Inland Waters & Catchment Ecology

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City of Playford Managed Aquifer Recharge Scheme: Carp Eradication Program

Leigh Thwaites, Josh Fredberg and David Strange

SARDI Publication No. F2017/000038-1
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SARDI Aquatics Sciences
PO Box 120 Henley Beach SA 5022

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PREMIUM FOOD AND WINE FROM OUR CLEAN ENVIRONMENT

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[1] SARDI Aquatic Sciences, PO Box 120, Henley Beach, SA, 5022
[2] City of Playford, 12 Bishopstone Road, Davoren Park, SA, 5113

South Australian Research and Development Institute
SARDI Aquatic Sciences
2 Hamra Avenue
West Beach SA 5024

Telephone: (08) 8207 5400
Facsimile: (08) 8207 5406
http://www.pir.sa.gov.au/research

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Author(s):	Leigh Thwaites, Josh Fredberg and David Strange
Reviewer(s):	Kate Frahn and Qifeng Ye
Approved by:	A/Prof Qifeng Ye Science Leader – Inland Waters & Catchment Ecology
Signed:	
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EXECUTIVE SUMMARY

Common carp (*Cyprinus carpio* L.) are a successful invader and a declared pest fish in several countries including Australia, New Zealand, Canada and the United States. Carp are “ecosystem engineers” and when in high abundance, cause detrimental changes to benthic habitats, water quality and the distribution and abundance of native flora and fauna. These impacts stem largely from carp’s bottom-feeding behaviour and are most commonly reported in shallow off-stream or within channel habitats where carp aggregate to feed and breed.

As one component of the Waterproofing Northern Adelaide project, the City of Playford made significant investment in the installation of a managed aquifer recharge (MAR) scheme. The scheme relies on constructed urban wetlands to improve the quality of intercepted stormwater prior to aquifer recharge and later reuse. To recharge, predefined water quality thresholds must be met including a turbidity level of <20 NTU. The scheme was fully operational before a carp population explosion. The bottom feeding behaviour of carp increased turbidity levels to a point that exceeded groundwater recharge thresholds effectively stranding the asset. The City of Playford attempted to remove carp using netting techniques but large numbers remained and turbidity’s still exceeded threshold levels. Draining was not considered an option due to concerns associated clay liner integrity and survival of aquatic vegetation. As such, the City of Playford engaged SARDI Aquatic Sciences to eradicate carp from the MAR scheme via the application of rotenone.

The eradication program was conducted under the Australian Pesticides and Veterinary Medicines Authority rotenone permit number PER13011 (APVMA 2011). Carp eradication occurred during 2014-2016 and was conducted in five interconnected water bodies associated with the MAR scheme. Depending on the size and depth of the water body, rotenone was either applied from a 4 m aluminium punt, a trailer mounted spray system or a combination of both. Euthanized carp were removed using landing nets and 30 m seine nets. All carp were counted and, with the exception of the first Munno Para treatment, a subsample measured (total length (TL), mm; weight, g). The average weight of carp removed during the first Munno Para treatment was calculated by bulk weighing a total of 30 carp on a set of 50 kg industrial scales. To evaluate changes in turbidity following each rotenone program, point source measurements recorded by an inline turbidity (NTU) monitoring system associated with each MAR wetland were provided by the City of Playford.

A total of 26,706 carp (12,381 kg) were removed from across the MAR scheme between 2014 and 2016. Mean carp density was 501 kg ha^{-1} ± 163 S.E. and ranged from 142 kg ha^{-1} in Seb-Curtis MAR wetland to 1,225 kg ha^{-1} in Munno Para MAR wetland. The results of the carp eradication program indicate that high carp densities were the primary cause of turbidity levels exceeding the groundwater recharge threshold (>20 NTU). Indeed, substantial improvements in turbidity were observed within two days across all rotenone treated water bodies with turbidity's decreasing from >32 NTU to <5 NTU.

The MAR scheme carp invasion may have occurred via translocation (i.e. illegal stocking), the introduction of carp during the filling process or a combination of both processes. To determine the most likely mechanism and develop appropriate management strategies, an evaluation of the abundance of carp required to seed the wetlands, availability of seed stocks and level of hydraulic connectivity within the immediate and surrounding catchments was conducted. The evaluation utilised anecdotal and hydrology information collected from the City of Playford, aerial imagery, regional fish assemblage data collected by SARDI Aquatic Sciences and carp population modelling.

The initial carp invasion of the MAR wetlands likely occurred by carp translocated from neighbouring catchments into the golf course wetland several years before the development of the MAR scheme. While there are no records of when carp first appeared in the golf course wetland, observations of several carp moving from the wetland toward Stebonheath MAR wetland as it was filled in 2007-2008 indicate a population had established prior to 2007. These observations also suggest that Stebonheath MAR wetland and the catchment basin were seeded by golf course carp during the initial stages of their operation. Indeed, the design of the MAR scheme permits unimpeded downstream movement through a series of channels connecting the golf course to Stebonheath via the catchment basin. Results of population modelling indicate as little as 3-4 adult female carp and at least one male would have provided sufficient seed stock in 2007 to achieve the abundance of carp removed during the 2014 eradication program. While Stebonheath was likely seeded during the filling event, both Munno para and Steb-Curtis MAR wetlands are upstream of the catchment basin suggesting that carp were translocated into these wetlands after they were filled by urban stormwater. It would have required the translocation of approximately 20 female carp and one male into Munno Para and only 1-2 adult females and one male into Steb-Curtis during the initial stages of their operation to achieve the abundances removed during the eradication programs.

The ease with which carp infestations can occur (and re-occur) and the cost associated with continual removal highlights the need to develop management strategies that aim to mitigate future incursions and/or the spread of carp throughout the scheme. The most appropriate strategy is to remove carp from across the entire system over one concerted eradication campaign. The eradication campaign should be conducted in conjunction with public education in an attempt to discourage the re-introduction of translocated carp. This strategy is likely to yield the greatest long-term benefits by eliminating seed stocks from within the catchment and attempting to mitigate translocation from neighbouring catchments.

