Mallee CMA

SDL Fish Management Plan
Hattah Lakes

December 2018

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Executive summary

Significance of Hattah Lakes for fish

Hattah Lakes is an extensive complex of lakes and floodplain set within the Hattah–Kulkyne National Park and the Murray–Kulkyne Regional Park. Twelve of the lakes are listed as internationally important wetland systems under the Ramsar Convention on Wetlands of International significance (the Ramsar Convention), primarily for their value as waterbird habitat and importance in maintaining regional biodiversity. The values that relate to the Ramsar criteria which relate to fish and need to be considered in any management actions are (detail in Section 9.1):

- Threatened fish species mentioned under these criteria were Murray cod (*Maccullochella peelii),* silver perch (*Bidyanus bidyanus), and* flat-headed galaxias (*Galaxias rostratus)*
- important for fish breeding and
- important nursery area for native fish

Current condition for fish

While the site is not within a weir pool, the general impact of river regulation has been to reduce peak flows, change the seasonality of flows and increase minimum flows. The condition of ecological values has declined in response to altered flow regimes. Aquatic habitat is available much less frequently and for shorter periods than under natural unregulated conditions. This decline has been exacerbated by drought and the lakes are less able to provide refuge during extended dry periods and less able to support local populations of aquatic fauna.

Up to 10 species of native freshwater fish inhabit the Hattah Lakes, with these dominated by the small-bodied generalist species that have flexible life-history strategies regarding flow conditions. From TLM and project specific monitoring at Hattah, there is a decline in the long-term population abundance and diversity trajectory of these small-bodied fishes (Ellis and Wood 2011; Henderson et al. 2012; 2013; 2014). Larger and medium bodied native fish species, such as golden perch, are more uncommon and this is because of the infrequent flood events which enable access to the Hattah Lakes from the nearby Murray River. No wetland specialist fish species, such as southern pygmy perch, are present reflecting broad-scale declines across the Murray-Darling Basin.

The Living Murray Program

- The Hattah Lakes is an Icon Site under The Living Murray (TLM) initiative, has had associated works completed and in operation, with nine ecological objectives created along with the hydrological regimes to meet the objectives. As a result, a permanent pump station on the Murray River, three major regulating structures and block banks were built to achieve the hydrological regimes. The operating scenarios (as detailed in the Hattah Lakes Operating Plan) are to:
    - Allow natural inflows/outflows
    - Enhance natural – extend duration (using natural flows)
    - Enhance natural – extend duration and extent (using natural then pumped flows)
    - Managed event (pumped flows) and
    - Maintenance (in years with no watering operation).

Basin Plan SDL Adjustment

The Hattah Lakes North Floodplain Management Project is a supply measure under the Murray-Darling Basin Plan's Sustainable Diversion Limit (SDL) adjustment mechanism. The Hattah Lakes North Project will allow inundation of the floodplain using smaller amounts of water than would typically be required, which in this case would be an overbank flood.

The project will complement existing environmental infrastructure constructed under The Living Murray program by significantly enhancing and extending environmental outcomes across the higher parts of the floodplain (to the north). The project will also provide the flexibility to better manage the frequency and duration of inundation across the whole of the Hattah floodplain system and tailor watering to ecological cues and requirements.

Fish Management Opportunities

Managed flooding of the Hattah Lakes is achieved via the Murray River pumps, so the wetlands represent a 'filtered' fish community. However, after natural flooding the forest, some native fish could potentially be rehabilitated and managed with top-up flows at a local wetland scale.

The main purpose of the Hattah Fish Management Plan is to:

1. provide the necessary design criteria to be incorporated into SDL detailed designs
2. provide the operational requirements that benefit native fish for the SDL site Operating Plans
3. establish prioritised ecological objectives and targets for fish at the site, and
4. understand the context of site operations and to maximise the ecological outcomes on a reach scale

To meet these goals, conceptual models were developed, based on the literature, to clearly articulate the life-history of fish and their relationship to local hydrology. This enabled clear identification of recovery actions and knowledge gaps. The major opportunities identified are:

i. Evaluate the current condition of fish communities at Hattah that could serve as a population source.

ii. Develop a series of permanent wetlands with a modified filling and top-up hydrology which contain optimum habitat characteristics and where water delivery can be easily to support reintroduced and local fish populations. Preliminary wetlands are Bulla, Arawak, and Brokie because they are small, terminal and at a low elevation so that there are maximum filling options. Chalka Creek could also be managed as a permanent refuge habitat.

iii. Recovery of small-bodied wetland generalist fish species in permanent wetlands because these have declined locally. These include unspecked hardyhead, flat-headed gudgeons, carp gudgeons, Australian smelt and Murray-Darling rainbowfish.

iv. Threatened species translocation of small-bodied fish species, potentially including unspecked hardyhead, Australian smelt, flat-headed gudgeons and Murray-Darling rainbowfish. There is potential to expand this approach to include several threatened species (e.g. southern pygmy perch and flat-headed galaxias (and the medium-bodied freshwater catfish) where permanent wetlands can be re-established.

In summary, for recovery of small-bodied fish at Hattah there is a need to develop and maintain a series of permanent wetlands, which are not dried out, and can act as a source for broad re-population.

A final opportunity was identified, which was to experimentally test whether Lake Kramen or Lake Bitterang could be restored to act as a nursery habitat for stocked golden perch larvae/fingerlings, including a detailed exit hydrograph to improve the return of fish to permanent habitats or to locations where they can be collected and transported to permanent habitats. A detailed framework is provided to test this initiative, which, if successful, has potential to contribute to regional populations. This initiative would represent the first restoration of a Murray Valley golden perch nursery habitat and has significant value as a progressive and sophisticated project for Mallee CMA. The key to this is to demonstrate the proof-of-concept experimental approach and the potential benefits. Importantly, there is very low to nil risk to existing golden perch or other native fish populations.

The preparation of this Fish Management Plan included a risk assessment to protect aquatic values of the Hattah Lakes from potential threats posed to them. The risk assessment concluded that, of the six threats initially identified as medium risk or higher, two threats remained a medium risk once mitigation measures were considered. A summary of these threats and recommended mitigation measures is provided in the table below:

Threat	Proposed mitigation measures	Residual risk
Permanent wetlands support the establishment of invasive plant and animal species.	• Manage water levels with permanent regime to support native species and interrupt invasive species breeding cycles. • Rotate target wetlands over the long term to remove invasive species. • Install mechanical exclusion devices when filling wetlands • Develop carp management plan for Hattah system • Introduce carp herpes virus.	Medium
Stocked species introduce diseases and pathogens into native populations.	• Ensure all stocked species are sourced from quality accredited hatcheries. • Monitor and adapt.	Low
Altered hydrological regime - wetlands supports the establishment of invasive plant and animal species.	• Manage water levels with permanent regime to support native species and interrupt invasive species breeding cycles. • Rotate target wetlands over the long term to remove invasive species. • Install mechanical exclusion devices when filling wetlands. • Develop carp management plan for Hattah system • Introduce carp herpes virus.	Medium

The Hattah Fish Management Plan provides a strategic and practical way forward in recovering local small-bodied native fish with potential future extension to threatened species.

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1. Introduction

1.1 Purpose

The purpose of the Fish Management Plan is:

1. to provide the necessary design criteria to be incorporated into SDL detailed designs
2. to provide the operational requirements that benefit native fish for the SDL site Operating Plans
3. to establish prioritised ecological objectives and targets for fish at the site
4. to understand the context of site operations and to maximise the ecological outcomes on a reach scale.

1.2 Background

Hattah Lakes is an extensive complex of lakes and floodplain set within the Hattah–Kulkyne National Park and the Murray–Kulkyne Regional Park. Twelve of the lakes are listed as internationally important wetland systems under the Ramsar Convention on Wetlands of International significance (the Ramsar Convention), primarily for their value as waterbird habitat and importance in maintaining regional biodiversity.

While the site is not within a weir pool, the general impact of river regulation has been to reduce peak flows, change the seasonality of flows and increase minimum flows. The condition of ecological values has declined in response to altered flow regimes. Aquatic habitat is available much less frequently and for shorter periods than under natural unregulated conditions. This decline has been exacerbated by drought and the lakes are less able to provide refuge during extended dry periods and less able to support local populations of aquatic fauna.

1.2.1 The Living Murray

The Hattah Lakes is one of six sites identified as an Icon Site under The Living Murray (TLM) initiative and has had works completed and in operation under this program. As part of TLM nine ecological objectives were created (refer Section 9.2) along with the hydrological regimes to meet the objectives. As a result a permanent pump station on the Murray River, three major regulating structures and block banks were built to achieve the hydrological regimes. The operating scenarios (as detailed in the Hattah Lakes Operating Plan) are to:

- allow natural inflows/outflows
- enhance natural – extend duration (using natural flows)
- enhance natural – extend duration and extent (using natural then pumped flows)
- managed event (pumped flows)
- maintenance (in years with no watering operation)

The details of the structures, operations and flow regimes under this program are in Section 4.

1.2.2 Basin plan SDL adjustment

The Hattah Lakes North Floodplain Management Project is a supply measure under the Murray-Darling Basin Plan's Sustainable Diversion Limit (SDL) adjustment mechanism. Supply measures are works, river operations or rules changes that use less water whilst still achieving Basin Plan environmental outcomes. The Hattah Lakes North Project will allow inundation of the floodplain using smaller amounts of water than would typically be required, which in this case would be an overbank flood.

The project will complement existing environmental infrastructure constructed under the TLM program by significantly enhancing and extending environmental outcomes across the higher parts of the floodplain (to the north). The project will also provide the flexibility to better manage the frequency and duration of inundation across the whole of the Hattah floodplain system and tailor watering to ecological cues and requirements.

The details of the structures, operations and flow regimes under this program are provided in Section 4.

1.3 Acknowledgements

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PART A –Context (desktop and field assessment)

2. Site context

2.1 Location

The Hattah Lakes are within the Hattah Kulkyne National Park and the Murray–Kulkyne Regional Park, 60 km south of Mildura on the Victorian floodplain of the Murray River.

It is an extensive complex of approximately 20 perennial and intermittent freshwater lakes, ranging in size from less than 10 ha to about 200 ha. Twelve of the lakes are listed as internationally important wetland systems under the Ramsar Convention on Wetlands of International significance (the Ramsar Convention), primarily for their value as waterbird habitat and importance in maintaining regional biodiversity. The Hattah-Kulkyne Lakes Ramsar site meets five of the Ramsar listing criteria based on internationally important wetlands. Those that relate to fish are because it:

- supports vulnerable, endangered, or critically endangered species or threatened ecological communities (Criterion 2)
- supports plants and/or animal species at a critical stage in their life cycles, or provides refuge during adverse conditions, (Criterion 4)
- is an important source of food for fishes, spawning ground, nursery and/or migration path on which fish stocks, either within the wetland or elsewhere, depend (Criterion 8)

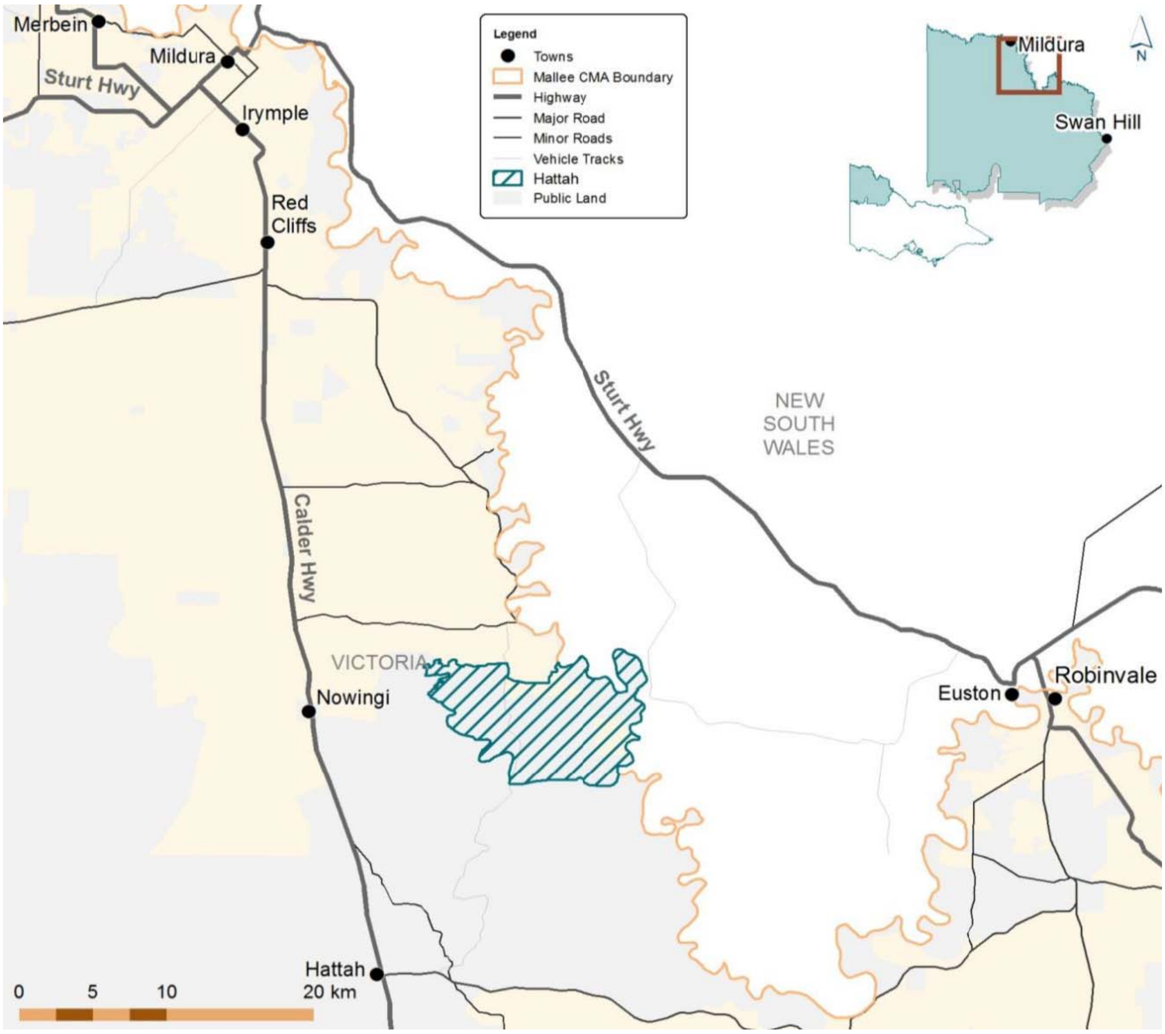
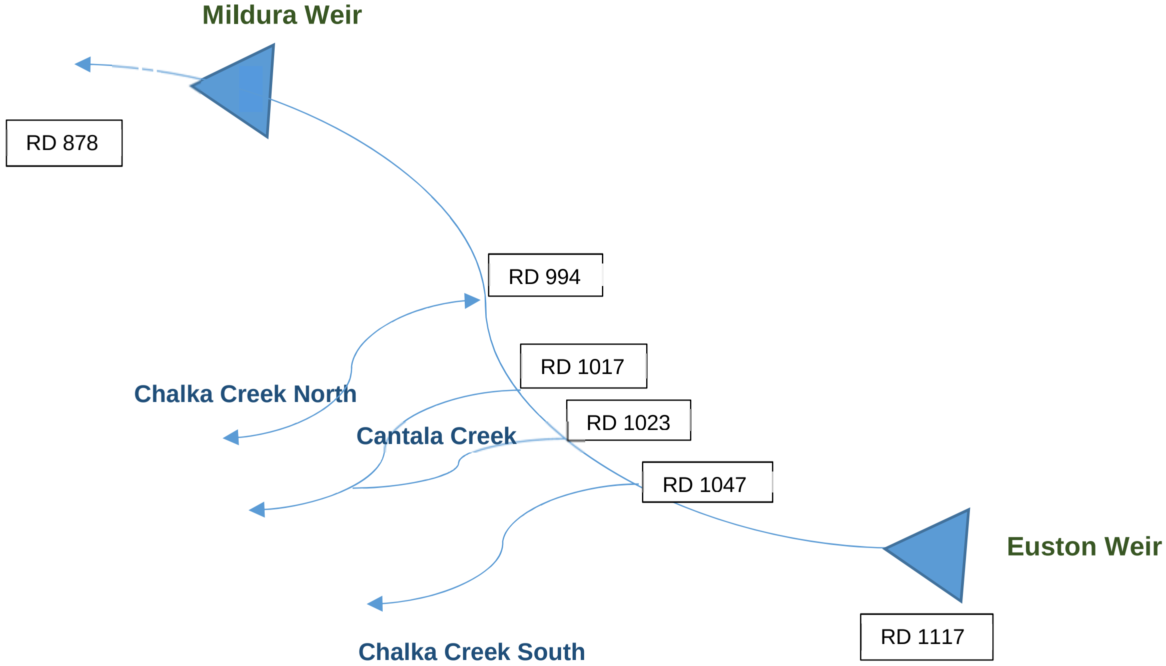


Figure 1 Hattah Lakes regional context

2.2 Site context in relation to the Murray River

The Hattah-Kulkyne National Park is located downstream of Euston Weir (Lock 15, RD 1117 river kms) and upstream of Mildura Weir (Lock 11, RD 878 river kms). Euston Weir is the closest weir to the Hattah Lakes inlet (Chalka Creek South) and the most reliable gauging location and so often has been used as a key site for flow references (Figure 2). There is a noted travel time of approximately 2 days from Euston Weir to Chalka Creek South Inlet (70 km downstream).

The entrance to Chalka Creek South is located at RD 1047 river kms, and the entrance to Chalka Creek North is located at RD 994 river kms. Cantala Creek separates off from the Murray River in two inlets (RD 1017 and RD 1023 river kms) which then combine to a single



channel, supplying Lake Cantala.

Figure 2 Hattah Lakes inlets and outlets on the Murray River

2.3 The Hattah Lakes

The lakes system at the Hattah-Kulkyne National Park is unique, consisting of over 20 lakes, of varying size and location, which can be connected to the Murray River by over 20 km of waterways.

While most of the lakes lie within the central lakes area, some are geographically distinct from these. A summary of the lakes and interconnections in provided below:

- Central lakes area (contains numerous lakes including Lakes Lockie, Hattah, Little Hattah, Yerang, Mournpall and Bulla)
- Lake Cantala, located north east of the central lakes area and with a separate inlet channel from the Murray River, this lake also connects with the main lakes system through Cantala Creek extending from Lake Cantala to Chalka Creek North.
- Lake Kramen, located south east of the central lakes, is one of the most estranged lakes in the system and is supplied in larger floods through overflows from Chalka Creek South or also through back-flooding from the central lakes system.

- Lake Bitterang, a larger lake located just north of, but separate to the central lakes area
- Dry Lakes –located far north-west of the central lakes system, and are relatively separated from the central lakes area. They were traditionally supplied through overflows in the Chalka Creek North branch, but are infrequently flooded.
- The Hattah Lakes Northern floodplain complex is 9,028 ha in size and comprises lakes and surrounding woodlands that receive water from the Murray River via Chalka Creek (Mallee CMA, 2014).

3. Hydrology

3.1 Murray River context

The Murray River has experienced a range of floods over recent recorded history. The significant flooding event in 1956 is regarded as an approximately 1 in 100-year event over much of the Murray River in this region.

The key recent flood events in this area are:

- 1956 Flood – no record at Euston but back noted to a flood level approximately 52.6 mAHD at Euston Weir (at Chalka Creek South inlet this corresponded to a flood level of approximately 47.4 mAHD)
- 1975 Flood – recorded as peaking on 27 November at a level of 51.745 mAHD and peak flow of 204,500 ML/d (at Chalka Creek South inlet this corresponded to a flood level of approximately 46.8 mAHD)
- 1993 Flood – recorded as peaking November at 51.4 mAHD, 170,000 ML/d

Table 1 (from MDBA, 2012a) shows the significant reduction in peak and duration of flooding events for different river flow scenarios for pre-development and then "Modelled Current", which is the scenario prior to the 2012 works undertaken at Hattah (using a threshold of 36,700 ML/d inception to flow). The comparison is then made with a median climate change scenario in place (at 2030) to show the continued trend anticipated. With the 2012 works in place, much of the central lakes area at Hattah can now be flooded much lower Murray River levels and independently of Murray River flows, due to the permanent pumping infrastructure in place and the lower threshold of inception to flow.

Table 1 Modelled reduction in flow peaks and duration, pre development to 2012

River flow (GL/day)	Flood count (% of years with flow peaks above threshold)			Effective flood (% of years flow exceeds the threshold for at least three months)		
	Modelled pre-development	**Modelled (2012)**	**Median climate change scenario at year 2030**	**Modelled pre-development**	**Modelled 2012**	**Median climate change scenario at year 2030**
40	82	47	37	48	20	11
60	59	31	22	21	7	3
75	47	23	12	16	7	3
100	36	12	8	19	8	4
150	18	6	2	4	2	1

There have also been times of extreme dry or drought in this region of the Murray River, including the:

- Federation drought (mid- 1890s to early 1900s)
- droughts around the World War II (1937 to 1945)
- short duration drought (1982 to 1983)
- the Millennium Drought (or 2000s Drought), from 1996 to early 2010, which severely impacted this part of the Murray-Darling Basin. The drought developed with low rainfalls in 1996 to 1997, a

condition which degenerated until 2003 when it was largely defined as the most severe drought on record. Drought conditions continued, with 2006 the most severe, until the drought concluded in 2010. During the drought, some minor level environmental pumping took place at Hattah Lakes to enable water into Lake Hattah and Lake Lockie at lower levels. Figure 3 shows the impact of the Millennium drought at Euston Weir.

3.1.1 Euston Lock and Weir

Euston Weir and lock was constructed from 1932 to 1937 and is located at RD 1,117 km. Situated approximately 45 km downstream of Belsar Island and just west (downstream) of Robinvale, the normal operating full supply level at Euston Weir is 47.6 mAHD (Ecological Associates, 2015).

Euston Weir consists of 12 bays with concrete piers and stop logs, a fish lock chamber and a Denil fishway. Euston weir pool extends up to 60 km at normal weir pool level and at this level the weir can store 76 GL of water with an approximate head difference across the weir of five metres. The upstream and downstream weir pools equalise at around 53,000 ML/d flows. The stop logs can be removed when flows rise to 40,000 to 50,000 ML/d, then replaced when flows fall in the range 30,000 to 56,000 ML/d.

Recent historical data at Euston Weir shows the weir has been operated at a range of weir pool levels in recent years, lowering 0.2 to 0.3 m below normal pool level and up to 0.6 m above weir pool level (ranging from 47.3 to 48.2 mAHD). Weir pool manipulations have been occurring on a seasonal basis in more recent years, with approximately four different weir pool level settings being used from July 2015 to June 2016 (Figure 3).

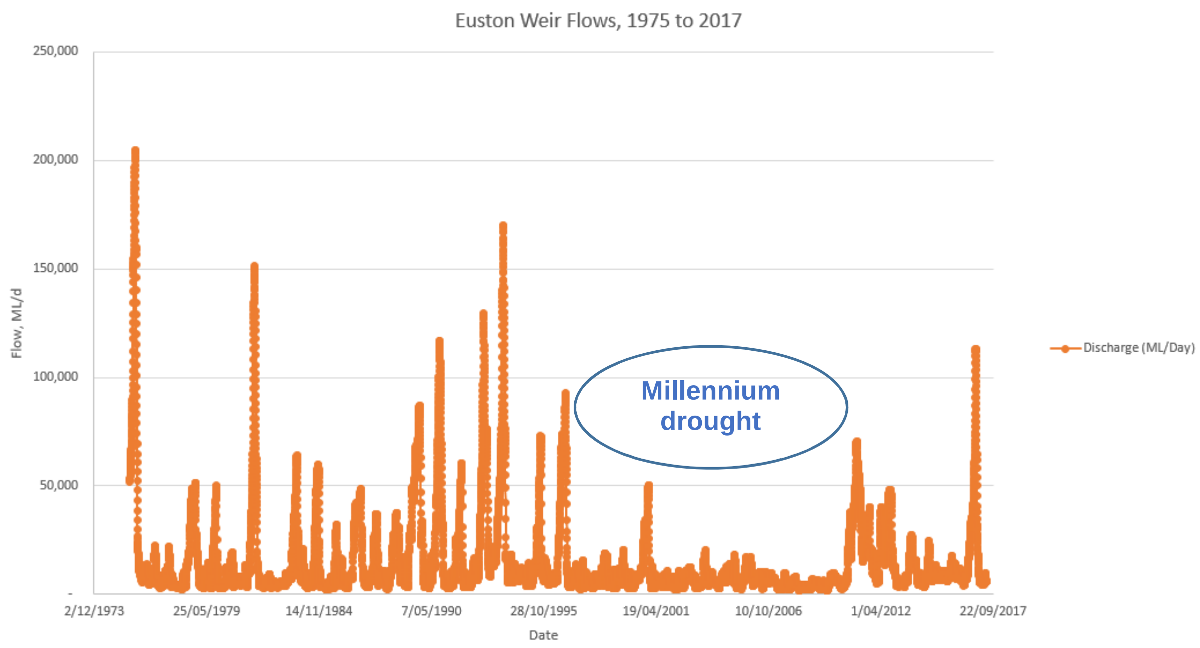


Figure 3 Flow information at Euston Weir from 1975 to 2017, MDBA (2017)

The initial Denil fishway retrofitted at Euston Weir on the right abutment (NSW side) in 1993 was based on the American salmon model and only allowing passage of larger native fish. In 1996 and 2000 modifications were undertaken to install fibreglass Denil inserts to address fish passage needs for smaller fish also (adjacent to NSW bank). In 2013 two extension ramps and two exits were added, providing a total of three exits, to enable more successful fish movement during weir pool manipulations. While this fishway generally provides passage for larger fish, the movement of juvenile or small bodied fish through the fishway remains limited.

