Lateral fish movement at the Hattah Lakes icon site

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Final Report prepared for the Mallee Catchment Management Authority by The Murray–Darling Freshwater Research Centre.

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Cover Image: Tagged Golden perch being released in Chalka Creek, Hattah Lakes, Victoria.

Photographer: David Wood

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The Murray–Darling Freshwater Research Centre offices are located on the land of the Latje Latje and Wiradjuri peoples. We undertake work throughout the Murray–Darling Basin and acknowledge the traditional owners of this land and water. We pay respect to Elders past, present and future.

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Executive summary

Understanding fish movement and the stimuli resulting in a movement response betters our general understanding of fish behaviour and biology. Fish movement is of particular importance between main river channels and off-channel habitats such as wetlands. Off-channel habitats provide a greater opportunity for fast growth and development than those in the main channel. This study will inform future operational management regarding the timing of watering events and the operation of regulatory structures with respect to the management of pest Carp and flow-dependent native fish species such as Golden perch, in the Hattah Lakes system.

The Hattah Lakes are a large wetland system located on the Murray River floodplain in North West Victoria. The Hattah Lakes have periodically received environmental water since 2006. In 2013, a works and measures program was commissioned that allowed watering of the Hattah Lakes and surrounding floodplain to a depth previously unable to be achieved except during large-scale natural flooding.

This report investigates aspects of fish movement in the Hattah Lakes in association with pumped filling of the Lakes from the Murray River. The objectives of this study were to: (1) assess the fish population in the Lakes and Chalka Creek prior to filling; (2) evaluate fish movement along Chalka Creek from the Lakes towards Messengers Crossing (water entry point) by sampling with nets; and (3) analyse movement patterns of tagged Carp (including existing Carp tagged in 2014) and newly tagged Golden perch and Murray cod during filling, using acoustic transmitters.

Prior to pumping 4.2 GL of water to the Hattah Lakes in Spring 2015, a survey of the fish fauna was undertaken in Chalka Creek, as well as in Lakes Lockie, Yerang, Hattah and Little Hattah (i.e. lakes likely to receive the water). Fish species caught during this survey reflected species previously recorded at Hattah Lakes. Carp gudgeon were the most common species, followed by Australian smelt. Oriental weatherloach were the most common non-native species.

During spring 2015, directional netting was undertaken in Chalka Creek, to sample fish moving ‘upstream’ toward the pumped inflowing water. Carp gudgeon was the most common species observed during these surveys, and individuals of this species tended to move toward water entering the system. Oriental weatherloach were also influenced by flow, with a rapid response of moving toward inflowing water. Australian smelt, Eastern gambusia, Flathead and Dwarf flathead gudgeon were not as influenced by flow; however, their abundance was significantly different between the two sampling sites.

Goldfish, Carp and Golden perch were the most common large-bodied species encountered during directional netting. Carp catches increased slightly as pumping increased flows. Goldfish and Golden perch catches showed a strong response to flow. Both Golden perch and Goldfish moved in greater abundance into the flow toward the Murray River. While Goldfish moved toward the flow for the whole pumping period, there was an apparent delay in the movement of Golden perch, with the majority of their movement occurring a week following the initiation of the flow.

While netting provides valuable location-specific data, using nets at particular sites makes it difficult to determine movement patterns of fish over a large area. Acoustic tracking provides information on individual fish (and groups of fish) detected over a wide area, using a series of stationary receivers of known location. Data collected can be modelled to interpolate movement between receivers and a trajectory of each fishe’s movements can be generated as a time-series. Using actual observations of fish speeds between receivers, we developed models of random movement (‘null-models’) for two species, Carp and Golden perch, i.e., models that simulate how individuals would move under the null-hypothesis that movement was random and not biased in any particular direction related to pumped inflows. Null model 1, simulates purely random movement. Null model 2, simulates random movement, but with some persistence, i.e. once moving in a direction the fish tends to continue in that direction. Null model 3, simulates random movement with persistence and directional bias

either upstream or downstream. We then fitted these models to the observed trajectories of each individual tagged fish, classifying them as ‘best-fitting’ null models 1, 2 or 3.

During spring 2014, 48 Carp in the Hattah Lakes were implanted (‘tagged’) with acoustic transmitters. An array of stationary receivers recorded the movement of these fish throughout the lakes system. Following filling of the lakes, water was released back to the Murray River as the lakes were drawn down. Initial analysis suggested that movements of Carp appeared random and largely unrelated to flow (Wood, Brown & Ellis 2015). Additionally, and importantly, none of the tagged Carp exited Hattah Lakes. Re-analysis of this acoustic data using the null-model approach found that tagged Carp in the Hattah Lakes (n=20) generally displayed random movement patterns during drawdown. However, six Carp displayed some directed movement of varying strength, with five of these fish moving toward (i.e. ‘downstream’) and one moving away from the Murray River (i.e. ‘upstream’).

During spring 2015, a further small filling of the Hattah Lakes occurred using the environmental pumps. Acoustic data collected during the event for three newly tagged Golden perch and the remaining Carp tagged in 2014, was analysed in regards to movement patterns. The majority of tagged Carp again displayed random movement patterns, with the exception of five fish, two of which exhibited directed movement toward the Murray River and three away from the river.

For three Golden perch tagged prior to the spring 2015 pumped inflow, sufficient data allowed analysis during the filling event. All of the Golden perch displayed strong directed movement toward the inflowing water. Later, during the flow, additional Golden perch, Murray cod and Carp were tagged and released.

Evidence gathered though directional netting surveys and acoustic data from tagged fish for this project indicates that the majority of Carp in Hattah Lake are not cued to respond to flows in or out of the system by way of mass directed movement. Conversely, preliminary findings suggest that Golden perch display a strong movement response toward water entering the Hattah Lakes (i.e. returning to the Murray River).

A short draining phase (8 days) was undertaken following filling in spring 2015. While outside the scope of this project, acoustic data indicates that three tagged Golden perch emigrated from the Hattah Lakes through Messengers Regulator with the water as it returned to the Murray River.

The present study demonstrates the proof-of-concept that environmental watering of the Hattah Lakes using existing infrastructure may facilitate the:

1. development and recruitment of Golden perch juveniles within the lakes resulting from eggs, larvae or early juveniles originating from the Murray River
2. return of adult Golden perch to the Murray River population to complete their life cycle.

Although Carp may also recruit to the Hattah Lakes population, as adults they are likely to remain within the lakes.

We recommend a hydrograph for further trial manipulation of the hydrology of the Hattah Lakes, using the existing regulators and infrastructure to facilitate the emigration of native fish species to the Murray River.

1 Introduction

Movement is an important behavioural trait to study in fish. Understanding the triggers causing movement is complex, with a large number of stimuli resulting in a movement response. Some stimuli are easier to attribute to a movement pattern such as breeding migrations, than others such as water chemistry. In environments where hydrology is unpredictable (and in particular, the frequency and duration of flows), fish need to be able to respond rapidly to changes in the aquatic environment to gain maximum benefit, whether for breeding, feeding or dispersal (Balcombe *et al.* 2007).

The frequency and duration of water in many of Australia's creeks and rivers is unpredictable (Puckridge *et al.* 1998). Consequently, native fish have adapted to survive under these conditions and make the most of water when it is available. In these environments, flow plays a crucial role in triggering fish behaviour, in particular movement.

Many native fish species of the Murray–Darling Basin are considered flow-dependent, with flow acting as a significant trigger to movement and determining patterns of movement (Harris & Gehrke 1994; Humphries, King & Koehn 1999; Baumgartner *et al.* 2013). Many studies that have assessed fish movement patterns in the Murray–Darling Basin have been undertaken in large rivers such as the Murray (Stuart & Jones 2006; Jones & Stuart 2007; Koehn *et al.* 2009; Leigh & Zampatti 2013) or Goulburn (Ryan & O'Mahoney 2005; Koster *et al.* 2014) rivers.

While hydrological changes in main river channels have been found to determine patterns of movement for some species, fish movement is of particular importance between main river channels and off-channel habitats, such as wetlands. Off-channel habitats provide a greater opportunity for fast growth and development than those in the main channel, due to their increased productivity (Junk, Bayley & Sparks 1989). Ideally, eggs and larvae enter a wetland and quickly develop and grow before a subsequent inundation allows them to return and disperse in the main river channel. Recent work (Conallin *et al.* 2010; Lyon *et al.* 2010; Ellis & Pyke 2011a; Bogenhuber *et al.* 2012; Ellis, Huntley & Lampard 2014) indicates that changes in hydraulic connectivity (i.e. flow) influence a number of different fish species.

Historically, fish movement has been assessed using netting and mark-recapture studies. While these are useful sampling methods, they can be very broad in time and space (mark-recapture), or very localised and time specific (directional netting). Movement of individual fish is inherently difficult to study, with visual assessment of fish in water difficult at the best of times and near impossible in turbid water (Lucas & Baras 2000), particularly for smaller fish. Advancements in technology have created more refined methods to track fish through physical or autonomous means (Cooke *et al.* 2013). One of the more recent common methods for determining movement of fish involves using acoustic telemetry. Fish are implanted or tagged with a uniquely-coded device that emits soundwaves, which are detected (when in range) and saved by a receiver. This data can be processed to provide a time-series of fish movement, which can then be tested against other known parameters.

While native fish tend to respond and move to changes in flow, non-native species from regions that historically have different environmental conditions may respond differently or not at all. With river systems in Australia as highly regulated as they are, these differences may have management implications for helping to control non-native populations and benefiting native populations. To determine these differences, if any, movements of native and non-native fish need to be studied with reference to various flow conditions.

In Australasia, the Common carp (*Cyprinus carpio*; hereafter referred to as Carp) is regarded as a significant ecological pest (Koehn, Brumley & Gehrke 2000). Carp have become the most abundant large-bodied fish (by biomass) in many of Australia's waterways, including the Murray–Darling Basin (Harris & Gehrke 1997). Studies into the movement of this species in Australia, using acoustic and radio technology, have included broad-scale movement in the Murray and Darling Rivers (see Chapter 2 (Gehrig & Thwaites 2013)) and Glenelg River (Thwaites, Fredberg & Ryan 2014), congregations or hotspots (Crook 2004; Macdonald & Wisniewski 2011) and localised effects of flow (Brookes 2012; Ellis, Huntley & Lampard 2014).

Golden perch are a widespread, flow-dependant species of the Murray–Darling system with high recreational importance. Golden perch movement has been studied extensively in the Murray–Darling Basin using acoustic and radio technology to determine home ranges and interactions with Carp (Crook 2004), movement patterns in relation to timing and environmental factors (Crook *et al.* 2001; Koster *et al.* 2014) and general movement patterns (O'Connor, O'Mahony & O'Mahony 2005).

Broad patterns in the movement of Golden perch and Carp have been determined, and some variation appears to exist in their behaviour. In a wetland environment, it was found that during drawdown or filling, Carp did not attempt to exit (Ellis *et al.* 2015). However, during draining, Carp enter *en-mass* (Jones & Stuart 2009; Conallin *et al.* 2012b). Golden perch tend to enter a wetland as eggs and larvae during high flow or environmental watering. Once they have grown, they will attempt to leave the wetland on subsequent fillings (Ellis & Pyke 2010, 2011a). If these traits hold true under a number of environmental conditions, they may be better used by water managers to improve the control of Carp while not disadvantaging Golden perch.

This study used acoustic telemetry to track Carp throughout the Hattah Lakes system (a large floodplain-lakes system of the Murray–Darling Basin and adjacent Murray River). At a later stage, Golden perch from the system were tagged and tracked. The aim was to initially investigate movement patterns in Carp behaviour relating to the drawdown of water off the floodplain back to the Murray River. During a subsequent filling, both Carp and Golden perch movements were investigated. Comparisons in Carp movement were made between drawdown and filling, as well as between Carp and Golden perch movement during filling. This study is the first to incorporate acoustic telemetry in a large-scale floodplain–lake system in Australia to investigate Carp movement in relation to hydrological changes.

1.1 Study site

The Hattah Lakes are part of the 48 000 hectare Hattah–Kulkyne National Park, which is located in the northwest corner of Victoria, Australia (Figure 1–1). The system comprises 18 semi-permanent freshwater lakes, which receive water from the Murray River via a feeder creek (Chalka Creek). The lakes start to fill when flows in the Murray River reach a critical level and water spills into Chalka Creek. The height and duration of flows in the Murray River determines the number of lakes that receive water.

Increased levels of water abstraction and extended drought conditions have resulted in a reduction in the frequency and duration of flooding in the Murray River (Maheshwari, Walker & McMahon 1995). Consequently, flooding frequency of the Hattah Lakes has declined. A recent works and measures program for the Hattah Lakes was completed to reinstate more frequent flooding to maintain the ecological character of the area (MDBA 2012). The program resulted in the installation of a pumping station, a series of regulators and a number of block banks, which allow 5583 hectares of the Hattah Lakes National Park to be artificially flooded (to an equivalent water level of 45 m Australian Height Datum) (MDBA 2012).

Figure 1–1. Location of Hattah–Kulkyne National Park.

1.2 Hydrology

Water in the Hattah Lakes has been managed with water additions via pumping since 2006. During the summer of 2010–11, natural flooding resulted in the inundation of the Hattah Lakes. The lakes were left to dry over the following years. Only a small residual pool remained in Lake Mournpall by October 2013, when a total of 61 GL of water was pumped into the system between October 2013 and January 2014. In autumn and winter 2014, a further 91.97 GL of water was pumped into the Hattah Lakes, filling them to maximum capacity. On 15 September 2014 shortly following the filling, water was released back to the Murray River via both the north and south branches of Chalka Creek. The regulators remained open, and by February 2015, water levels in the Hattah Lakes had fallen below the Chalka Creek sill level resulting in the cessation of flow back to the Murray River. By May 2015, many of the creeks and lakes had become disconnected. By August 2015, Lake Lockie and Lake Little Hattah were predominantly dry.