1. INTRODUCTION

1.1. Background

Common carp (*Cyprinus carpio* L.) are a successful invader and declared pest fish in several countries including Australia, New Zealand, Canada and the United States (Koehn 2004). The success of carp stems from their intermediate life history strategy (opportunistic/periodic), high fecundity (100,000 eggs kg^{-1}; up to 1 million eggs y^{-1}), early maturation (~1 year for males; ~2 years for females), longevity (28+ years), ability to occupy a broad range of habitats and tolerance to extreme environmental conditions (Winemiller and Rose 1992; Brown et al. 2003; Smith 2005; Bajer and Sorenson 2010; Koehn et al. 2016). Carp are "ecosystem engineers" and when in high abundance, cause detrimental changes to benthic habitats, water quality and the distribution and abundance of native flora and fauna (Gehrke and Harris 1994; Miller and Crowl 2006; Matsuzaki et al. 2009). Previous research has demonstrated a significant increase in turbidity at carp densities of 50-75 kg ha^{-1} (Zambrano and Hinojosa 1999), a significant negative effect on water transparency and aquatic macrophyte cover at a mean density of 68 kg ha^{-1} (Vilizzi et al. 2014), decline in vegetation cover and waterfowl at ~100 kg ha^{-1} (Bajer et al. 2009), a shift from clear to turbid water state at 174-300 kg ha^{-1} (Williams et al. 2002; Parkos et al. 2003; Haas et al. 2007; Matsuzaki et al. 2009) and detrimental effects on aquatic macrophytes at 450 kg ha^{-1} (Hume et al. 1983; Fletcher et al. 1985; Osborne et al. 2005; Pinto et al. 2005). These impacts stem largely from carp's bottom-feeding behaviour (Sibbing et al. 1986) and are most commonly reported in shallow off-stream or within channel habitats (Parkos et al. 2003) where carp aggregate annually to feed and breed (Smith and Walker 2004; Stuart and Jones 2006).

As one component of the Waterproofing Northern Adelaide project, the City of Playford made significant investment in the installation of a managed aquifer recharge (MAR) scheme. The scheme relies on constructed urban wetlands to improve the quality of intercepted stormwater prior to aquifer recharge and later reuse (e.g. irrigation of public land). To recharge, predefined water quality thresholds must be met including a turbidity level of <20 NTU. Playford's MAR scheme was fully operational for approximately two years post construction, however carp invaded and spread through the scheme most likely via illegal stocking and connected waterways. MAR wetlands provide shallow, well-vegetated, slow-flowing habitat which is characteristic of areas that carp actively seek for spawning/nursery sites and improved foraging opportunities (Koehn and Nichol 1998; Smith and Walker 2004; Stuart and Jones 2006; Jones and Stuart 2007; Butler and Wahl 2010; Conallin et al. 2012). As such, the incursion resulted in rapid population growth and the associated environmental impacts increased turbidity levels to a point that exceeded groundwater recharge thresholds effectively stranding the assets. This represents a costly and potential ongoing management issue without the use of appropriate carp control/eradication strategies.

Carp control methods rely on a strong understanding of the species ecology and aim to target or sabotage exploitable behaviours (i.e. migrations, spawning). The utility of each method is site specific and dependent on several factors including season (i.e. spring vs. winter), scale (i.e. individual wetlands, river reach), hydrology, resource availability and operational objectives. Specific options for control include operational and intervention techniques or a combination of both. To date, these largely rely on commercial fishing, steel mesh carp exclusion screens in wetland flow control structures to restrict access to spawning sites (French et al. 1999; Hillyard et al. 2010), electrical barriers to restrict movements (Verrill and Berry 1995), barrier netting to exclude carp from preferred spawning habitat (Inland Fisheries Service 2008), applying lime to destroy eggs (Inland Fisheries Service 2008), tracking acoustic or radio tagged carp to locate and harvest aggregations (Inland Fisheries Service 2008), jumping traps (William's carp separation cages; Stuart et al. 2006; Thwaites 2011), push traps (Thwaites et al. 2010), pheromone traps (Sorensen and Stacey 2004), chemical piscicides such as rotenone (Clearwater et al. 2008) and water level manipulations or draining to reduce access to littoral spawning sites or expose eggs and fish to desiccation (Shields 1957; Yamamoto et al. 2006). Of these techniques, commercial fishing (i.e. netting), draining and the application of chemical piscicides were considered the only methods to potentially meet the operational objectives of the MAR scheme (i.e. annual stormwater harvesting and groundwater recharge, public amenity). However, initial attempts to control carp using netting techniques were largely unsuccessful and although draining/desiccation would achieve complete eradication it was considered to pose an unacceptable risk to the health of aquatic reed beds, the integrity of the clay liner and also detract from the aesthetic value of the wetlands (David Strange, City of Playford, pers. comm.). As such, eradication of carp via the application of rotenone was considered the only viable option.

Rotenone is a natural toxin derived from the roots of certain tropical species of Leguminosae including barbasco (*Lonchocarpus utilis* and *L urucu*), derris (*Derris elliptica*) and rosewood (*Tephrosia* spp.). It is a highly specific metabolic poison that is rapidly absorbed across the gill epithelium. Once absorbed, it reduces cellular uptake of oxygen by blocking electron transport. This results in increased blood pO_2, compensatory increases in cellular anaerobic metabolism and an associated increase in lactic acid which causes blood acidosis (Ling 2002). Exposed fish die within hours as a result of tissue anoxia, especially cardiac and neurological failure (Ling 2002). Rotenone has been used for centuries by indigenous people to capture fish for human consumption and by fisheries managers since the 1930s for the management, control, research and eradication of freshwater fish (Finlayson et al. 2000; Ling 2002; Rayner and Creese 2006). It is recognised as the most environmentally benign of the commonly used fish poisons (Ling 2002).

1.2. Objectives

The objectives of this study were to:

- Utilise rotenone to eradicate carp from five interconnected water bodies associated with the MAR scheme owned and operated by the City of Playford, South Australia.
- Report changes in turbidity associated with the eradication of carp.
- Evaluate the likely mechanism of the initial (and future) carp incursion and subsequent spread throughout the scheme.
- Provide management recommendations for the ongoing control of carp within MAR schemes.

2. METHODS

Australian Pesticides and Veterinary Medicines Authority permit number PER13011

The eradication program was conducted under the Australian Pesticides and Veterinary Medicines Authority rotenone permit number PER13011 (APVMA 2011). This permit details the directions for use including restraints (i.e. do not treat drinking water), environmental and procedural considerations, rotenone concentrations and application procedures.