A fishlock was constructed in 2013 adjacent to the lock chamber (on Victorian bank side), particularly targeting smelt and other small bodied fish. The upstream gate ranges from 46.20 to 48.24 mAHD and the downstream gate ranges from 42.5 to 47.64 mAHD, targeting small fish up to 44.0 mAHD and larger fish above that level (J Smart, pers. comm.).

The fishways operate within the range of 3,500 ML/d to 35,000 ML/d, with the Denil operating up to maximum operating level. PIT (Passive Integrated Transponder) tag systems have been installed at Euston Weir to track fish movement of tagged fish (Ecological Associates, 2015).

Recent hydrological investigations (Fluvial Systems, 2014; Ecological Associates, 2015) have revealed significant reduction in frequency and duration of flooding at Euston. For flows ranging from 20,000 to 170,000 ML/d, frequency of flooding has reduced by 50 to 70% from pre-regulated events. Duration of flooding has also reduced by approximately 50% from pre-regulated events in the flow range of 20,000 to 60,000 ML/d. Analysis indicates that the duration of the events is still comparable for events more than 90,000 ML/d. There are more events in the lower threshold range of 10,000 ML/d but they have a much shorter duration than pre-regulated conditions (current duration less than one month, pre-regulation six months to one year).

3.1.2 Mildura Lock and Weir

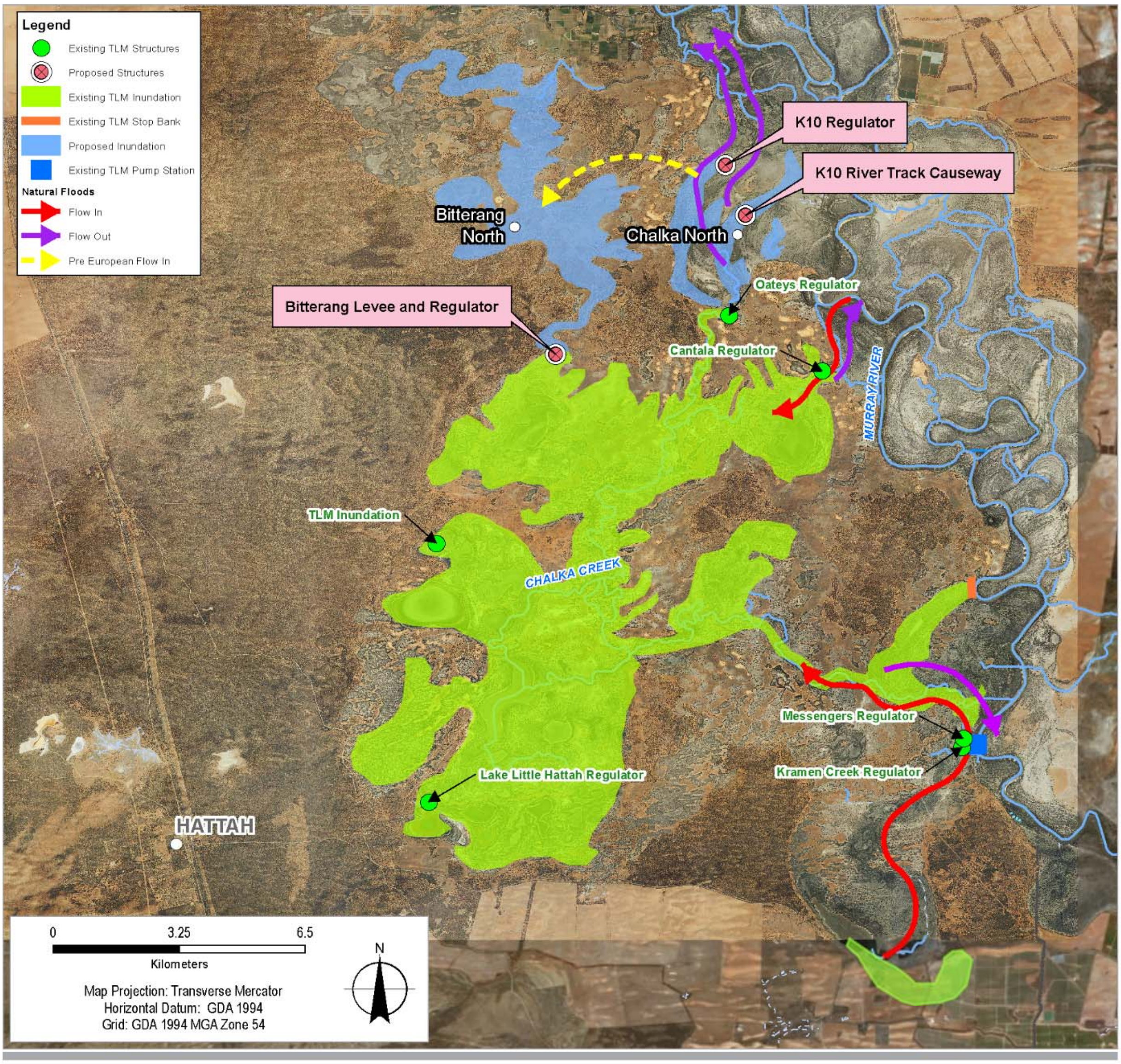
Mildura Weir and lock (Lock 11) was constructed from 1923 to 1927 and is located at RD 878 km. The normal operating full supply level at Mildura Weir is 34.4 mAHD. Mildura Weir is a Dethridge weir, consisting of 24 steel trestles that run on rails from the invert of the river and can be removed by winching. Mildura weir pool extends to approximately 35 km upstream at normal weir pool level (Bottle Bend/Karadoc area) and at this level the weir can store 36 GL of water with an approximate head difference across the weir of 3.6 metres. There is no indication that Mildura Weir has been operated under any significant weir pool manipulation regime.

The Mildura Weir had a Denil fishway retrofitted on the left abutment (Victorian side) in 2013. The fishway targets medium to large fish (>100 mm) and consists of six ramps and six resting pools, with an upstream operating range of 34.25 to 34.50 mAHD and a downstream operating range of 30.64 to 32.65 mAHD, equating to a flow of 33,000 ML/d. Above this flow the fishway is removed (J Smart, personal communications October 2017).

The Hattah Lakes system (including Chalka Creek South and Chalka Creek North) are not impacted by Mildura Weir pool levels as the Hattah National Park has inlets and outlets from RD 1047 to RD 994, at least 116 km upstream of Mildura Weir and well beyond the weir pool influence of 35 km upstream.

3.2 Hattah Lakes

The Hattah Lakes have varying volumes, depths and interconnections (Table 2). Water enters the system from Chalka Creek South into Lake Lockie, which acts as a central distribution lake. Water then works its way either up north to the Lake Mournpall/Lake Konardin/Lake Yelwell complex or down south to the Lake Little Hattah/Lake Hattah complex (Figure 4). Flows paths during TLM pumped events and for the proposed SDL structures are outlined in Section 4.



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Data source: VicMap, DELWP, 2017, Mallee CMA & Lower Murray CMA Imagery and GHD. Created by:sacevedo

Figure 4 Flow paths during natural flood event.

An analysis of expected lake heights with reference to the flow rates at Euston are described in Table 3. Water is retained longer in the larger and deeper lakes such as Lake Mournpall, Lake Hattah, Lake Arawak, Lake Brockie and Lake Bitterang (Table 4).

Table 2 Critical flow thresholds: Hattah Lakes (Source: SKM, 2004; Ecological Associates, 2007a; Ecological Associates, 2007b), Mallee CMA, 2014, MDBA, 2012a).

Lake	Lake Area (ha)	Lake Volume (ML)	Flow in Murray River at Euston for lake to fill (ML/d)			Wetland water regime (DELWP 2017)	Travel Time from Euston (days)
			Current	Prior to 2010	Natural#		
Chalka Creek (South)	-	-	>20,000	36,700	48,900		2
Arawak	40	617	50,500	50,500	50,500	Periodically Inundated - Intermittent	16
Bitterang	73	885	70,000	70,000	70,000	Periodically Inundated - Intermittent	32
Boich	<10	<110	54,000	54,000	54,000	Periodically Inundated - Episodic	23
Boolca	25.4		180,000			Periodically Inundated - Episodic	
Brockie	28	345	53,000	53,000	53,000	Periodically Inundated - Intermittent	21
Bulla	40	740	45,000	45,000	48,900	Periodically Inundated - Intermittent	14
Cantala	101	1233	45,000	45,000	45,000	Periodically Inundated - Intermittent	4
Dry Lakes	Approximately 200		180,000				
Hattah	61	1476	>20,000	36,700	48,900	Periodically Inundated - Intermittent	11
Kramen	161	221	152,000	152,000	152,000	Periodically Inundated - Episodic	>32
Konardin	121	1476	60,000	60,000	60,000	Periodically Inundated - Intermittent	11
Little Hattah	<10	<110	>20,000	36,700	48,900	Periodically Inundated - Seasonal Or Intermittent	11
Lockie	141	1291	>20,000	36,700	48,900	Periodically Inundated - Intermittent	6

Lake	Lake Area (ha)	Lake Volume (ML)	Flow in Murray River at Euston for lake to fill (ML/d)			Wetland water regime (DELWP 2017)	Travel Time from Euston (days)
			Current	Prior to 2010	Natural#		
Marramook	<10	<110	52,000	52,000	52,000	Periodically Inundated - Intermittent	18
Mournpall	243	2220	40,000	40,000	40,000	Periodically Inundated - Intermittent	9
Nip Nip	<10	<110	65,000	65,000	65,000	Periodically Inundated - Episodic	28
Roonki	42.2					Periodically Inundated - Episodic	
Tullamook	<10	<110	55,000	55,000	55,000	Periodically Inundated - Seasonal Or Episodic	26
Yelwell	81	738	55,000	55,000	55,000	Periodically Inundated - Intermittent	9
Yerang	65	787	40,000	40,000	40,000	Periodically Inundated - Intermittent	7

Table 3 Flow rate and lake level relationships for Hattah Lakes – Flow rate at Euston, ML/d (Source: MDBA, 2012b and SKM, 2006).

	Lake level				
Lake	43.00 m	43.50 m	44.00 m	44.50 m	45.00 m
Arawak	69,161	76,743	84,325	113,399	154,936
Bitterang	92,871	102,669	128,955	164,776	230,500
Boich	74,575	79,803	85,031	113,399	154,936
Brockie	77,121	81,242	85,364	113,399	154,957
Bulla	69,161	76,743	84,325	113,399	154,936
Boolca and Dry Lakes	194,375	211,043			
Cantala	81,361	86,497	110,447	147,508	223,806
Hattah	65,618	74,741	83,863	113,399	154,936
Konardin	76,319	81,079	85,838	122,209	165,673
Kramen	Not available				
Little Hattah	65,618	74,741	83,863	113,399	154,936
Lockie	52,747	67,466	82,184	113,399	154,957
Marramook	70,802	77,671	84,539	113,399	154,957
Mournpall	75,473	80,624	85,776	122,209	165,673
Nip Nip	72,944	78,882	84,819	113,399	154,936
Roonki	Not available				
Tullamook	74,575	79,803	85,031	113,399	155,833
Woterap	94,290	103,029	128,955	164,776	230,500
Yelwell	67,390	76,807	86,223	123,763	165,673
Yerang	60,144	72,392	84,640	121,356	165,440

Table 4 Water retention depths and duration in lakes under previous and current scenarios for known lakes

Lake	Retention level, mAHD			Depth of water retained, m			Drying time (months)			Inferred invert
	Natural	Developed (pre 2012)	Post 2012/2013, TWL 43.5	Natural	Developed (pre 2012)	Post 2012/2013, TWL 43.5	Natural	Developed (pre 2012)	Post 2012/2013, TWL 43.5	Current
Arawak	42.8	41.8	43.5	2.8	1.8	3.5	26	17	34	40
Bitterang	42.5	42.5	43.5	2.5	2.5	3.5	24	24	34	40
Boich	42.8	41.8	43.5	1.9	0.9	2.6	20	10	25	40.9
Brockie	42.8	41.8	43.5	2.8	1.8	3.5	26	18	34	40
Bulla	42.8	41.8	43.5	2.8	1.8	3.5	27	18	34	40
Cantala	0	0	0	1.8	1.8	1.8	17	17	17	-
Hattah	42.8	41.8	43.5	2.8	1.9	3.6	26	17	35	39.9
Konardin	42.5	42.5	43.5	1.9	1.9	2.9	20	20	27	40.6
Kramen	41.8	41.8	43.5	0.7	0.7	2.4	8	8	23	41.1
Little Hattah	42.8	41.8	43.5	1.5	0.5	2.2	13	3	21	41.3
Lockie	42.68	41.8	43.5	1.2	0.4	2.1	12	2	20	41.4
Marramook	42.8	41.8	43.5	1.9	0.9	2.6	20	10	25	40.9
Mournpall	41.5	41.5	43.5	2	2	4	21	21	39	39.5
Nip Nip	42.8	41.8	43.5	1.9	0.9	2.6	20	10	25	40.9
Tullumook	42.8	41.8	43.5	1.9	0.9	2.6	20	10	25	40.9
Yelwell	42	42	43.5	0.9	0.9	2.4	10	10	22	41.1
Yerang	41.3	41.3	43.5	0.4	0.4	2.6	2	2	25	40.9

4. Water management infrastructure, operations and water regimes

4.1 Water management infrastructure

4.1.1 The Living Murray

These works are able to replicate inundation extents of floods up to 90,000 ML/d in the central lakes area and in excess of 150,000 ML/d at Lake Kramen.

Messengers, Oateys and Cantala regulators and Breakout, Cantala and Bitterang track raising manage water to more than 6000 ha of the Central lakes, Lake Kramen and associated riparian and floodplain areas

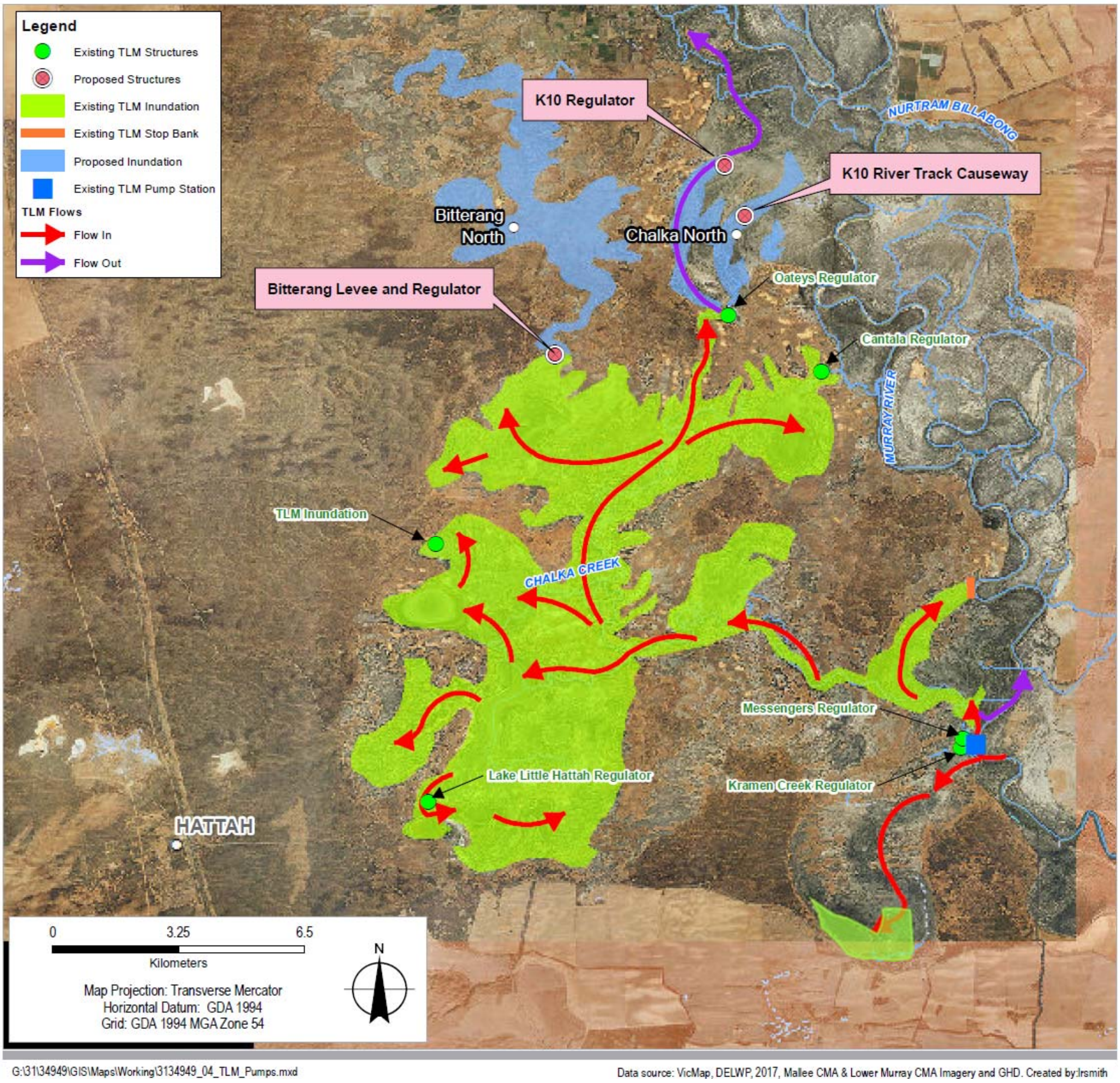


Figure 5 TLM structures and pumped flow paths

A summary of the completed TLM works, their purpose and operation is summarised in Table 5.

Constraints to the operation of these structures are addressed in Section 4.3.2.

Table 5 The Living Murray works and Inundation area

Completed Works	Purpose	Operation
Messengers Pump Station 7 variable speed axial flow pumps to pump water from Murray River to Chalka Creek and Lake Kramen.	Pumps water from the Murray River to Chalka Creek and Lake Kramen.	Lifts water from the Murray River into Chalka Creek to a water level of up to 45.5 m AHD
Messengers Regulator 2 no. 2 m wide by 4.5 m high combination (over / under) vertical penstock gates. Designed to pass up to 1000 ML/d when the Murray River is high.	Allow natural floodwaters in. Retain water within the system. Extend the duration of natural inflows. Release retained water.	Initially the top panel is lowered providing overshot flow. Once the top panel is fully lowered, both panels are then raised together to provide undershot flow for the final draining
Oateys Regulator 2 no. 2 m wide by 6.5 m high combination (over / under) vertical penstock gates. Designed to pass up to 1000 ML/d when the Murray River is high.	Allow natural floodwaters in. Retain water within the system. Extend the duration of natural inflows. Release retained water	Initially the top panel is lowered providing overshot flow. Once the top panel is fully lowered, both panels are then raised together to provide undershot flow for the final draining
Cantala Regulator Designed to pass up to 1000 ML/d when the Murray River is high.	Allow natural floodwaters in. Ponds water within Cantala creek and lake Extend the duration of natural inflows.	
Kramen Regulator	Allow natural floodwaters in. Retain water within the system. Extend the duration of natural inflows.	
Breakout, Cantala and Bitterang track raising.	Pond water on the floodplain by preventing water flowing back to the Murray River during operations	Floodplain areas

4.1.2 Proposed SDL works at Hattah Lakes North

This project will enable significantly larger inundation events to the northern Hattah Lakes floodplain. It will provide for the inundation of up to 1130 ha of water-dependent habitats including red gum and black box woodlands.

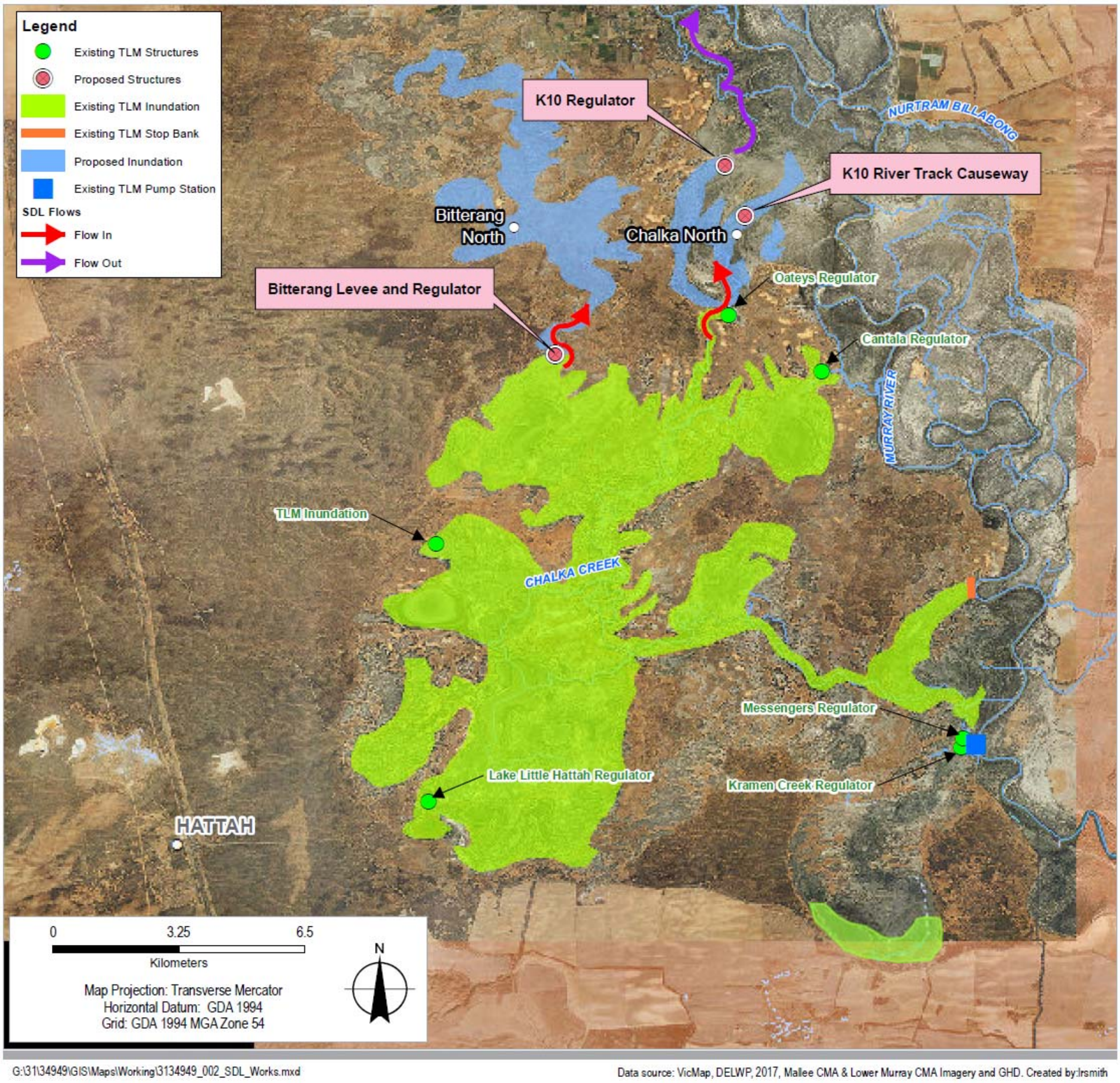


Figure 6 SDL works flow paths

The proposed package of works for the Hattah Lakes North consists of the construction of two regulators, a causeway across an existing track and 1.7 kilometres of levees on an existing track alignment (Table 6). The works have been designed to ensure compatibility with the existing Hattah Lakes TLM infrastructure. Operation of the proposed works is dependent on the operation of the existing TLM infrastructure.

Table 6 SDL works and inundation area

Site	Proposed works	Area inundated
Chalka North	K10 regulator K10 river track Causeway	420 ha
Bitterang North	Bitterang regulator Bitterang temporary pumps	300 ha (via gravity) + 410 ha (pumped) 710 ha

K10 regulator

K10 is a new regulator on Chalka Creek North that controls movement of water into the north-eastern section of the Hattah Floodplain. It comprises three bays with 2000 mm wide x 4000 mm high hydraulically actuated dual leaf combination gates.

There will be 680 m of track raising on the existing track at Raak crossing and a 350 m section upstream of the regulator structure to prevent a breakout occurring to the north.

K10 river track causeway

The K10 track raising and culvert works are on the existing River Track to maintain access into and out of the Hattah-Kulkyne National Park when the Chalka North pool is in operation (it will include regulators to enable free passage of water when not in operation).

The River Track will be raised a length of 710 m across the creek. The structure comprises three 1800 wide x 1200 high box culverts with penstock gates.

Bitterang regulator

The Bitterang Levee was constructed under The Living Murray program.

A new regulator will be installed in a widened section of the existing (TLM) Bitterang levee to allow delivery of environmental water to the Lake Boolca area. The regulator will comprise five 1200 mm wide x 1200 mm high box culverts with mechanically actuated penstock gates.

The existing levee will be widened along a length of 570 m to accommodate the new regulator.

4.2 Proposed operations

There are two possible ways in which the site infrastructure could be operated:

- the existing TLM works operated without the inclusion of the SDL infrastructure
- the existing TLM works operated with the SDL infrastructure.

These two scenarios are described below.