During August and September 2015, small inflows occurred (pump tests), which partially inundated Lake Lockie and caused a shallow connection between Lake Lockie and Little Hattah Lake and Lake Yerang. The same inflows resulted in the connection of pools that had formed in Chalka Creek during drawdown. A total of 4.178 GL of water was pumped into the Hattah Lakes from 12–23 October 2015. Water from this pumping made it as far as Lake Mournpall to the north and Lake Bulla to the south. Shortly following filling, Messengers Regulator was opened on 10 November 2015, discharging water back to the Murray River for 9 days before the regulator was closed.

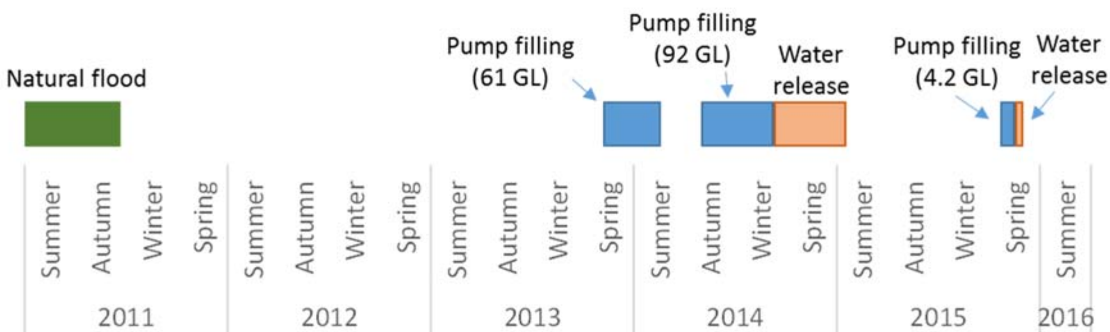


Figure 1–2. Hydrology timeline for filling and water releases to and from the Hattah Lakes since natural flooding in 2010–11.

2 Project objectives

The main objectives of this project were to:

1. assess the fish populations currently in the lake system, with emphasis on the lakes most likely to connect to Chalka Creek during this event and pools in Chalka Creek
2. determine the directional movement of fish between the lakes (Lakes Lockie) and Messengers Regulator and if aggregation occurs near the pump outflow
3. capture and tag Golden perch, Murray cod and Carp with acoustic tags prior to pumping. Analyse movement responses of tagged Carp already in the Hattah Lakes and the movement of newly tagged fish using acoustic receivers in response to flow created by the pumping.

3 Pre-pumping surveys September–October 2015

3.1 Method

Prior to pumping water into the Hattah Lakes in October 2015, a fish survey of residual pools within Chalka Creek and the lakes likely to be influenced by pumped water, was undertaken to assess the resident fish community. Pre-pumping surveys were undertaken from 30 September to 7 October 2015. Sampling locations comprised of two sites in southern Chalka Creek (east and west ends), three sites in Lakes Yerang and Lockie, two sites in Lake Hattah and a single site in Lake Little Hattah (Figure 3–1). During sampling, water levels in Lakes Lockie, Yerang and Little Hattah were low. Thus, only a single site in Lake Little Hattah was able to be sampled. Lake Hattah is larger and deeper and is connected to Lake Little Hattah. Two sites in Lake Hattah were sampled.

At each lake site, two coarse mesh fyke nets and two small mesh fyke nets were deployed overnight for a single night. For each site in Chalka Creek, four small mesh fyke nets and four coarse mesh fyke nets were deployed overnight for two consecutive nights.

Coarse mesh fyke nets have a single wing (8 m x 0.65 m) attached to the first supporting hoop (Ø = 0.55 m) with a 32 cm stretched entry. Each coarse mesh fyke net has a stretched mesh size of 28 mm. Small mesh fyke nets have dual wings (each 2.5 m x 1.2 m), with a first supporting hoop (∅ = 0.4 m) fitted with a square entry (0.15 m x 0.15 m) covered by a plastic grid with rigid square openings (0.05 m x 0.05 m). Small mesh fyke nets have a stretched mesh size of 2 mm.

All fish captured were identified to species and enumerated. The first 30 fish of each species, at each site, per gear type (for each of fine mesh and coarse mesh fyke nets), were measured. Standard length only was measured for small-bodied species, whereas standard length, fork/total length and mass were assessed for large-bodied species. All fish were returned to the water at their point of capture, including non-native species, so as not to affect results obtained during directional surveys.

All fish sampling was undertaken in accordance with appropriate La Trobe University animal ethics approval (AEC-13-27) and Victorian fisheries permits RP1014 and NP123.

Figure 3–1. Location of sampling sites in the Hattah Lakes and Chalka Creek.

3.2 Results

The fish community of the Hattah Lakes and Chalka Creek was represented by 11 species (7 native, 4 non-native) prior to spring pumping. The most numerically abundant species was the Carp gudgeon, followed by the Australian smelt (Table 1). Catches of fish from all locations were relatively similar in terms of species and abundance.

The most abundant non-native species was the Eastern mosquitofish, while the most abundant large bodied non-native species was the Carp. No adult Carp were recorded, with all Carp detected in Lake Lockie as young-of-year (standard length 8–22 mm). Nine Golden perch and a single Murray cod were sampled.

Table 1. Raw abundance of fish from Chalka Creek and Lakes Hattah, Little Hattah, Lockie and Yerang sampled prior to pumping.

	Species Name	Chalka Creek	Lake Hattah	Lake Little Hattah	Lake Lockie	Lake Yerang
Native	Australian smelt	2261	322	214	177	658
	Carp gudgeon	7408	1470	2850	1552	8696
	Dwarf flathead gudgeon	2	5	5	2	11
	Flathead gudgeon	5	3	1		2
	Golden perch	8				1
	Murray cod	1				
	Un-specked hardyhead					4
Non-native	Common carp	7			20	
	Eastern mosquitofish	15		16	9	10
	Goldfish	5		1	1	
	Oriental weatherloach	3	3	6	4	4

3.3 Discussion

With the exception of Dwarf flathead gudgeon, all species detected during this survey have been recorded from the Hattah Lakes previously (Table 2). Dwarf flathead gudgeon are regarded as being patchily distributed (Lintermans 2007) and have previously been recorded in the Murray River adjacent to the Hattah Lakes. Species not captured during this survey, Silver perch, Spangled perch and Murray–Darling rainbowfish have also been previously recorded in the Hattah Lakes; however, these occurrences have been highly variable though space and time. Bony herring was also not identified during this survey, but has previously been a common species captured from the Hattah Lakes.

Table 2. List of species previously caught from the Hattah Lakes (Henderson *et al.* 2014) in relation to the species caught during the pre-pumping survey (September–October 2015) in this study.

	Common name	Species name	Oct 2015
Native	Australian smelt	*Retropinna semoni*	✓
	Bony herring	*Nematalosa erebi*	
	Carp gudgeon	*Hypseleotris* spp.	✓
	Dwarf flathead gudgeon	*Philypnodon macrostomus*	✓ *
	Flathead gudgeon	*Philypnodon grandiceps*	✓
	Golden perch	*Macquaria ambigua*	✓
	Murray cod	*Maccullochella peelii peelii*	✓
	Murray–Darling rainbowfish	*Melanotaenia fluviatilis*	
	Silver perch	*Bidyanus bidyanus*	
	Spangled perch	*Leiopotherapon unicolor*	
	Un-specked hardyhead	*Craterocephalus stercusmuscarum fulvus*	✓
Non-Native	Common carp	*Cyprinus carpio*	✓
	Eastern mosquitofish	*Gambusia holbrooki*	✓
	Goldfish	*Carassius auratus*	✓
	Oriental weatherloach	*Misgurnus anguillicaudatus*	✓

*Species recorded for the first time in the Hattah Lakes

Carp gudgeon and Australian smelt are common species in the Murray–Darling Basin. Previous fish surveys at the Hattah Lakes have detected them, at times, in comparatively high abundances (Henderson *et al.* 2014). The Oriental weatherloach, a non-native species, is a relatively new migrant to the Hattah Lakes, first discovered in 2011. It is thought that this species' invasion west and south was strongly influenced by floodwaters in 2010–11, increasing its rate of dispersal (Fredberg, Thwaites & Earl 2014).

Non-native fish species have previously been highly abundant in residual pools that form as the Hattah Lakes drawdown (Henderson *et al.* 2013). It does not appear that non-native species (particularly Eastern mosquitofish and Carp) dominated the fish community during the most recent drawdown in this study. This may be an artefact of filling, whereby pumped inundation leads to lower occurrences of non-native species than flooding (Vilizzi *et al.* 2013).

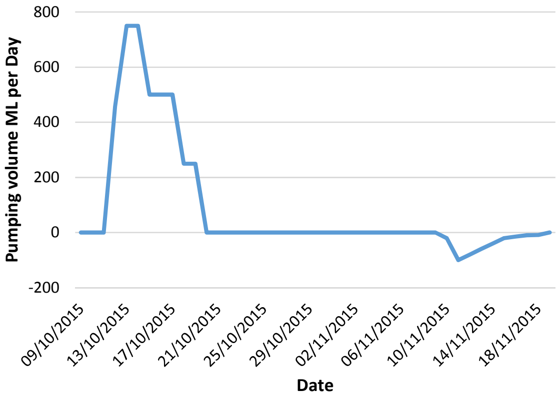
4 Directional fish surveys during pumping October 2015

4.1 Method

During October 2015 water was delivered to Hattah Lakes via pumping from the Murray River into Chalka Creek using the permanent pumping station located at Messengers Crossing. Pumping commenced on 12 October 2015 and continued until 23 October 2015, at which time a total of 4.178 GL had been delivered (Figure 4–1). During pumping, fish netting was undertaken in Chalka Creek to determine fish movement toward the inflowing water.

At two sites within Chalka Creek (Figure 3–1), a single dual wing coarse mesh fyke net was deployed spanning the creek channel to sample large-bodied fish moving toward the water entering the Hattah Lakes. Four small mesh fyke nets were also deployed at each site such that they would catch fish moving toward the flow (Figure 4–2). Nets were deployed at both sites from the beginning of the pumping event and left permanently at the site for the duration of the flow (excluding the weekend period, Friday 16 October to Monday 19 October). Nets were checked, cleared and the catch emptied during each day of deployment.

Fish identification and enumeration was undertaken as for the pre-pumping surveys (see section 3.1). All fish were returned to the water on the upstream side of the directional nets to allow them to complete their journey without confounding later directional capture results.



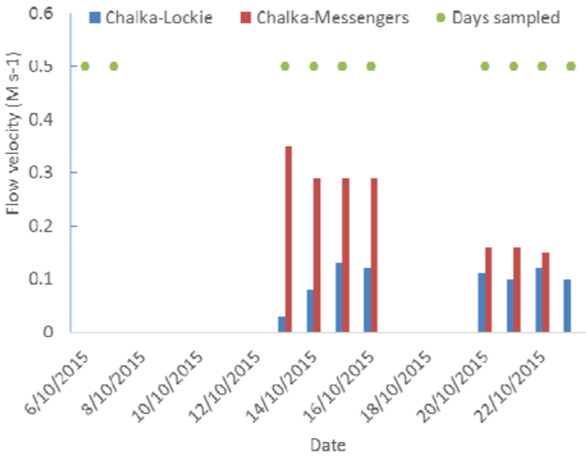


Figure 4–1. Hydrograph of pumped water to the Hattah Lakes (left) (negative values represent the return of water to the Murray River). Mid-channel flow velocity measured at two sites in Chalka Creek during filling and drawdown events (right).

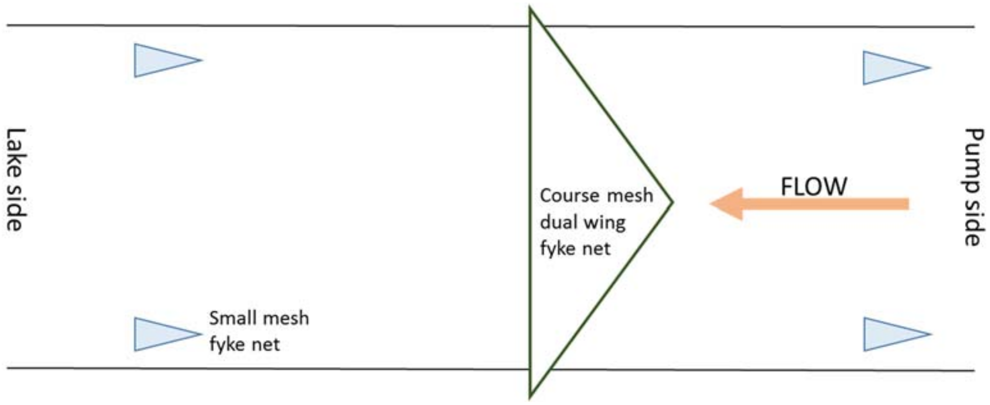


Figure 4–2. Configuration of nets (including net direction) at the two sites in Chalka Creek for undertaking the directional fish surveys during pumping.

4.1.1 Analysis

Where applicable, fish catch data was standardised by calculating catch per unit effort (CPUE) for each net type (small and coarse mesh fyke nets), during both pre-pumping and pump surveys. The abundance of each species, for each net, was divided by the net soak time and multiplied by 24 to calculate catch per net per 24 hours. The average CPUE and standard errors for each net type for pre-pumping and pump surveys were then determined.

Size structure for species that were highly abundant or of particular interest was undertaken by plotting length-frequency distributions. Lengths of small-bodied species were categorised into 5 mm classes while large-bodied species were categorised into 25 mm classes.

The dual wing coarse mesh fyke nets were set singly, at each site, as they broadly cover the whole channel and sample all large-bodied fish movement past the site. This meant that there was no daily replication at the site level for fish sampled only in the dual wing fyke nets. Analytically, replication was possible by combining days at the ‘weekly’ level. Sampling with dual wing coarse mesh fyke nets occurred in the week prior to and 2 weeks after the flows commenced in Chalka Creek. We analysed CPUE for each species from dual wing fyke nets with General Linear Models (GLMs), which provide relatively statistically robust analyses for unbalanced designs.

The small mesh fyke nets were replicated at each site on each day to ensure that it was possible to investigate how CPUE varied throughout the study by time (sample-dates) at each site, for species captured in this gear. The design was balanced, allowing for a multiple analysis of variance (MANOVA) to be undertaken.