Rotenone treatment sites

Carp eradication was conducted in five interconnected water bodies associated with the MAR scheme owned and operated by the City of Playford, South Australia (Figure 1 and Table 1). The scheme is located in Smith Creek Catchment which is characterised by a series of intermittent creeks that drain farm land and urban development. The MAR wetlands comprise a series of clay lined earthen ponds separated by relatively shallow reed beds (*Juncus* spp., *Baumea* spp., *Buloschoenus* spp. and *Schoenoplectus* spp.) systematically planted at regular intervals. Each wetland is bounded by a combination of gabion basket walls and earthen banks. The Steb-Curtis catchment basin and golf-course wetland have similar geomorphology to the MAR wetlands however, as these wetlands are not used to treat stormwater they contain fewer reed beds.

The scheme receives urban stormwater runoff collected from the surrounding catchment via a series of creeks, drains and pipes. Individual wetlands are connected by surficial drains or underground pipes. These drains and pipes permit overflow management during high rainfall events and completely dry out between events. Stormwater flows in a south-west direction with Munno Para MAR wetland and the golf course wetland at the top of the system and Stebonheath MAR wetland at the bottom. Overflow exits Stebonheath via Smith Creek tributary (Figure 1). Wetland connectivity may permit some movement of carp between wetlands, however due to the design of the system (i.e. overflow weirs, graded pipes) this is largely restricted to one-way movements during high rainfall events (Figure 1). Two-way movement may occur via an underground overflow pipe connecting Steb-Curtis MAR wetland and Steb-Curtis catchment basis, however this is only likely to occur on rare occasions when pumps are not in operation and water depth within the MAR wetland drops below the catchment basin.

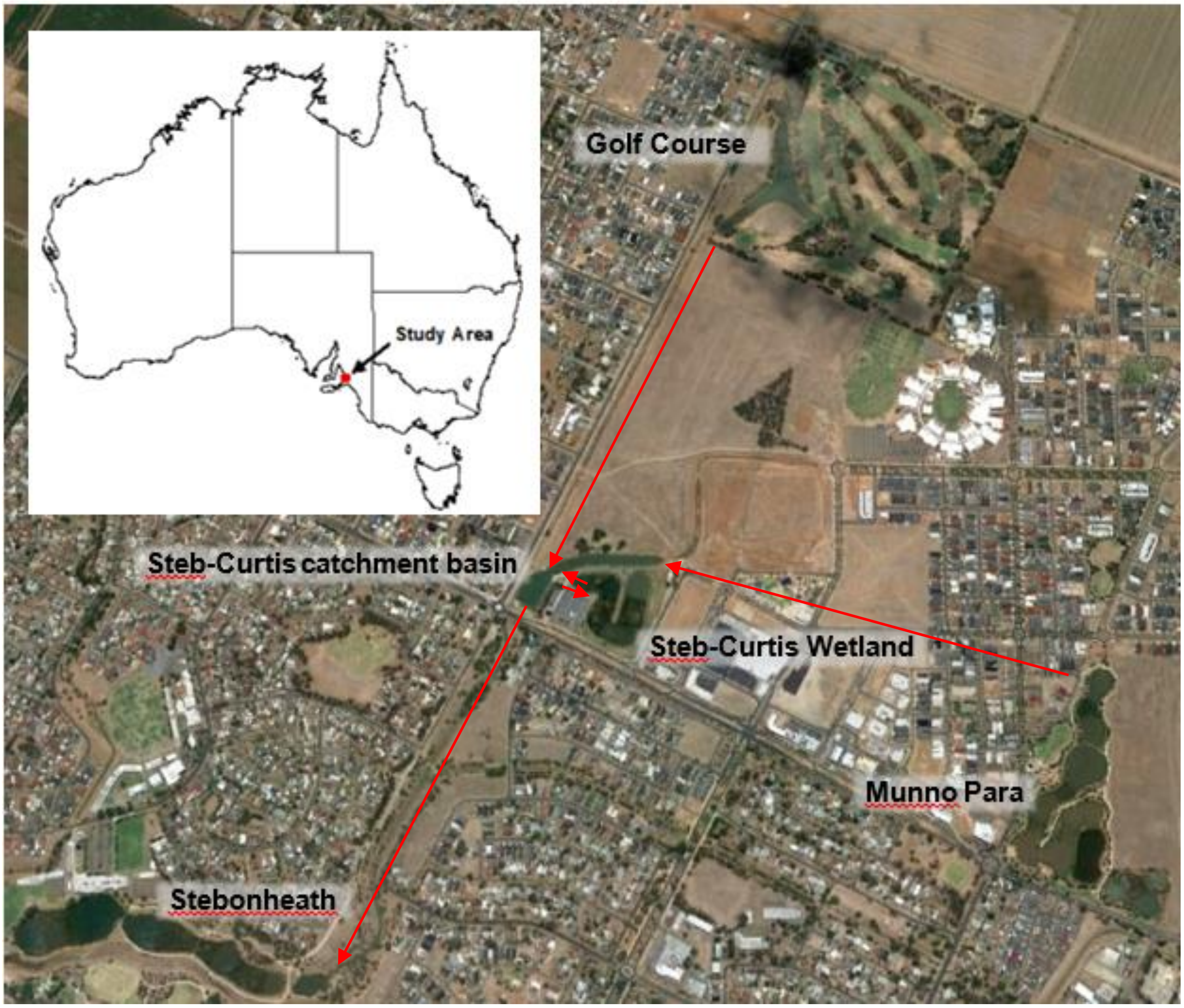

Figure 1. Aerial image of the managed aquifer recharge scheme wetlands. Red arrows indicated potential direction of carp movement during high rainfall events.

Initial site survey

The week prior to the application of rotenone each water bodies' fish assemblage was sampled using a combination of multi-panel monofilament gill nets (15 m total length, 3 m depth and 3 panel mesh at 45 mm, 57 mm, 115 mm) and small-mesh fyke nets (6 mm stretched mesh, 5 m leader, 3 m funnel, 7 support rings and 3 chambers). The total numbers of nets varied based on the size of the water body, however no less than 6 fyke nets and 2 gill nets were set on each occasion. Nets were set for 24 h and captured fish were identified to species and counted.

Table 1. Summary data for rotenone treated water bodies associated with the City of Playfords managed aquifer recharge scheme.