4.2.1 The Living Murray works operations

Four operational scenarios (plus maintenance) are possible for providing water to the Central Lakes and floodplain areas using the current infrastructure. These scenarios aim to enhance natural or provide managed inundation to the system. Transitioning between scenarios is also possible and provides a high level of operational flexibility when delivering planned watering events or responding to natural inflows. The operational scenarios are:

- natural inflows/outflows
- enhance natural – extend duration (using natural flows)
- enhance natural – extend duration and extent (using natural then pumped flows)
- managed event (pumped flows)
- maintenance (in years with no watering operation)

Managed operations can be conducted independent of flow levels in the Murray River, assuming the river level is above the minimum 38.3 m AHD required to operate the pumps. Operations to water Lake Kramen are possible during any operational scenario (MDBA, 2016).

Table 7 Operating scenarios for The Living Murray works (MDBA, 2016)

Scenario	Description
Scenario 1 Natural inflows/ outflows	Allows natural inflows and outflows to occur without intervention. This operating scenario can transition to any of the other operating scenarios ***Small Flooding*** Natural inflows will enter the Hattah Lakes system via Chalka Creek South. Inflows reach Messengers Regulator when flows exceed 26,000 ML/d at Euston. ***Large Flooding*** Natural inflows will occur via Chalka Creek South, Chalka Creek North and Cantala Creek. This relates to approximately 26,000 ML/d, 45,000 ML/d and 70,000 ML/d at Euston respectively and will inundate large areas of the floodplain.
Scenario 2 Enhance natural inflows (extend duration)	Retain natural inflow volumes in the lakes and Chalka Creek by closing regulators at the peak of inflows. This will retain water within the central lakes as necessary to meet ecological requirements.
Scenario 3 Enhance natural inflows (extend duration and extent)	Improve the duration and extent of natural floodwaters in the lakes via pumping, where natural inflows don't meet environmental objectives. Requirements will be assessed according to modelled natural flows, environmental requirements and availability of environmental water. This scenario has two options: 1. Increase duration of inflows i.e. maintain water levels by offsetting evaporation and seepage infiltration using pumped environmental water 2. Increase duration and extent by pumping water in excess of the amount needed to offset evaporation and seepage, in order to extend the area inundated and prolong the duration of inundation of natural inflows.
Scenario 4 Managed Event	Increase the frequency of inundation, where unmanaged inundation events don't match the ecological requirements of the site. The pump station can be used to provide water to Chalka Creek, the central lakes and Lake Kramen in the absence of natural inflows, provided that water levels in the Murray River exceed 38.3 m AHD (approximately 5000 ML/d at Euston). This scenario can be provided under both regulated and unregulated flow conditions. Requirements for pumped inflows will be assessed according to environmental requirements, modelled natural flows and the availability of environmental water.
Maintenance	During years where no watering operation is planned, GMW will undertake maintenance operations at GMW's discretion, as required to maintain the infrastructure – particularly the pump station. This may introduce up to 2 GL of additional water into Chalka Creek. Maintenance operations are detailed in the Operations and Maintenance manual and are conducted at the discretion of the water authority.

Table 8 Summary of operating scenarios and gate positions (MDBA 2016)

Operating Scenario				
	Natural inundation event – no management intervention	Enhanced natural event – increase duration of natural inundation	Enhanced natural event — increase duration and extent	Managed event – pumping from dry
River Condition (ML/day at Euston)	> 26,000	> 26,000	> 26,000 plus Additional water ordered as per licence conditions.	< 26,000 Water ordered as per licence conditions.
Messengers regulator	Open to allow natural inflows and outflows	Open to allow natural inflows Close when natural flows peak to retain natural inflows Open once target duration reached	Open to allow natural inflows Close when natural peak passes to retain natural and pumped inflows Open once target duration and extent reached	Closed to retain pumped inflows Open once target duration and extent reached
Oateys regulator	Open	Open to allow natural inflows Close as natural peak passes to retain natural inflows Open once target duration reached	Open to allow natural inflows Close as natural peak passes to retain natural and pumped inflows Open once target duration and extent reached	Closed to retain pumped inflows Open once target duration and extent reached
Cantala Regulator	Open	Open Close once natural peak passes Keep closed until dry – not to be used for releases unless water height is equal on both sides	Open Close once natural peak passes Keep closed until dry – not to be used for releases unless water height is equal on both sides	Closed Keep closed until dry – not to be used for releases unless water height is equal on both sides
Little Lake Hattah regulator	Open	Open	Open	As required, depending on size of event
Messengers pumping station	Off	Off	As required	As required
Block banks	Overtopped with additional 0.5m freeboard if flood > 45m AHD	-------	-------	-------

4.2.2 The Living Murray and SDL works operations

The Hattah Lakes North water management works have been designed to provide maximum operational flexibility and can be used in conjunction with the existing TLM works to complement Basin Plan flows environmental benefits. Four scenarios have been developed to summarise the range of operations possible. These include:

- default
- river red gum
- black box
- natural flood.

Each of the scenarios align with the water regime classes for Hattah North, as illustrated in Table 9 below.

Table 9 Links between the operating scenario and water regime class (Mallee CMA 2014)

Water Regime Class	Corresponding river flow (ML/day)			
	80,000	**120,000**	**>120,000**	**Default**
Red Gum Forest and woodland	**River red gum**	**Black box**	**Black box**	**Natural flows** **All structures open**
Black box woodland				
Episodic wetlands				

4.2.3 Default

This scenario is the default configuration for the proposed works, during normal operations when environmental water is not being delivered. In this scenario, neither the TLM works nor the proposed works will be in use. All regulators will be open, allowing natural flows, if they occur, to inundate the areas as per usual.

4.2.4 River red gum

Most of the red gum which can be influenced using the proposed works occurs within the Chalka Creek North area. Using the existing TLM works, water will be ponded within Chalka Creek and the central lakes area using Oateys, Messengers and Cantala regulators and their associated support structures to a target level of 43.5 m. The pool may be filled by gravity, using pumped water or by capturing natural flood peaks. During this operation, water will be released from Oateys regulator. Using the proposed works, water released through Oateys Regulator may be detained using K10 regulator and the K10 River Track Causeway. Once environmental water requirements of the Chalka Creek North wetlands and floodplain have been met, water can be released via K10 regulator and Chalka Creek North, to the Murray River.

4.2.5 Black box

The majority of black box which can be influenced using the proposed works occurs within the Bitterang north area. During TLM operations (floodplain inundation scenario to 45 m AHD) water can be allowed to flow into the Bitterang floodway by gravity via the Bitterang Regulator. Under this scenario the pool will generate a gravity flow of approximately 100 ML/d at the regulator and over 30 days will distribute water over approximately 300 ha, including Lake Boolca (GHD, 2012). Under the TLM program it is planned to operate the floodplain inundation scenario to 45 m AHD approximately one year in eight years (Greenfield, 2013). Temporary pumps may also be used to supplement floods or managed flows, to speed up delivery and achieve a greater area of inundation. In this scenario, the regulator would be closed to retain either natural or TLM operations water. A temporary pump can be used to re-lift water over the levee from Lake Bitterang to the Bitterang floodway. At a flow of 300 ML/d, a level of 45.11 m AHD can be achieved against the northern side of the levee which distributes water to over 710 ha.

It is proposed to operate the levee and regulator to augment flooding to meet environmental water requirements. The decision to inundate the Bitterang North area will be based on the duration since the last event. It will be important to limit the interval between floods so that the health and age structure of black box woodland is maintained and the value of these trees as habitat for terrestrial fauna and as a component of the wetland ecosystem during floods is preserved.

4.2.6 Natural flood

To minimise the impact of the infrastructure on natural flooding patterns all existing TLM and proposed regulating structures will be open during natural flooding events allowing full connectivity between the Murray River, Chalka Creek, the central lakes, the Chalka Creek North, Bitterang North areas and the floodplain.

4.2.7 Transition between operating scenarios

For a range of reasons, it may be necessary to change between operation scenarios during a watering event. Factors that may influence a decision to transition between scenarios may include:

- inflows causing increase in environmental water allocations
- inflows generating natural flooding
- response to ecological opportunities or to mitigate risks
- response to operational opportunities or to mitigate risks
- response to water quality risk mitigation requirements.

4.3 Watering regimes

4.3.1 The Living Murray Works

Each year, watering events are planned in advance according to site ecological objectives, water availability and operational constraints for the water year. Water managers and the Hattah Operations Group use a standard set of watering regimes as a basis for planning and means to address monitoring and reporting requirements of events.

Table 10 describes the standard watering regimes and provides examples of duration and frequency (based on historical natural inflows), used for initial planning purposes. These watering regimes are not the only watering options, and are considered by managers and the Hattah Operations Group to be illustrative rather than preferred or prescribed watering options.

Table 10 Standard watering regimes, including example duration and frequency of watering (based on historical natural inflows) (MDBA 2016)

	Small watering (e.g. 43.5 m AHD)	Large watering (e.g. up to 45m AHD)	Large watering up to 45 m AHD including Lake Kramen (to 46.2 m AHD at the regulator)
Season	Late winter to late spring or with natural flow pulse	Winter to early spring or with natural flow pulse	Late autumn to late winter
Duration	1-3 Months	1-3 months (be careful to not retain water for too long)	1-3 months (be careful to not retain water for too long)
Frequency	1:2	1:8	1:10
Climate conditions	Median to Wet year	Wet year	Wet year
Maximum area inundated (ha)	2,653 ha	5583 ha	> 6000 ha
Indicative net environmental water use (from dry)	41 GL	52 GL	65 GL (13 GL to Kramen if watering from dry)
Specific objectives	Restore a mosaic of hydrological regimes Maintain and restore the ecological character of the Ramsar site Restore the macrophyte zone around at least 50% of the lakes Improve the quality and extent of deep freshwater meadow and permanent open freshwater wetlands Maintain habitat for the freckled duck, grey falcon and white-bellied sea eagle Successful breeding events for colonial waterbirds at least two years in 10	As for small watering and Maximise use of floodplain habitat for fish recruitment	As for large watering

	Small watering (e.g. 43.5 m AHD)	Large watering (e.g. up to 45m AHD)	Large watering up to 45 m AHD including Lake Kramen (to 46.2 m AHD at the regulator)
	Provide habitat for migratory bird species Increase distribution, number and recruitment of wetland fish		

4.3.2 Constraints

Messengers Regulator

Erosion risk in Chalka Creek and the height/passing flow in the Murray River limit the release rate under low Murray River flow conditions. As of 2016, new design and remedial works on the Chalka Creek South rock chute limit the maximum outflow for Messengers Regulator to 600 ML/day (dependent on Murray River passing flow conditions).

Oateys Regulator

Erosion risk in the Chalka Creek North rock chute limits releases to a maximum of 400 ML/d (dependent on Murray River passing flow conditions).

4.3.3 SDL Works and Hattah Lakes North

The proposed works will provide flexibility to deliver a wide range of environmental watering events to meet the ecological objectives described in Section 9.4.

Table 11 provides a comparison of the water regime that can be provided by the proposed measure with the following water regimes:

- natural
- baseline condition (current condition)
- basin Plan (2750) without the measure

Basin Plan flows will contribute toward achieving the environmental water requirement of Hattah North compared to baseline conditions. The proposed measure is required to bridge the gap between Basin Plan flows and the environmental water requirements of Hattah North.

Table 11 Comparison of water regimes provided by natural, baseline, Basin Plan and the Hattah Lakes North measure. Natural, baseline, Basin Plan (Gippel, 2014, in Mallee CMA 2014)

Threshold (ML/d)	WRC	Scenario	Frequency mean (/100 years)	Duration Median (days)	Event start date median (day of year, 1 Jan =1)	Prevalence years with event 5
80,000	Red gum forest and woodland	With measure[1]	60	50	244	60
		Natural	50.9	55	252	46

[1] based upon interpretation of the preliminary operations plan adapted from Ecological Associates 2014c

Threshold (ML/d)	WRC	Scenario	Frequency mean (/100 years)	Duration Median (days)	Event start date median (day of year, 1 Jan =1)	Prevalence years with event 5
		Baseline	17.5	40	258	15
		Basin Plan 2750 without measure	21.9	37	259	19
120,000	Black box woodland	With measure[1]	25	30	244	25
		Natural	27.2	27	256	24
		Baseline	8.8	40	242	8
		Basin Plan 2750 without measure	9.6	41	237	8
140,000	Episodic wetlands	With measure[1]	15	30	244	15
		Natural	17.5	29	257	16
		Baseline	6.1	62	237	5
		Basin Plan 2750 without measure	7	37	236	6

5. Native fish

5.1 Listed species

There has been a broad decline in native fish species in the MDB but species which are listed under Federal and/or Victorian legislation that occur or are likely to occur at Hattah include the freshwater catfish (*Tandanus tandanus*), golden perch (*Macquaria ambigua*), Murray cod, Murray-Darling rainbowfish (*Melanotaenia fluviatilis*) and silver perch.

Table 12 Native fish expected to occur at Hattah Lakes

Common Name	Scientific Name	EPBC ActStatus	FFG Act Status	DELWP Advisory	Likelihood of Occurrence
Flathead galaxias	*Galaxias rostratus*	CR	N	V	Unlikely
Freshwater catfish	*Tandanus tandanus*	-	L	EN	Likely
Golden perch	*Macquaria ambigua*	-	I	NT	Certain
Macquarie perch	*Macquaria australasica*	EN	L	EN	Unlikely
Murray cod	*Maccullochella peelii*	VU	L	V	Certain
Murray hardyhead	*Craterocephalus fluviatilis*	EN	L	CR	Unlikely
Murray-Darling rainbowfish	*Melanotaenia fluviatilis*	-	L	V	Certain
Silver perch	*Bidyanus bidyanus*	CR	L	V	Certain
Unspecked hardyhead	*Craterocephalus stercusmuscarum fulvus*	-	-	-	Certain
Carp gudgeon	*Hypseleotris klunzingeri*	-	-	-	Certain
Bony herring	*Nematalosa erebi*	-	-	-	Certain
Flathead gudgeon	*Phylipnodon grandiceps*	-	-	-	Certain
Dwarf flat-headed gudgeon	Philypnodon macrostomus	-	-	-	Certain
Australian smelt	*Retropinna semoni*	-	-	-	Certain
Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) status: EXtinct, CRitically endangered, ENdangered, VUlnerable, Conservation Dependent, Not Listed Flora and Fauna Guarantee Act 1988 (FFG Act) status: Listed as threatened, Nominated, Delisted, Never Listed, Ineligible for listing DELWP Advisory status: presumed EXtinct, Regionally Extinct, Extinct in the Wild, CRitically endangered, ENdangered, Vulnerable, Rare, Near Threatened, Data Deficient, Poorly Known, Not Listed (DSE 2013)					

The habitat requirements and life cycles of the species likely to occur at Hattah are described in Section 6.

6. Conceptual models of native fish life cycles and habitat requirements

The following information on fish describes the fish community and provides conceptual models to guide the fish recovery strategy. Conceptual models are representations of complex systems that use available data and the present understanding of causal factors to show links, interactions and processes. The strength of conceptual models is that they link components of a system together to present a holistic view. The model, and the process of constructing the model, can highlight knowledge gaps, identify research and monitoring priorities, and clarify and synthesise thinking.

A potential weakness of conceptual models is that the relative strengths of various links, based on the data, are often not explicit and the model can sometimes be viewed as having more validity than the data suggests. Conceptual models need to be viewed as tools that need constant review and updating, rather than providing an absolute explanation. They are presented in this report as a resource to describe the present understanding and to be constantly refined.

Conceptual models are useful in natural resources management as they attempt to provide an understanding of why biota are present or absent in different habitats (i.e. reasons or causes), rather than only a description of distribution (i.e. effects). A good example of these differences is the area of fish passage. Providing fishways enable fish to move past a barrier (i.e. effect) but the conceptual model behind it may be that fish are moving to spawning habitat, feeding habitat, or countering downstream displacement as larvae. The conceptual model would then provide guidance for complementary actions, such as improving spawning habitat.

The conceptual models below contain life-history, ecology, obligate habitat requirements and associated hydrological/flow requirements for these species in the southern Murray-Darling Basin. The models are based on the recent published and unpublished research. For each species/group a concise description in text is provided, followed by a pictorial representation of the model.

6.1 Murray cod

Murray cod (*Maccullochella peelii* [Mitchell]) occasionally grow to 1.5 m long and 50 kg and can live for up to 50 years. Murray cod inhabit many of the waterways of the Murray-Darling Basin (MDB) (ACT, SA, NSW, Qld and Vic) and live in a wide range of aquatic habitats that range from clear, rocky streams to slow flowing turbid rivers and billabongs (Lintermans, 2007).

Table 13 Conceptual model Murray cod

Habitat use

1. Prefer permanent flowing river reaches and creeks with hydraulic complexity/diversity.
2. Require woody debris (snags), debris piles and bank side vegetation (e.g. Murray River, Mullaroo Creek; Kaye and Sharpe 2009).
3. In the southern reaches of the MDB, the status of Murray cod populations is influenced by habitat availability, flow regime, hydrodynamic diversity (water velocity, depth and turbulence) and connectivity (Henderson et al. 2010a,b; Mallen-Cooper et al., 2013; Mallen-Cooper and Zampatti, 2015a; Mallen-Cooper and Zampatti 2017).
4. Recruitment potential may be increased when additional habitat resources such as food and shelter are created as river benches, snags and rocks and riparian zones are inundated by rising flows.
5. Eggs and larvae require a steady flow increase and very little daily variations in water level (e.g. 0.1 m) to maximise spawning success.

Diet

6. Diet changes with age with the typical adult diet consisting of spiny crayfish, yabbies and shrimps (National Murray Cod Recovery Team 2010)
7. Predominantly piscivorous and feed on native and exotic fish species e.g. [native species - other cod (*Maccullochella* spp.), golden perch, bony bream (*Nematalosa erebi*), freshwater catfish, western carp gudgeon (*Hypseleotris klunzingeri*)], [exotic species - redfin perch (*Perca fluviatilis*), carp (*Cyprinus carpio*) and goldfish (*Carassius auratus auratus*)].
8. Less common animals found in the diet include ducks, cormorants, grebes, tortoises, water dragons, snakes, mice, frogs and mussels (Rowland, 1996).
9. Upon hatching, larvae are 5–8 mm long and within 8–10 days can feed on zooplankton. After reaching a length of 15–20 mm, they are also able to feed on aquatic insects (King, 2005).

Spawning

10. Occurs annually during October, November and December each year (Humphries, 2005; Koehn and Harrington, 2005), during base flows and during river rises (King et al., 2009a; Ye et al., 2008).
11. Display complex pre-spawning courtship behaviour (during winter and spring) and females may spawn with more than one male.
12. Females lay their eggs into nests (i.e. stable habitat such as logs, rock and root ball hollows). The male guards the nest for up to two weeks while the eggs hatch. Juveniles leave the nest and move into littoral or snag habitats.

13. Despite often being classified as a ‘flow independent spawner’ Murray cod do require permanent flowing water for optimal recruitment (Stuart and Sharpe, 2017; 2018).
14. Can spawn and recruit during low stable flows, rising flows and floods.
15. Floods are not necessary for spawning but in some cases, appear to enhance subsequent recruitment (King et al., 2009a).

Recruitment

16. Recruitment is almost always associated with flowing water habitats (Sharpe and Stuart 2016; 2018).
17. There is high mortality of young fish but those that survive their first summer and winter and grow to 90-140 mm long tend to have a good chance of recruiting into the sub-adult population (250-600 mm long) (Baumgartner et al., 2006).
18. Mature late (3-5 years) and at a reasonably large size (>600 mm long) but females have relatively low egg numbers (fecundity).
19. Long-lived (>40 years) and can grow to a large size (e.g. 1.4 m and 45 kg) where they become the apex aquatic predator (Anderson et al., 1992a; Ebner, 2006).
20. Where riverine stocking occurs there can be significant augmentation of natural populations (Forbes et al., 2016).

Movement and migration

21. May move large distances (e.g. up to 120 km) but generally only up to 30 km (Leigh and Zampatti, 2011; 2013; Saddlier et al. 2008).
22. Move from their home snag to spawning areas in July/August/September on rising water temperature in winter and early spring (Jones and Stuart, 2007; Saddlier et al. 2008).
23. Both adult and juvenile fish are strongly associated with snags with a ‘home’ snag with adult fish often returning to the same snag (Koehn, 2009).
24. In recent years, the need to provide fish passage for Murray cod to escape anoxic ‘black water’ events has been demonstrated in the lower Murray, most recently in late 2016, when large numbers of fish were killed in the lower and mid-Murray River, Edward-Wakool system, Frenchman’s Creek, Rufus River and Mullaroo Creek (Tonkin et al., 2017).

Implications for Victorian environmental flows

25. A specific Murray cod hydrograph should be implemented where population recovery is required (Sharpe et al. 2015; Sharpe and Stuart 2018).
26. Fast flowing riverine sites (e.g. >0.3m/s) can be considered ecological priorities for Murray cod recovery.
27. Application of the Murray cod hydrograph, especially permanent flow in winter, is required on an annual basis (Sharpe and Stuart 2015; Sharpe and Stuart 2018).

Implications for flow monitoring

28. Flow-event monitoring is crucial to identify the specific components of the hydrograph (shape, timing, frequency, duration, height, discharge, velocity) that influence population dynamics.

Threats

29. Lack of fast flowing water habitats with a low density of snags because of past de-snagging, regulation transforming the hydrodynamic nature of many rivers from flowing rivers to weir pools and cold water discharge from large river storage dams (Mallen-Cooper and Zampatti 2017).

30. Loss of permanent flows when rivers and anabranches are de-watered during winter.

31. In many regulated rivers and anabranches (e.g. Gunbower Creek, Gulpa Creek, Edward River, Mullaroo Creek) there are two major hydrological constraints on Murray cod population recovery

- intense fluctuation in river discharge causing rapid decreases in river level and interruption of spawning/recruitment processes,
- low or zero winter flows that appear to be population 'bottlenecks' because this forces all fish into the deeper refuge pools for up to 3 months each year (Sharpe and Stuart, 2015).

Knowledge and data limitations

32. Wide-scale implementation, refinement and evaluation of the Murray cod hydrograph

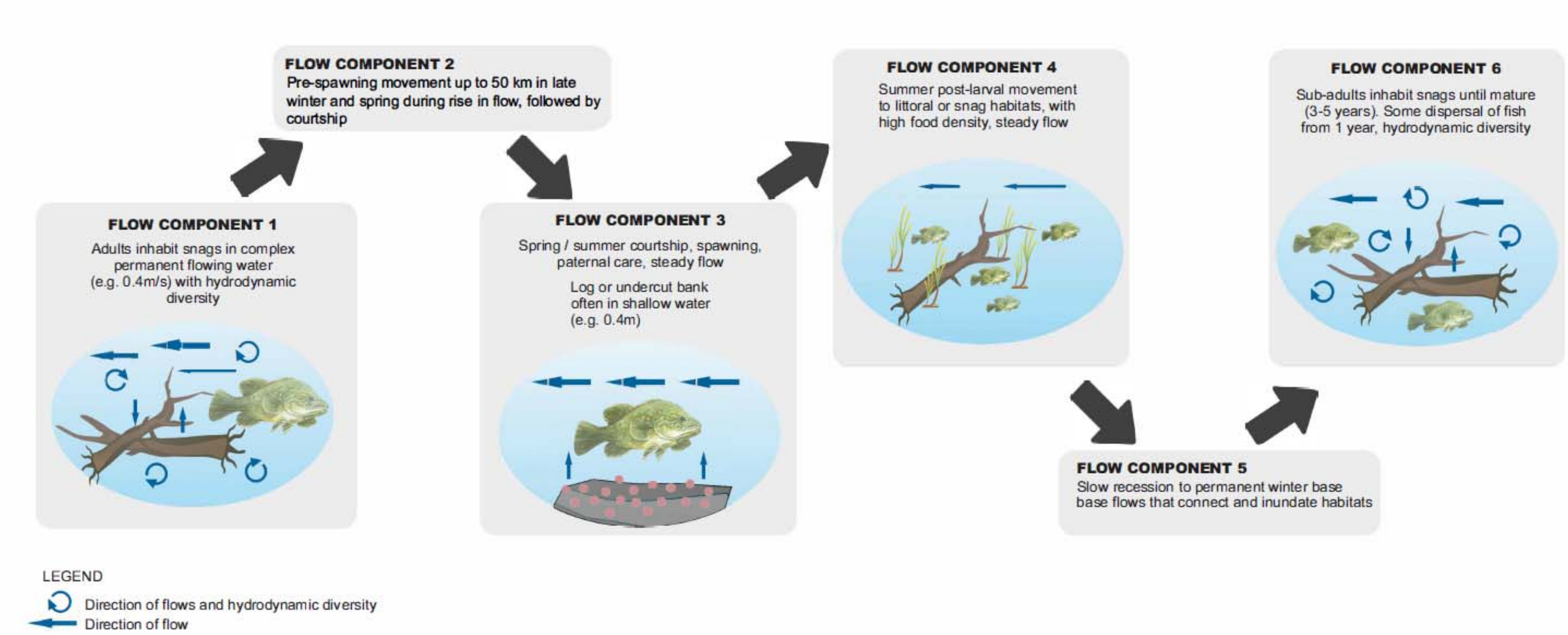
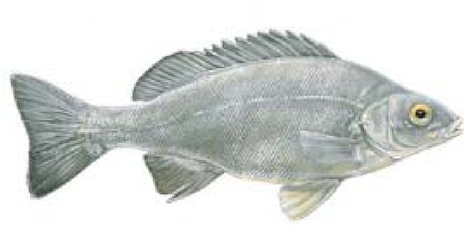


Figure 7 Conceptual model Murray cod

6.2 Silver perch



Silver perch (*Bidyanus bidyanus* [Mitchell]) long-lived, river channel specialist with drifting egg/larvae stages. Commonly grows to 400 mm long and 1.5 kg. They can live for 25+ years but most riverine fish are <10 years old (Mallen-Cooper and Stuart, 2003).