Large-bodied fish

The CPUE for each large-bodied fish species caught in the dual wing fyke nets was used as the response variable (Y). For each species, a GLM was run of Y on three fixed factors for Site (two levels, east and west), Hydrology (two levels, pre-and post-flow) and Time (three levels, week 1 before flow, and weeks 2 and 3 after flow had commenced) (R Development Core Team 2013). For count data such as this, the GLM used a Poisson error distribution with a logit-link function to stabilise the error-variance. The full model was examined and if necessary the error distribution was changed to *quasipoisson* to correct for over dispersion. Bony herring and Murray cod were excluded from this analysis due to there being insufficient data for these species. The full model was reduced to remove non-significant interactions and main effects to leave a model that gave the most parsimonious description of the data, i.e., the model that provided an adequate description of the data with the fewest terms. The model was reduced using a simplification process to run sequential Chi-squared comparison tests on nested-pairs of models, with-and-without non-significant interaction terms and non-significant main-effects that did not appear in any remaining significant interactions (Crawley 2013).

Small-bodied fish

The CPUE data for each species caught in small fyke nets was used as the response variable (Y). For each species, we ran a GLM of Y on fixed factors for Site (two levels for sites east and west), Hydrology (two levels for pre- and post-flow commencement) and Time (ten levels for each of the sampling days) as explanatory variables (R Development Core Team 2013). Model simplification was used to produce the most parsimonious model for each species.

4.2 Results

Large-bodied fish

Carp, Goldfish and Golden perch were the most common large-bodied fish species during this survey (Figure 4–3). All three species were caught during both pre-pumping (still water) and pumping (water entering the Hattah Lakes) surveys. Additionally, a single Bony herring and two Murray cod were caught during pumping surveys.

Overall, more Golden perch were caught at the Messengers Crossing end of the creek ($P<0.001$). Following the start of the pumping, it appeared that Golden perch were not attracted to the water entering the Hattah Lakes. However, in the third week, one week after the initiation of the flow, there did appear to be a response with an increase in the number of fish caught and most of these were at the Messengers Crossing end of Chalka Creek ($P<0.001$) (Table 3) (Figure 4–3, upper panel). However, the pattern of change in CPUE at each site did not change significantly over time (i.e. the interaction Site×Week was not significant). This means that we cannot statistically attribute the increase in CPUE at the Messengers Crossing end of the Creek with any change that occurred over time, such as the increased flow.

Table 3. General Linear Model Deviance table for Golden perch CPUE from dual wing fyke nets in Chalka Creek (see Figure 4–3) for two sites, Chalka–Lockie and Chalka–Messengers, over three weeks of sampling.

	DF	Deviance residual	DF residual	Deviance	P-value	
Null			19	87.0		
Site	1	29.4	18	57.6	<0.001	***
Week	2	37.8	16	19.8	<0.001	***

Golden perch captured during pumping (in flowing water) tended to be larger (>300 mm standard length) than fish caught during still-water conditions (Figure 4–4).

Carp did not appear to have been influenced strongly by the pumping, with similar numbers of fish caught across all surveys, regardless of hydrology or site (Table 4) (Figure 4–3 middle panel). However, the pattern of CPUE of Carp at a site may have been related to hydrology, with slightly more on average being caught pre-flow at the Messengers Crossing end of the creek and more after flow commenced at the Lake Lockie end ($P=0.002$).

Table 4. General Linear Model Deviance table for Carp CPUE from dual wing fyke nets in Chalka Creek (see Figure 4–3) for two sites, Chalka–Lockie and Chalka–Messengers, at two levels of hydrology (pre-flow and during flow).

	DF	Deviance residual	DF residual	Deviance	P-value	
Null			19	33.71		
Site	1	1.99	18	31.72	0.17	
Hydrology	1	0.92	17	30.81	0.36	
Site×Hydrology	1	10.71	16	20.10	0.002	**

There was no difference in Carp size between those caught pre-flow and during the flow (Figure 4–4).

Goldfish were more commonly caught at the Lake Lockie end of the creek (P=0.001) and may have been slightly influenced by pumping, with more fish moving after the flow commenced, although the results suggest that the statistical significance of this was marginal (P=0.078) (Table 5) (Figure 4–3, lower panel).

Table 5. General Linear Model Deviance table for Goldfish CPUE from dual wing fyke nets in Chalka Creek (see Figure 4–3) for two sites, Chalka–Lockie and Chalka–Messengers, at two levels of hydrology (pre-flow and during flow).

	DF	Deviance residual	DF residual	Deviance	P-value	
Null			19	123.38		
Site	1	56.44	18	66.94	0.001	**
Hydrology	1	16.50	17	50.43	0.078	.

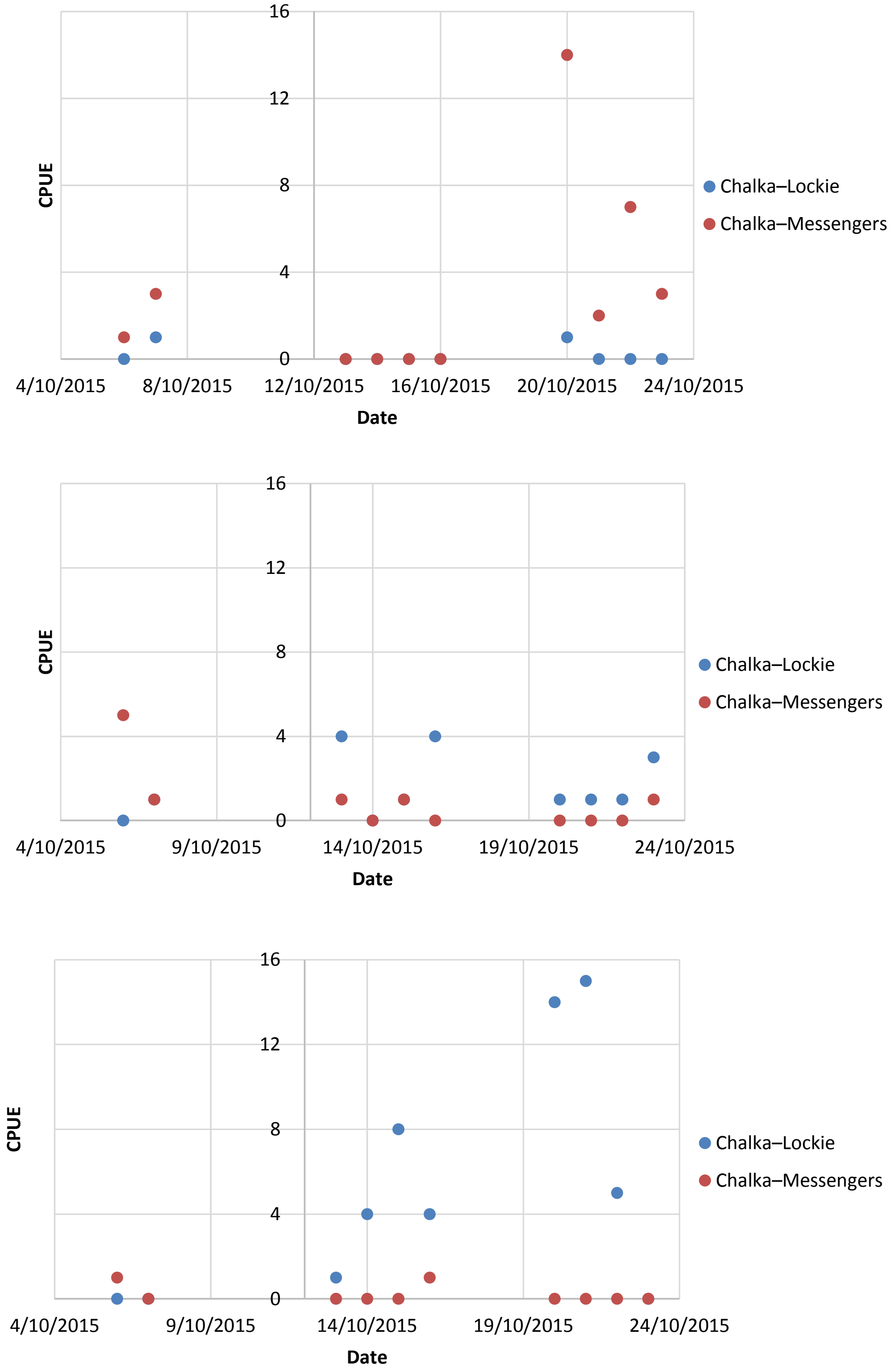


Figure 4–3. Catch per unit effort (per net 24 h) of Golden perch (top), Carp (middle) and Goldfish (bottom) caught by dual wing coarse mesh fyke net in Chalka Creek for the pumping and pre-pumping surveys. Vertical axis crosses at the time when pumping commenced.

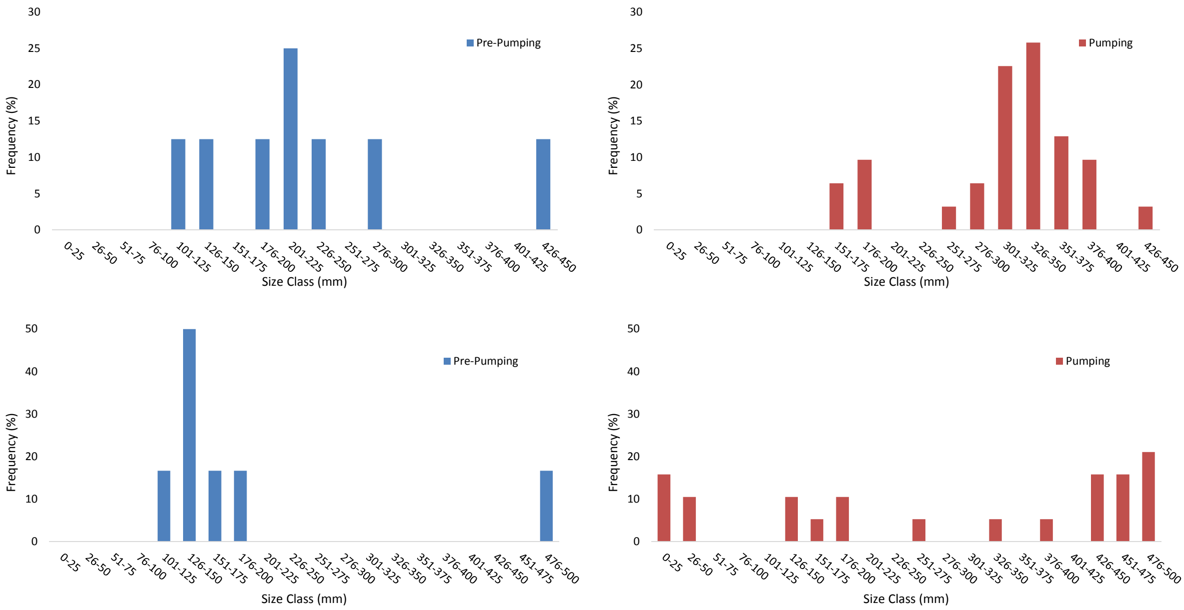


Figure 4–4. Length frequency (as a percentage) of Golden perch (top) and Carp (bottom) in Chalka Creek for the pre-pumping (left) and pumping (right) surveys (all net types).

Small-bodied fish

Carp gudgeon were the most common species encountered during all surveys. The pattern of changing catches at each site over time suggested that there may have been a preference to move towards the water entering the lakes (i.e. upstream) (P=0.045, Table 6). This was most apparent for fish exiting the lakes to enter Chalka Creek (compared with at the Messengers end of Chalka Creek) after an initial delay in their response of approximately 1 week (Figure 4–5).

Oriental weatherloach catches were highly variable on a day-to-day basis, and more common (P<0.001) at the Messengers Creek end of Chalka Creek where catches responded quickly (within two days) (P<0.001) to water entering the Hattah Lakes (Figure 4–5). The overall pattern of catches over time depended upon the site sampled, suggesting that there was movement of fish upstream into the site at the Messengers end of Chalka Creek (P=0.008).

Australian smelt were the second most common species encountered (Figure 4–5). They were more commonly caught during pre-pumping surveys (P<0.001, Table 6), than during pumping surveys despite high variability (Figure 4–5). More Australian smelt were caught pre-flow at the Lockie end of Chalka Creek than during-flow (P<0.001, Table 6), and they were also scarce at the Messengers Crossing end of the creek. It is possible that flow dispersed them into Lake Lockie.

For Flathead gudgeon, only Site explained any significant differences in the CPUE data, with higher numbers caught at the Lake Lockie end of Chalka Creek (P<0.001) (Figure 4–6). Dwarf flathead gudgeon showed a similar pattern of abundance between Sites (P<0.001) and Times (P<0.001), but the higher catches later during the flow period did not depend upon site sampled.

Catches of Eastern mosquitofish only varied significantly by Site, being more abundant at the Lockie end of Chalka Creek (P<0.001) (Figure 4–6).

Two Un-specked hardyhead were caught during the pumping surveys.

Table 6. General Linear Model Deviance tables for the CPUE results of the most abundant small-bodied fish from small fyke nets in Chalka Creek (see Figure 4–5 & Figure 4–6) for two Sites, Chalka–Lockie and Chalka–Messengers at two levels of Hydrology (pre-flow and during flow), over 10 levels of Time (in days). Non-significant terms have only been shown if they make a significant contribution to the most parsimonious model.

