp	b	502	1772	153.26	Angled
Carp	i	690	5550	153.26	Re-used tag
Carp	b	640	3470	153.27	Angled
Carp	i	695	5950	153.4	Tag active
Carp	i	480	1936	153.41	Tag active
Carp	i	605	3934	153.42	Tag active
Carp	i	470	1506	153.43	Mortality

Species	Zone	Length (mm)	Weight (g)	Fish ID	Transmitter status
Carp	i	715	6050	153.44	Tag active
Carp	b	635	4230	153.6	Tag active
Carp	i	640	4530	153.8	Tag active
Carp	i	550	2950	153.9	Tag active
Carp	b	590	3040	173.1	Tag active
Carp	b	680	4840	173.2	Tag active
Carp	i	580	3250	173.23	Tag active
Carp	b	555	2590	173.27	Tag active
Carp	b	565	2720	173.28	Tag active
Carp	b	680	5250	173.3	Tag active
Carp	i	386	1180	173.37	Tag active
Carp	d	669	5138	173.38	Mortality
Carp	d	437	1514	173.44	Re-used tag
Carp	i	390	930	173.44	Angled
Carp	i	490	1890	173.46	Tag active
Carp	b	504	1920	173.8	Tag active
Carp	b	645	3050	173.9	Mortality
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	234.5	Tag active
Carp	i	515	1670	153.1a	Tag active
Carp	d	545	2222	153.2a	Tag active
Carp	i	585	2830	153.3a	Tag active
Carp	i	590	3515	153.5a	Tag active

a. Golden Perch marked with an * indicate that they have been tagged with an acoustic tag and not a radio tag.

b. The status of some Murray cod in the system remains unknown following the blackwater event that killed some Murray Cod

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

Table A2: Comparison between potential models for Murray cod ever moving between Murray River and anabranch systems.

Model	AICc	ΔAICc	Evidence Ratio
Length + Period	176.4		
Length * Period	178.0	1.6	2.2
Period	185.9	9.5	115.6
Length	186.2	9.8	134.3
Null	195.1	18.7	11498.8

Table A3: Parameter estimates for the Murray cod ever move between Murray River and Anabranch model. Estimates are in logit (log-odds) scale and zLength is the 42tandardized lengths of the fish.

Parameter	Estimate	Standard error	p-value
Intercept	0.165	0.247	0.504
Period: Earlier	-1.256	0.376	0.001
zLength	0.638	0.198	0.001

Table A4: Comparison between potential models for Murray cod staying in the anabranch or moving to the Murray River. DoY stands for Day-of-Year, zDischarge and zTemperature stand for 42tandardized Mullaroo discharge and temperature respectively.

Model	AICc	ΔAICc	Evidence Ratio
s(DoY) + zTemperature	787.4		
s(DoY) + zDischarge	790.1	2.7	3.900000e+00
s(DoY)	793.8	6.4	2.450000e+01
s(Temperature)	852.6	65.2	1.438799e+14
s(Discharge)	861.4	74.0	1.171914e+16
Null	885.6	98.2	2.107944e+21

Table A5: Comparison between potential models for Murray cod staying in the Murray River or moving to the anabranch. DoY stands for Day-of-Year, zDischarge and zTemperature stand for standardised Mullaroo discharge and temperature respectively.

Model	AICc	ΔAICc	Evidence Ratio
s(Discharge)	568.9		
s(Temperature)	601.2	32.3	1.032419e+07
s(DoY) + zTemperature	601.9	33.0	1.465072e+07
s(DoY) + zDischarge	603.1	34.2	2.669535e+07
s(DoY)	607.0	38.1	1.876333e+08
Null	645.5	76.6	4.300101e+16

Table A6: Comparison between potential models for Golden perch ever moving between Murray River and anabranch systems.

Model	AICc	ΔAICc	Evidence Ratio
Length	79.2		
Null	91.6	12.4	492.7

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Table A7: Parameter estimates for the Golden perch ever move between Murray River and Anabranch model. Estimates are in logit (log-odds) scale and zLength is the standardised lengths of the fish.

Parameter	Estimate	Standard error	p-value
Intercept	1.215	0.313	0.000
zLength	1.170	0.356	0.001

Table A8: Comparison between potential models for Carp ever moving between Murray River and anabranch systems.