The main MDB silver perch population is centred in the mid-Murray River (Yarrawonga to Euston), with occupancy in the Edward-Wakool, Lower Darling, Murrumbidgee, Warrago/Condamine, Victorian tributaries (Loddon, Campaspe, Goulburn, Ovens) with low numbers present in SA. Since European settlement their distribution and abundance has severely declined with their remaining stronghold in the Lock 11 to Lock 26 reach of the Murray River (Mallen-Cooper and Brand, 2007; Lintermans, 2007). Catches of silver perch in the mid-Murray have declined by 94% over a 50-year period (Mallen-Cooper and Brand, 2007).

Despite annual stocking few other self-sustaining populations exist though they can still be found in the Murrumbidgee River and several other NSW and Victorian tributaries.

Table 14 Conceptual model for silver perch

Habitat use
1. Main river channel habitats used for feeding, refuge, spawning, survival and recruitment. 2. Found in the Lock 11-26 reach of the Murray River because this encompasses the longest unregulated river reach on the main stem of the Murray River and thus provides 500+ km of their preferred flowing water habitat. 3. Habitat specialists (obligate riverine species) predominantly occupying large fast flowing river regions (e.g. Murray, Darling) over sand and structure (Clunie and Koehn, 2001a; Merrick and Schmida, 1984) to the slow flowing, turbid waters of lower reaches (Rowland 1995) while Cadwallader and Backhouse (1983) suggest they prefer open waters devoid of snags. Small numbers of fish utilise tributaries of main channel. 4. Consistently reported by anglers and researchers to show a general preference for faster-flowing water, including rapids and races, and more open sections of river, throughout the MDB. 5. Are rarely collected in floodplain lakes. 6. Winter is a critical period for young-of-year fish survival (i.e. fish that are less than one year old and the result of spawning in the previous spring).
Diet
7. Adults are omnivorous, taking a variety of small prey including zooplankton, aquatic insects, molluscs, small crustaceans and worms as well as algae.
Spawning
8. Long-lived (17 years [river], 27 years [dam]), show variable growth, (Mallen-Cooper and Stuart, 2003) and no parental care. 9. Widespread spawning from Mildura to Upper Victorian tributaries (King et al., 2009b) including Lower Darling. 10. Sexually dimorphic species: males maturing at three years (250mm) and females at 4-5 years (300mm).

11. Seek flowing water (e.g. 0.3 m/s) in river channel habitats in which to spawn, so their eggs and larvae can drift downstream.
12. Spawning occurs annually in spring and early summer (late-October to mid-February King et al., 2005; King et al., 2009a; Raymond et al., 2014).
13. First major spawning event during a coinciding rise in water temperature (2.5^{o}C in prior seven days) and a rise in water level and a second major spawning event in December 2005 as flows were declining (King et al., 2009a).
14. Fecundity is high, with females often laying 300,000 or more non-adhesive, semi-pelagic eggs (Merrick and Schmida, 1984; Merrick, 1996, Rowland, 2009).
15. Eggs sink in the absence of current (Lake, 1967), hatch within 30 to 36 hours, and have a two-week larval stage (NSW DPI, 2006).
16. An aggregate spawning species, with large schools forming around known spawning period following upstream migration (Lintermans, 2007; Koehn and O'Connor, 1990).
17. Spawning intensity increased with greater flows, particularly above flood levels and was enhanced when temperatures were rising (King et al., 2016). Spawning intensity declined with increasing number of flood days in preceding three months (King et al., 2016).
18. There is no evidence that silver perch directly use ephemeral floodplains for spawning.
19. Spawning in the Upper Victorian Murray and lower Goulburn rivers does not appear to result in localised recruitment (King et al., 2009b), late-stage larvae and early juvenile fish are rare.

Recruitment

20. Have a drifting larval phase of up to 15 days (NSW DPI, 2006).
21. Larvae believed to be at risk of high mortality in weir pools due to; reduced flows, decreased temperature, lack of food and anoxic conditions (e.g. Yarrawonga and Torrumbarry, Euston).
22. Recruit in flood and non-flood years with some fish recruiting from offstream floodplain habitats (e.g. Lake Boga; Mallen-Cooper and Stuart, 2003; Tonkin et al. 2017).
23. The level of recruitment upstream of Torrumbarry Weir is a knowledge gap but may be low. Hence, northern Victorian rivers appear heavily reliant on re-colonisation migrations of juvenile and adult silver perch from downstream and connectivity with the Victorian Murray (Tonkin et al. 2017). However, it is also likely that a small proportion of silver perch population is derived from the Darling system where there is a flow spike or flood (Sharpe and Stuart 2018).
24. There is no evidence for enhanced silver perch recruitment from deliberate creation of 'slackwaters'.
25. Recruitment is generally believed to be tied to high flows in spring or summer that stimulate fish to move upstream and spawn, inundate floodplains and produce food for larvae (Lake, 1967; Reynolds, 1983; Gehrke, 1992; Harris and Gehrke, 1994).

Movement and migration

26. Most tagged fish in the lower Murray River moved upstream, with one individual recorded to move 570km in 19 months (Reynolds, 1983).

27. Juveniles in the mid-Murray River moved upstream from October to April; adults moved upstream from November to February which was believed to be spawning related (Mallen-Cooper, 1999).
28. Thousands of immature fish, that are one year and older, migrate upstream, responding to increased flow (e.g. +0.15m/24h) (Torrumbarry Weir data).
29. There is no upstream migration of YOY silver perch (Mallen-Cooper and Stuart, 2003).

Implications for Victorian environmental flows

30. Increase short-term flow variability (1-2 days, height changes up to 0.2m) to 50% of natural flows to stimulate silver perch movements (Koehn et al., 2014).
31. Spawning flows can be implemented in spring/early summer. Tributary (e.g. Campaspe, Loddon, Gunbower, Darling etc) flows are highly unlikely to result in spawning due to the limited spatial scale and low hydraulic diversity (unless the tributaries contribute to higher flows in the Murray, where spawning may occur).
32. Spawning flows can be 1-in-1 year in channel style events, with strong variability, and should be based on the natural hydrograph
33. Re-colonisation flows in early summer (e.g. January-March) can attract upstream migrating yearlings and juvenile fish into the Victorian Murray and tributaries in the Echuca-Yarrawonga reach, especially if synchronised with rising flows in the Victorian Murray (Sharpe, 2011; Stuart and Sharpe, 2015).
34. Using environmental flows to create hydrodynamic diversity is the major objective for successful silver perch outcomes.
35. Weir pool lowering can also be used in conjunction with environmental flows to maximise hydraulic diversity over large spatial scales (Ye et al., 2008).
36. Landscape scale planning and monitoring is required to maximise silver perch outcomes, such as providing Victorian re-colonisation flows after high flows in the lower Murray/Darling systems (Sharpe et al., 2015).
37. Protecting the integrity of flows over large spatial scales (e.g. 300-500 km), with a co-ordinated multi-state cooperation is required to enhance silver perch population dynamics.
38. Increased spawning of silver perch through environmental flows aimed at mimicking natural flood events has been demonstrated (King, 2008).
39. Increase flow rate through weir pools to > 0.3m/s, can be achieved via increased flow delivery (20,000 ML/d) or through physical lowering of weir (flows of 10,000 ML/d) to achieve the same ecological output.
40. Mitigating low winter flows (to more natural winter flows) could improve fish condition and have flow on benefits for recruitment (Koehn et al., 2014).
41. Low winter flows increase the risk to fish through increased predation and competition, habitat loss, drying, poor water quality, lower egg and larval survival rates (Koehn et al., 2014) and the potential lack of flow cues and gonad development in larger fish.

Implications for flow monitoring

42. Flow-event monitoring is crucial to identify the specific components of the hydrograph (shape, timing, frequency, duration, height, discharge, velocity) that influence population dynamics of silver perch.

43. Flow evaluation analysis should target the fish-and-flow event relationship through metrics such as: size/age distribution, emigration, immigration, movement, recruitment and spawning (King et al., 2009b). Broad-scale analyses of abundance (CPUE) are of very limited use.

Threats

44. River regulation and diversion restricts juvenile and adult movement, prevents dispersal and recolonization of extensive stretches of river and increases risk of localised extinction and fragmentation.
45. Impact and loss of in channel peaks, including the loss of small floods (5000-10,000ML/d) occurring in the Murray River have decline by half over the past 50 years (Close, 1990).
46. Weirs may trap eggs and early larvae causing them to settle and die (Baumgartner et al., 2014a).
47. Undershot weirs kill >90% of larvae (Boys et al., 2010)
48. Thermal issues will limit spawning below weirs and possibly increase larvae survivorship.
49. Silver perch are highly susceptible to several diseases including EHNV (Langdon 1989).
50. Low level of genetic variation in natural silver perch populations (Keenan et al., 1996).

Knowledge gaps and data limitations

51. Downstream movement of silver perch
52. Recruitment dynamics and relationship with flows have components which remain unclear. The role of larger floods in the life-history of silver perch is also still unclear; with observations of increased spawning at Barmah but this does not always result in recruitment. Ellis and Pyke (2011) indicate that successful recruitment can occur via pumping (to Margooya Lagoon) when carp exclusion screens are in place.
53. Impact of weir pools on survivorship of larvae.
54. A major knowledge gap is larval drift distance and survival upon entering a weir pool (e.g. larvae from the lower Goulburn River and mid-Murray River drifting into the Torrumbarry Weir pool)
55. Improve knowledge of recruitment links to flows (intervention and monitoring).

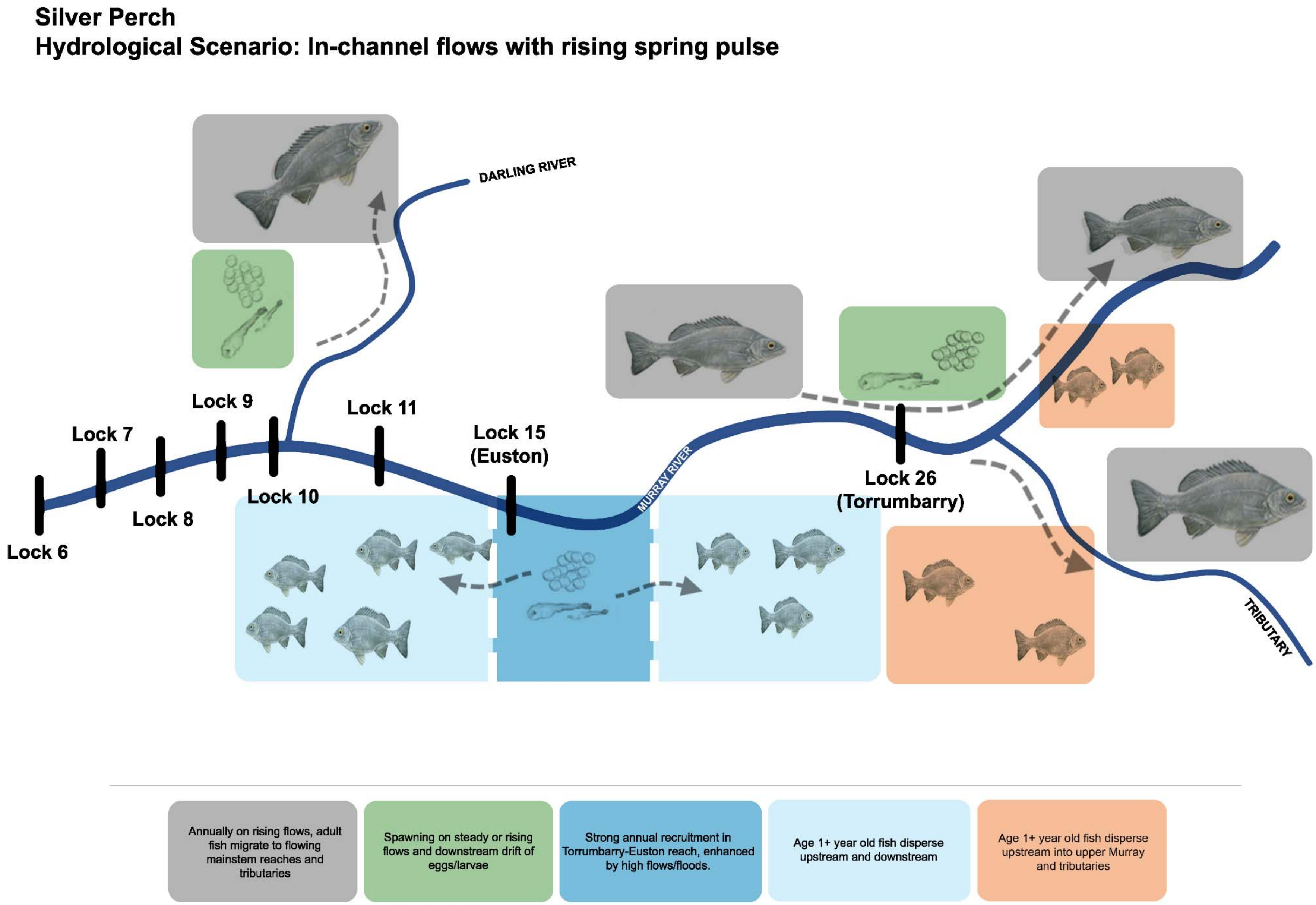


Figure 8 Conceptual model for silver perch

6.3 Golden perch

Golden perch (*Macquaria ambigua* [Richardson]), which commonly grow to 600 mm long and 3 kg are widespread throughout the Murray-Darling Basin, especially in the lower and mid reaches, but have severely declined above dams in the upper reaches of most tributaries. They are predominantly found in the lowland, warmer, turbid, slow flowing rivers. Golden perch have a maximum life-span of 25 years and commonly reach 600 mm long.

Table 15 Conceptual model for golden perch

Habitat use
1. Inhabit a wide variety of aquatic habitats, including slow flowing rivers, fast flowing rivers at landscape scales (e.g. 500 km; Mallen-Cooper and Zampatti, 2015b), lakes, anabranches and billabongs. 2. Diverse aquatic habitats are important to provide shelter and a productive food web, especially so these fish can feed in winter. 3. Main river habitats are used for feeding and are also an important refuge and overwintering habitat. 4. Habitat generalists often associated with physical habitat ('snags'), drop offs and deep water (Crook et al., 2001). 5. Winter is a critical period for young-of-year fish survival (i.e. fish that are less than one year old and the result of spawning in the previous spring).
Diet
6. The species is an opportunistic carnivore. The diet of adults consists mainly of shrimps, yabbies, small fish and benthic aquatic insect larvae (Baumgartner 2007). 7. Juveniles consume more of the smaller items such as aquatic insect larvae and microcrustaceans (Lintermans, 2007).
Spawning
8. Long-lived, show variable growth and females are highly fecund, they display no parental care (Anderson et al., 1992b; Mallen-Cooper and Stuart, 2003). 9. Spawning occurs in spring and summer with the Darling River potentially later (October-March; >17°C; King et al., 2009a; Sharpe 2011; Sharpe and Stuart 2018). 10. Fish spawn during 1-in-1 year bank full flows that have variability (e.g. 0.15 m/24 h) and during over bank flows. 11. A small to large rise in water level, or flow pulse (e.g. 0.3 m/s), is the proximate cue to initiate spawning so eggs and larvae can drift downstream (Lake, 1967; King et al., 2009a; Sharpe, 2011). 12. Eggs hatch after 1-2 days and larvae drift downstream, where larval transition to early juveniles occurs in the main river channel if sufficient food resources for young fish also occur (Sharpe, 2011). Drift can be prolonged at up to 35-40 days and travel distances at >1000 km where larvae settle into floodplain lakes or along the channel margins (Sharpe and Stuart 2018). 13. Larval passage through under-shot weir gates results in high mortality (Baumgartner et al. 2006). Irrigation offtakes also receive drifting larvae, depending on the proportion of flow diverted (King and O'Connor, 2007).

14. There is no evidence that golden perch directly use ephemeral floodplains for spawning in the Murray system but floodplain lakes are important nurseries.
15. Outside of the Murray main river channel (and associated anabranches) spawning has only been recorded in the Goulburn River, with no other confirmed records of spawning in Victorian rivers (e.g. Ovens, Broken and Campaspe rivers). Spawning is regularly documented in the Darling and Murrumbidgee rivers (Sharpe and Stuart 2018). Most of the Lower Murray golden perch population are likely to be derived from a combination of Murray and Darling system spawnings.
16. Spawning in the Upper Victorian Murray and lower Goulburn rivers does not appear to result in localised recruitment (King et al., 2009a; Koster et al., 2014) whereby records of late-stage larvae and early juvenile fish are rare.

Recruitment

17. Recruitment occurs during within-channel flows and especially during over-bank flows when ephemeral floodplains are inundated increasing productivity and larval survival (Mallen-Cooper and Stuart, 2003; Ye et al., 2008; Ebner et al., 2009; Sharpe 2011; Zampatti and Leigh, 2013; Sharpe and Stuart 2018).
18. Recent research indicates that the juvenile population, in the lower Murray and at least upstream to Torrumbarry, can be made up of significant numbers of fish spawned in the Darling River, with 1+ fish migrating downstream in the Darling and then upstream in the Murray River (Zampatti et al., 2015; Sharpe and Stuart 2018).
19. The level of recruitment in the Murray River upstream of Torrumbarry Weir is a knowledge gap but may be low. Hence, northern Victorian rivers appear heavily reliant on re-colonisation migrations of juveniles and adults from downstream and connectivity with the Victorian Murray.
20. There is no evidence for enhanced recruitment from deliberate creation of ‘slackwaters’.
21. Young fish settle into off-stream floodplain or littoral riverine nursery habitats (Sharpe 2011).
22. Populations in the Murray River and tributaries are episodic in age structure, often being dominated by only a few distinct year classes. Strong natural recruitment occurs following high flow or flood years (Ye et al., 2008; Mallen-Cooper and Stuart, 2003; Sharpe, 2011; Ferguson and Ye, 2012; Zampatti et al., 2015; Crook et al., 2016).
23. In extreme cases, one year class can represent more than 60% of the adult population in broad reaches of the Murray River (Zampatti et al., 2015).
24. In particular rivers, low-levels of recruitment occur in most years, such as the Goulburn (Zampatti et al., 2015; Crook et al., 2016) but in others such as the Murray and Edward-Wakool (an anabranch of the Murray) there are successive years of recruitment failure and populations are dominated by particular year classes, when strong natural recruitment and emigration has occurred (Ye et al., 2008; Zampatti et al., 2015; Thiem et al., 2017).
25. In those rivers, fragmented demographics have been attributed to a combination of spawning limitations, recruitment failure and barriers to dispersal (Mallen-Cooper and Stuart, 2003; Leigh and Zampatti, 2011, 2013, Stuart et al., 2008; Sharpe, 2011; Sharpe et al., 2015; Zampatti et al., 2015; Thiem et al., 2017).

Movement and migration

26. During in-channel flows, especially in tributaries, golden perch often display site fidelity but there can be major home range shifts (Crook, 2004) and there is strong movement between the Murray River and tributaries (Koster et al., 2014).
27. Adults move upstream in the mainstem, often through fishways, of the Murray River in spring and summer and this is often spawning related (Mallen-Cooper, 1999; Stuart et al., 2008; Baumgartner et al., 2014a).
28. Movement is strongly cued by rising/falling flow and water temperature with much less migration in stable flow and in winter.
29. Also move downstream in spring, summer and autumn (O'Connor et al., 2005).
30. Thousands of immature golden perch, that are one year and older, migrate upstream, responding to increased flow (e.g. +0.15m/24h) and these migrate into early autumn.
31. Mature and immature fish may aggregate for days or weeks at weirs, if flows provide sufficient stimulus, or they may return downstream to seek alternative migration pathways. Aggregations below barriers can quickly disperse downstream as flows recede.
32. Juveniles make staged re-colonisation migrations, responding to a flow in a movement pulse and then stopping during stable flows.
33. Migrations are usually over the scale of 100s of kilometres although some can be over 10s of kilometres (Reynolds, 1983; O'Connor et al., 2005; 2015).
34. A greater proportion of the fish population migrates during major over-bank flood events such as the 2010/11 floods. For example, major increases in abundances and biomass within the Victorian upper Murray reach were a result of adult immigration from downstream sources (Lyon et al., 2014).

Implications for Victorian environmental flows

35. Designing flows to cue fish migration and movement through Victorian fishways is possible by releasing near bank full flows for short periods (days to weeks per event) in spring and summer.
36. Spawning flows can be implemented in the Victorian Murray and lower Goulburn rivers in spring/early summer. Tributary (e.g. Campaspe, Loddon, Gunbower etc) flows are highly unlikely to result in spawning due to the limited spatial scale and low hydraulic diversity.
37. Spawning flows can be 1-in-1 year bankfull events, with strong variability, and should be based on the natural hydrograph.
38. Prioritising 'slackwater' habitats for larvae in these tributaries is highly unlikely to result in enhanced recruitment.
39. Re-colonisation flows in early summer (e.g. January-March) can attract upstream migrating yearlings and juvenile fish into Victorian tributaries and in the Victorian Murray in the Echuca-Yarrawonga reach, especially if synchronised with rising flows in the Victorian Murray (Sharpe, 2011; Stuart and Sharpe, 2015).
40. Using environmental flows to create a hydrodynamic diversity is the major objective for successful golden perch outcomes (Zampatti and Leigh, 2013; Koster et al., 2014; Sharpe et al., 2015). The 'slackwater' model has little empirical support.
41. Weir pool lowering can also be used in conjunction with environmental flows to maximise hydraulic diversity over large spatial scales (Ye et al., 2008).

42. Protecting the integrity of flows over large spatial scales (e.g. 300-500 km), with a co-ordinated multi-state cooperation is required to enhance golden perch population dynamics.
43. Landscape scale planning and monitoring is required to maximise golden perch outcomes, such as providing Victorian re-colonisation flows after high flows in the lower Murray/Darling systems (Sharpe et al., 2015).

Implications for flow monitoring

44. Flow-event monitoring is crucial to identify the specific components of the hydrograph (shape, timing, frequency, duration, height, discharge, velocity) that influence population dynamics of golden perch.
45. Flow evaluation analysis should target the fish-and-flow event relationship through metrics such as: size/age distribution, emigration, immigration, movement and spawning. Broad-scale analyses of abundance (CPUE) are of very limited use.

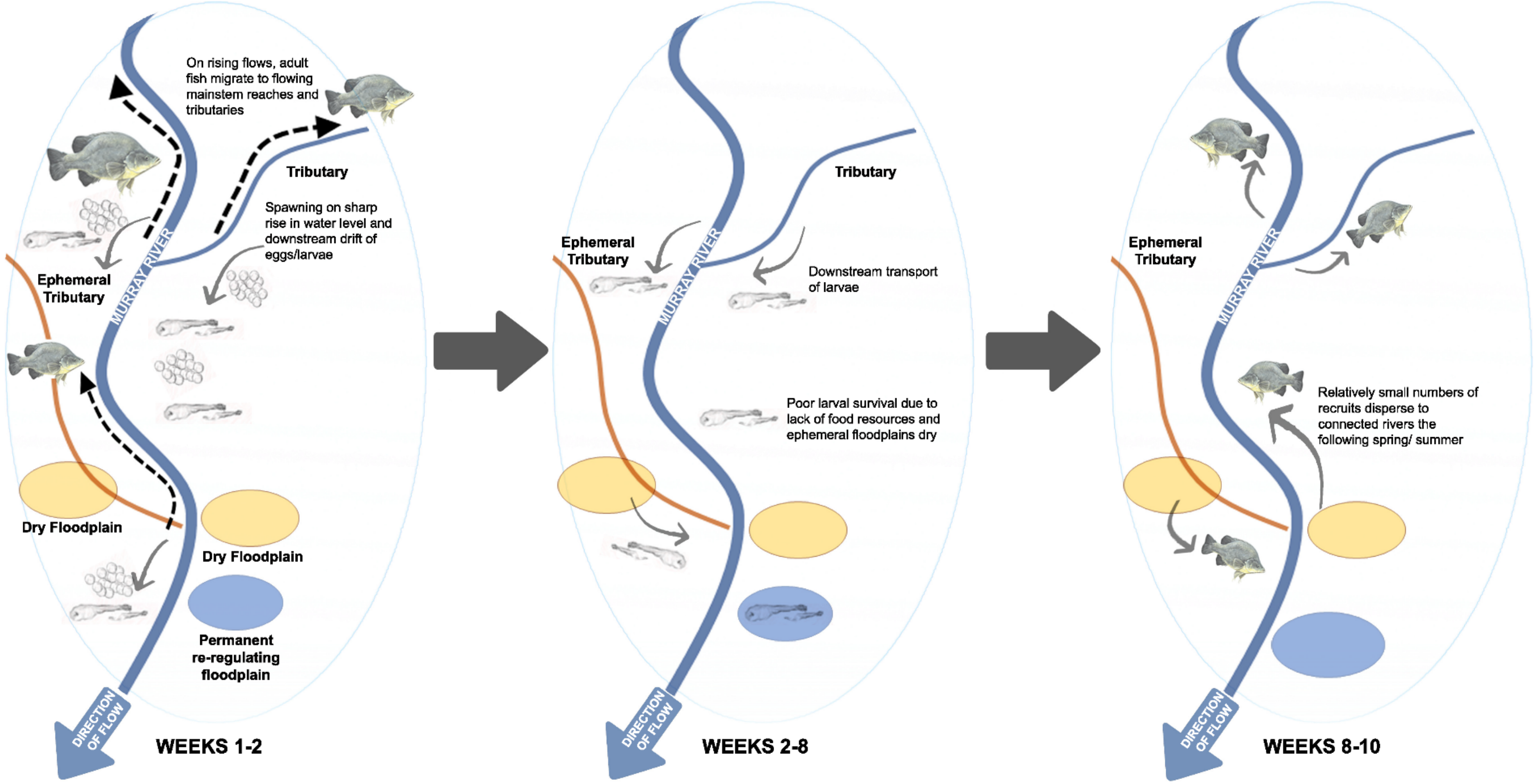
Threats

46. Loss of connectivity to floodplain nursery habitats
47. River regulation and diversion restricts juvenile and adult movement, prevents dispersal and recolonization of extensive stretches of river and increases risk of localised extinction and fragmentation
48. Weirs may trap eggs and early larvae causing them to settle and die (Baumgartner et al., 2014a)
49. Undershot weirs kill >90% of larvae (Boys et al., 2010)
50. Thermal issues will limit spawning below weirs and possibly decrease larvae survivorship
51. Loss of off-channel floodplain nursery habitats
52. Impoundment of riverine flowing water habitats

Knowledge and data limitations

53. Implementation of catchment scale flow planning to recover populations
54. A major knowledge gap is larval drift distance and survival upon entering a weir pool (e.g. larvae from the lower Goulburn River and mid-Murray River drifting into the Torrumbarry Weir pool).