Water body	Purpose	Constructed	Surface area (ha)	Total Volume (ML)	Dates treated	Volume treated (ML)	Rotenone (kg)*
Munno Para	MAR wetland	2009-10	5	60	5-9 May 2014	37	112
					11-15 April 2016		
Stebonheath	MAR wetland	2007-08	3.39	33	27-31 Oct 2014	24	72
Golf course	Irrigation/aesthetics	1992-93	1.29	18	4-8 May 2015	15	45
Steb-Curtis	Catchment basin	2011-12	0.85	17	4-8 May 2015	10	30
					23-27 May 2016		
Steb-Curtis	MAR wetland	2011-12	1.75	20	23-27 May 2016	14	44

*Quantity of rotenone required when adjusted for actual concentration of rotenone in product (AVPMA 2011)

Rotenone application

For each water body, the required quantity of rotenone (kg) was calculated from the permitted concentration (adjusted for rotenone concentration on certificate of analysis; g/m^3; AVPMA 2011) and the water bodies total volume (m^3) at the time of treatment (Table 1). During the treatment process, each MAR wetland was drawn down to a series of disconnected pools while the catchment basin and golf course wetland were treated at capacity. The catchment basin and the golf course were treated within one day while the disconnected pools associated with each MAR wetland were treated over a three to four day period, with one or two pools treated each day.

To mitigate rotenone clumping when added to water, the required quantity was sub-divided into 2 kg batches. Each batch was then vigorously mixed with water in 20 L buckets using an electric paint stirrer. This mixture was either applied directly or diluted further for application. All staff in direct contact with rotenone powder used appropriate personal protective equipment including disposable head to ankle overalls, latex gloves, safety goggles and respirators.

Depending on the size and depth of the water body, rotenone was either applied from a 4 m aluminium punt, a trailer mounted spray system or a combination of both. The trailer system comprised a 1000 L holding tank, petrol operated water pump, high pressure hose and a spray nozzle. This system was used to spray a diluted rotenone solution across smaller pools and to target shallow and vegetated areas. The punt was used to disperse rotenone through deeper sections of larger pools. Initial treatments from the punt were achieved by slowly dripping the 20 L rotenone mixture into the turbulence created by the prop as the boat was systematically navigated throughout the water body. Subsequent treatments utilised a scaled down version of the trailer system (150 L) to inject a diluted solution into the prop. To ensure homogenous mixing throughout the water column, each water body was “stirred” opportunistically during the treatment process and for 20-30 min post application using the outboard motors of either one or two aluminium punts.

Euthanized carp were removed using combination of landing nets and 30 m seine nets. All carp were counted and, with the exception of the first Munno Para treatment, a subsample measured (TL, mm; weight, g). The average weight of carp removed during the first Munno Para treatment was calculated by bulk weighing a total of 30 carp on a set of 50 kg industrial scales.

To evaluate changes in turbidity following each rotenone program, point source measurements recorded by inline turbidity (NTU) monitoring systems associated with each MAR wetland were provided by the City of Playford.

Public engagement

Prior to each treatment event, the City of Playford conducted a comprehensive public awareness campaign. The campaign included mail outs, advertising in print and electronic media as well as the provision of information on council's website. The campaign provided educational material detailing the benefits of MAR schemes, the impact of carp within these schemes, the rotenone carp eradication program, dates over which each program will occur and dates when public access would be restricted. To further ensure public safety, signage and security officers were deployed at each wetland during, and for up to two days post rotenone treatment.

MAR scheme carp invasion and management

The MAR scheme carp invasion may have occurred via translocation (i.e. illegal stocking), the introduction/spread of carp during the filling process or overflow events or a combination of these processes. To determine the most likely mechanism and develop appropriate management strategies, an evaluation of the abundance of carp required to seed the MAR wetlands, availability of seed stocks and level of hydraulic connectivity within the immediate and surrounding catchments was conducted. The evaluation utilised anecdotal and hydrology information collected from the City of Playford, aerial imagery, regional fish assemblage data collected by SARDI Aquatic Sciences and carp population modelling. The population model evaluated the introduction of either adult, fingerling or larval carp and used age specific carp survival rates associated with artificially inundated floodplains (i.e. using a flow regulator) (Table 2; Koehn et al. 2016). The abundance of adult, fingerling or larval carp introduced in the initial stage of each MAR wetland was adjusted until the total population size at the time of each eradication program was achieved. For both Munno Para and Steb-Curtis, the model was run for a total of four breeding seasons (four years) while Stebonheath was run for a total of 6 breeding seasons (six years). The population model assumed that:

- Adult female carp (2.5 kg) were introduced within one month after filling, or either larval or fingerling carp where introduced during the filling process.
- Adult carp remained at their initial weight and maintained an annual survival rate of 84% (Koehn et al. 2016).

- Larvae and fingerlings were introduced in a 1 to 1 sex ratio.
- Carp reached sexually maturity at 3 years of age.
- Each female carp could lay 100,000 eggs kg^{-1}.
- Sufficient males were introduced to permit successful spawning.
- Spawning and recruitment occurred each breeding season.
- Female and male carp recruitment occurred at a 1 to 1 sex ratio.
- No further adult, larval or fingerling carp were introduced after the initial incursion.
- Age specific survival rates remained the same from filling until the eradication program.

Table 2. Age specific carp survival rates associated with artificially inundated floodplains on the River Murray (adapted from Koehn et al. 2016).

	% Survival		**% Survival**
Egg	12.2	**Age 2**	54
Larvae	11.7	**Age 3**	67
Fingerling	13.5	**Age 4**	74
Young-of-year	26.3	**Age 5**	78
Age 1	20	**Age 6**	80

3. RESULTS AND DISCUSSION

Site surveys

Common carp were the only species captured during pre-eradication fish surveys with a total of eight captured from Munno Para MAR wetland during the first survey (May-June 2014), nine from the Golf course wetland and 23 from Steb-Curtis catchment basin (Table 3). Even though a relatively high abundance of carp were present within other sites and during subsequent sampling rounds, no other carp were captured. Given the abundance of carp removed during each eradication program (Table 3), the relatively small catch rates indicate a high level of net avoidance. Indeed, netting only captured 1.35% ± 0.8 S.E. of the total abundance removed during the eradication campaign.

Table 3. Dates, gear and catches for fish assemblage sampling conducted across the managed aquifer recharge scheme prior to the application of rotenone.