Species	Model component	Df	Deviance	Residual DF	Residual Dev	Pr(>χ^2)	
Carp gudgeons	NULL	82	93985				
	Site	1	34913	81	59072	<0.001	***
	Time	9	13940	72	45132	0.002	**
	Site:Time	9	9107	63	36025	0.045	*
Australian smelt	NULL	82	13605.9				
	Site	1	1491.5	81	12114.4	<0.001	***
	Hydrology	1	4744.2	80	7370.2	<0.001	***
Oriental weatherloach	NULL	82	339.6				
	Site	1	60.669	81	278.93	<0.001	***
	Time	9	157.113	72	121.82	<0.001	***
	Site:Time	9	28.317	63	93.5	0.008	**
Flathead gudgeon	NULL	82	147.97				
	Site	1	42.56	81	105.41	<0.001	***
Dwarf flathead gudgeon	NULL	82	141.828				
	Site	1	32.649	81	109.178	<0.001	***
	Time	9	44.825	72	64.353	<0.001	***
	Site:Time	9	4.834	63	59.52	0.819	
Eastern mosquitofish	NULL	82	180.64				
	Site	1	38.253	81	142.38	<0.001	***

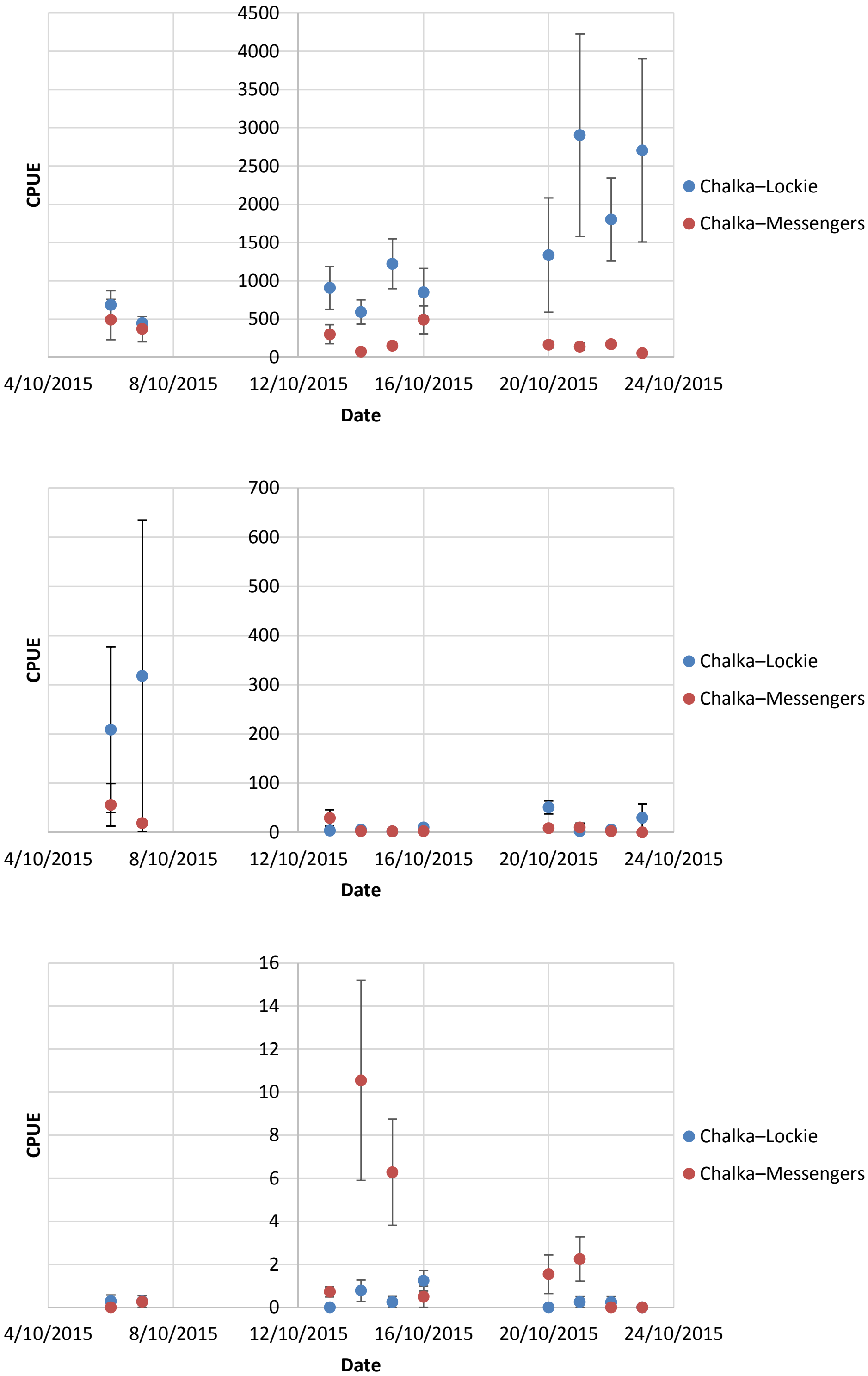


Figure 4–5. Catch per unit effort (per net 24h) of Carp gudgeon (top), Australian smelt (middle) and Oriental weatherloach (bottom) caught by small mesh fyke nets in Chalka Creek for the pre-pumping and pumping surveys. Error bars represent standard errors. Vertical axis crosses at the time when pumping commenced.

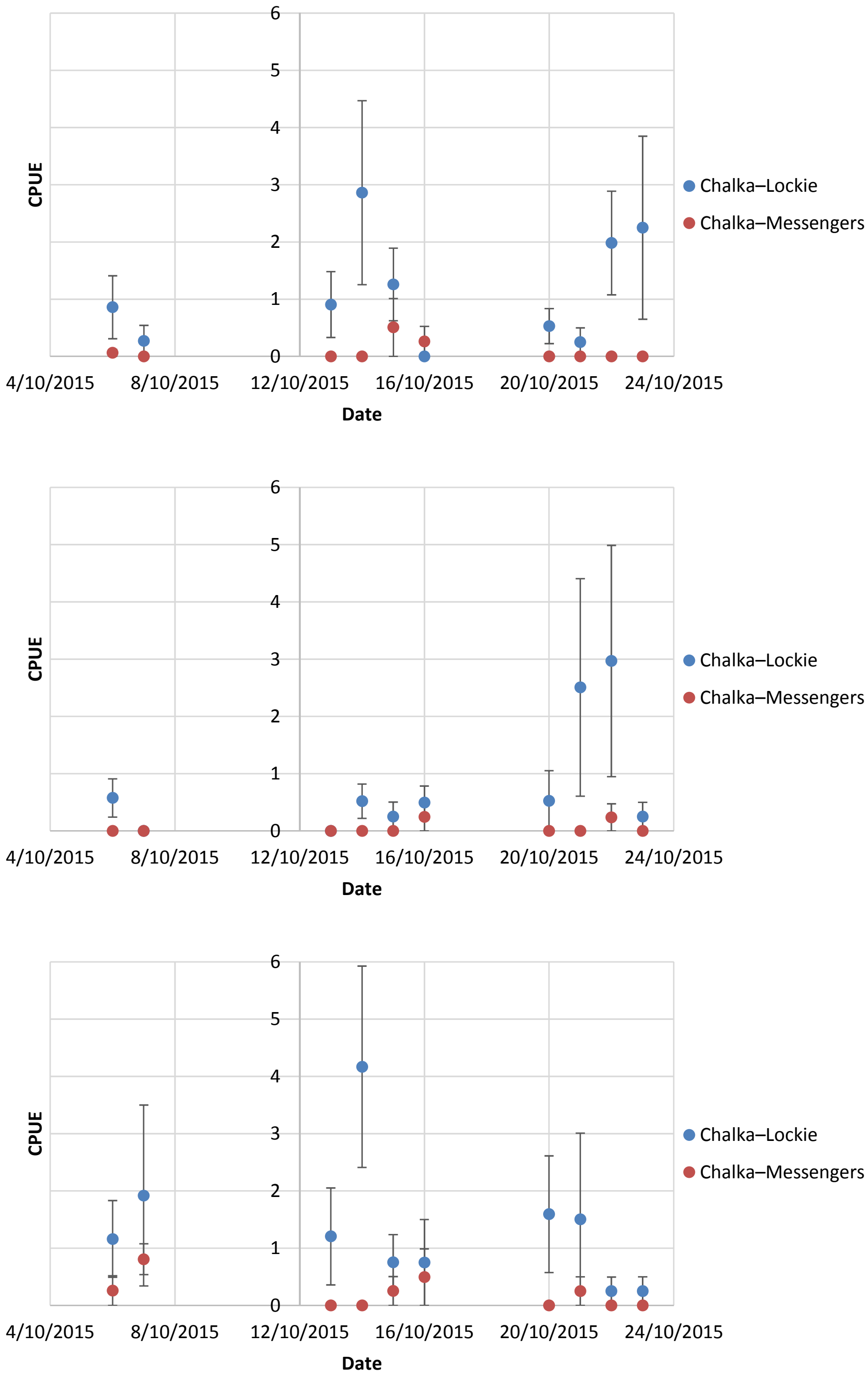


Figure 4–6. Catch per unit effort (per net 24h) of Flathead gudgeon (top), Dwarf-Flathead gudgeon (middle) and Eastern mosquitofish (bottom) caught by small mesh fyke nets in Chalka Creek for the pumping and pre-pumping surveys. Error bars represent standard errors. Vertical axis crosses at the time when pumping commenced.

4.3 Discussion

Previous surveys of the Hattah Lakes, undertaken during pumping in 2013 and 2014, sampled large numbers of Golden perch and Murray cod as eggs and larvae being pumped into the Lakes (Brown *et al.* 2015). The presence of both species in this survey is encouraging and demonstrates that the Hattah Lakes provide habitat to support these species. However, it has been demonstrated elsewhere (Ellis & Pyke 2011a, b) that if Golden perch, in particular, grow into sub-adults in an off-channel habitat, they tend to return to the main river channel (the Murray River in the case of the Hattah Lakes) if given the opportunity. The response is similar regardless of the method of water delivery — whether it be flow through a natural channel or pumped water.

As found in other studies, Golden perch were attracted toward the inflowing water; however, the peak of movement along Chalka Creek was delayed by around a week. The majority of Golden perch were caught at Messengers end of Chalka Creek (closest to the Murray River), indicating moderate numbers of Golden perch attempting to exit the lakes. Due to unknown survival rates, the population size of Golden perch in the Hattah lakes at the start of the present study cannot be determined. Even given the appropriate flow-stimulus to emigrate, the numbers of fish available to emigrate may be low. Perhaps as a consequence of the closest lakes (Lakes Lockie, Yerang and Little Hattah) being relatively shallow in October 2015, holding very little water and thus not supporting a large population of adult fish. Chalka Creek maintained deeper pools containing large-woody debris, presumably providing better habitat for larger fish to reside in. Thus, these habitats may have been the source for the majority of Golden perch caught during pumping. When the netting data is combined with data collected on Golden perch from acoustic movement studies in the same location (discussed in section 5.2.2), Golden perch behaviour more closely holds true to the expected response of fish showing a strong preference to move towards the source of inflows and leave the off-channel habitat.

There was no indication from the directional netting data that Carp were influenced to move upstream by water entering the Hattah Lakes from the Murray River. This pattern is consistent with findings from some other studies on wetland hydrology and Carp movement (Conallin *et al.* 2010; Ellis, Huntley & Lampard 2014) (section 5.2.2). However, other studies indicate that strong movement behaviour can be shown by Carp at hydrological management infrastructures, such as fishways (Cooper 1990; Baumgartner *et al.* 2014) and wetland regulators (Thwaites *et al.* 2010; Conallin *et al.* 2012a) — *we discuss this apparent contradiction further in section 5.3.*

Oriental weatherloach has been studied extensively across its native range; however, this species is relatively new to Australia (c. 1980's) and very little is known about its impact on Australian ecosystems (Lintermans & Burchmore 1996). This study shows a preference for this species to rapidly respond to water entering a wetland system by moving toward the inflowing water. It is uncertain as to whether a similar response has been recorded elsewhere in Australia, or indeed if this is a common response. As Oriental weatherloach become more common in Australian waterways, more targeted research into this species is needed to determine particular behaviours in Australian systems, such as that displayed at the Hattah Lakes, which may be exploited to assist with control measures.

Small-bodied fish species tend to move with water as it enters or leaves a wetland (Lyon *et al.* 2010; Ellis & Pyke 2011b; Ellis, Huntley & Lampard 2014). Movement depends on flow rate; the higher the flow the higher the abundance of fish moving, although this may be confounded by swimming ability. The low flow velocities generated along Chalka Creek provided Carp gudgeon with the opportunity to move toward the flow in greater numbers (compared with during periods of still water). Again, this suggests that there may be a low-velocity threshold that enables active movement of some small-bodied species upstream against the flow.

One of the differences between the current study and others looking at the influence of hydrology on fish behaviour is the size of the system. Previous studies have looked at a single, small to medium sized wetland (Lyon *et al.* 2010; Ellis & Pyke 2011a). The Hattah system is very large in comparison, and includes up to 18 interconnected wetlands. As the water moves thought the system, its presence may not be felt for many days after the water initially entered the system. Also, many of the connecting channels may take time to reach a depth capable of supporting the movement of fish, particularly for larger individuals. Consequently, a delay of days and even weeks, in fish response to the water could be expected.

The length of pumping (12 days) and the volume of water delivered to the system during October 2015 had a limited area of influence, and thus fish response. Water only travelled as far as Mournpall to the north and Lake Bulla to the south. Sufficient channel depth for fish passage between lakes may not have been reached by the end of the pumping (and sampling period). It is believed that the area of influence during this study would have primarily been Chalka Creek, and Lake Lockie. This is reflected in the results with the majority of larger fish (i.e. Golden perch) being caught close to Messenger Crossing (likely originating from Chalka Creek), while a greater number of smaller species (e.g. Goldfish and Carp gudgeon) were caught in Chalka Creek closer to the lakes.

5 Acoustic Tracking

5.1 Method

Coarse mesh fyke nets (single wing 8 m x 0.65 m attached to the first supporting hoop Ø = 0.55 m and a stretched mesh size of 28 mm) were used to sample fish of suitable size to acoustic tag in the Hattah Lakes.

All acoustic transmitters (or 'tags') used for this project were manufactured by VEMCO (Bedford, Nova Scotia, Canada). Two transmitter sizes were selected for 2014; V9-2X (9 X 29 mm) and V13-1X (13 X 36 mm) resulting in battery lives of approximately 913 days and 1805 days, respectively. Only V9 tags were used during 2015. Both models operate at a frequency of 69 kHz and were set to low power, based on a range-finding experiment by Linklater and Ellis (2013). A nominal ping delay of 150 seconds (variation 120–180 seconds) was selected for this project, based on advice from the manufacturer. Ideally tag weight should be kept to less than 2% of the fish's body weight (Heupel *et al.* 2006). Therefore, only fish heavier than 235 g were tagged with the V9 (4.7 g) and fish heavier than 550 g were tagged with the V13 (11 g).