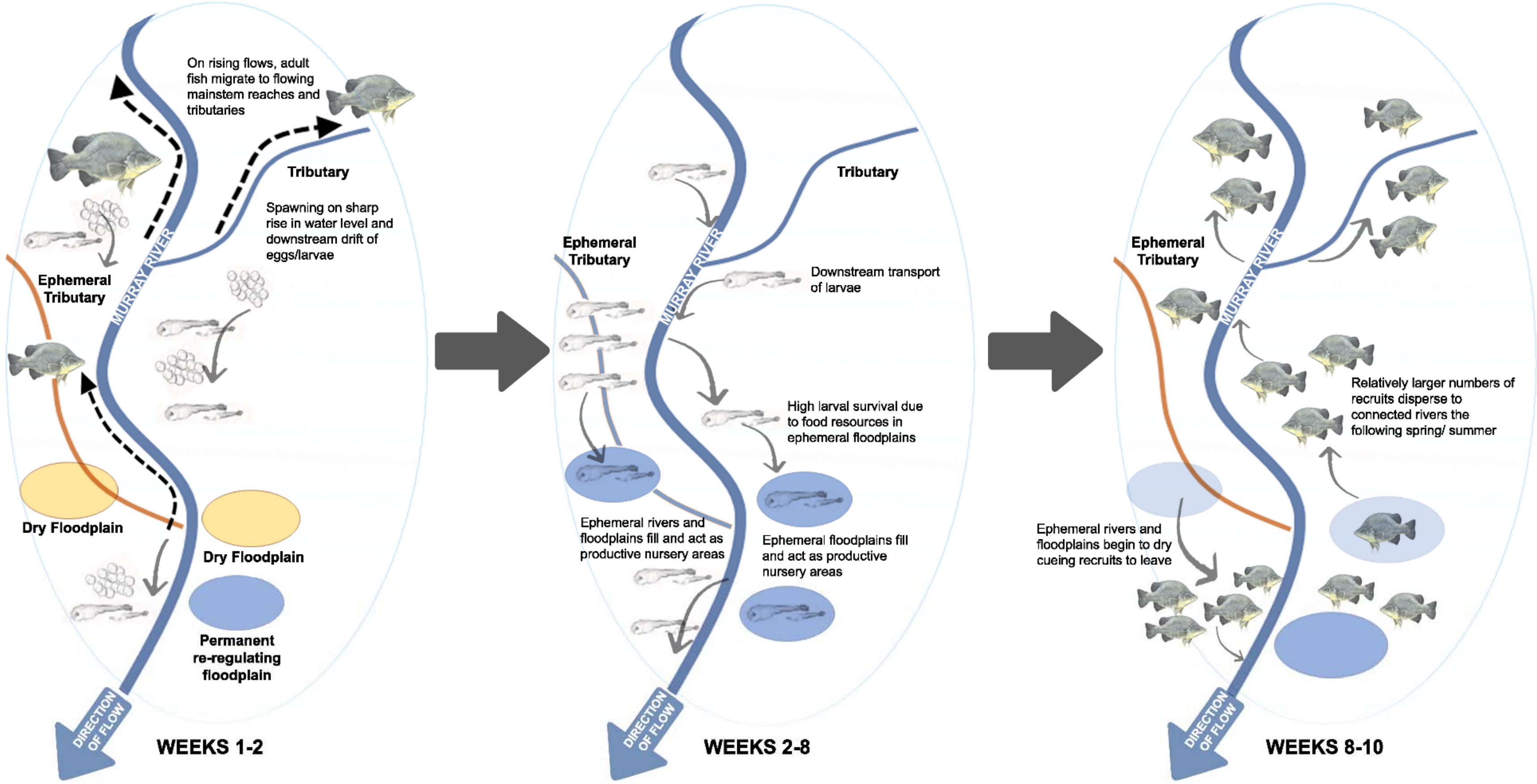
Golden Perch
Hydrological Scenario: rising in-channel flows in lower Murray River and tributaries



SPATIAL SCALE: > 500 KM

Figure 9 Conceptual model for golden perch

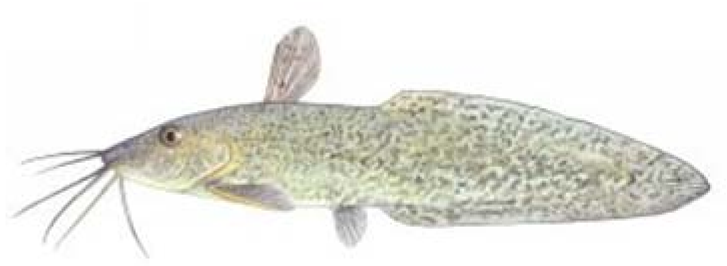
Golden Perch
Hydrological Scenario: over-bank flows
in lower Murray River and tributaries



SPATIAL SCALE: > 500 KM

Conceptual model for golden perch (continued)

6.4 Freshwater catfish



Freshwater catfish (*Tandanus tandanus* [Mitchell]) are a large, stocky, largely benthic freshwater fish that are an opportunistic carnivore. They commonly reach lengths of 500 mm and 2 kg in weight and can live for 10-12 years.

Freshwater catfish occur throughout the lowlands of the MDB and east coast rivers. In the southern MDB, populations persist in the main channel of the Murray, Darling and several small and large tributaries. In the Mallee, catfish can be found in the Murray River, Mullaroo Creek, Kings Billabong, Sandilong Creek and some local irrigation networks. The Mallee region is one of only four self-sustaining populations of freshwater catfish in Victoria.

Freshwater catfish have severely declined throughout their range and they are listed as endangered in Victoria and NSW.

Table 16 Conceptual model for freshwater catfish

Habitat use
1. Benthic species, preferring permanent flowing rivers, creeks, lakes, waterholes and wetlands with complex physical structure (e.g. snags, undercuts, rocks and vegetation). 2. Can be found in highly turbid habitats with fine silt substrates or clear streams with sand, gravel or cobble substrates, 3. Can be found in slow flowing habitats and (although not found in the Lower Murray) also inhabits pool-run sequences and flowing waters. 4. Prefers steady water levels, with small (e.g. <0.1 m) daily variations in water level, where courtship, nesting and recruitment processes can be completed. 5. A survey in northern Victoria found that freshwater catfish only occurred in standing waters such as lakes if there was low turbidity and abundant aquatic plants. 6. Other sites where populations have been known to have existed in Victoria (such as Cardross Lakes, Lake Victoria [near Maryborough], Tahbilk Lagoon) also possess abundant submerged and emergent aquatic plants. 7. Recruitment potential may be increased when additional habitat resources such as when food and shelter are created as river benches, snags and rocks and riparian zones are inundated by rising flows. 8. Juveniles often found in proximity to macrophytes and littoral areas with structural habitat (e.g. snags).
Spawning
9. In the temperate reaches of northern Victoria, southern NSW and SA, Murray cod spawn in October/November and sometimes December each year. 10. Spawning occurs annually in spring and summer in water temperatures above 24°C (Lake, 1967). In Lake Victoria (near Maryborough), however, spawning was recorded in water temperatures from 21°C to 28.6°C (Pam Clunie, ARI pers. comm.) and extended from November to February.

11. Spawning occurs during base flows and river rises. Often use permanent floodplain lakes as spawning habitat.
12. Although rising water levels may hasten spawning, they are not a necessary trigger. Strong daily fluctuations in water level, such as when small lagoons are pumped, likely reduce nesting/recruitment success since fish often build nests along the shallower edges of waterbodies.
13. Pair formation occurs prior to spawning and adults display complex pre-spawning courtship behaviour. Females may spawn with more than one male. Spawning occurs 1-4 weeks after nest construction.
14. Males build neat circular nests, up to 0.5 to 2.5 m wide, from sand, pebbles and gravel in shallow warm habitats. Several males may use a single nest site during the breeding season, and males may attract multiple females to the one nest (Clunie and Koehn, 2001b).
15. In Lake Victoria, nests have been recorded in water depths ranging from 0.35 m to 1.6 m (usually <1 m).
16. The female deposits the eggs within the nest before leaving. Up to 20,000 eggs are laid, and they hatch after approximately seven days. The larvae are free swimming by 12-14 days and feeding by 20 days (Lake, 1967). Males guard the eggs.

Recruitment

17. Recruitment appears to be linked to floods where there is enhanced survival of juveniles associated with increased productivity and connectivity of floodplains and rivers. Significantly increased numbers of juvenile and adult catfish were reported following the 2010/11 flood but few were reported in the decade of drought preceding.

Movement and migration

18. Generally considered non-migratory but conflicting evidence has been collected from different locations in Australia.
19. Early tagging studies indicated most fish stay within 5 km of home locations. A more recent active tagging project in Tahbilk Lagoon also indicated limited home range.
20. Can be found in fishways in very low numbers or occasionally in the north of the MDB in reasonable numbers associated with a river rise.
21. Predominately nocturnal with less movement during daylight.
22. Post-larval fish which leave the nest tend to ‘scatter’ into littoral habitats.

Implications for Victorian environmental flows

23. Flows which connect floodplains and rivers appear important for the species’ recruitment and movement.
24. Steady water levels in permanent wetlands are important, especially for nesting and recruitment into littoral macrophytes. Wetlands with highly variable water levels (i.e. when there is rapid irrigation drawdown) can negatively impact on breeding processes.
25. Provision of water to permanent high-quality floodplain wetlands important for maintaining populations (e.g. Kings Billabong).
26. For the few remaining permanent wetlands where catfish still reside there are significant risks of returning to a ‘natural’ wetting/drying regime.

27. Controlling carp, which negatively impact on water quality and macrophytes, is a priority in wetlands.

Implications for flow monitoring

28. Implementation of a catfish hydrograph in high priority wetlands is required. The hydrograph needs to include: steady water levels during the breeding season and opportunities for fish to disperse to other nearby permanent wetlands and rivers.

Threats

29. Loss of permanent floodplain wetlands which support populations.
30. Regulation of rivers, loss of minor and moderate floods and overt water level variation in remaining habitats.
31. Impacts of carp and loss of macrophytes and negative interactions with other non-native fish (e.g. redfin).

Knowledge and data limitations

32. Prioritisation of remaining permanent wetlands for recovery and hydrographs with key components to support catfish populations, such as: (i) stable water levels for nesting and (ii) littoral inundation for recruitment.
33. Connectivity requirements for population dispersal and movement.

6.5 Small-bodied wetland generalists

Wetland generalists are characterised by species that are short-lived, inhabit backwaters and floodplain wetlands rather than rivers and require over-bank flooding to facilitate dispersal and re-colonisation of floodplain wetlands.

They have flexible spawning and recruitment strategies, and move among habitats over a broad range of flow conditions (Baumgartner et al., 2014b). These fish are generally only limited by habitat availability.

The small-bodied wetland generalists are presented here as a guild, rather than individually as many aspects of their life-history and ecology are similar. Carp gudgeons (*Hypseleotris spp.*), flat-headed gudgeons (*Philypnodon grandiceps* [Krefft]), dwarf flat-headed gudgeons (*Philypnodon macrostomus* [Hoese & reader]), unspecked hardyhead (*Craterocephalus fulvus* [Ivantsoff, Crowley & Allen]) and Murray-darling rainbowfish (*Melanotaenia fluviatilis* [Castelnau]) are the predominant small-bodied native fish found throughout the Mallee SDL sites.

Table 17 Conceptual model for small-bodied wetland generalists

Habitat use
1. Can inhabit riverine or wetland habitats, prefer floodplains with complex and diverse macrophyte assemblages, and usually prefer slow flowing habitats but often found where there is hydraulic diversity (Baumgartner et al., 2014b).
2. Often found in small shallow ephemeral floodplain wetlands, which flood regularly and have intact riparian canopy.
3. Are usually tolerant to a broad range of water quality conditions but are intolerant of low dissolved oxygen and high salinity (McNeil and Closs, 2007). Some species can survive and even thrive in wetlands which have significantly degraded habitats and/or water quality).
4. Generally there are population declines with increasing salinity.
5. The greatest diversity of generalist species usually inhabits permanent wetlands that reconnect to the main river via small floods, or are permanently inundated as their inlets are connected to weir pools, or they are in close proximity to permanent rivers/creeks or temporary flood runners that have a relatively regular commence-to-flow frequency (i.e. 1-in-1 year; Lyon et al., 2010).
6. Can do well in permanent weirpool low-productivity style wetlands and do not require flooding.
7. A mosaic of wetland types and regular connection is essential for wetland specialists but these fish probably need at least three floods per decade to maintain populations (McNeil et al., 2008; Baumgartner et al., 2014b).
Diet
8. Appear to require flooding of new floodplain habitats and productivity boom with a variety of food organisms (e.g. invertebrates, zooplankton and shrimp).
9. Do not thrive in permanent low-productivity style wetlands.

Spawning

10. Generally they are highly fecund and spawn over a protracted period independent of river flows.
11. Eggs are sticky and demersal, laid onto aquatic vegetation in shallow water habitats (e.g. <0.3 m deep) (Lintermans, 2007).
12. Fish spawn annually, most often in spring, and there is no parental care except for carp gudgeons.
13. Hatching occurs after 2-10 days with larvae feeding on plankton.

Recruitment

14. Recruitment occurs annually and is influenced by food and physical habitat resources – healthy and diverse macrophytes may increase recruitment rates.

Movement and migration

15. Move among riverine and floodplain habitats, usually in spring and summer, when wetlands become available as the river rises (Stuart et al., 2008; Lyon et al., 2010).
16. Movement ecology is unusual among the broader native fish community and requires specific and regular management to achieve connectivity objectives. Wetland species require regular flooding to disperse to new floodplain wetland habitats where a healthy fish community is one which is present in multiple wetlands.
17. During a floodplain inundation event, these fish appear to be 'first colonisers' of newly inundated wetlands (Hammer and Wedderburn, 2008).
18. Tend to move on low regulated flows with relatively little riverine movement during high flows and floods.
19. Can recover quickly where there is connectivity to the main river channel.

Implications for Victorian environmental flows

20. Water management to suit macrophytes is advantageous since these species prefer floodplains with complex and diverse macrophyte assemblages, and slow flowing habitats.
21. Inhabit a variety of wetland types but these are generally slow-flowing habitats.
22. Require regular (annual) flooding and populations which can likely be enhanced with wetland water level variation and environmental watering of floodplains to recreate wetland mosaics.
23. Fish move at low regulated flows. They often suffer severe population declines during major floods but usually recover quickly where connectivity is adequate.
24. Fish are resilient to low flows.
25. One of the ecological priorities for Hattah is to maintain and enhance the small-bodied generalist native fish community. This can be achieved via establishing diverse and complex macrophytes and by keeping wetlands full and periodically connected so that fish can use source populations to establish in newly inundated wetlands.

Threats

26. Predation, competition and habitat damage by invasive fish, especially carp, redfin and gambusia (*Gambusia holbrooki*) (Macdonald et al., 2012; Tonkin et al., 2008).

27. Drying of wetlands with diverse macrophytes and small-bodied fish assemblages.
28. Changes to hydrology have reduced altered diversity and accessibility of wetland habitats (King et al., 2007).
29. Strong regular variations in wetland water levels.
30. Loss of wetland macrophytes.
31. Significant reduction in connectivity to main channel habitats; regulated conditions have caused loss of small and medium flood events. Connectivity is required for regular exchange of fish and nutrients and to prevent complete drying.

Knowledge and data limitations

32. Application of conceptual model and reference sites consisting of high quality wetlands and fish communities to test and inform interventions to recover degraded wetlands.

6.6 Wetland specialists

Wetland specialists are characterised by species that specifically require access to floodplain wetlands, rather than being able to inhabit both river and wetland systems in the way that wetland generalists can.

The wetland specialists are presented here as a guild, rather than individually as many aspects of their life-history and ecology are similar.

Table 18 Conceptual model for wetland specialists

Habitat use
1. Wetland specialists are often found in small shallow ephemeral floodplain wetlands which flood regularly and have intact riparian canopy.
2. Wetland specialists are also found in permanent wetlands which can act as a population source.
3. Wetland specialists have broad physical habitat requirements and can be found among fine woody debris, leaf litter and branches, aquatic macrophytes and open water. They are not necessarily associated with macrophytes which differentiates them from the generalists but re-establishing complex macrophytes is likely to still be highly advantageous for recovery (Smith et al. 2009; Hammer et al. 2012).
Hydrology
4. Wetland specialist fish naturally inhabit the full mosaic of wetland types across a floodplain landscape but these are generally slow-flowing permanent habitats.
5. During annual flows that reconnect wetlands, or during small (e.g. up to 25,000 ML/d), medium (e.g. 35-60,000 ML/d) and large flood events (e.g. >60,000 ML/d) fish move among wetlands, even colonising temporary habitats.
6. Fish require this regular (annual) and long duration flooding and populations can likely be enhanced with wetland water level variation and environmental watering of floodplains to recreate wetland mosaics (Meredith et al. 2009).
Water quality
7. Some species can survive and even thrive in wetlands which have significantly degraded habitats and/or water quality, such as southern pygmy perch in Black Charlie Lagoon, lower Ovens River floodplain wetlands, Tarma and Flat swamps in Barmah (McNeil and Closs 2007; McNeil et al. 2008; Tonkin et al. 2008).
8. Generally, there are population declines with increasing salinity, with the notable exception of Murray hardyhead (*Craterocephalus fluviatilis*).
Diet
9. Appear to require flooding of new floodplain habitats and productivity boom with a variety of food organisms (e.g. Invertebrates, zooplankton and shrimp).
10. Do not thrive in permanent weir pool low-productivity style wetlands.
Spawning and recruitment
11. Low fecundity (< 200 eggs per female)
12. Spawn adhesive eggs on floodplain vegetation.

Movement
13. Wetland specialist fish can form self-sustaining populations in floodplain billabongs. Dispersal can only be facilitated by producing specific and regular management to achieve connectivity objectives. In brief, wetland species require regular flooding to disperse to new floodplain wetland habitats where a healthy fish community is one which is present in multiple wetlands which have a mosaic of hydrologies (from permanent to ephemeral). 14. During a floodplain inundation event, these fish appear to be 'first colonisers' of newly inundated wetlands (Hammer et al. 2009). 15. Once wetland specialists have been lost from a region they are highly unlikely to recolonise even during the most major flooding (i.e. 1-in-100 year). For example, southern pygmy perch from the lower Ovens system were not able to recolonise the Barmah Lakes during the major floods of 2016/17.
Implications for Victorian environmental flows
16. Water management to suit macrophytes is advantageous since these species prefer floodplains with complex and diverse macrophyte assemblages, and slow flowing habitats. 17. Inhabit a variety of wetland types but these are generally slow-flowing habitats. 18. Require regular (annual) flooding and populations which can likely be enhanced with wetland water level variation and environmental watering of floodplains to recreate wetland mosaics. 19. Fish move at low regulated flows and during floods. Dispersal to new habitats is a major differentiation between wetland generalists and specialists. 20. Specialists are less resilient to low flows than generalists. 21. Will not recolonise Hattah without a re-stocking intervention and there are significant ecological and hydrological uncertainties in terms of maintaining populations.
Threats
22. The decline of wetland specialists is directly linked to reduced floodplain inundation frequency and duration where fish move among habitats (Wedderburn et al. 2017). 23. Changes to flood hydrology and simplification of wetland types, loss of permanent habitats or access to permanent habitats by floodplain regulators and levees (King et al. 2007). 24. Changes to hydrology have reduced diversity and accessibility of wetland habitats (King et al. 2007). 25. Returning one component of environmental flows cannot re-establish wetland specialists and a specific hydrograph is required at high priority sites. 26. Impacts of invasive fish, especially carp, redfin perch and gambusia (Tonkin et al. 2008; 2014; Macdonald et al. 2012). 27. Homogenisation of wetlands with stable water levels, uniform habitats, and low levels of natural disturbance undoubtedly has favoured native generalists and alien species, led to reductions in required specific micro-habitats, and severed metapopulation processes that formerly tied their association to the Lower River Murray (Hammer et al., 2012; Lloyd and Walker, 1986).

28. Loss of remnant wetland specialist populations during the Millenium drought, for example southern pygmy perch at Barmah.

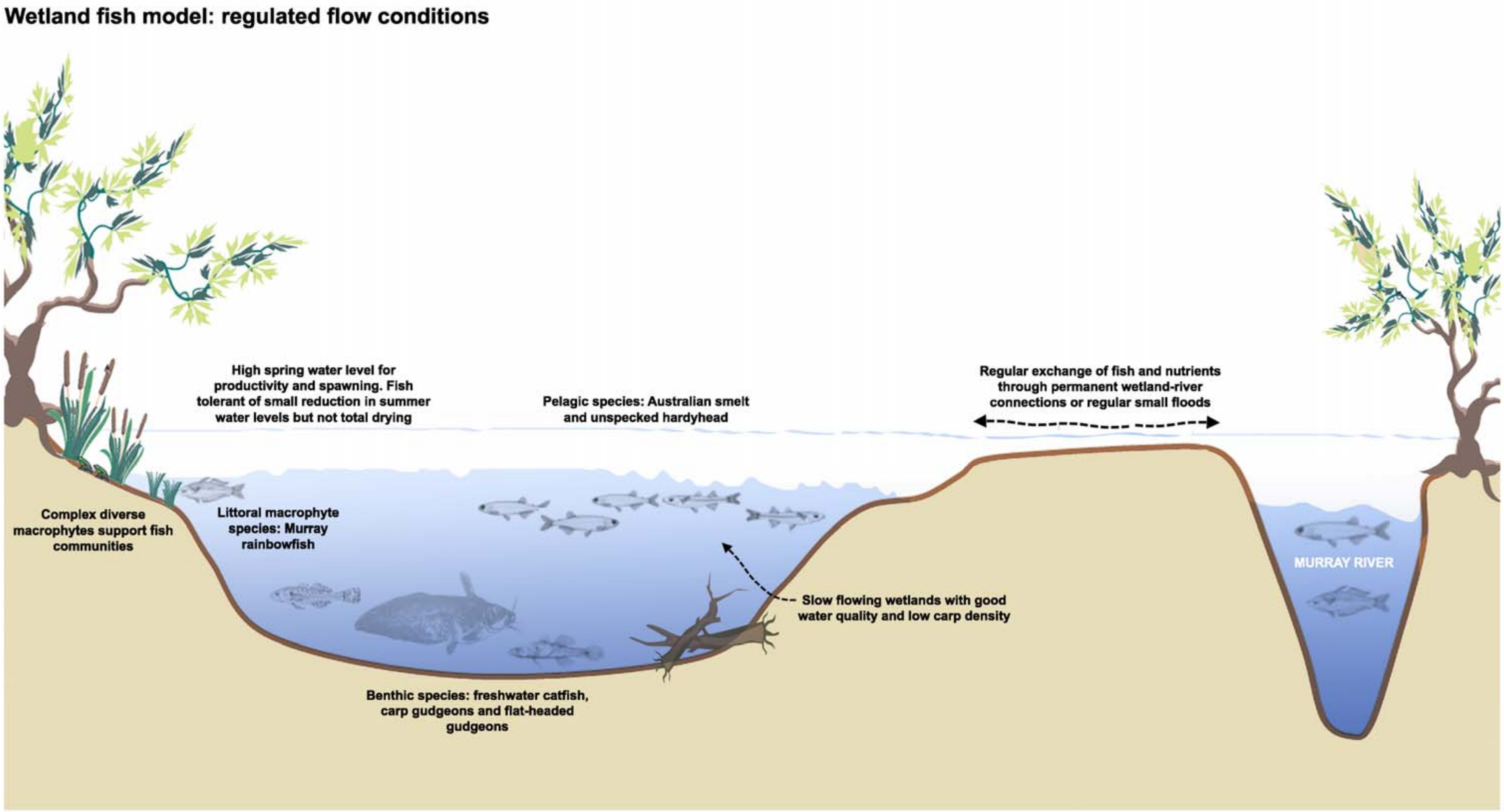


Figure 10 Conceptual model for wetland fish

7. Exotic Fish

7.1 Exotic fish species present and their threat

Five exotic fish species are present at Hattah or in the nearby Murray River, including carp, goldfish, redfin perch, gambusia and oriental weatherloach (*Misgurnus anguillicaudatus*) (Henderson et al., 2013). These fish all pose a risk to native fish, water quality and macrophyte outcomes for the site.