Water body	Purpose	Dates sampled	Sampling gear	Catches
Munno Para	MAR wetland	30 May-2 June 2014	6 x gill nets	8 carp
			12 x fyke nets	
Stebonheath	MAR wetland	23-24 October 2014	4 x gill nets	0
			8 x fyke nets	
Golf course	Irrigation	29-30 July 2015	4 x gill nets	9 carp
			6 x fyke nets	
Steb-Curtis	Catchment basin	29-30 July 2015	4 x gill nets	23 carp
			6 x fyke nets	
Munno Para	MAR wetland	11-15 April 2016	2 x gill nets	0
			9 x fyke nets	
Steb-Curtis	Catchment basin	22-25 May 2016	2 x gill nets	0
			6 x fyke nets	
Steb-Curtis	MAR wetland	22-25 May 2016	2 x gill nets	0
			9 x fyke nets	

Carp eradication program

Munno Para MAR wetland- May 2014 and April 2016

A total of ~12,000 carp (1,225 kg ha^{-1}) were removed from Munno Para MAR wetland during 2014 (Table 4) and a further 3,515 carp (360 kg ha^{-1}) removed during April 2016 (Table 4 and Figure 2). The length-frequency distribution of carp removed during 2016 was bimodal with a total of 48 carp (40%) in the 120-240 mm total length (TL) size class and 67 carp (55.8%) in the 280-500 mm TL size class. Carp >500 mm TL represented 4.1% (*n*=5) and the largest carp measured was 680 mm TL. Length at age relationships established from carp sampled in the Murray River (Smith 2005) indicate that carp within the 120-240 mm TL size class range from 1 to 2 years of age and carp 280-500 mm TL range from 2 to 5 years of age. Carp >540 mm TL are likely to be >6 years of age.

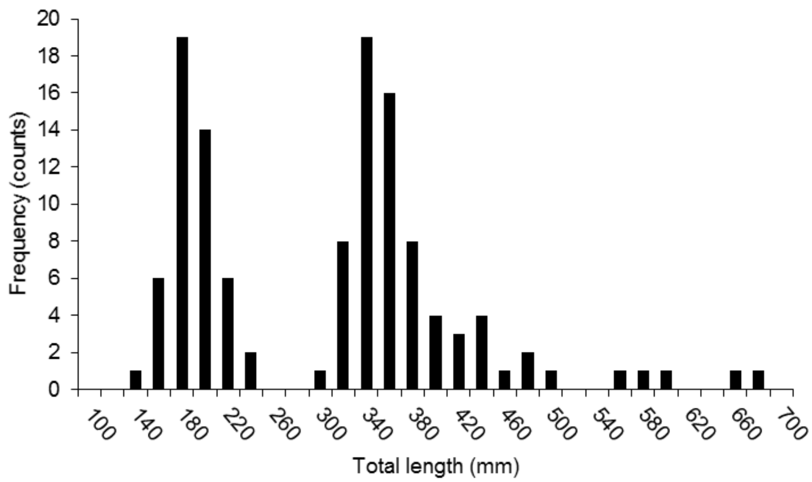

Figure 2. Length-frequency distribution for carp removed from Munno Para managed aquifer recharge wetland during the April 2016 eradication program (*n*=120).

A total of 2,073 carp removed during the second eradication program (April 2016) were >2 years of age (>280 mm TL) indicating they survived the first eradication program (May 2014). Back calculating the average size/weight of these carp suggests a density of ~115 kg ha^{-1} remained in Munno Para and that the first eradication program achieved a density reduction of ~91%. Thus, the total density of carp in Munno Para at the time of the first program was ~1340 kg ha^{-1}. The reason for the relatively high survival rates is unclear, however these carp were only ~40-60 mm TL and may have sought refuge in areas where rotenone may have not permeated such as partially inundated reed beds, drains and cavities within the gabion basket walls that fringe the wetland.

Stebonheath MAR wetland- October 2014

A total of ~9,000 carp (998 kg ha^{-1}) were removed from Stebonheath MAR wetland during October 2014 (Table 4 and Figure 3). The length-frequency distribution of carp was unimodal with a total of 104 carp (86.7%) in the 100-340 mm TL size class and the highest frequency count of 38 carp (31.7%) in the 200-240 mm TL size class. Carp >340 mm TL represented 13.3% (*n*=16) and the largest carp measured was 592 mm TL. Length at age relationships (Smith 2005) indicate that carp within the 100-340 mm TL size class range from ~1 to 3 years of age, carp 350-600 mm TL range from ~3 to 9+ years of age.

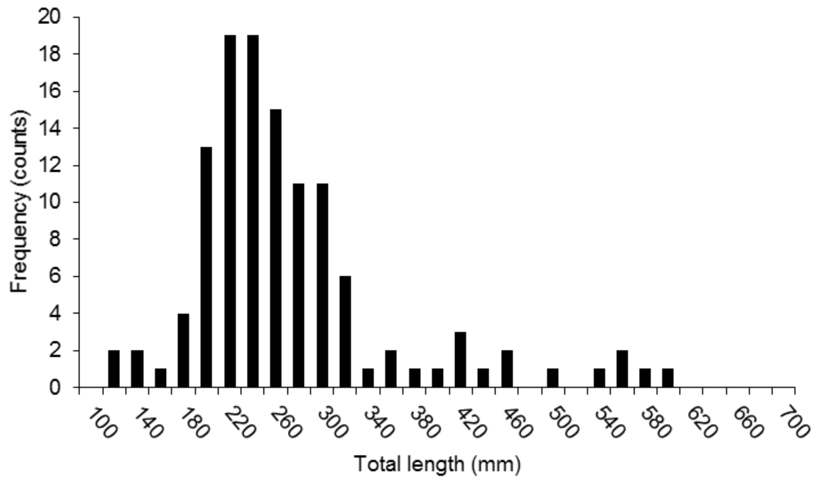

Figure 3. Length-frequency distribution for carp removed from Stebonheath managed aquifer recharge wetland during the October 2014 eradication program (*n*=120).

Golf course wetland- May 2015

A total of 449 carp (362 kg ha^{-1}) were removed from the golf course wetland during May 2015 (Table 4 and Figure 4). The length-frequency distribution of carp was multimodal with 6 carp (10%) in the 120-180 mm TL size class and 46 carp (76.7%) in the 220-460 mm TL size class. Carp >560 mm TL represented 13.3% (*n*=8) and the largest carp measured was 860 mm TL. Length at age relationships (Smith 2005) indicate that carp within the 100-120 mm TL size class are <1 year of age, carp 220-460 mm TL range from 1 to 4 years of age and carp >560 mm TL are >7 years of age.