Surgery for acoustic tag insertion was undertaken using a modified method proposed by Leigh and Zampatti (2013). Fish ready for surgery were sedated (Carp; 0.11 ml L^{-1} Aqui-S, Golden perch; 0.05 ml L^{-1} Aqui-S) and the appropriately sized acoustic tag was inserted into the peritoneal cavity. The incision was closed and the fish placed in a recovery tub before being released.

Thirty acoustic receivers (VR2W 69 kHz, VEMCO; Bedford, Nova Scotia, Canada), forming an array, were strategically deployed throughout the Hattah Lakes and in the adjacent Murray River. Receiver locations were selected to maximise the detection of fish moving between key points in the lakes, connecting flood runners and Chalka Creek. Receivers were also placed in the Murray River, both upstream and downstream of each of the northern and southern confluences of Chalka Creek. During 2015, receivers no longer underwater were relocated to the southern end of Chalka Creek to detect finer scale movements by tagged fish during the pumped filling period.

Receiver arrays at Hattah can be considered as a network of connected, one-dimensional routes along which fish can travel either 'forwards' or 'backwards' from their release location. The acoustic receivers are locations in these networks where a fish's presence is logged against time. In reality fish movement is likely to be at least two-dimensional, with lateral movements in between receivers. Detections at neighbouring receivers, of known linear distances apart, mark the minimum distance moved over time and therefore the potential minimum speed of travel.

All downloaded data from acoustic receivers was managed by product-specific software VUE (VEMCO; Bedford, Nova Scotia, Canada). Fish movement was visualised using Eonfusion software (Myriax; Hobart, Tasmania, Australia) and movement models developed using this software were used to characterise and quantify individual fish movements for further analysis.

A 10 day 'settling period' post-surgery after the last fish release (23 October 2014) was implemented to allow recovery from any stress associated with capture, surgery and handling. Data collected during this period was not included in the analysis presented in this report. Data analysis spanned from 3 November 2014 to 15 December 2014, at which point many of the lakes and connecting channels became too shallow for fish passage. For this period, 33 Carp were identified in the receiver array. Of these, 20 Carp provided sufficient data for analysis. That is, they were observed on at least five receivers.

The second analysis period occurred during the pumped filling into the southern arm of Chalka Creek during spring 2015. Prior to this, 5 Golden perch and a single Murray cod were acoustic tagged and released, with a 5 day settling period to allow from the fish to recover from surgery. This period spanned from 12 October 2015 to 23 October 2015. During this period, one Murray Cod, four Golden perch and 20 Carp were active within the receiver array. Of these, three Golden perch and 16 Carp provided sufficient data for analysis. That is they were observed on at least five receivers (compromised due to small sample-size to four receivers for Golden perch, to enable data from a third fish to be analysed).

5.1.1 Analysis

The curve described by an animal when it moves is its trajectory. Trajectory analysis is often employed following animal movement studies where the observations of location are made via direct observation or using a GPS transmitter attached to the study animal. GPS-telemetry allows an animal's position to be recorded at discrete, often regular, intervals of time whilst moving in three-dimensional space (e.g. longitude, latitude and elevation) (Millspaugh *et al.* 2012). In contrast, acoustic telemetry data from fish (of the type recorded in many, including the present study) occurs typically at discrete locations where the receivers are deployed and at irregular intervals of time (Cooke *et al.* 2013) and often only in two dimensions. For acoustic telemetry data, the time series of locations in between receivers is unknown. For individual fish we estimated the time and location in between receivers based on the assumptions that (1) there was a linear relationship between speed and distance in between receivers (i.e. constant speed), and (2) fish movement between receivers follows a track defined by following the thalweg of creeks and channels between lakes and the shortest straight-line distance across lakes. This predicted track was sampled at discrete regular time-intervals (hourly) to generate a Type II, regular trajectory (Calenge, Dray & Royer-Carenzi 2009).

We consider the array of acoustic receivers deployed around the Hattah Lakes as nodes in a network of linear 'tracks', and that movement of fish around this network can therefore be simplified as one-dimensional for questions and hypotheses at the scale of interest (i.e., is the fish moving towards or away from the river). Each node is given an index such that during the wetland drawdown phase of interest, movement towards the Murray River results in successive index values increasing; and movement away from the Murray River results in successive index values decreasing. At any given time a fish can either be moving towards the river, away from the river, or remaining stationary within this network.

We use the concept of null models to analyse the observed trajectories of fish tagged with acoustic transmitters and test hypotheses about behavioural processes that may have generated these trajectories. A null model can be defined as *'a pattern generating model that is based on randomisation of ecological data or random sampling from a known or imagined distribution. The null model is designed with respect to some ecological or evolutionary process of interest. Certain elements of the data are held constant and others are allowed to vary stochastically to create new assemblage patterns. The randomisation is designed to produce a pattern that would be expected in the absence of a particular ecological mechanism'* (Gotelli & Graves 1996).

Our null models were a series of 'random-walk' models created in Microsoft Excel that simulated an individual fish position at hourly time-steps, given four parameters for movement rates, and movement persistence:

Z probability of staying stationary (stay, go)

D probability of direction (forward, backward)

S probability that movement direction in time step *i* remains the same as in time step *i*-1

Fish speed (V) was drawn with equal probability from a distribution of observed fish-speeds (km h^{-1}) between adjacent pairs of acoustic receivers and was species-specific (Carp, n=540; Golden perch, n=255). Distance moved is a product of speed and direction. Three null-model types were developed with increasing complexity from simple random diffusion (model 1); then random diffusion including directional persistence (model 2) to diffusion with directional persistence and a potential directional bias (model 3).

Model 1: $D=0.5$, $Z \geq 0$, $S=0$ An uncorrelated unbiased random-walk in one dimension (i.e. simple diffusion). At each time step, the fish has a randomly selected probability of staying stationary; if it moves, its direction has an equal probability of being +ve or -ve.

Model 2: $D=0.5$, $Z \geq 0$, $S \geq 0$ A correlated, unbiased random-walk in one dimension (i.e. movement with persistence). Behaviour at time step T can be correlated with movement at time step T-1. Based on model 1, but with persistence as a probability, randomly selected from a uniform distribution. Therefore the simulation either persists with, or switches direction at each time step.

Model 3: $D \neq 0.5$, $Z \geq 0$, $S \geq 0$ A correlated, biased random-walk in one dimension. Based on models 1 and 2 above with an unequal probability of moving forwards or backwards tending to produce net movement in one direction.

Suitability of each type of model (e.g. simple diffusion, unbiased direction with persistence, or biased direction with persistence) as a descriptor of Carp movement during wetland drawdown was assessed based on matching individual fish movement patterns to models 1, 2 or 3. The hypothesis of interest concerns whether acoustically tagged Carp move back towards the Murray River during wetland drawdown (i.e. with the flow). If so, then observations should best fit Model 3 with $D>0.5$ (note: Model 3 with $D<0.5$ would equal movement bias away from the Murray River). The strength (%) of this directional bias may be assessed using the parameter for direction, D as $[(D-.5)/0.5]*100$.

If tagged fish showed random or undirected movement with respect to their distance from the Murray River, then Model 1 or 2 would adequately describe the observed data.

The time series of locations for each tagged fish that was evaluated (i.e. distance moved relative to their release point) was compared to simulated locations using all three random-walk models. For each model the parameters for movement rates (D), waiting rates (Z) and persistence (S) were estimated by minimising the least-squares sum of the residuals using non-linear optimisation routines provided by the excel 'add-ins' *Solver* and *Poptools* (Hood 2011). The best parameter set was then used to run a Monte-Carlo simulation (MCS) (1000 iterations) to produce distributions of estimated positions (i.e. distance from release in either direction) for that fish. During the 2014 drawdown, Carp trajectories were analysed for up to 42 days; during the shorter 2015 wetland-fill, Carp and Golden perch trajectories were analysed for up to 10 days. To determine if the observed movement could be explained by one of the types of model above; for each daily observed location, MCS was used to construct an approximate statistical probability (P-value) based on the location of the observed position within the distribution of MCS results for fish position. P-values ≥ 0.05 indicated a statistical fit between the movement model and the observed movement by that date.

5.2 Results

5.2.1 Tagged fish

During September and October 2014, a total of 48 Carp were tagged with either V9 (n = 24) or V13 (n = 24) acoustic transmitters. Tagged Carp length from 2014 ranged between 203 and 508 mm standard length (average 352 ± 11.3 mm) (**Error! Reference source not found.**) and weights ranged between 245 and 2919 g (average 1072 ± 91 g). Acoustic transmitter (or tag) weight (in water) as a proportion of fish weight ranged from 0.3 to 1.9% (i.e. tag weight as a proportion of fish weight remained < 2% of total body weight). Of the tagged fish, 40 were identified as male and 3 as female, with the sex of the remaining 5 fish undetermined.

During October 2015, a further 32 fish (24 Golden perch, 6 Carp and 2 Murray cod) were tagged with V9's and released back to the Hattah Lakes. Tagged Golden perch length from 2015 ranged between 220 and 432 mm standard length (average 326.2 ± 10.7 mm) (**Error! Reference source not found.**) and weights ranged between 283 and 2355 g (average 1164 ± 107 g). Additionally, 6 Common Carp, with standard lengths ranging from 340 to 630 mm (average 482.5 ± 42.4 mm) (**Error! Reference source not found.**) and weights ranging between 1129 and >5000 g (average 2194.8 ± 365.3 g), were tagged. Two Murray cod were also tagged (300 and 265 mm standard length; 325 and 269 g, respectively). Acoustic transmitter (or tag) weight (in water) as a proportion of fish weight ranged from <0.1 to 1.75% for all fish tagged in 2015.

5.2.2 Movement

Carp during wetland drawdown (spring–summer 2014)

During wetland drawdown in spring–summer 2014, no tagged Carp left the Hattah Lakes system. Few fish were recorded visiting Messengers Regulator (n=4), and Oaties Regulator (n=4) during the drawdown period. In addition, there appeared to be no common migration of Carp, *en masse*, to any particular location within Hattah Lakes during this time. Informal analysis of Carp movement tracks, visualised as an animation using Eonfusion software, suggested that the movement of tagged Carp during this drawdown was generally random in nature. Following disconnection of the majority of the lakes and channels, most of the tagged Carp (still being detected) resided in a lake habitat as opposed to the channels (e.g. Chalka Creek).

Re-analysis using the null-model approach showed that of the 20 Carp tested during the 2014 drawdown period, the observed behaviours for 14 of these fish were best explained by model 1 or 2 (Figure 5–1), where both of these models represent a random pattern of movement (See appendix, Table 7). The behaviour patterns of the remaining Carp (n=6, 30%) were best fitted to model 3, which defines a pattern of movement where the trend is biased in one direction. Of these fish, five were associated with movement toward the Murray River (with the out-flowing water) while one was determined to be moving away (against the out-flowing water). Three Carp with trajectories that best fitted model 3 showed only weak directional bias with the flow (18–27%); two showed moderate to strong directional bias with the flow (43% and 78%, respectively); and the remaining Carp showed weak directional bias against the flow (-11%).

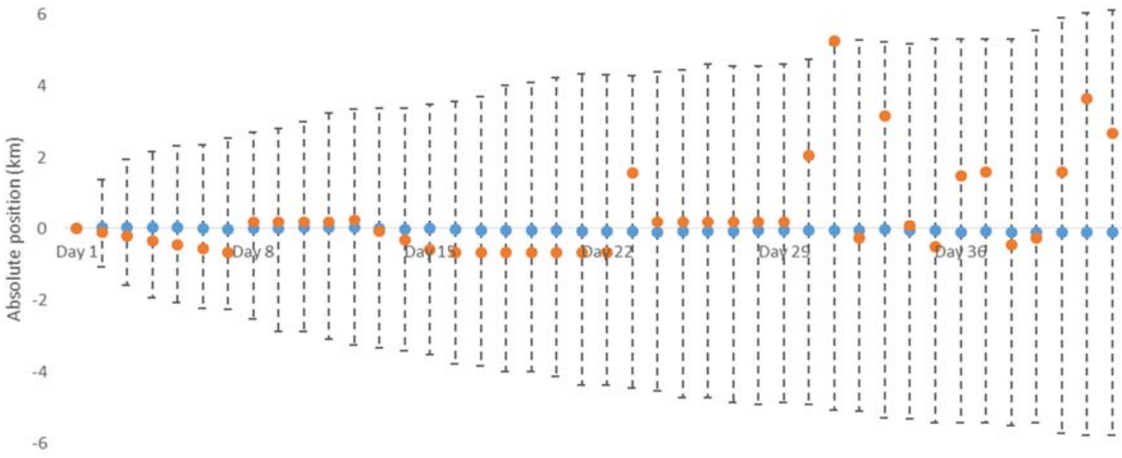
Carp, Golden perch and Murray cod during wetland filling (spring 2015)

Carp: During the spring 2015 filling event (Figure 4–1), sixteen Carp were detected on at least five receivers and their movement trajectories were analysed using the three null-models (appendix, **Error! Reference source not found.**). Models were modified to examine the shorter duration of this event (up to 12 days) and to enable consistent comparison among individual fish we focussed on the initial 10 day period. The movement trajectories of the majority of Carp (n=11) were best described by random (model 1) or correlated random (model 2) walks. As for the previous year's drawdown event, movements of approximately one third of the Carp (n=5, 31%) were better described by the directed-movement model (model 3). However, the direction of bias was not clearly towards (n=2; 46 and 64%), or away from (n=3; -67, -1 and -90%) the Murray River, indicating that there was a similar number of Carp moving with the inflowing water as against it.