7.1.1 Carp

Carp are very efficient invaders and colonisers, and have established themselves in river systems all over the world (Koehn, 2004; Koehn et al., 2017). The Hattah Lakes favour carp because the pumped water creates shallow warm floodplain waters with low velocity which is ideal for carp spawning (Stuart and Jones, 2006). They can survive a wide range of aquatic conditions, including high temperatures and low oxygen levels, and they breed prolifically (Koehn et al., 2000). Carp are commonly collected in Hattah, including a broad range of age/size classes (Henderson, 2013; Wood and Brown, 2016).

Carp can affect the natural values of the Hattah floodplain in many ways, including directly competing with native fish for food and space, damaging macrophyte beds and re-suspension of sediment and nutrients (Koehn et al., 2000; Gilligan et al., 2010). Carp can also occupy habitat that would otherwise be available for large-bodied native fish in the restricted habitats that result between significant flow events. There may also be direct interactions between carp and native fish e.g. the disturbance of freshwater catfish nests.

A "*Carp Management Strategy for Hattah Lakes*" was developed in 2013 which made recommendations for operational regimes and interventions to control carp (Stuart, 2013). The report emphasised Integrated Pest Management (IPM) principles, including setting clear objectives and controlling the damage done by carp to an acceptable level (i.e. managing environmental values), rather than simply reducing carp numbers (Stuart, 2013). More recent population modelling has also emphasised the regional contribution that managed flooding can make to carp populations and mitigation strategies (Koehn et al., 2017).

7.1.2 Goldfish, redfin perch, weather loach and gambusia

The other four exotic fish species found at Hattah are abundant in inland waterways and have a range of potential impacts. Goldfish and weatherloach compete for food and space with native fish while also re-suspending nutrients and sediments (Keller and Lake, 2007). Redfin perch and gambusia directly prey upon native fish and can influence the structure of fish communities (Macdonald et al., 2012). These species pose a reasonable level of threat to the natural values of Hattah Lakes and are likely advantaged by managed static flooding.

7.2 Potential carp herpes virus impacts

A National Carp Control Plan (NCCP) is being prepared to explore the release of the carp virus cyprinid herpesvirus-3, or CyHV-3. The virus is highly contagious for carp and is most effectively transmitted through carp-to-carp contact and can survive in water without a host for approximately three days.

A range of research projects are currently underway and these are due for completion in late 2018, informing the final decision concerning the virus release. If the carp virus is released in Australia, it is expected to initially kill more than 70% of infected carp. Carp that survive will carry the virus for life and, when stressed, may eventually succumb to disease. They will also continue to pass the virus on to uninfected carp, a process expected to provide long-term carp control.

At Hattah, it could be expected that the carp virus would be at the more efficient end of its effectiveness because the prevailing water temperatures are very suitable (e.g. between 15-30°C). The virus damages the kidneys, skin and gills of carp, the later causing death as soon as 24 hours after these signs develop.

For Hattah Lakes, where a reasonably high biomass of carp resides, there is a strong likelihood of mass carp die-offs, especially in the first spring/summer following virus release. The National Carp Control Plan includes a series of projects to help plan for clean-up of dead carp, estimation of tonnages and potential off-target impacts (e.g. water quality).

8. Previous watering outcomes for fish

Annual fish community monitoring is conducted in the Hattah Lakes by the Murray-Darling Freshwater Research Centre (MDFRC). The results of this monitoring have demonstrated that the mode of filling dry wetlands can influence the composition of the fish community that becomes established in the newly inundated habitat (Ellis and Wood, 2011).

8.1 Pumping

8.1.1 Temporary pumps in 2005/06

Pumping of the Hattah Lakes using temporary pumps after dry spells in 2005/06 and 2009/10 resulted in colonisation of the lakes system and Chalka Creek by up to nine species of native fish (Sharpe and Vilizzi, 2011 cited in Ellis and Wood, 2011) and two species of exotic fish. Notably absent from the Hattah Lakes fish community after the most recent watering event was gambusia despite it being present in the adjacent Murray River from which the environmental water was pumped. Only very low abundances of carp had colonised the Hattah Lakes via the pump system (Ellis and Wood, 2011).

8.1.2 TLM permanent pumping station

The TLM environmental works pump station was commissioned between October 2013 and January 2014. A second more substantial volume (91 GL) was pumped in May-September 2014. A total of 685 fish were sampled in Chalka Creek comprising six native and four exotic species of fish, plus fish eggs (n=12) and freshwater shrimps (n=1228) and a single yabby.

Bony bream, Australian smelt, carp gudgeons, golden perch and gambusia made up the majority of native fish sampled although freshwater shrimp were an order of magnitude more abundant than any species of fin-fish. Other species including silver perch, Un-specked hardyhead (*Craterocephalus stercusmuscarum fulvus*), goldfish and weatherloach, were sampled at a count of five or fewer individuals. Silver perch (n=4) and weatherloach (n=5) were recorded in Chalka Creek, but not in the Murray River.

There have been some differences in the fish community which establishes in Hattah during the different pumping events and this is linked to different survival rates among species and life-stages (i.e. larger sizes have greater mortality) and the timing of the pumping event (Brown et al., 2015).

Watering the Hattah Lakes via environmental pumps has allowed the establishment of a fish community of both valuable native and unwanted exotic species in this system of shallow productive wetlands. Furthermore, during reconnection with the Murray River, native and exotic fish transported to, and raised in, the lakes chose to move back from the lake habitats towards the river. The environmental watering clearly allows the Hattah Lakes to provide some functionality as a nursery-environment for a range of small-bodied generalist species found within the southern MDB. Where floodplains naturally connect to the Murray River then exchange of fish would likely enable a diverse and abundant community, particularly of the small-bodied generalist species (Ellis and Pyke, 2010; Lyon et al., 2010).

8.2 Overbank flows

Filling of the Hattah Lakes in late 2010 by overbank river flows saw colonisation by nine species of native fish and four exotic species in high abundances, including the previously absent gambusia, and weatherloach.

8.3 Lake Kramen

Lake Kramen had been dry for 17 years prior to 2010 when flooding in the Murray River resulted in natural overbank flows to Chalka Creek and many of the lakes within the Hattah Lakes system. The flooding of Chalka Creek provided opportunity to fill Lake Kramen by pumping 600 ML of water from Chalka Creek into a 10 km long flood runner, which terminated in Lake Kramen. The pumps used for the delivery of the water had a 12 inch diameter delivery and suction pipe which could deliver a total of 80 ML/day. The filling of Lake Kramen was conducted between 8 October 2010 and 3 December 2010.

The Lake Kramen survey demonstrated that only 25% of fish survived the passage from Chalka Creek through the pump mechanism and moved along 10 km of shallow flood runner to Lake Kramen; with only two carp gudgeon being recorded (Ellis and Wood, 2011, Brown et al., 2015).

The geographic and hydrological isolation of Lake Kramen means that there is very little chance that fish could return to the Murray River without an intervention (see Section 10.3.7 for further detail in Section 10.3.7. An email from Mallee CMA (A Greenfield 2017 pers. comm., 30 October) provided advice that anecdotal). Anecdotal observations from field workers operating around Lake Kramen suggest that there were substantial numbers of carp found dead following the drying period (email from Mallee CMA, A. Greenfield 2017 pers. comm, 30 October)..

9. Ecological objectives and targets

9.1 Hattah Lakes Ramsar ecological character description

The Hattah Kulkyne Lakes are a Ramsar site under which the Ecological Character Description (ECD) and limit of acceptable change in ecological character has been described.

The *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) prohibits actions that are likely to have a significant impact on the ecological character of a Ramsar wetland unless the Commonwealth Environment Minister has approved the taking of the action, or some other provision in the EPBC Act allows the action to be taken.

The *Water Act 2007* requires that in preparing the Murray-Darling Basin Plan, the Murray-Darling Basin Authority (MDBA) must take into account ECDs of declared Ramsar wetlands prepared in accordance with the National Framework.

9.1.1 Ramsar listing criteria

The Hattah-Kulkyne Lakes Ramsar site meets five of the Ramsar listing criteria. Those that relate to fish species are outlined in Table 19.

Table 19 Ramsar listing criterion and justification

Ramsar Criterion	Justification
Criterion 2: ***A wetland should be considered internationally important if it supports vulnerable, endangered, or critically endangered species or threatened ecological communities.***	Threatened fish species mentioned under this criteria were Murray cod (*Maccullochella peelii),* silver perch (*Bidyanus bidyanus), and* flat-headed galaxias (*Galaxias rostratus)* (Butcher and Hale, 2011).
Criterion 4: A wetland should be considered internationally important if it supports plants and/or animal species at a critical stage in their life cycles, or provides refuge during adverse conditions.	The site is considered important for fish breeding.
Criterion 8: A wetland should be considered internationally important if it is an important source of food for fishes, spawning ground, nursery and/or migration path on which fish stocks, wither within the wetland or elsewhere, depend.	This site is considered to be an important nursery area for native fish. Recruitment of juveniles back into the adult population is dependent on the water levels of the lakes being maintained, and for large bodied river specialists there needs to be reconnection to the Murray River for species to return to the riverine habitat. Small bodied wetland specialists breed in the site, with young of the year from fly-specked hardyhead (*Craterocephalus stercusmuscarum*), carp gudgeon (*Hypseleotris* spp.), flat-headed gudgeon (*Philpnodon grandiceps*) and Australian smelt (*Retropinna semoni*) recorded from the site.

9.1.2 Limit of acceptable change

Limits of acceptable change are defined as, "*the variation that is considered acceptable in a particular component or process of the ecological character of the wetland, without indicating change in ecological character that may lead to a reduction or loss of the criteria for which the* *site was Ramsar listed" (DSEWPC, 2012)*. The measurement of acceptable change with regards to fish at the site is:

Presence of the following wetland specialist species of native fish recorded over any three sampling events over a five year period in which at least three of the lakes are inundated (Butcher and Hale, 2011).

- Australian smelt *Retropinna semoni*
- Bony bream *Nematalosa erebi*
- Carp gudgeon *Hypseleotris spp.*
- Western carp gudgeon *Hypseleotris klunzingeri*
- Fly-specked hardyhead *Craterocephalus stercusmuscarum*

9.2 The Living Murray

The vision of the Hattah Lakes Icon site is to:

Preserve and where possible enhance the biodiversity values of Hattah Lakes; and restore healthy examples of all original wetland and floodplain communities which represents the communities which would be expected under natural flow conditions

Ecological objectives were developed for hydrology, vegetation, fish and waterbirds (Table 20).

Table 20 Overarching and detailed TLM ecological objectives

Overarching	Specific
Restore a mosaic of healthy wetland and floodplain communities to maintain the ecological character of the Ramsar site	Restore a mosaic of hydrological regimes, which represent pre-regulation conditions (to maximise biodiversity) Maintain and, where practical, restore the ecological character of the Ramsar site with respect to the Strategic Management Plan (2003) Restore the macrophytes zone around at least 50% of the lakes to increase fish and bird habitat. Improve the quality and extent of deep freshwater wetlands so that species typical of these ecosystems are represented.
Maintain high quality habitat for native fish in wetlands and support successful breeding events	Increase distribution, number and recruitment of local wetland fish—including hardyhead, Australian smelt and gudgeon by providing appropriately managed habitat Maximise use of floodplain habitat for recruitment of all indigenous freshwater fish
Provide feeding and breeding habitat for a range of waterbird species, including threatened and migratory species Provide conditions for successful breeding of colonial nesters at least twice every ten years	Maintain habitat for the freckled duck, grey falcon and white-bellied sea eagle in accordance with action statements. Increase successful breeding events for colonial waterbirds to at least two years in 10 (including spoonbills, egrets night herons and bitterns).

Overarching	Specific
	Provide suitable habitat for a range of migratory bird species(including Latham's snipe, red-necked stint and sharp-tailed sandpiper).

9.3 Sustainable diversion limit business case

Ecological objectives have been developed for the Hattah Lakes North site, drawing on a range of approaches and recommended lines of enquiry including:

- the overarching objectives in Schedule 7 of the Basin Plan
- the Basin-wide Environmental Watering Strategy (MDBA, 2014)
- a review of relevant literature including monitoring data from the TLM initiative (Bayes et al., 2010; Henderson et al., 2012; Henderson et al., 2013; Henderson et al., 2014)
- desktop and field based flora and fauna surveys (Australian Ecosystems, 2013 and GHD, 2014)
- site visits
- an ecological objectives workshop with an expert panel comprised of aquatic, wildlife, and restoration ecologists and key project stakeholders from DEPI and the Mallee CMA.

The preliminary broad ecological objectives for the SDL works outlined in the Hattah Lakes North Business case were set for two distinct water-dependant habitat types at Chalka Creek North and Bitterang North.

Chalka Creek North

"to protect and restore the productivity and integrity of floodplain vegetation and its capacity to support floodplain fauna" (Ecological Associates, 2014).

Bitterang North

"to provide important flood-dependent habitat components for terrestrial vertebrate fauna when the lakes are dry and to retain the capacity to provide a productive and diverse wetland habitat when the lakes are inundated" (Ecological Associates, 2014).

There were no specific ecological objectives or targets for fish in the Hattah Lakes North Business Case.

Table 21 SDL ecological objectives and targets

Specific objective	Ecological targets	Water regime class	Associated Basin Plan Objective
Protect and restore floodplain productivity to maintain resident populations of vertebrate fauna including carpet python, lace monitor and bats	Total bat abundance to increase by 25% from 2015 levels by 2030.	Red Gum Woodland, Black Box Woodland, red gum woodland, black box woodland	1, 2, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14
Provide occasional breeding habitat for waterbirds	Any species of waterfowl, crake, rail, waterhen or coot to breed in at least six seasons between 2025 and 2035.	red gum woodland, episodic wetlands	1, 2, 4, 6, 7, 8, 9, 10, 11, 12
Maintain the health and age structure of red gum and black box trees	All red gum and black box stands within the project area achieve a health score of moderate or better under Cunningham (2011) tree health monitoring for all years between 2025 and 2035.	red gum woodland, black box woodland	1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14
Maintain a plant community of drought-tolerant wetland species in infrequently inundated areas	The drought-tolerant wetland species *Cyperus gymnocaulos* and *Eleocharis acuta* are to be present in vegetative form in 75% of wetlands following any filling event.	episodic wetlands	1, 2, 3, 4 , 6, 7, 8, 9, 10, 11, 12, 13, 14
Contribute to the carbon requirements of the Murray River channel ecosystem	The average annual carbon load (dissolved and particulate) to the Murray River from Hattah Lakes North for the period 2025 to 2035 is double 2015 to 2020 levels.	red gum woodland, black box woodland	2,7

The stated ecological benefits of the proposed inundation as it relates to fish at Hattah Lakes North was “to maintain the integrity and productivity of floodplain habitats. Inundation promotes germination of aquatic plants, which provide understorey habitat for a range of aquatic fauna species including fish” (Mallee CMA 2014).

9.4 Basin Plan

The environmental objectives set by the Basin Plan which have been attributed to Hattah North are all of those listed below except for number 5.

1. to protect and restore a subset of all water-dependent ecosystems in the Murray-Darling Basin ensuring that:

    a. declared Ramsar wetlands that depend on Basin water resources maintain their ecological character: and

    b. water-dependent ecosystems that depend on Basin water resources and support the lifecycles of species listed under the Bonn Convention, CAMBA, JAMBA or ROKAMBA continue to support those species: and

    c. water-dependent ecosystems are able to support episodically high ecological productivity and its ecological dispersal.

2. to protect and restore biodiversity that is dependent on Basin water resources, including by ensuring that: are protected and, if necessary, restored so that they continue to support those life cycles

    d. water-dependent ecosystems that:

        - Depend on Basin water resources: and
        - Support the lifecycles of a listed threatened species or listed threatened ecological community, or species treated as threatened or endangered in State or Territory law.

    e. representative populations and communities of native biota are protected and if necessary restored.

3. that the water quality of Basin water resources does not adversely affect water-dependent ecosystems and is consistent with the water quality and salinity management plan.

4. to protect and restore connectivity within and between water-dependent ecosystems including by ensuring that:

    a. the diversity and dynamics of geomorphic structures, habitats, species and genes are protected and restored; and

    b. ecological processes depend on hydrologic connectivity longitudinally along rivers, and laterally, between rivers and their floodplains (and associated wetlands) are protected and restored: and

    c. the Murray Mouth remains open at frequencies, for durations and with passing flows, sufficient to enable the conveyance of salt, nutrients and sediment from the Murray-Darling Basin to the ocean: and

    d. the Murray Mouth remains open at frequencies, and for durations, sufficient to ensure that the tidal exchanges maintain the Coorong's water quality within the tolerance of the Coorong ecosystems' resilience and

    e. barriers to the passage of biological resources (including biota, carbon and nutrients) through the Murray Darling Basin are overcome or minimised.

5. that natural processes that shape landforms (for example, the formation and maintenance of soils) are protected and restored.

6. to provide habitat diversity for biota at a range of scales (including, for example, the Murray–Darling Basin, riverine landscape, river reach and asset class).

7. to protect and restore food webs that sustain water-dependent ecosystems, including by ensuring that energy, carbon and nutrient dynamics (including primary production and respiration) are protected and restored.
8. to protect and restore ecosystem functions of water-dependent ecosystems that maintain populations (for example recruitment, regeneration, dispersal, immigration and emigration) including by ensuring that;
    a. flow sequences, and inundation and recession events, meet ecological requirements (for example, cues for migration, germination and breeding); and
    b. habitat diversity that supports the life cycles of biota of water dependent ecosystems (for example habitats that protect juveniles from predation) is maintained
9. to protect and restore ecological community structure and species interactions.
10. that water-dependent ecosystems are resilient to climate change, climate variability and disturbances (for example, drought and fire)
11. to protect refugia in order to support the long-term survival and resilience of water-dependent populations of native flora and fauna, including during drought to allow for subsequent re-colonisation beyond the refugia.
12. to provide wetting and drying cycles and inundation intervals that do not exceed the tolerance of ecosystem resilience or the threshold of irreversible changes.
13. to mitigate human-induced threats (for example, the impact of alien species, water management activities and degraded water quality).
14. to minimise habitat fragmentation.

9.5 Basin-wide environmental watering strategy

The Basin-wide Environmental Watering Strategy (MDBA, 2014) builds on the Basin Plan and is intended to help environmental water holders, Basin state governments and waterway managers plan and manage environmental watering at a Basin scale and over the long term to meet the environmental objectives.

The expected environmental outcomes that can be achieved beyond 2019 by the Basin-wide Environmental Strategy for fish to “Maintain current species diversity, extend distributions, improve breeding success and numbers are:

Improved distribution:

- of key short and long-lived fish species across the Basin

Improved breeding success for:

- short-lived species (every 1-2 years)
- long-lived species in at least 8/10 years at 80% of key sites
- Mulloway in at least 5/10 years

Improved populations of

- short-lived species (numbers at pre-2007 levels)
- long-lived species (with a spread of age classes represented)
- Murray cod and golden perch (10-15% more mature fish at key sites)

Improved movements:

- more native fish using fish passage

Hattah Lakes were identified in the Basin-wide Environmental Water Strategy as an important Basin environmental asset for native fish as a:

- site of other significance
- dry period/drought refuge

9.6 Summary ecological objectives for fish

A summary of the fish related ecological objectives for the site is summarised in Table 22 below.

Table 22 Summary of current ecological benefits, objectives and listed fish species

Strategic Link	Ecological benefits or objectives
Threatened Species contributing to Ramsar listing	Murray cod -*Maccullochella peelii,* Silver perch -*Bidyanus bidyanus,* Flat-headed galaxias - *Galaxias rostratus*
The Living Murray	Restore the macrophytes zone around at least 50% of the lakes to increase fish and bird habitat.
	Improve the quality and extent of deep freshwater wetlands so that species typical of these ecosystems are represented.
	Increase distribution, number and recruitment of local wetland fish—including hardyhead, Australian smelt and gudgeon by providing appropriately managed habitat
	Maximise use of floodplain habitat for recruitment of all indigenous freshwater fish
SDL Ecological benefits	Inundation promotes germination of aquatic plants, which provide understorey habitat for a range of aquatic fauna species including fish
Basin Plan ecological objectives	Declared Ramsar wetlands that depend on Basin water resources maintain their ecological character
	Water-dependent ecosystems are able to support episodically high ecological productivity and its ecological dispersal
	To protect and restore ecosystem functions of water-dependent ecosystems that maintain populations (for example recruitment, regeneration, dispersal, immigration and emigration) including by ensuring that; • flow sequences, and inundation and recession events, meet ecological requirements (for example, cues for migration, germination and breeding); and • habitat diversity that supports the life cycles of biota of water dependent ecosystems (for example habitats that protect juveniles from predation) is maintained To protect refugia in order to support the long-term survival and resilience of water-dependent populations of native flora and fauna, including during drought to allow for subsequent re-colonisation beyond the refugia. To minimise habitat fragmentation.

Strategic Link	Ecological benefits or objectives
Basin-wide environmental watering strategy	***Improved distribution:*** • of key short and long-lived fish species across the Basin ***Improved breeding success for:*** • short-lived species (every 1-2 years) • long-lived species in at least 8/10 years at 80% of key sites ***Improved populations of*** • short-lived species (numbers at pre-2007 levels) • long-lived species (with a spread of age classes represented) • Murray cod and golden perch (10-15% more mature fish at key sites) ***Improved movements:*** • more native fish using fish passage Important Basin environmental asset for native fish with respect to • site of Other significance • dry period/drought refuge

PART B – Outcomes and Recommendations

10. Fish related opportunities

By way of background, a separate document details the objectives and potential opportunities for fish recovery in the Murray River which integrates with the present plan. The present plan, however, does not explicitly focus on the Murray main channel. The Hattah Lakes are typical of the Murray floodplain, where human development over the past 100+ years has led to major changes in wetland function and a severe reduction in abundance of many native fish species. The native fish community has become dominated by small-bodied wetland generalist species such as carp gudgeon species, although small-bodied wetland specialists such as flat-headed galaxias and southern pygmy perch (*Nannoperca australis*) are absent (McCarthy et al., 2008; Vilizzi et al., 2013).).

Similar to many floodplain wetlands along the Murray corridor, the native small-bodied fish community of the Hattah Lakes dominated by generalist species, such as carp gudgeons (Vilizzi, 2013). Nevertheless, the historic fish community still provides a strong indication of the potential to support greater fish abundances and diversity of native fish, especially a more diverse small-bodied generalist fish community. Of the 10 native fish species that were historically present or expected to occur in the past, six species are still present, whilst the remaining four species are considered locally extinct (Table 23).

For Mallee CMA, the question now is: "to what extent can these fish populations be recovered?" This question is addressed in the following section where we recommend:

1. a recovery framework for wetland generalist species and then
2. an experimental method to test whether Lake Kramen could be used as golden perch recruitment habitat via fingerling stocking.

The logic of fish recovery actions for Hattah is presented in Figure 11.

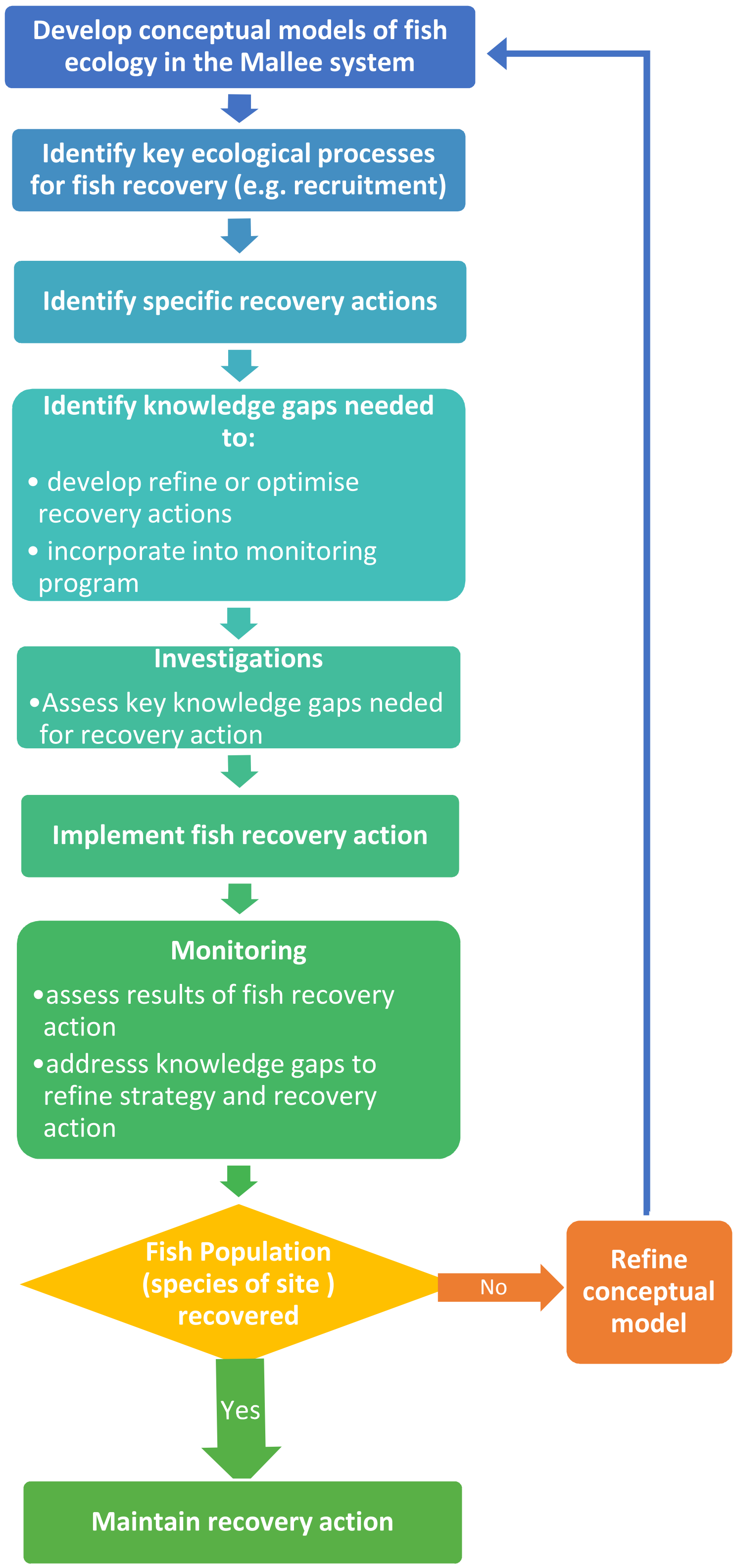


Figure 11 Hattah recovery actions flow chart

10.1 Recovery of small-bodied wetland generalist species

10.1.1 Background

The off-channel permanent floodplain lakes of Hattah, within the red gum and black box forests, are not generally favoured by medium-bodied fish species (e.g. golden perch) but by small-bodied native fish which specifically use these habitats. A significant characteristic of the *off-channel wetlands* is their diversity in size, morphology, aquatic macrophytes, permanence and riparian zone. This diversity provides opportunities for sustaining populations of small-bodied fish species, especially the more common species that are now uncommon at Hattah (e.g. Murray-Darling rainbowfish and unspecked hardyhead).