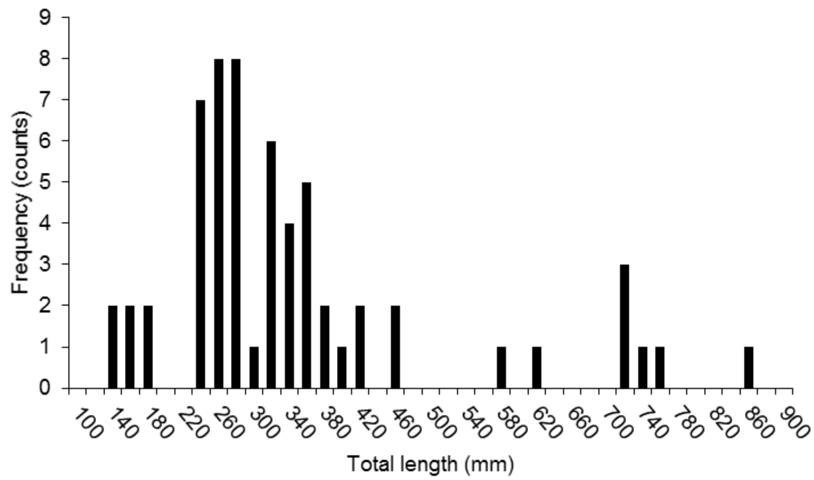

Figure 4. Length-frequency distribution for carp removed from the golf course wetland during the May 2015 eradication program (*n*=60).

Steb-Curtis catchment basin- May 2015 and May 2016

A total of 696 carp (208 kg ha^{-1}) were removed from the Steb-Curtis catchment basin during May 2015 (Table 4 and Figure 5). The length-frequency distribution of carp was bimodal with a total of 43 carp (41.7%) in the 80-160 mm TL size class and 54 carp (52.4%) in the 180-340 mm TL size class. Carp >360 mm TL represented 5.8% (*n*=6) and the largest carp measured was 690 mm TL. Length at age relationships (Smith 2005) indicate that carp within the 80-160 mm TL size class are <1 year of age, carp 180-340 mm TL range from ~1 to 3 years of age, carp >360 mm TL are 3+ years of age and carp >600 mm TL are likely to be >10 years of age.

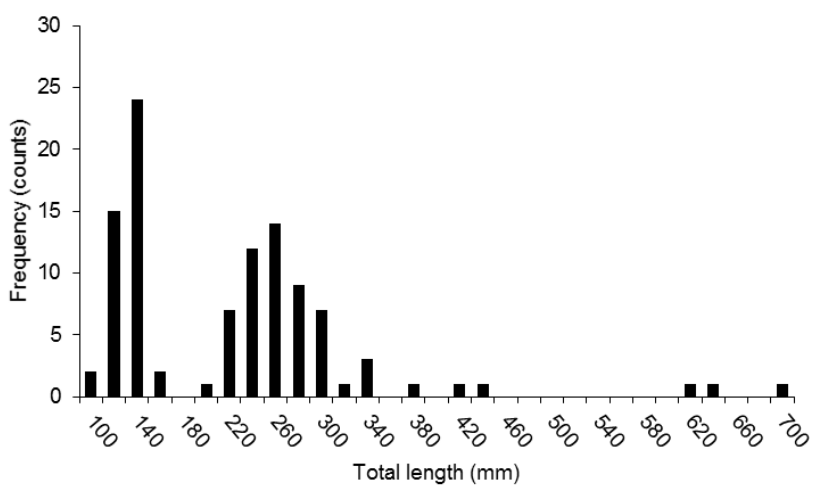

Figure 5. Length-frequency distribution for carp removed from the Steb-Curtis catchment basin during the May 2015 eradication program (*n*=103).

A total of 239 carp (210 kg ha^{-1}) were removed during May 2016 (Table 4 and Figure 6). The length-frequency distribution of carp (*n*=20) was unimodal with a total of 17 carp (85%) in the 220-360 mm TL size class and the highest frequency count of 5 carp (25%) in the 280-300 mm TL size class. Carp >520 mm TL represented 15% (*n*=3) of the population and the largest carp measured was 600 mm TL. Length at age relationships (Smith 2005) indicate that carp within the 220-360 mm TL size class range from 1 to 3 years of age while carp >520 mm TL are >6 years of age.

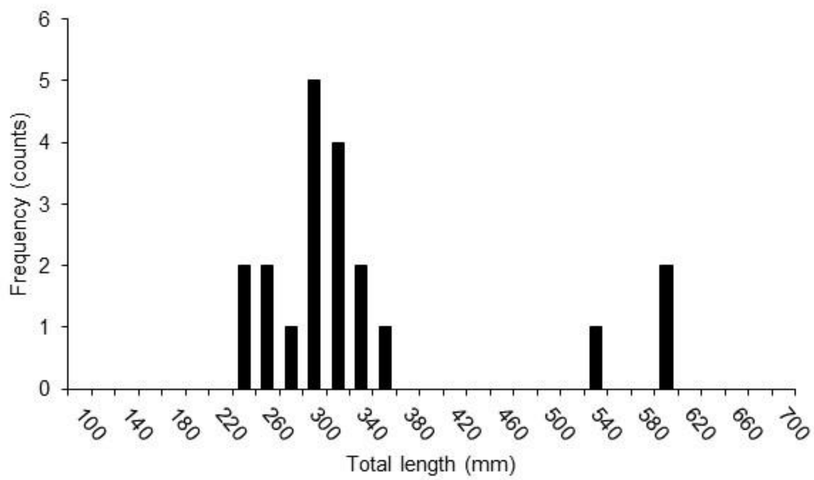

Figure 6. Length-frequency distribution for carp removed from Steb-Curtis catchment basin during the May 2016 eradication program (*n*=20).

Carp removed from the Steb-Curtis catchment basin during the second program were likely a combination of fish that survived the first eradication program (May 2105) and fish that migrated downstream into the wetland from Munno Para MAR wetland, Steb-Curtis MAR wetland and the golf course wetland. Indeed, all three upstream wetlands are connected to the catchment basin via surficial drains or underground pipes, they were all observed to overflow on several occasions between the May 2015 and May 2016 (David Strange, City of Playford, pers. comm) and at least two of these wetlands contained seed stock during this period (Munno Para and Steb-curtis MAR wetlands; see above). While an eradication program was conducted in the golf course during May 2015, assuming a 91% density reduction (see above) suggests it may have also contained a low abundance of survivors.