Model	AICc	ΔAICc	Evidence Ratio
Null	49.2		
Length	51.4	2.2	3

Table A9: Comparison between potential models for Catfish ever moving between Murray River and anabranch systems.

Model	AICc	ΔAICc	Evidence Ratio
Null	29.7		
Length	31.5	1.8	2.5

Table A10: Comparison between potential models for Golden perch staying in the anabranch or moving to the Murray River. DoY stands for Day-of-Year, zDischarge and zTemperature stand for standardised Mullaroo discharge and temperature respectively.

Model	AICc	ΔAICc	Evidence Ratio
s(DoY) + zTemperature	856.3		
s(DoY)	862.9	6.6	2.710000e+01
s(DoY) + zDischarge	864.9	8.6	7.370000e+01
s(Temperature)	906.8	50.5	9.245612e+10
s(Discharge)	918.8	62.5	3.729946e+13
Null	934.6	78.3	1.006072e+17

Table A11: Comparison between potential models for Golden perch staying in the Murray River or moving to the anabranch. DoY stands for Day-of-Year, zDischarge and zTemperature stand for standardised Mullaroo discharge and temperature respectively.

Model	AICc	ΔAICc	Evidence Ratio
s(Discharge)	506.2		
s(DoY) + zDischarge	525.9	19.7	1.895840e+04
s(DoY) + zTemperature	527.5	21.3	4.219260e+04
s(DoY)	532.3	26.1	4.650964e+05
s(Temperature)	549.6	43.4	2.655769e+09
Null	553.0	46.8	1.453754e+10

Table A12: Comparison between potential models for Carp staying in the anabranch or moving to the Murray River. DoY stands for Day-of-Year, zDischarge and zTemperature stand for standardised Mullaroo discharge and temperature respectively.

Model	AICc	ΔAICc	Evidence Ratio
s(DoY) + zDischarge	722.8		
s(DoY)	724.8	2.0	2.700000e+00
s(DoY) + zTemperature	725.9	3.1	4.700000e+00
Temperature)	777.4	54.6	7.181900e+11
s(Discharge)	828.6	105.8	9.422759e+22
Null	841.1	118.3	4.881110e+25

Table A13: Comparison between potential models for Carp staying in the Murray River or moving to the anabranch. DoY stands for Day-of-Year, zDischarge and zTemperature stand for standardised Mullaroo discharge and temperature respectively.

Model	AICc	ΔAICc	Evidence Ratio
s(DoY)	375.7		
s(DoY) + zDischarge	375.7	0.0	1.000000e+00
s(DoY) + zTemperature	377.5	1.8	2.500000e+00
s(Discharge)	400.7	25.0	2.683373e+05
s(Temperature)	422.6	46.9	1.528289e+10
Null	442.8	67.1	3.720316e+14

Table A14: Parameter estimates for the transition models for fish moving between Murray River and Anabranch on given day. Estimates are in log scale and zDischarge is the standardised daily discharge for the Mullaroo Creek. The Parameter estimates for the day-of-year smoother are not meaningful to look at, and therefore are not included.

Species	Model	Parameter	Estimate	Standard error	p-value
Carp	Stay in anabranch	Intercept	6.732	0.611	0.0000
Carp	Stay in anabranch	zMullDischarge	0.172	0.090	0.0549
Carp	Stay in Murray	Intercept	6.618	0.410	0.0000
Golden perch	Stay in anabranch	Intercept	5.590	0.126	0.0000
Golden perch	Stay in anabranch	zMullTemp	1.047	0.343	0.0023
Golden perch	Stay in Murray	Intercept	5.160	0.136	0.0000
Carp	Stay in anabranch	Intercept	6.732	0.611	0.0000
Carp	Stay in anabranch	zMullDischarge	0.172	0.090	0.0549
Carp	Stay in Murray	Intercept	6.618	0.410	0.0000

Table A15: Parameter estimates for the smoothing terms from the transition models for fish moving between Murray River and Anabranch on given day. The individual parameter estimates for the smoothers are not meaningful to look at, and therefore are not included.

Species	Model	Smoother	Effective degrees of freedom	p-value
Carp	Stay in anabranch	DoY	9.785	0
Carp	Stay in Murray	DoY	8.286	0
Golden perch	Stay in anabranch	DoY	8.762	0
Golden perch	Stay in Murray	Discharge	4.130	0
Carp	Stay in anabranch	DoY	9.785	0
Carp	Stay in Murray	DoY	8.286	0

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