Golden perch and Murray Cod: Four tagged Golden perch were detected during the filling event (Figure 4–1). One of these was only detected on two receivers and was excluded from the analysis. The remaining three Golden perch were detected on 4, 9 and 13 receivers, respectively (Appendix, Table 9**Error! Reference source not found.**) and their movement trajectories were analysed using the null-model approach described above.

The movement trajectories of all three Golden perch were best described by model 3 and parameter solutions for D indicated strong movement bias (72%, 77% and 78%, respectively) towards the Murray River, against the inflows during wetland filling (Table 9).

Only a single Murray cod was tagged prior to filling. This fish was only detected on a single receiver during the spring 2015 filling, so no further analysis was possible for this species at this time.



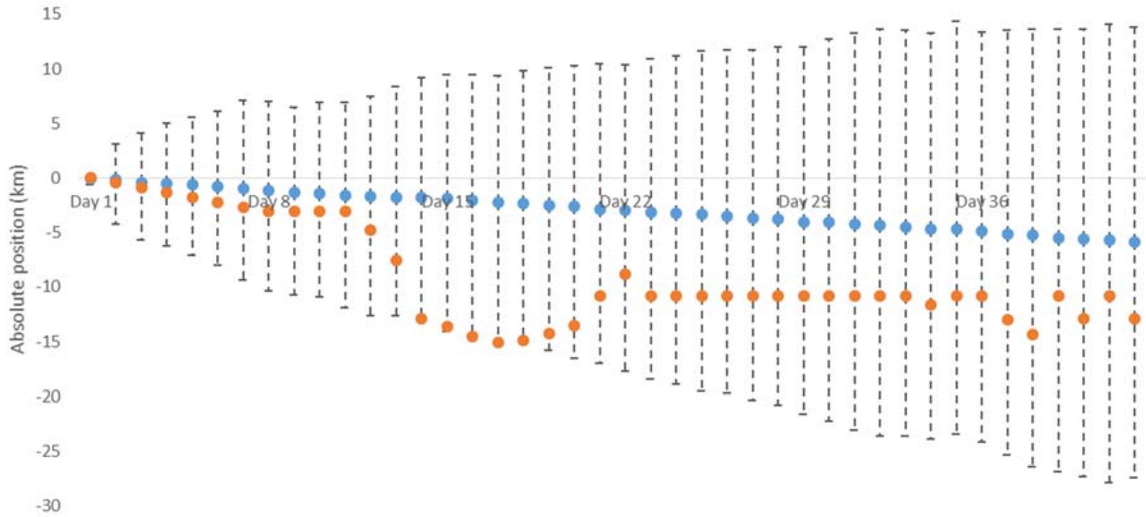


Figure 5–1. Most Carp demonstrated a pattern of movement similar to Carp 23689 (top) (orange points), as shown with respect to observed absolute position (km) relative to start location, during 42 days (horizontal axis) of the Hattah Lakes drawdown in 2014. Positive change represents movement towards the Murray River (vertical axis); negative change represents movements away from the Murray River. Simulation using model 1, an uncorrelated, unbiased, random walk best fits this movement trajectory. The parameter solution for the trajectory in model 1 is used for 1000 Monte Carlo simulations to predict the mean location each day (blue points) ± 95% confidence limits (dashed bars). All but one of the observations, on day 31, are statistically likely under model 1, and models 2 or 3 provided no better fit. Few Carp showed any trend for directed movement; as an example, Carp 23819 (lower) observed positions (orange points) and simulation using model 3, a correlated, biased, random walk that best fit this movement trajectory. Model 3 predicted mean location each day (blue points) ± 95% confidence limits (dashed bars) and shows a trend for movement away from the Murray River.

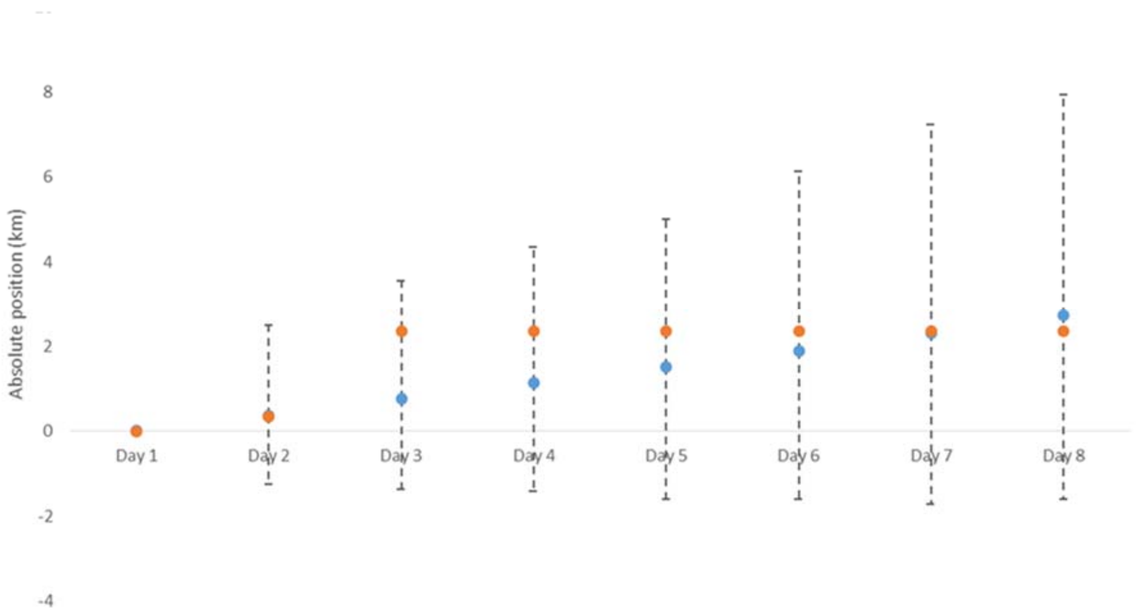


Figure 5–2. All Golden perch showed a pattern of movement similar to Golden perch 56893. Orange points show observed absolute position (km) relative to start location during 8 days (horizontal axis) of the Hattah Lakes filling in 2015. Positive change (vertical axis) represents movement towards the Murray River against the inflows. Simulation using model 3, a correlated, biased, random walk best fit this movement trajectory. Parameter solution for this trajectory in model 3 is used for 1000 Monte Carlo simulations to predict the mean location each day (blue points) ± 95% confidence limits (dashed bars).

Carp and Golden perch during wetland connection and flow back to the Murray River (spring 2015).

Although not part of the original project outline, a brief description of important tagged fish movement during a subsequent drawdown is noted here.

Two weeks after pumped filling had ceased, the regulator gates at Messengers Crossing were opened, allowing water (and fish) to return to the Murray River (Figure 4–1). This occurred between 11 and 18 November 2015. Despite the two-week hiatus in flows, three tagged Golden perch (of 24 tagged; 19 detected) emigrated from the Hattah Lakes (Chalka Creek) and were detected in the Murray River during this period. These results prove the concept that this method for returning fish, in particular Golden perch, to the Murray River from the Hattah Lakes may be a viable management technique. It is also noted that no tagged Carp exited the system during this drawdown. This is consistent with the earlier, more substantial drawdown event in 2014, where no tagged Carp were recorded exiting the Hattah Lakes to the Murray River.

5.3 Discussion

Acoustic telemetry in the Hattah Lakes provided a useful technique to determine movement patterns of non-native Carp and native Golden perch. At the velocities observed, it appears that Carp throughout the Hattah Lakes, whether during filling or drawdown, are not cued to move in a predictable fashion in response to flowing water. Our best understanding indicates that Carp movement maintains a degree of randomness regardless of filling or draining of the Hattah Lakes. The behaviour of Carp at the Hattah Lakes supports the findings of other similar studies, where Carp movements have not been strongly directed by flow (Brookes 2012; Ellis *et al.* 2015). This seems in apparent contradiction to a clear directional response to flow in other studies in some circumstances, such as those where fishways (Cooper 1990; Baumgartner *et al.* 2014) and/or wetland regulators (Thwaites *et al.* 2010; Conallin *et al.* 2012a) have been installed. While some direction bias (in relation to flow) was detected in the movement trajectories for a small proportion of Carp, the bias was bi-directional during both drawdown and filling events, with no clear preference for moving toward or away from flowing water. The solution for this contradiction is not clear. In the present study, fish throughout the Hattah Lakes would have experienced variable, but quite low flow velocities at both drawdown and filling events until they moved into Chalka Creek (see Figure 4–1 right) and even then maximum flow velocities at the sites sampled did not exceed 0.35m s^{-1}. In contrast, studies reporting strong directional movement seem to be located around structures where flow velocities would be relatively high. We suggest that there may be a critical velocity threshold before response to flow becomes a dominant descriptor of movement behaviour in Carp.

Carp have not evolved in the Australian environment where water availability is highly unpredictable. Thus, subtle changes in hydrology may not maintain as greater influence over Carp behaviour and their biology as for native species. In a radio-telemetry study comparison with three large native fish species in the mid-Murray River area, Carp showed low site-fidelity and high movement (Koehn & Nicol 2016). We suggested that the movement behaviour of Carp during moderate hydrological disturbance in these environments is influenced more strongly by factors other than flow; such as searching for suitable habitat or mates, thermoregulation and foraging for better food resources. The absence of any tagged Carp exiting the Hattah Lakes during the early stages of drawdown perhaps indicates that conditions within these off-channel habitats provided an adequate environment for this species.

Golden perch behaviour response to hydrology was in stark contrast to that of the Carp in Hattah Lakes. Golden perch were not tagged during the initial drawdown due to the small size of individuals available in the lakes, and the earlier focus on Carp as a target species for investigation. However, during a later filling event, following strong growth of the available Golden perch, a small number were able to be tagged. While only three fish provided sufficient data for analysis (at that stage there were only four tagged in total), all three (i.e., 75%) displayed a relatively strong trend of movement toward the inflow. While this preliminary data is perhaps not robust on its own, when coupled with directional netting data (Section 4) and other studies of this nature (Ellis & Pyke 2011a; Ellis *et al.* 2015), the link between movement patterns and the hydrological connection between off-channel habitats and the main channel has been strengthened for this species.

In the highly regulated southern connected system of the Murray–Darling Basin, the connections between off-channel habitats and the main channels are now largely dependent upon active river management. The natural interaction between these two environments is an important aspect of native fish ecology (Stoffels *et al.* 2013; Stoffels *et al.* 2015). Being able to maintain the link between the two habitats has becoming increasingly dependent upon the infrastructure used to control water movement between the two. Fish, particularly as eggs and juveniles, can be delivered into off-channel wetland systems by almost all methods of water delivery (Baumgartner *et al.* 2009; Beesley *et al.* 2014a; Brown *et al.* 2015). This is often desirable as filling wetlands make excellent nursery habitat for juvenile fishes, resulting in strong growth and survival. However, returning fish to the main channel can be inherently difficult. Without return to the river, some species such as Golden perch cannot complete their life cycle (Baumgartner *et al.* 2013). Fish in these habitats will be stranded and may perish during a drying phase or become much more vulnerable to predation by piscivorous birds (Maher 1991).

Manipulating water levels in the main channel for draining and filling off-channel habitats, while providing the most natural conditions, is not always viable as a method of active river management due to the large quantities of water required. The present study provides some evidence that by understanding movement responses of species of interest (i.e. Golden perch), water might be artificially manipulated between the two habitats to create a predictable behavioural response that can be used to (1) take advantage of the innate productivity of wetlands under a wetting and drying regime as nursery areas for juvenile fish and (2), return particular species to the main channel after an enhanced juvenile growth phase to complete their life-cycles in a riverine environment. The Hattah Lakes offers an opportunity to manipulate these processes for *smart river management* on an unprecedented scale. Manipulation of draining and filling at Hattah appears to have had some success in returning Golden perch to the Murray River during spring 2015. The initial filling of the lakes via pumps was shown to attract Golden perch to the flow (section 4). Upon ceasing pumping and (2 weeks later) opening Messengers Regulator to return water to the Murray River, approximately 16% (n=3 from 19 tagged and subsequently detected fish) of tagged golden perch exited the Hattah Lakes. While both the filling and draining phases were relatively short in duration, there is proof-of-concept for a management technique for returning Golden perch from the Hattah Lakes to the Murray River.

Acoustic telemetry data from fish is complex and can be a challenge to evaluate quantitatively (Jonsen, Flemming & Myers 2005; Demšar *et al.* 2015). The present study used an innovative approach to create 'regular-trajectories' (Calenge, Dray & Royer-Carenzi 2009), using third-party software (Eonfusion) to model interpolation between irregular observations at fixed points (Pauly *et al.* 2008). This pre-analysis enables a null-model approach, used more typically for animal movement data from GPS-locator collars or tags, to evaluate the likelihood of individuals and groups of fish following particular behaviour patterns. Our hypotheses focussed on movement towards or away from the river in an off-channel system of wetlands. As such, present application of this method is robust against the assumptions made about: (1) constant linear movement between observations, and (2) simplified movement behaviour between observations. While neither assumption is probably true, departures from these assumptions are probably not important for answering questions about directed movement at the scale of interest (i.e. the whole system). As such, this method could be applied to many acoustic telemetry studies of fish in river networks. Ours is a simple example which could be extended relatively easily to more complex 2-D and 3-D animal movement trajectories, where data is initially obtained from acoustic telemetry at fixed points and irregular times.

Currently, tagged fish are still present in the Hattah Lakes and associated habitats. The tags will remain active until batteries expire between April 2017 and October 2019 (depending upon batch); and are a valuable asset to allow the continued study of directed movement of Carp, Golden perch and Murray cod.

Further study and understanding of the movement patterns of certain fish species, in relation to flow and other environmental and biological triggers, is important to optimise the efficient use of environmental watering and associated infrastructure to manage the full cycle of productive connections between the river and its floodplain. Future work at Hattah and other wetlands managed by the Mallee Catchment Management Authority should build upon this study and existing work (Stuart 2013; Beesley *et al.* 2014a; Beesley *et al.* 2014b; Brown *et al.* 2015); focusing on fish movement in complex wetlands and using flow to manipulate the entry or exit of desirable fish species, or to develop control measures for non-native species based on predictable movement patterns. As a follow-up to the present study, we have made a number of recommendations that are described in the next section.