Steb-Curtis MAR wetland- May 2016

A total of 807 carp (142 kg ha^{-1}) were removed from the Steb-Curtis MAR wetland during May 2016 (Table 4 and Figure 7). The length-frequency distribution of carp was unimodal with a total of 78 carp (97.5%) in the 160-380 mm TL size class and the highest frequency count of 17 carp (21.3%) in the 220-240 mm TL size class. Carp >560 mm TL represented 2.5% (*n*=2) and the largest carp measured was 640 mm TL. Length at age relationships (Smith 2005) indicate that carp within the 160-380 mm TL size class range from 1 to 3 years of age while carp >560 mm TL are likely to be >7 years of age.

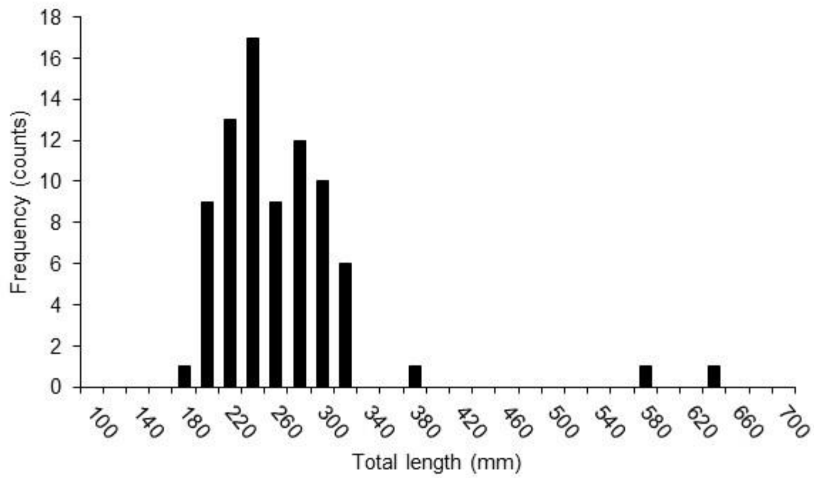

Figure 7. Length-frequency distribution for carp removed from Steb-Curtis managed aquifer recharge wetland during the May 2016 eradication program (*n*=100).

Non-target species

The rotenone carp eradication programs had negligible impacts on non-target species. No dead/sick birds, amphibians or terrestrial reptiles and mammals were recorded, there were no reported impacts on the community or pets and post rotenone seining captured several live yabbies and shrimp. While there may have been a decrease in the biomass of some aquatic macro-invertebrates, these communities have been observed to recover quickly after the application of rotenone (Ling 2002; SARDI, unpublished data).

Table 4. Summary statistics for City of Playford managed aquifer recharge scheme carp eradication program.

	Munno Para	**Stebonheath**	**Golf Course**	**Steb-Curtis Catchment basin**	**Munno Para 2**	**Steb-Curtis Wetland**	**Steb-Curtis Catchment basin 2**
Abundance of carp removed	12,000*	9,000	449	696	3,515	807	239
Mean TL (mm) ± S.E	300**	264.3 ± 8.3	339.5 ± 21.1	215.0 ± 10.5	298.5 ± 10.4	255.0 ± 7.7	334.4 ± 24.2
Mean weight (g) ± S.E	510	376.3 ± 48.0	1041.2 ± 267.7	254.4 ± 60.7	511.8 ± 63.5	307.7 ± 60.1	747.3 ± 210
Total weight of carp removed (kg)	6,123	3,386	468	177	1,799	249	179
Wetland area (ha)	5	3.39	1.29	0.85	5	1.75	0.85
Density of carp removed (kg ha^{-1})	1,225	998	362	208	360	142	210
Estimated density before*** (kg ha^{-1})	1340	1084	393	226	391	173	228
Estimated density after*** (kg ha^{-1})	115	86	31	18	31	14	18
Turbidity before	32	45	Turbid	Turbid	38	34	Turbid
Turbidity after	3	5	Clear	Clear	5	4	Clear

*7,000 carp removed during rotenone eradication program; 5,000 carp captured in netting activities conducted by the City of Playford prior to the application of rotenone.

**Estimated from length-weight relationship derived from the second treatment of Munno Para managed aquifer recharge wetland (Munno Para 2).

***Estimated densities before and after assume the eradication programs achieved a density reduction of ~91% (see Munno Para above).

Water Quality

The results of the carp eradication program indicate that high densities of carp were the primary cause of turbidity levels exceeding the groundwater recharge threshold (>20 NTU). Indeed, substantial improvements in turbidity were observed within two days across all rotenone treated wetlands (Table 4). Plotting turbidity (NTU) as a function of carp densities before and after each eradication program (kg ha^{-1}) shows a rapid increase in turbidity at densities of ~173 kg ha^{-1} with turbidity <5 NTU below this threshold and >32 NTU above (Figure 8). This is consistent with previous research that demonstrated a shift from clear to turbid water state at carp densities >174 kg ha^{-1} (Williams et al. 2002; Parkos et al. 2003; Haas et al. 2007; Matsuzaki et al. 2009).

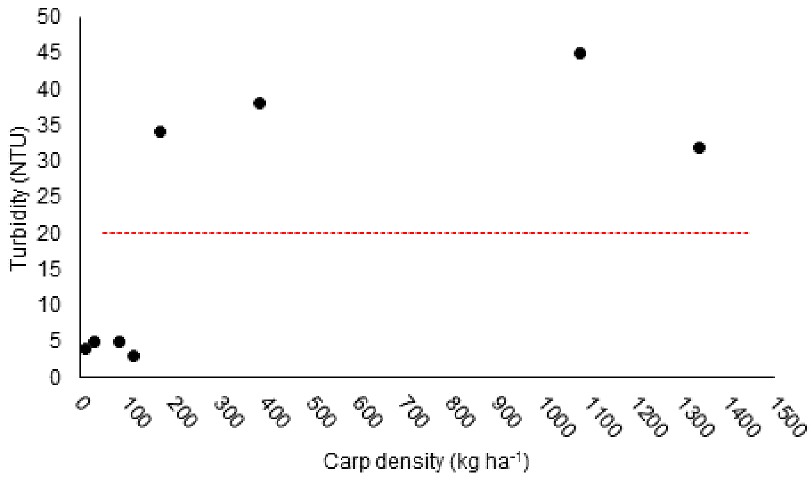

Figure 8. Turbidity (NTU) as a function of carp density (kg ha^{-1}) (from Table 4). Dashed red line indicates the 20 NTU groundwater recharge threshold.