These *small off-channel wetlands* have been more affected by river regulation and reduced flooding frequency than many other aquatic habitats and they were the first to dry out with reduced natural flooding (Mallen-Cooper and Zampatti 2017). Hence, critical off-channel refuges for small-bodied fish have been lost. The loss of these habitats has had a direct impact on these species (refer Table 23 for past and predicted trends in small-bodied fish abundance). These wetlands, being highly affected by flow regulation and a potential habitat for threatened species, are key habitats for restoration that will require specific management.

Management implication

The new infrastructure at Hattah Lakes enables the forest floodplain to be flooded and thus rehabilitated during in-channel Murray flows and over-bank floods. By flooding the forest, small-bodied fish can be rehabilitated at a local wetland scale.

Table 23 Past and predicted fish populations in the Hattah Lakes and Mallee area of the Murray River. Data from the scientific literature

Abundance: ✓✓✓✓ Abundant, ✓✓✓ Common, ✓✓ Uncommon, ✓ Rare, - Absent

Population Trend in Hattah:
↑ Slight increase; ↑↑ Moderate increase; ↑↑↑ Major increase; ▬ No Change
↓ Slight decline; ↓↓ Moderate decline; ↓↓↓ Major decline

	Past abundance	Present abundance	Estimated Population Change	Predicted Population Change with all Impacts addressed
Small-bodied species(20-90 mm)				
Carp gudgeons	✓✓✓	✓✓✓✓	↑	▬
Flat-headed gudgeon	✓✓✓	✓	↓↓	↑↑
Un-specked hardyhead*	✓✓✓	✓	↓↓	↑↑
Australian smelt	✓✓✓	✓✓	↓	↑↑
Dwarf flat-headed gudgeon	✓✓✓	✓	↓↓	↑↑
Murray–Darling rainbowfish	✓✓✓	✓	↓↓	↑↑
Southern pygmy perch	✓✓✓	-	↓↓↓	↑↑↑
Southern purple-spotted gudgeon	✓✓	-	↓↓↓	↑
Flat-headed galaxias	✓✓✓	-	↓↓↓	↑↑
Olive perchlet	✓	-	↓↓↓	↑

10.1.2 Rationale for recovery

The TLM sampling has shown a long-term decline in the abundance and diversity of small-bodied native fish at Hattah (Henderson et al. 2012; 2013; 2014). These fish are short-lived (e.g. 1-2 years) and thus can be very vulnerable to short term impacts, such as anoxic blackwater or wetland drying. Recent local TLM survey data for Hattah Lakes suggests a long-term decline in small-bodied generalist fish populations (Henderson et al. 2012; 2013; 2014).

Consideration of the small-bodied fish species that are present or expected at Hattah (see Ellis and Wood, 2011) and the aquatic habitats that can be rehabilitated, suggests at least five species have high potential for recovery (Table 23). With limited riverine connectivity, fish dispersal migrations only really occur during infrequent floods, thus generalist species rely on the creation of regularly connected wetlands to support strong populations.

The wetland specialists undertake local recolonization movements during floods and the loss of the regular small and medium floods is a major reason why these species have declined regionally. Once these fish have disappeared they are unlikely to recolonise as they do not make large scale dispersal movements. For the wetland specialists, there are no nearby source populations. An initial stocking or translocation would be the most effective method to re-establish populations. There are however significant uncertainties concerning the fish ecology and current research at Barmah may be informative before considering a Hattah intervention. In the immediate term, maintaining and enhancing the existing wetland generalist fish community and establishing strong local source populations is the major ecological priority.

10.1.3 Recovery investigations and actions

Investigations

1. Analyse temporal pattern of fish populations and trends from TLM condition data.
2. Assess current condition of source fish populations with the lakes and creeks of Hattah.
3. Identify habitat characteristics associated with robust small-bodied fish populations (e.g. size, geomorphology, density and types of aquatic plants, flow regimes, carp density).
4. Identify specific wetlands/sites in Hattah that contain optimum habitat characteristics and where water delivery can be easily managed to support reintroduced and local fish populations (Bulla, Arawak, Brokie suggested because they are small, terminal and at a low elevation so that there are maximum filling options). Chalka Creek could also be managed as a permanent refuge habitat.
5. Identify through field investigations direct and indirect threatening processes associated with the fish species' decline (e.g. competition or predation associated with carp; effects of regulated flow regimes on recruitment and dispersal) to determine which of the threatening processes most impacts their results

Actions

1. Identify and apply management options at specific sites to remove direct and indirect threats (e.g. drying of particular wetlands to remove exotic species; reintroduction of indigenous aquatic plants; management options to maintain drought refuges [e.g. pumping]; dispersal pathways).
2. Prioritise permanent wetlands with strong littoral macrophyte assemblages for small-bodied fish restoration which can act as source populations.
3. Re-create and maintain small permanent wetland habitats with pumped water until natural inflow events bring in extra nutrients and enable broad-scale fish movement.
4. Enhance regular connectivity of wetlands during managed inundation events to facilitate fish exchange from source wetlands to newly wetted habitats

5. Target restoration of small-bodied generalist fish that have declined locally (e.g. unspecked hardyhead, flat-headed gudgeons, Australian smelt and Murray-Darling rainbowfish).
6. Where the conceptual model and permanent wetland management regime provide support: reintroduce southern pygmy perch and enable movement of unspecked hardyhead, Murray-Darling rainbowfish, Australian smelt and flat-headed gudgeons into a selected range of habitats including medium and small forest wetlands.
7. Translocate freshwater catfish to permanent floodplain habitats.
8. Implement carp control actions (e.g. Hattah Strategic Carp Control Plan, Stuart, 2013).
9. Monitor status of reintroduced populations.
10. Revise conceptual models to emphasize that maintaining permanent wetlands is critical to source populations and that drying events need to be strategically planned with the goal of maintaining fish communities.

The objectives and hydrological requirements for these activities are summarised in Table 24.

Table 24 A wetland management plan for small-bodied generalist native fish

Location and hydrological scenario	Target native fish	Objective	Justification for hydrograph	Hydrology
Hattah wetlands Natural inflows	Wetland generalists	Identify wetlands to be managed as permanent	To support small-bodied native fish communities	A series of permanently inundated wetlands
Hattah wetlands Natural inflows	Wetland generalists	Enable exchange of riverine and floodplain fish and resources	Temporary connection to Murray River required for generalist native fish exchange with Hattah floodplain Spring/Summer fish spawning in shallow littoral habitats (e.g. to 20 cm depth) and hence rapid water level fluctuations not required Maintain littoral macrophytes	Overbank flows that connect existing wetlands and fill temporary habitats
Hattah wetlands Managed inflows	Wetland generalists	Annual spawning and recruitment and self-sustaining source populations Maximise macrophyte diversity and complexity Dispersal of fish among wetlands and to newly inundated habitats to maximise spatial distribution	Spring/Summer fish spawning in shallow littoral habitats (e.g. < 20 cm depth) Connection among wetlands to enable fish movement Stimulate primary productivity and macrophytes Maintain water levels in refuge habitats	Monthly top-up flows throughout spring and summer at 1 per month @5ML/d for 8-12 days. Water level variation <0.1/day in spring Water level variation in winter and can be at up to 0.25 m/day to stimulate primary productivity processes Maintain high quality habitat for native fish source wetlands and support successful breeding events Top up events to ensure wetlands retain healthy littoral habitats which support small-bodied fish

Location and hydrological scenario	Target native fish	Objective	Justification for hydrograph	Hydrology
				Where possible annual connection events among wetlands be initiated or maintained during spring for fish colonisation

10.2 Threatened species translocation

10.2.1 Background and rationale

The wetland specialist species that have medium/long-term potential for recovery and have small-scale dispersal movements include the small-bodied threatened species (southern pygmy perch, olive perchlet, flat-headed galaxias, southern purple spotted gudgeon) and freshwater catfish. Southern pygmy perch, southern purple spotted gudgeon and olive perchlet breed easily in captivity and government breeding programs currently exist for these species at Narrandera Fisheries Centre in NSW. In South Australia, there is also a breeding program for southern purple spotted gudgeon.

Translocation of southern pygmy perch to farm dams that had wetland characteristics (as refuges during the last drought) has been very successful. This species has also been successfully reintroduced into wetland habitats at Deniliquin, Washpen Creek (near Euston), and Thurgoona NSW (John Conallin, Murray CMA pers. comm; Dean Gilligan, NSW Fisheries pers. comm.). Reintroduction of southern pygmy perch to the Barmah Forest is also being considered (Jarod Lyon, ARI, pers. comm.). Olive perchlet have been re-introduced into selected wetlands in southern NSW, which has either been very successful or failed. Flat-headed galaxias can be easily transported but appear difficult to breed in captivity (Llewellyn, 2005), so direct translocation of fish from healthy populations would likely be the most effective method.

Reintroduction of threatened fish is a strong long-term management option but one that needs to be carefully planned. Importantly, if the causes (e.g. alteration of flows) and impacts of exotic fish (e.g. competition with gambusia and carp destroying wetland vegetation) for the decline of the species are not addressed then the reintroduction is unlikely to result in a self-sustaining population.

In Victoria, the “Guidelines for the Translocation of Aquatic Organisms in Victoria” provide a risk management framework for approval to move fish, which might require approval under the relevant Acts (e.g. Fisheries Act 1995 and FFG Act). For species with conservation significance, such as southern pygmy perch, there is a reasonable expectation that reintroduction would be positively considered by the relevant authorities.

There are examples of translocations of threatened fish species from one population to another e.g. freshwater catfish into the Wimmera, and stockings of trout cod and Macquarie perch.

More information in stocking and translocating in Victoria can be found at the DPI website:

http://www.new.dpi.vic.gov.au/fisheries/about-fisheries/legislation-and-regulation/Moving-and-stocking-live-aquatic-organisms/protocols-for-the-translocation-of-fish

A proposal to translocate fish would need to consider:

1. nearest source of fish for genetic integrity (e.g. Barmah Forest for southern pygmy perch)
2. number of fish required
3. priority locations and habitats for reintroduction
4. a monitoring program.

The habitat preferences and ecology of threatened species are generally less well known compared to common species, and thus some specific knowledge gaps exist. These gaps would need to be addressed as part of any reintroduction program to maximise the likelihood of self-sustaining populations establishing.

In summary, with habitat rehabilitation as described in this Plan, mitigation of direct and indirect threats and a reintroduction plan with monitoring, the likelihood of recovery is very high for four small-bodied fish species (unspecked hardyhead, Australian smelt, flat-headed gudgeons and Murray-Darling rainbowfish) with potential extension to several threatened species (e.g. southern pygmy perch, flat-headed galaxias and freshwater catfish).

The major recommendation for small-bodied wetland specialist fish is to delay implementing any initiatives until the current stocking of southern pygmy perch into Barmah wetlands has been completed and the factors that influenced success/failure fully documented.

Management Implication

At Hattah there is a very strong likelihood that small-bodied generalist fish can be restored via providing wetland conditions that support their populations. The small-bodied specialist species will require a stocking intervention and there is significant uncertainty into the hydrological conditions that will support population recovery. The priority therefore is to restore wetlands for small-bodied generalist species and to gather more information from current stocking initiatives for wetlands specialists (e.g. at Barmah) and apply a wetland specialist recovery program in the medium term.

10.3 Creating a golden perch nursery ground

10.3.1 Objective

To experimentally test whether the Hattah Lakes can be managed as a golden perch nursery habitat to produce a major regional golden perch recruitment event.

10.3.2 Rationale

Large deflation basin wetlands are important nursery habitats for golden perch and thus the Hattah Lakes this function (Sharpe 2011). Unfortunately, large floodplain lakes that act as golden perch nurseries are now absent in the Hattah region but these could be re-instated to serve this function for regional population benefits. For Mallee CMA, what is required is a targeted and sophisticated management intervention.

Fish surveys in the Hattah Lakes following pumping detected a ‘filtered’ native fish community, including minor recruitment of golden perch which were likely the surviving 25% of larvae from prior Murray River pumping (Brown et al., 2015). This result indicates that with careful planning the recruitment of golden perch from Hattah Lakes could be enhanced to become a contributor to regional populations, which represents an important and exciting opportunity for beneficial fish outcomes. In another recent example, stocking of fingerlings into a floodplain lake at Ta-Ru wetlands, near Lock 8, also demonstrated the potential of floodplain wetlands to be used as nursery areas and thus help recover golden perch populations (Ellis, 2016; Bicknell, 2017). While golden perch are the current priority species given their life-history strategy is intimately linked to floodplain inundation, this initiative could be subsequently be extended to silver perch.

10.3.3 Characteristics of Hattah to provide a nursey habitat for golden perch

Hattah is ideally located *geographically*, where a long stretch of unregulated Murray River exists upstream in which golden perch spawn annually and larvae drift downstream past the pump station inlets (Mallen-Cooper and Stuart, 2003; Brown et al., 2015). Small numbers of golden perch can recruit in Hattah although only 25% survive the pumping process. Previous mortality data was based on testing two-phase impeller and centrifugal pumps with 300-900 mm intake pipe diameters (Baumgartner et al., 2009).

Hattah is also ideal *geomorphically*, where the interconnected extant lakes were once part of a much larger palaeo-mega-lake, surrounded by terraced dunes and on the eastern side by vegetated lunettes (Butcher and Hale, 2011). This geomorphic profile is like the remaining known nurseries for golden perch in the large ephemeral deflation basins, such as Menindee Lakes (Sharpe, 2011).

Under regulated conditions, the Hattah Lakes are not *hydrologically* suited for golden perch recruitment because the lakes no longer flood frequently and rely on pumping. Nevertheless, the diversity of wetland hydrology, with permanent wetlands, temporary wetlands and episodic wetlands provides for the life-history of golden perch larvae which recruit most strongly from newly inundated floodplain lakes (Lake, 1967; Rowland, 1996; Sharpe, 2011).

A final key characteristic that indicates that Hattah could become a major golden perch nursery area is preliminary data on the water quality, phytoplankton and zooplankton food resources of the lakes indicates that these would support recruitment of fish larvae (EPA and MDFRC, 2008; McCarthy et al., 2008). Each of these components is dealt with in more detail below.

Summary

A priority habitat to test the golden perch model is Lake Kramen or Lake Bitterang where restoring the functionality of deflation basin wetlands for golden perch, by stocking early juveniles, is a progressive management opportunity for Mallee CMA. This opportunity can potentially contribute to enhancing regional populations. The key to this is to demonstrate the proof-of-concept experimental approach and the potential benefits. Importantly, there is very low to nil risk to existing golden perch or other native fish populations as the generalist populations co-exist with this early life-phase of golden perch in other locations (e.g. Menindee lakes, Lake Eyre; Sharpe 2011; Ellis 2016).

Management implication

Hattah Lakes are likely to be geographically and geomorphically well-suited to provide nursery conditions for golden perch larvae, with similarly supportive zooplankton food resources and water quality conditions. Hydrologically the lakes also appear to be well-suited for golden perch except for the lack of safe entry conditions via the pumps. Improving golden perch ecology may also have social benefits.

10.3.4 Golden perch reproduction and recruitment in nature

The adjacent floodplain lakes along the Murray River mainstem once formed important fish habitats, particularly for grow-out of early stage juvenile fish such as golden perch and silver perch. Under regulated conditions, few if any of these floodplains remain as functioning fish nursery habitats because they are:

- permanently inundated for water storage (e.g. Kow Swamp)
- regulated so that fish no longer can enter or exit (e.g. Lake Victoria, Euston Lakes and Lake Boga) and
- impacted by low dissolved oxygen due to infrequency of regular flooding (e.g. Barmah and Moira lakes, and Koondrook-Pericooota).

The life-cycle of golden perch is adapted to a broad range of river conditions, including droughts and floods (Lintermans 2007). During a river rise or flood, many adult fish move upstream for spawning which is followed by downstream drift of larvae over large distances (e.g. > 500 km; Reynolds 1983). Downstream drifting larvae can recruit in the main river channel but there is far greater recruitment when they drift into newly filled highly productive floodplain lakes, such as Hattah (Sharpe 2011).

Unfortunately, along the Murray River corridor, very few floodplain lakes remain connected to their floodplain and consequently golden perch populations have declined. One of the last remaining major floodplain lakes that serves as a golden perch nursery are the Menindee Lakes which provides an important template management at Hattah. The latest monitoring data (i.e. autumn/winter 2017) demonstrated that young golden perch have high growth rates in their first few months in Menindee when there is a productivity pulse as the dry lakes first fill. Some 3-12 months later, the young golden perch disperse back into the main river channel, moving both upstream and downstream.

At Hattah Lakes, river regulation has reduced the floodplain inundation frequency and spatial wetted area and hence is the major reason why pumped flooding events now occur. Fish community monitoring following the pumped flooding demonstrated establishment of a native fish community and also raised the potential for the Hattah Lakes to act as a nursery for native fish (Brown et al. 2015). Hattah, however, is more akin to a deflation lake than a redgum billabong so that issues with low dissolved oxygen, high tannin and high lignin levels will not likely cause adverse water quality conditions for golden perch larvae (Gehrke 1992). Hence, based on the Menindee example, there is great potential for Hattah Lakes to also serve as a golden perch nursery highlighting an important role for maintaining fish populations in the lower Murray. Improving golden perch recruitment may also have social benefits.

Management implication

Riverine spawning of golden perch in the Murray River upstream of Hattah and downstream drift of larvae past the Hattah pumps provides an important opportunity to utilise Hattah as a nursery habitat, based on functional ecological templates, such as Menindee Lakes. This logic signifies a potentially important role for Hattah in enhancing lower Murray golden perch populations and potentially having social benefits.

10.3.5 How pond production of golden perch can inform management of Hattah Lakes

In the early days of native fish research there was interest in developing hatchery techniques to restock golden perch into areas where they had declined. The first ground-breaking experiments showed this potential (Lake 1967). Natural recruitment in rivers provided the original model for the hatchery work and by the 1980s these hatchery techniques, including over-summer pond grow-out of young fish, were perfected (Rowland 1996; Table 25). Since then many millions of fingerlings have been restocked into rivers and impoundments (Rowland 1996).

To maximise fingerling production, larvae produced from hatcheries are stocked into earthen ponds with appropriate sized zooplankton and there is high (40-90%) survival of larvae where. Keys to the success of this extensive grow-out systems include:

- ponds were left dry over-winter
- ponds were filled 10-14 days before fish stocking
- there is high availability of suitable sized zooplankton at the commencement of feeding of juvenile golden perch

Table 25 Biological attributes of golden perch critical for fingerling grow-out in ponds.

Biological Attribute	Details	Reference
Size	Commonly to 600 mm long and 3 kg	Lintermans (2007)
Spawning	Spring and summer were water temperature is >18oC	Lintermans (2007)
Age at Maturity	3 and 4 years for males and females, respectively. Max. age 26 years	Mallen-Cooper and Stuart (2003)
Fecundity	>500,000 eggs for a large female (>2.5 kg)	Rowland (1983)
Egg size	3-4 mm water hardened	Rowland (1983)
Hatch time	1.5-2 days	Rowland (1983)
Larval size	3.5-4.0 mm TL	Rowland (1996)
Yolk sac life-span	2 days	Rowland (1996)
Stocking age	2 days after hatch	Rowland (1996)
First external feeding age	5-6 days	Arumugam and Geddes (1987), Rowland (1996)
Preferred larval food	Copepod nauplii, Boeckella fluviatilis, cladocerans	Arumugam and Geddes (1987), Rowland (1996)
Optimal plankton density in aquaria	500-3000 zooplankers L-1	Rowland (1996)
Pond growth	Nominally 1 mm per day (mean)	Rowland (1996)
Optimal pond preparation	Ponds left dry during winter and spring and filled 10-14 days before stocking	Matt McLellan, NSW Fisheries, pers. comm.
Stocking density	300,000 larvae per pond (0.3ha)	Matt McLellan, NSW Fisheries, pers. comm.
Pond production time before fingerling harvest	6-8 weeks, fish 30-40 mm long	Matt McLellan, NSW Fisheries, pers. comm.
Typical larval pond survival	70-80%	Matt McLellan, NSW Fisheries, pers. comm.

10.3.6 Actions to stock golden perch

From the current scientific knowledge of golden perch breeding in natural and artificial production in ponds there is potential to test Hattah as a nursery habitat. The priority lakes for golden perch stocking are listed in Table 26.

A summary of actions is presented in Figure 12 and Table 27.

Table 26 A list of lakes for the golden perch stocking experiment with the priority lakes identified as High or Low

Lake	Lake Area (ha)	Lake Volume (ML)	Wetland water regime (DELWP 2017)	Potential for golden perch stocking
Chalka Creek (South)	-	-		Low
Arawak	40	617	Periodically Inundated - Intermittent	Low
Bitterang	73	885	Periodically Inundated - Intermittent	High

Lake	Lake Area (ha)	Lake Volume (ML)	Wetland water regime (DELWP 2017)	Potential for golden perch stocking
Boich	<10	<110	Periodically Inundated - Episodic	Low
Boolca	25.4		Periodically Inundated - Episodic	Low
Brockie	28	345	Periodically Inundated - Intermittent	Low
Bulla	40	740	Periodically Inundated - Intermittent	Low
Cantala	101	1,233	Periodically Inundated - Intermittent	Low
Dry Lakes	200			
Hattah	61	1,476	Periodically Inundated - Intermittent	Low
Konardin	121	1,476	Periodically Inundated - Intermittent	Low
Kramen	161	221	Periodically Inundated - Episodic	High, but no escape flow path.
Little Hattah	<10	<110	Periodically Inundated - Seasonal Or Intermittent	Low
Lockie	141	1,291	Periodically Inundated - Intermittent	Low
Marramook	<10	<110	Periodically Inundated - Intermittent	Low
Mournpall	243	2,220	Periodically Inundated - Intermittent	Low
Nip Nip	<10	<110	Periodically Inundated - Episodic	Low
Roonki	42.2		Periodically Inundated - Episodic	Low
Tullamook	<10	<110	Periodically Inundated - Seasonal Or Episodic	Low
Yelwell	81	738	Periodically Inundated - Intermittent	Low
Yerang	65	787	Periodically Inundated - Intermittent	High

Hydrological Processes	Ecological Processes
Preparation (autumn/winter)	
Drain lakes	Order 1-2 million golden perch larvae from hatchery
Spring	
Fill main Hattah Lakes via pumping. Do not fill golden perch lakes.	Golden perch breeding in October/November
Spring	
Fill experimental lakes (e.g. Kramen & Bitterang) in late October	Monitor phytoplankton and productivuty pulse response in lakes.
Spring/summer	
Keep wetlands topped up with water until January	Stock larvae into lakes with phytoplankton in mid-November
Monitoring	
	Monitor golden perch survival and growth
Wetland draining/drying	
From late January/February begin to drain wetlands to cue fish to leave into Chalka Creek/Murray River	
In the case of Lake Kramen allow to dry if necassary and remove stranded fish	
Golden Perch Recruitment	
Monitor golden perch recruitment event and dispersal back to permanent habitats (e.g. Murray River) from late Januray to March	

Figure 12 Actions to test Hattah as a nursery habitat for golden perch.

Table 27 Summary of water management requirements for golden perch recruitment

Timing	Action
2017/18	Monitor zooplankton diversity and abundance, particularly in high priority lakes that may be considered for a golden perch stocking trial. This is likely to be Lake Kramen or Lake Bitterang.
February-April	Drain or exclude water from priority lake in preparation for spring re-fill
September /October	Re-fill in spring to create a productivity pulse
October	Sample and confirm phytoplankton and zooplankton abundance
November	Artificially stock golden perch larvae/fingerlings
November-January	Top-up lake levels, as required
From February	Where possible, drain fish back to Chalka Creek and Murray River using recession hydrograph
May-August	Drain and/or draw-down of lakes

10.3.7 Fish exit from floodplain lakes

Testing proof-of-concept for the golden perch nursery lakes concept is likely to eventually require a fish exit plan. Fish exit hydrographs have recently been highly successful in terms of stimulating golden perch to leave a managed inundation on Gunbower floodplain (Sharpe et al. 2016; Figure 13).