5.4 Recommendations

Manipulating the hydrology of the Hattah Lakes, using existing infrastructure, may provide a valuable tool for returning large-bodied native fish species such as Golden perch, to the Murray River to complete their life-cycle; while undesirable species such as Carp remain behind.

A further trial should feature a designed hydrograph to stimulate Golden perch movement towards, and exit to the Murray River. A draft experimental hydrograph is outlined below. The final design should be in consultation with the relative land and water managers.

- A filling-flow of at least 10 days duration, peaking at 800 ML day^{-1}, using the environmental-pumps to ensure key lakes are connected and to attract Golden perch towards the eastern end of Chalka Creek at Messengers Crossing (Figure 5–3).
- The filing-flow should be immediately (minimise pause between pumping and regulator opening) followed by a short release of water to the Murray using the Messengers Crossing Regulator (100-200 ML day^{-1}).
- Golden perch and Carp movement behaviour should be monitored before, during and after the manipulations using the acoustic telemetry array and a combination of existing tagged fish and newly-tagged additional fish (to account for tag loss and mortality leading up to the trial).
- If sufficient water was available, this manipulation could be repeated 2–3 times within a two month period, to determine if serial stimulation produces greater attraction and to replicate the trial multiple times. Alternatively, a single trial could be scaled-up at both inflow and outflow stages to form a stronger and longer stimulus for fish movement.
- Evaluation of any trial is essential and would be more cost-effective if at least some existing tagged fish could be re-used for the proposed trial, prior to any complete or severe dry-down of the Hattah Lakes resulting in the mortality of tagged fish, and prior to the scheduled tag expiry dates. Current data suggests spring is a suitable time of year to conduct a further trial.

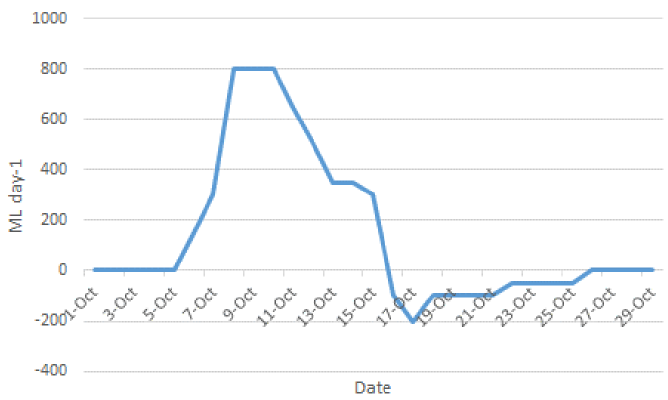


Figure 5–3. Proposed experimental hydrographs for stimulating the emigration of Golden perch recruits from the Hattah Lakes. Positive volumes represent inflows through the environmental pumps; negative volumes represent return releases through the Messengers Regulator. This figure shows a single 4100 ML event.

Appendix

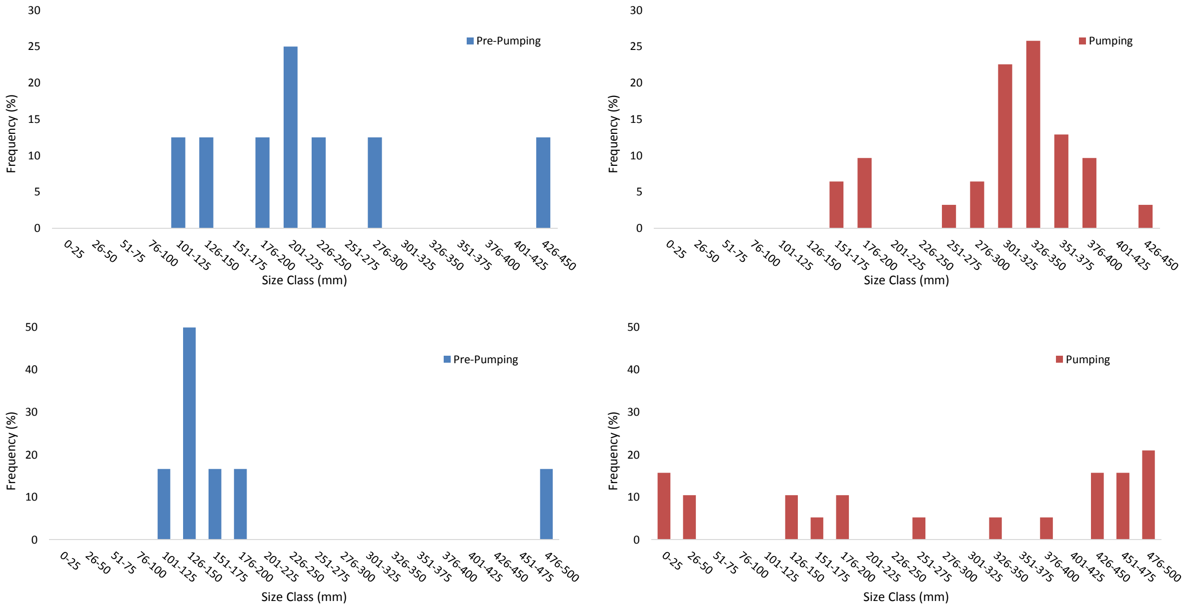


Figure A 1. Length frequency (as a percentage) of Golden perch (top) and Common carp (bottom) in Chalka Creek for the pre-pumping (left) and pumping (right) surveys (all net types).

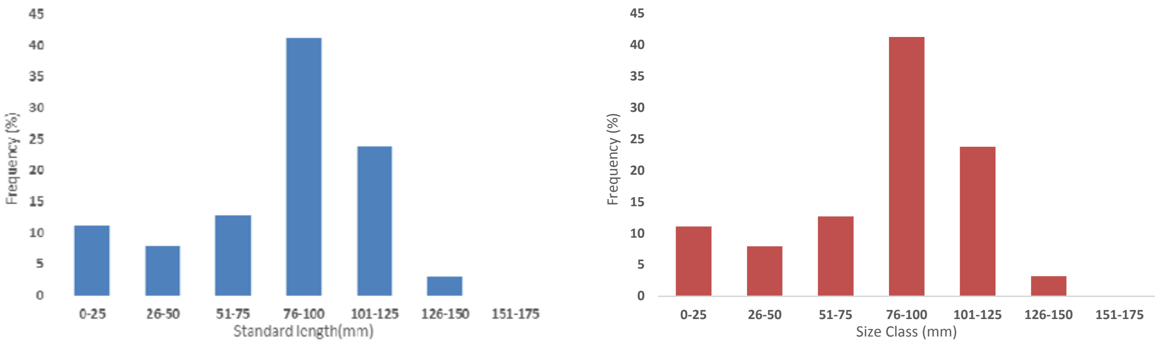


Figure A 2. Length frequency (as a percentage) of Goldfish in Chalka Creek for the pre-pumping (left) and pumping (right) surveys (all net types).

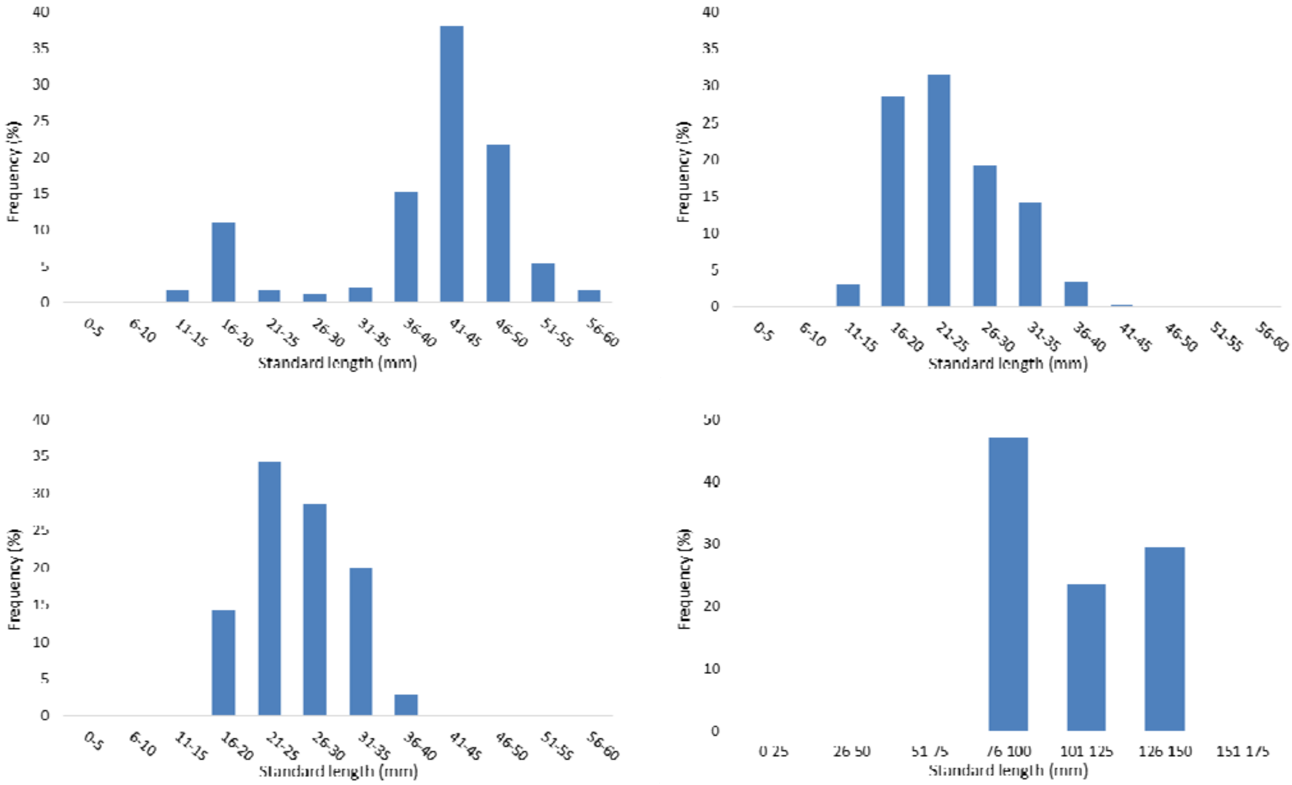


Figure A 3. Length frequency (as a percentage) of Australian smelt (top left), Carp gudgeon (top right), Eastern gambusia (bottom left) and Oriental weatherloach (bottom right) in the lakes prior to pumping.

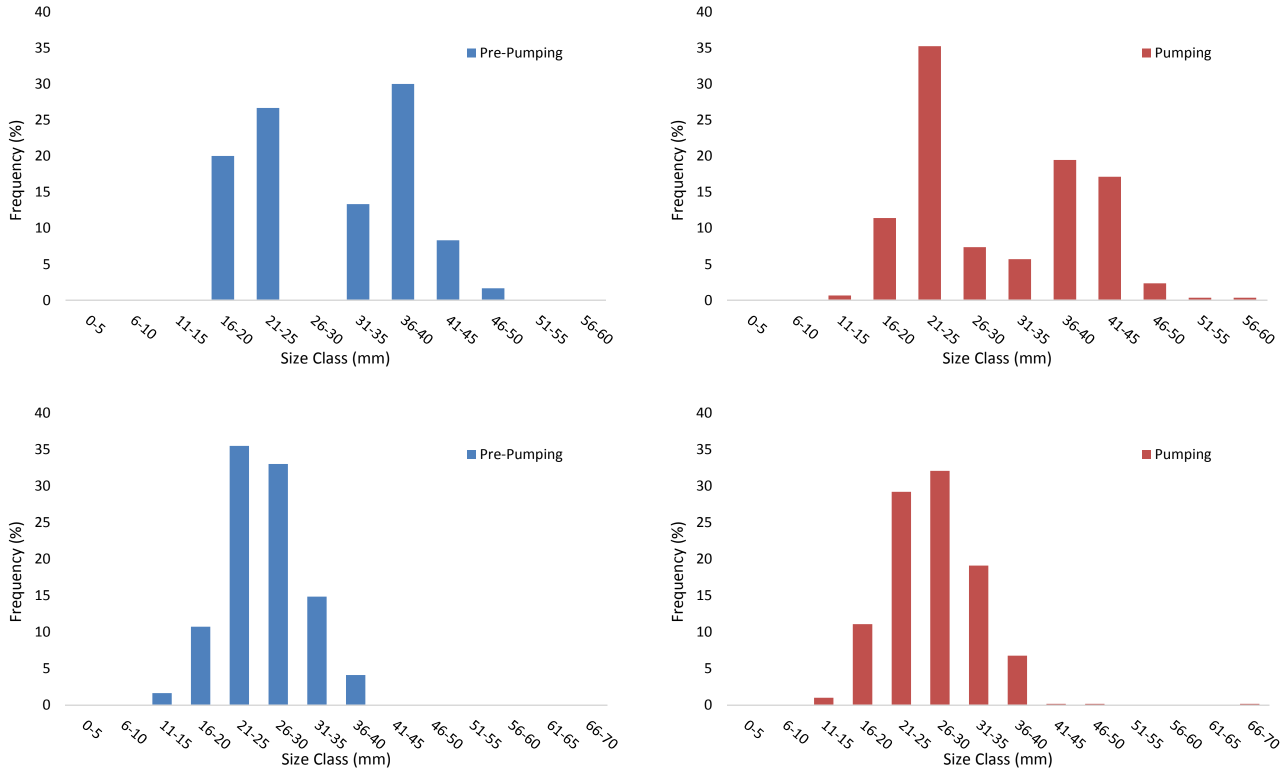


Figure A 4. Length frequency (as a percentage) of Australian Smelt (top), Carp gudgeon (bottom) in Chalka Creek for the pre-pumping (left) and pumping (right) surveys.