The pre-eradication turbidity levels can be attributed to the high density and benthic feeding behaviour of carp (Sibbing et al. 1986). Benthic feeding commences at 20-25 mm SL (standard length) and represents the primary feeding mechanism of adult carp (Vilizzi and Walker 1999; Smith 2005). The mechanism involves carp drawing mouthfuls of sediment into the oral cavity. Food items including molluscs, invertebrates, detritus and seeds are retained by the pharyngeal slits while finer particles (i.e. sediment) are expelled behind the opercula (Hall 1981; Sibbing 1982; Sibbing et al. 1986; Callan and Sanderson 2003; Makiguchi et al. 2012). The behaviour results in a "cloud" of suspended sediment forming behind foraging fish and an associated reduction in water clarity (i.e. increased turbidity). Significant increases in turbidity can occur at carp densities as low as ~50 kg ha^{-1} (Zambrano and Hinojosa 1999).

MAR scheme carp invasion and management

The MAR scheme is situated in Smith Creek catchment which is characterised by intermittent drains and creeks that dry between rainfall events. The absence of permanent aquatic habitat suggests the initial Smith Creek catchment incursion resulted from deliberate introduction of carp translocated from outside the catchment. In this regard, sampling across 50 sites in the North Para, Gawler and Little Para rivers between 2011-2014 detected 227 carp indicating the presence of established populations within relatively close proximity (<10 km; SARDI unpub. data). While it is difficult to determine the actual origin of fish without the use of DNA technology or otolith microchemistry, these populations represent the most likely source of introduced carp.

The golf course wetland was constructed during 1992-1993, approximately 14 years before the first MAR wetland (Stebonheath). While there are no records of when carp were translocated into this wetland, observations of several carp moving from the wetland toward Stebonheath during its filling process in 2007-2008 (David Strange, City of Playford pers. comm) indicate a population had established prior to 2007. The results of the eradication program suggest that this may have even occurred within a few years following the wetlands construction. Indeed, 52 carp (~11%) removed during the program were >600 mm TL (>12 years old) with the largest carp being 860 mm TL (>16 years). Regardless, carp were present within the golf course wetland prior to development of the MAR scheme and this population represents the likely seed stock that eventually spread throughout the scheme.

The observation of carp moving from the golf course wetland toward Stebonheath during its filling process suggest this MAR wetland and Steb-Curtis catchment basin were seeding in the initial stages of their operation. The design of the MAR scheme permits unimpeded downstream movement through a series of channels connecting the golf course to Stebonheath via the catchment basin (Figure 1). The results of the population modelling indicate that, if survival rates within MAR wetlands are similar to artificially inundated floodplain, as little as 3 adult female carp and at least one male or 2,932 fingerlings or 21,700 larvae were required to seed the wetland during 2007 to achieve the abundance of carp removed during the 2014 eradication program (Table 5).

While Stebonheath was likely seeded during the filling event, both Munno Para and Steb-Curtis MAR wetlands are upstream of the catchment basin suggesting that carp were initially translocated into these wetlands. Indeed, length at age relationships indicate that several carp removed from both Munno Para and Steb-Curtis were older than the wetlands (see above). If survival rates are similar to artificially inundated floodplains, it would have required the translocation of only 1-2 adult females and one male into Steb-Curtis and approximately 20 female carp and one male into Munno Para during the initial stages of their operation to achieve the abundances removed during the eradication programs (Table 5). Given the proximity of established seed stocks (i.e. Stebonheath <1.5 km), translocation would have been a relatively simple process.

Table 5. Abundance of adult (2.5 kg), fingerling and larval carp required in the initial stages of each managed aquifer recharge wetland to facilitate the level of population growth needed to achieve the total number of carp removed during the rotenone programs.

MAR wetland	No. of carp removed	Adult females	Fingerlings	Larvae
Munno Para	12,000	20.4	17,130	126,800
Stebonheath	9,000	3.5	2932	21,700
Steb-Curtis	1,046	1.6	1,306	9,670

While it is likely that carp were periodically spread across the MAR scheme via translocation and overflow events, this evaluation demonstrates the ease with which carp infestations can occur/persist and highlights the need to develop management strategies that aim to mitigate future incursions and the subsequent spread of carp. Given that carp can move throughout the MAR scheme via connecting drains/pipes and translocation, it is recommended that future control programs aim to eradicate carp from the entire scheme over one concerted campaign. To increase the probability of complete eradication, the highest permitted rotenone dosage rates should be utilised. Greater effort should be applied at partially inundated reed beds, submerged/inundated drains and cavities within the gabion basket walls as these locations may provide refuge for juvenile carp during the treatment process. To mitigate the possibility of carp re-seeding wetlands via connected drains/pipes over the duration of the campaign, it should be conducted in late summer, water bodies drawn-down and rotenone systematically applied from upstream to downstream. To discourage translocation of carp from within the system or neighbouring catchments, the campaign should be conducted in conjunction with on-going public education and security guards should be deployed for the duration of the campaign. This strategy is likely to yield the greatest long-term benefits by eliminating seed stocks from within the catchment and targeting translocation from neighbouring catchments as a primary vector for re-introduction.

4. CONCLUSION

Rotenone is an effective tool for controlling carp in constructed urban wetlands. As a result of the rotenone carp eradication program a total of 26,706 carp (12,381 kg) were removed from across the City of Playfords MAR scheme between 2014 and 2016. Substantial improvements in turbidity were observed within two days across all rotenone treated wetlands indicating that carp were the primary cause of elevated levels (>20 NTU). However, the ease with which carp infestations can occur/persist and the cost associated with continual removal highlights the need for management strategies that aim to mitigate future incursions and the spread of carp throughout the scheme. The most appropriate strategy is to eradicate carp from across the entire system over one concerted eradication campaign and discourage cross catchment translocation via a public education program. This strategy is likely to yield the greatest long-term benefits by eliminating seed stocks from within the catchment and attempting to mitigate translocation of carp from neighbouring catchments.

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