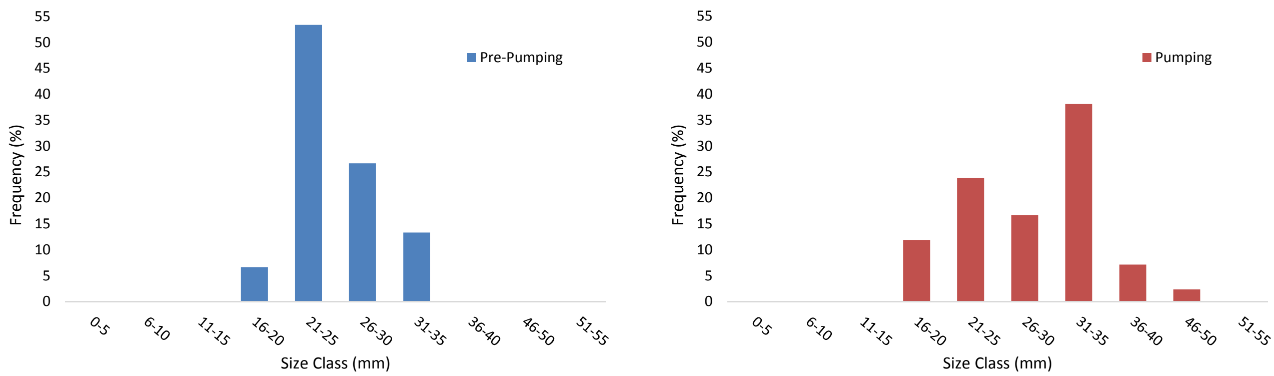


Figure A 5. Length frequency (as a percentage) of Eastern Gambusia in Chalka Creek for the pre-pumping (left) and pumping (right) surveys.

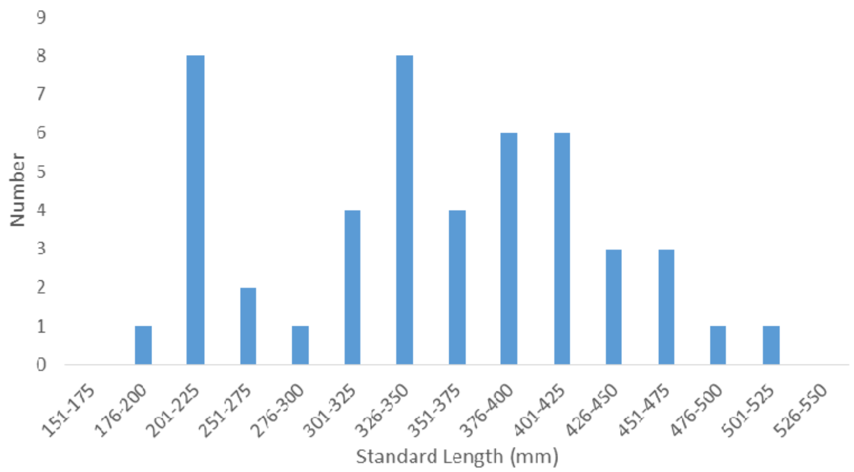


Figure A 6. Length frequency distribution of Carp (n = 48) tagged in the Hattah Lakes during September and October 2014.

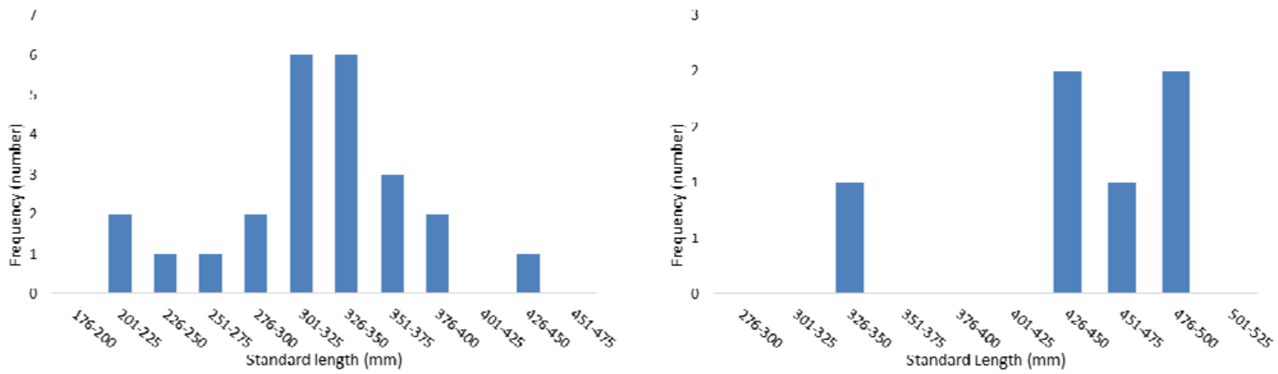


Figure A 7. Length frequency distribution of (left) Golden perch (n = 24) and (right) Common carp (n=6) tagged in the Hattah Lakes during October 2015.

Table 7. Null model analysis for Carp during Spring 2014 watering event (drawdown) between 3 November and 15 December. (42-days) Model 1 = uncorrelated unbiased random-walk. Model 2 = correlated unbiased random-walk. Model 3 = correlated, biased random-walk. Models 1, 2 and 3 were fitted sequentially to each fish trajectory, and the 'best' model chosen that fitted the most observed daily positions and where the daily observed positions were closest to the mean simulated position (i.e. had the highest P-value for each modelled day). A P-value of <0.05 indicates that fish movement was outside the modelled prediction of expected fish movement.

Start location	**i.d.**	**'Best' Model**			**P(Move)**		**P(Stay)**	**P(Persist)**	**P-values (Days from first detection)**						**mean p**	**n days**	**% days**	**N**
	Carp	**1**	**2**	**3**	**D**		**Z**	**S**	**Day 7**	**Day 14**	**Day 21**	**Day 28**	**Day 35**	**Day 42**		**p<0.05**	**p<0.05**	**receivers**
Arawak	23684		✓		0.5		0.99	0.581	0.796	0.68	0.6	0.4	0.548		*0.605*	0	0.00%	6
Arawak	23685		✓		0.5		0.995	0.215	0.023	0.191	0.241	0.306	0.351	0.4	*0.252*	6	14.30%	6
Arawak	23686	✓			0.5		0.997	0	0.137	0.22	0.296	0.58	0.591	0.193	*0.336*	4	9.50%	12
Arawak	23688		✓		0.5		0.996	0.158	0.888	0.792	0.721	0.619	0.654		*0.735*	1	2.40%	6
Arawak	23692	✓			0.5		0.994	0	0.02	0.075	0.566	0.541	0.169	0.525	*0.316*	3	7.10%	6
Bitterang run.	23703		✓		0.5		0.987	0.221	0.831	0.107	0.651	0.781	0.935	0.848	*0.692*	0	0.00%	8
Bulla	23689	✓			0.5		0.989	0	0.778	0.609	0.622	0.463	0.593	0.168	*0.539*	1	2.40%	12
Bulla	23695	✓			0.5		0.997	0	0.932	0.882	0.838	0.21	0.254		*0.623*	0	0.00%	5
Bulla East	23694	✓			0.5		0.997	0	0.938	0.863	0.841	0.816	0.56	0.549	*0.761*	0	0.00%	6
Chalka Ck. 1	23819			✓	0.446		0.926	0.352	0.698	0.975	0.856	0.791	0.737	0.758	*0.803*	0	0.00%	11
Chalka-mid. N	23816		✓		0.5		0.929	0.041	0.921	0.866	0.794	0.874	0.851		*0.884*	0	0.00%	13
Little Hattah	23696	✓			0.5		0.992	0	0.934	0.874	0.907	0.883	0.853	0.827	*0.88*	0	0.00%	7
Lockie	23810			✓	0.588		0.913	0.178	0.74	0.716	0.205				*0.554*	0	0.00%	9
Lockie	23701	✓			0.5		0.994	0	0.195	0.206	0.383	0.74	0.712		*0.447*	1	2.60%	5
Lockie South	23825			✓	0.891		0.991	0.057	0.915	0.907	0.852	0.937	0.963	0.009	*0.764*	4	9.50%	9
Mournpall	23814		✓		0.5		0.983	0.021	0.679	0.952	0.955	0.78	0.9	0.892	*0.86*	0	0.00%	11
Mournpall	23700			✓	0.596		0.965	0.233	0.111	0.26	0.474				*0.282*	1	4.50%	11
Mournpall	23820			✓	0.713		0.965	0.128	0.789	0.427	0.527	0.594	0.817	0.906	*0.677*	0	0.00%	8
Yerang	23687			✓	0.637		0.985	0.027	0.015	0.232	0.329	0.41	0.013	0.852	*0.309*	6	14.30%	14
Yerang	23699		✓		0.5		1	0.048	0.981	0.957	0.929	0.911	0.9	0.874	*0.925*	2	4.80%	5
	Mean				**0.544**		**0.979**	**0.113**	**0.616**	**0.59**	**0.629**	**0.646**	**0.633**	**0.6**	**0.612**	**1.45**	**0.04**	
	SD				**0.102**	**0.026**		**0.152**	**0.369**	**0.333**	**0.244**	**0.221**	**0.28**	**0.317**	**0.223**	**2.04**	**0.05**	

Table 8. Null model analysis for Carp during the spring 2015 watering event (filling) from 12–23 October. Model 1 = uncorrelated unbiased random-walk. Model 2 = correlated unbiased random-walk. Model 3 = correlated, biased random-walk. Models 1, 2 and 3 were fitted sequentially to each fish trajectory, and the 'best' model chosen that fitted the most observed daily positions and where the daily observed positions were closest to the mean simulated position (i.e. had the highest P-value for each modelled day). A P-value of <0.05 indicates that fish movement was outside the modelled prediction of expected fish movement.

Start Location	**i.d.**	**'Best' Model**			**P(Move)**	**P(Stay)**	**P(Persist)**	**P-values (Days from first detection)**					**mean p**	**n days**	**% days**	**N**
	Carp	**1**	**2**	**3**	**D**	**Z**	**S**	**Day 2**	**Day 4**	**Day 6**	**Day 8**	**Day 10**		**p<0.05**	**p<0.05**	**receivers**
Bulla East	23686		✓		0.5	0.9942	0.37	0.943	0.868	0.8	0.064	0.858	*0.707*	0	0.00%	5
Bulla East	23688			✓	0.731	0.8781	0.123	0.794	0.857	0.819	0.784	0.912	*0.833*	0	0.00%	5
Hattah	23684		✓		0.5	0.9903	0.292	0.914	0.139	0.219	0.841	0.614	*0.621*	0	0.00%	5
Hattah	23685		✓		0.5	0.97	0.75	0.905	0.199	0.782	0.341	0.609	*0.639*	0	0.00%	5
Hattah	23689		✓		0.5	0.9894	0.199	0.892	0.15	0.255	0.623	0.908	*0.566*	0	0.00%	5
Hattah	23814			✓	0.497	0.916	0.097	0.551	0.415	0.446	0.649	0.607	*0.534*	0	0.00%	5
Hattah	23692		✓		0.5	0.9938	0.096	0.93	0.119	0.149	0.247	0.822	*0.453*	0	0.00%	5
Hattah	23694		✓		0.5	0.997	0.294	0.977	0.934	0.086	0.094	0.826	*0.583*	0	0.00%	7
Hattah	23695	✓			0.5	0.9943	0	0.93	0.101	0.95	0.272	0.662	*0.583*	0	0.00%	5
Hattah	23696		✓		0.5	0.9969	0.672	0.985	0.032	0.971	0.083	0.909	*0.596*	1	9.10%	5
Junction South	23823			✓	0.049	0.9753	0.221	0.871	0.887	0.879	0.78	0.686	*0.821*	0	0.00%	5
Mournpall	23687			✓	0.163	0.9336	0.394	0.448	0.174	0.275	0.521	0.592	*0.402*	0	0.00%	6
Mournpall	23699		✓		0.5	0.6965	0.089	0.507	0.432	0.322	0.592	0.614	*0.493*	0	0.00%	11
Mournpall	23820	✓			0.5	0.2587	0	0.489	0.244	0.463	0.467	0.461	*0.425*	0	0.00%	8
Mournpall	23703	✓			0.5	0.9349	0	0.592	0.054	0.763	0.963	0.965	*0.667*	0	0.00%	11
Mournpall	23816			✓	0.821	0.9502	0.728	0.95	0.883	0.234	0.513	0.699	*0.656*	0	0.00%	7
	Mean				**0.554**	**0.759**	**0.154**	**0.596**	**0.355**	**0.435**	**0.675**	**0.718**	**0.556**	**0**	**0%**	
	SD				**0.131**	**0.261**	**0.285**	**0.177**	**0.292**	**0.223**	**0.197**	**0.178**	**0.075**	**0**	**0%**	

Table 9. Null model analysis for Golden perch during the spring 2015 watering event (filling) from 12–23 October. Model 1 = uncorrelated unbiased random-walk. Model 2 = correlated unbiased random-walk. Model 3 = correlated, biased random-walk. Models 1,2 and 3 were fitted sequentially to each fish trajectory, and the 'best' model chosen that fitted the most observed daily positions and where the daily observed positions were closest to the mean simulated position (i.e. had the highest P-value for each modelled day). A P-value of <0.05 indicates that fish movement was outside the modelled prediction of expected fish movement.

Start Location	Species/ i.d.	'Best' Model			P(Move)	P(Stay)	P(Persist)	P-values (Days from first detection)					mean p	n days	% days	N
		1	2	3	D	Z	S	Day 2	Day 4	Day 6	Day 8	Day 10		p<0.05	p<0.05	receivers
	Golden perch															
Chalka Mid	56929			✓	0.889	0.9625	0.002	0.23	0.605	0.819	0.912	0.968	*0.707*	0	0%	4
Lockie-Chalka	56893			✓	0.886	0.9459	0.007	0.595	0.544	0.791	0.909		*0.71*	0	0%	9
Mournpall	56880			✓	0.862	0.9498	0.318	0.924	0.895	0.895	0.815	0.815	*0.764*	0	0%	13
	Mean				**0.879**	**0.953**	**0.109**	**0.583**	**0.681**	**0.835**	**0.879**	**0.892**	**0.727**	**0**	**0%**	
	SD				**0.015**	**0.009**	**0.181**	**0.347**	**0.188**	**0.054**	**0.055**	**0.108**	**0.032**	**0**	**0%**	

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