At this stage, the most appropriate lake, from an operational and ecological viewpoint, is likely to be Lake Kramen and/or possibly Lake Bitterang. For Lake Kramen, this is because watering is via pumps in Chalka Creek, a process that is totally managed, with a low risk of carp invasion and low risk of stocking impacts on other native fish because the pumping process into Lake Kramen enables negligible fish survival (Ellis and Wood 2011).

Following construction of the TLM works Lake Kramen can be filled by diverting flow from one of the TLM pumps to the flow path to fill Lake Kramen. A flow rate of approximately 100 ML per day can be delivered via this flow path. A regulator on the flow path may be closed during pumping to ensure that pumped water does not flow back to Chalka Creek. The default position for this regulator is open to allow natural flows (greater than 152,000 ML day in the Murray) to enter the lake unhindered.

Lake Kramen does not appear to have return flow to Chalka Creek and hence if it were used as a proof-of-concept lake then a specific intervention would be required to catch and move the young fish. In many other lakes a drop in water level will cause fish to exit the lake and return to permanent habitats. Hence, there is an opportunity to collect fish as the water level in Kramen Lake drops via evaporation. FishFish will be stimulated to leave and they will move to the deepest point, where they can be manually collected (e.g. with seine nets) and returned to permanent habitats.

Lake Kramen has been selected as a proof of concept because it is isolated. If the initiative is successful then it could be transferred to another lake (e.g. Bitterang) where naturally stimulating fish to leave would have a higher probability of success, limiting human intervention.

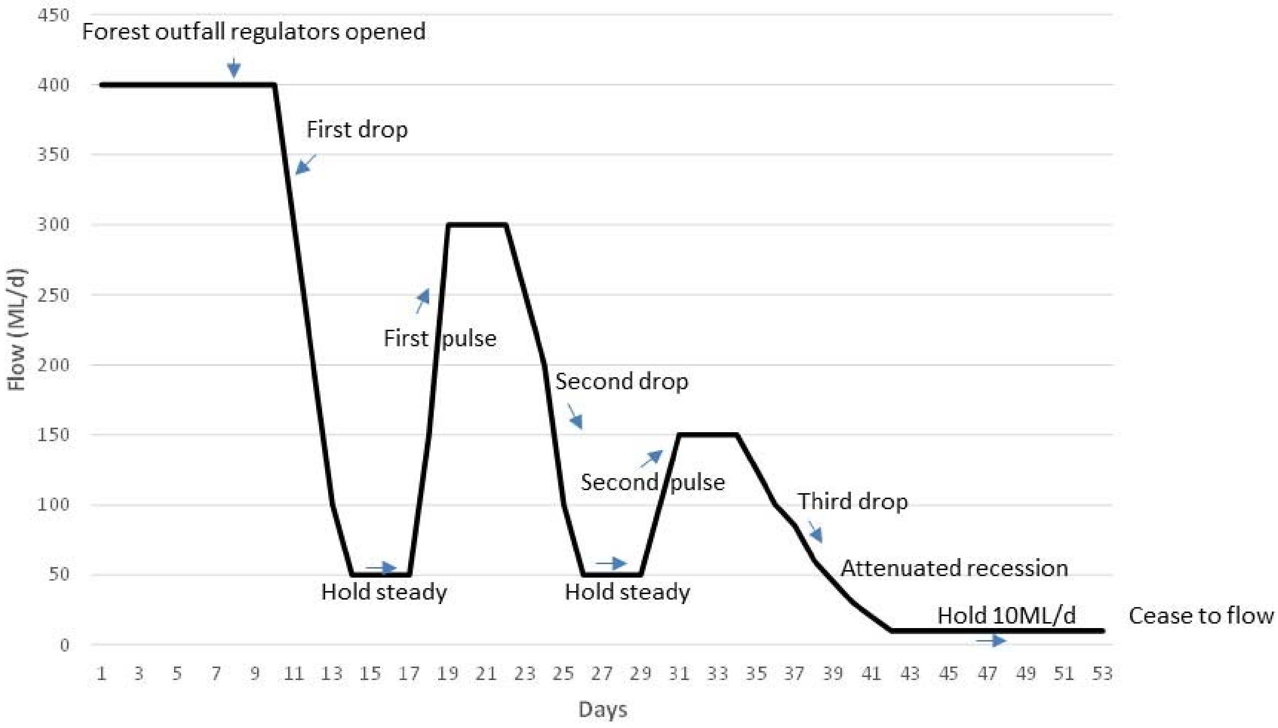


Figure 13 A successful fish exit hydrograph (conceptual) developed and implemented for golden perch on Gunbower floodplain (Sharpe et al. 2016).

10.3.8 Uncertainty and adaptive management

In the last decade there has been substantial research on the behaviour of fish on floodplains.. The response of native fish, however, is less certain in forest floodplains during managed inundations where the floodplain and river hydrology are not synchronised. Predictions can be made on fish behaviour, based on the conceptual models presented in Section 6, but the certainty varies.

The approach to address these knowledge gaps and uncertainty is to use adaptive management. The objective is to: maximise recruitment opportunities for stocked golden perch larvae in the Hattah Lakes. The response of fish will be totally reliant on the inundation regime and may not be fully planned for until the event and monitoring are underway. Hence, adaptive management as the event unfolds would be the most effective method to minimise risks and optimise outcomes.

This adaptive management will require real-time data on fish growth, survival and exit from the floodplain to provide guidance on flow management in particular, timing and duration of watering to give fish appropriate growing conditions and exit pathways back to Chalka Creek and the Murray River. Real-time data are also needed to provide advice on food resources in the lakes, growth and survival of the recruits and the need for manual collection and rescue of stranded native fish. These aspects require responsive management and co-operation with fish biologists and the asset/regulator operators.

10.3.9 Operational implications and risks

Stocking of golden perch larvae or fingerlings into the Hattah Lakes can be considered experimental but there are several ways to reduce operational risks. The risks fall into three categories:

1. program continuity
2. infrastructure and operations
3. fish responses

These risks and mitigation measures are listed in Table 28. They represent both high-level risks and detailed risks of individual on-ground structures/works.

Table 28 Risks and mitigations of the Hattah Lakes golden perch nursery initiative.

RISK	MITIGATION
Program Continuity	
Lack of monitoring On-ground works can often receive priority as they are at the beginning of the program.	Ensure funding for monitoring tracks alongside capital works. Communicate the value of monitoring and continue updates and reporting
Lack of stakeholder engagement	Ensure Communications Strategy runs in parallel with recovery actions. Request annual feedback from stakeholders and be responsive to changing communication needs.
Infrastructure and Operation	
Lakes not filled at appropriate time for fish stocking	Operators aware of critical timing for fish larvae stocking.
Regulator operation not optimised	O&M to include operation for fish objectives. Operators trained and supportive of fish objectives. Liaison with operating staff; include annual meeting to receive feedback from operators.
Pumped inundations of lakes trap and strand native fish.	Real-time fish monitoring of pumped inundations. Plan availability of required resources to rescue stranded fish.
Fish Responses	
Adequate zooplankton food resources not realised	Monitoring zooplankton communities and adaptive management.
Non-native fish species. Carp and gambusia establish in grow-out wetlands and compromise habitat for golden perch recruits.	Ongoing low-level (e.g. annual) monitoring to assess carp populations. Active management of non-native fish species.
Knowledge Gaps Unknown aspects of fish biology and recruitment conditions.	Monitoring of populations, with scope for more detailed investigations if recruitment response of golden perch is poor. Experimental approach to larval stocking to understand underlying reasons for recruitment.

10.4 Connection to other sites

The Hattah Fish Management Plan connects to other sites within the region via the Murray River and any benefits, particularly for recruitment of golden perch, could have benefits more broadly. There main action at Hattah that will have regional implications is in safely exiting golden perch from the Hattah lakes and into the Murray River.

10.5 Complementary Measures

Complementary measures are activities that address non-flow related threats to achieving Basin Plan Objectives. Whilst flows and habitat restoration will improve fish communities, the most significant impact will be through a combination of interventions. Examples of fish related complementary measures include fish passage structures, fish friendly pump screens, in-stream habitat, carp control, and native fish re-stocking.

Complementary measures that could improve outcomes for native fish in addition to the recommendations in this plan include (ranked in order of relevance):

- the use of a conservation stocking program to provide a source of locally and regionally extinct fish into watered sites (where water security can be assured)
- carp control through the potential release of the CHV-3 virus could substantially improve localised outcomes for small bodied native fish within the Hattah Lakes system
- improvements in Murray main channel habitat through targeted resnagging programs could aid survival of fish which were returned to the river from this site (ie allowing Hattah to become a more viable source population to the larger meta-population at the lower connected basin scale)
- improvements in fish passage (ie construction of a fishway on Balranald Weir) could provide greater connectivity for golden perch populations entering and moving out of the Hattah/Murray main channel area

11. Proposed ecological objectives and targets

The proposed ecological objectives for fish at Hattah have been developed with consideration of the objectives outlined in Section 9. As a contracting partner to the Ramsar Convention, Australia is obliged to promote the conservation of listed species and wetlands. Particular attention needs to be paid to the Ramsar Ecological Character Description and Limit of Acceptable Change (LAC).

For fish the Limit of Acceptable Change is measured by

Presence of the following wetland specialist species of native fish recorded over any three sampling events over a five year period in which at least three of the lakes are inundated.

- Australian smelt (*Retropinna semoni)*
- Bony bream (*Nematalosa erebi*)
- Carp gudgeon (*Hypseleotris spp*.)
- Fly-specked hardyhead (*Craterocephalus stercusmuscarum)*

The main fish related objectives set under previous programs are listed in Table 29 and cross referenced in Table 30.

Fish related opportunities and objectives are entwined with other ecological objectives set for the site, including vegetation and birds. A balance between all ecological objectives and their required hydrological requirements will need to be assessed by water managers.

The most important aspects to recognise are the frequency and duration of watering required to establish and maintain native fish populations in the lakes selected for wetland specialists and the golden perch nursery. Potential impacts to these values may be in the timing of drying lakes though only a small sub-section of lakes will be targeted for drying and wetting under these fish objectives.

Table 29 Previous related ecological objectives

Plan	Objective
The Living Murray	1. Restore the macrophytes zone around at least 50% of the lakes to increase fish and bird habitat. 2. Improve the quality and extent of deep freshwater wetlands so that species typical of these ecosystems are represented. 3. Increase distribution, number and recruitment of local wetland fish—including hardyhead, Australian smelt and carp gudgeons by providing appropriately managed habitat 4. Maximise use of floodplain habitat for recruitment of all indigenous freshwater fish
SDL ecological benefits	5. Inundation promotes germination of aquatic plants, which provide understorey habitat for a range of aquatic fauna species including fish
Basin Plan	6. to protect and restore a subset of all water-dependent ecosystems in the Murray-Darling Basin ensuring that: a. declared Ramsar wetlands that depend on Basin water resources maintain their ecological character: and b. water-dependent ecosystems are able to support episodically high ecological productivity and its ecological dispersal.

	7. to protect and restore ecosystem functions of water-dependent ecosystems that maintain populations (for example recruitment, regeneration, dispersal, immigration and emigration) 8. to protect refugia in order to support the long-term survival and resilience of water-dependent populations of native flora and fauna, including during drought to allow for subsequent re-colonisation beyond the refugia. 9. to minimise habitat fragmentation.
Basin-wide environmental strategy	10. Improved distribution: of key short and long-lived fish species across the Basin 11. Improved breeding success for: • short-lived species (every 1-2 years) • long-lived species in at least 8/10 years at 80% of key sites 12. Improved populations of • short-lived species (numbers at pre-2007 levels) • long-lived species (with a spread of age classes represented) • Murray cod and golden perch (10-15% more mature fish at key sites) 13. Improved movements: • more native fish using fish passage 14. Important Basin environmental asset for native fish with respect to • site of Other significance • dry period/drought refuge

Table 30 Proposed ecological objectives for fish and links to previous objectives

Target fish community	Ecological objective	Links to other objectives
Small bodied generalist and some medium-bodied native fish.	Enable exchange of small-bodied and some medium bodied native fish among riverine and floodplain habitats.	3,4, 6, 7, 9, 13
Small bodied generalist native fish	Recreate and maintain small-permanent wetland habitats with pumped water Promote connectivity of wetlands during managed inundation events Promote connectivity to river during natural flood events to introduce nutrients, raise water levels and allow broad scale fish movement.	Ramsar LAC 3,4, 6, 7, 9, 13
Small-bodied generalist species	Promote annual spawning and recruitment and self-sustaining wetland generalist fish populations Maximise macrophyte diversity and complexity Promote dispersal of wetland generalist fish among wetlands and maximise spatial distribution	Ramsar LAC 3,4, 5, 6, 7, 9, 13

Target fish community	Ecological objective	Links to other objectives
	Maintain refuge habitats	
Golden perch	Test the efficacy of Hattah Lakes as a regional golden perch nursery. Provide conditions in appropriate lakes for Golden Perch stocking and growth. Where appropriate cue fish to leave wetlands and recruit in permanent habitats.	4, 6, 7, 11, 12, 13
Wetland specialist fish	Where wetlands support self-sustaining populations of small bodied generalist fish, stock native freshwater catfish	4,5,12

12. Recommended SDL design criteria for native fish

The proposed SDL designs are detailed in Section 4.1.2 and summarised as

Table 31 SDL works and inundation area

Site	Proposed works	Area inundated
Chalka North	K10 regulator K10 river track Causeway	420 ha
Bitterang North	Bitterang regulator Bitterang temporary pumps	300 ha (via gravity) + 410 ha (pumped) 710 ha

The specifications outlined in the design report for the Hattah North SDL infrastructure, mainly K10 and Bitterang regulators broadly satisfy fish passage requirements and no design changes are recommended (Jacobs 2016a). The engineering inputs utilise current best practice fish passage standards and it is recommended to adopt those designs without compromise to the fish passage components (O'Connor et al. 2015).

Major fish passage requirement	Achieved at K10 and Bitterang regulator detailed designs	Design change recommendation
Fishway for upstream fish passage	Not provided, unlikely to be required due to local hydraulic conditions and low abundance of migratory fish 1v:20h rock ramp provided as erosion protection below the end sill on the tailwater apron to ensure a drop does not develop over time	nil
Water velocities through regulators to be within fish swimming tolerances	Best practice water velocity inputs from DELWP integrated No constriction to channel area Culvert floor below bed level	nil
Over-shot gates for safe downstream fish passage	Provided with dual leaf gates or single sluice gates	nil
Plunge pool provides safe hydraulics for downstream migrating fish	No dissipater blocks Depth >40% of head drop provided by tailwater apron end sill Culvert floor below bed level	nil
Gates to be operated as either fully open or fully closed – not in regulating mode	Recommended in engineering report	nil

13. Recommended operational regimes

The following table outlines the proposed ecological objectives and the operational regimes required to meet them.

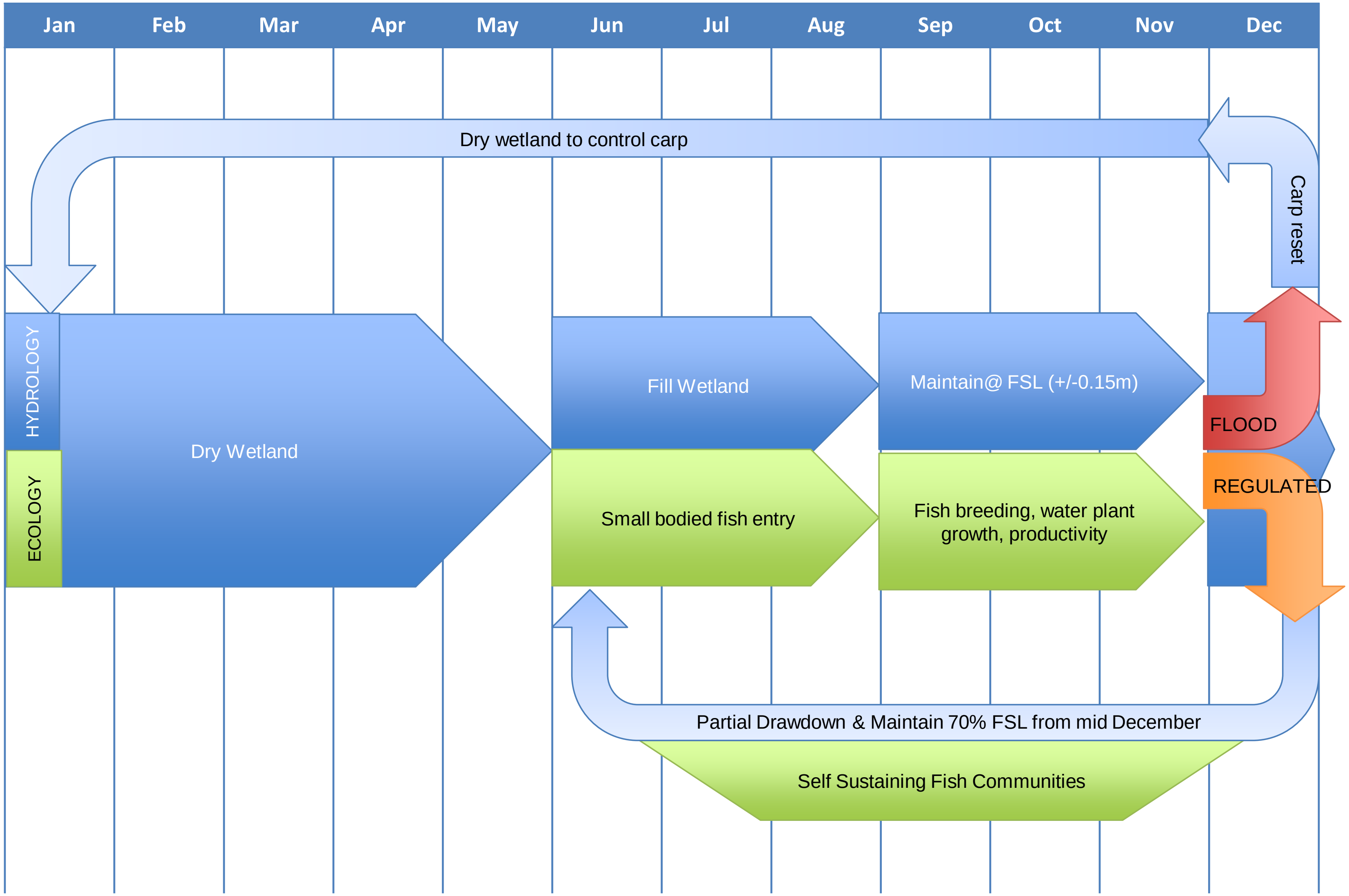
Table 32 Proposed ecological objectives and operational regimes to meet them

Ecological objective	Hydrological scenario	Operational regime
Dispersal of wetland generalist fish among wetlands and maximise spatial distribution	Managed inundation of Hattah North	All regulators open
Enable exchange of small-bodied and some medium bodied native fish riverine and floodplain fish and resources	Natural inflows	All regulators open: Overbank flows that connect existing wetlands and fill temporary habitats
Annual spawning and recruitment and self-sustaining wetland generalist fish populations Maximise macrophyte diversity and complexity Dispersal of wetland generalist fish among wetlands and maximise spatial distribution Maintain refuge habitats	Managed inundation	Regulators to provide maximum hydrological connectivity among wetlands: Maintain through flow where possible Monthly top-up flows throughout spring and summer at 1 per month @5ML/d for 8-12 days. Water level variation <0.1/day in spring Water level variation in winter and can be at up to 0.25 m/day to stimulate primary productivity processes Maintain high quality habitat for native fish in wetlands and support successful breeding events Top up events to ensure wetlands retain healthy littoral habitats which support small-bodied fish Where possible annual connection events among wetlands be initiated or maintained during spring for fish colonisation

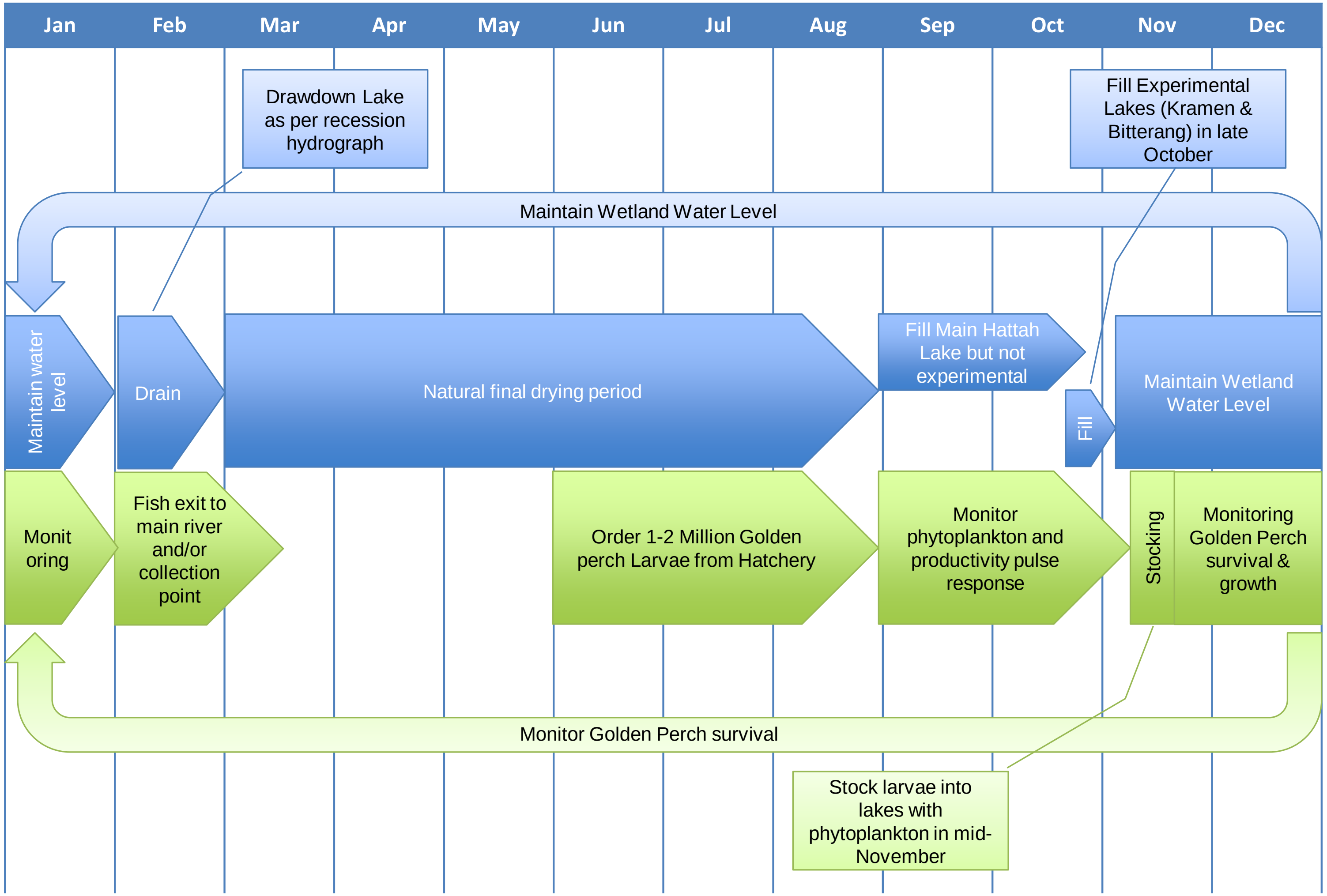
14. Conceptual models of water management options

Conceptual models detailing the hydrological conditions and expected ecological outcomes for each managed action are provided in the following pages.

PERMANENT WETLAND OPERATIONS MODEL: Small-bodied wetland generalists



HATTAH OPERATIONS MODEL: Golden Perch Nursery Ground



15. Risk assessment

15.1 Risk Management

The purpose of risk assessment is to inform decisions based on the outcomes of the risk analysis. Once the level of risk has been determined, a decision can be made on whether the risks are acceptable, or whether they require further treatment to lower the level of risk prior to the action going ahead. An approach to risk management is presented in Table 33.

Table 33 Risk management rating and action definitions

Rating	Action
Severe	Do not go ahead with action unless significant treatments result in mitigation of risk to acceptable level
High	Do not go ahead with action unless treatments result in mitigation of risk to acceptable level
Medium	Risks rated at this level should be considered for further treatment, but action may still go ahead under defined conditions
Low	Risks considered to be adequately managed and not requiring further treatment

15.2 Risks assessed as part of proposed TLM and SDL operations

A risk assessment was undertaken as part of the SDL Business and the TLM Operating Plan in line with the requirements of AS/NZS ISO 31000:2009. The following risks were identified that may affect fish. It is important to note that most of the risks identified in this table exist in both an “existing conditions” (including TLM works) or “Basin Plan without works” scenario, but are included because the proposed works provide mitigation opportunities.

Table 37 contains a sub-section of this risk assessment that relate either directly or indirectly to fish. No risks were considered more than moderate post mitigation.

15.3 Risks assessed as part of the Fish Management Plan

A risk assessment was undertaken as part of the Fish Management Plan development process. The risk assessment followed the EPA Victoria-developed Ecological Risk Assessment process:

- identification of the values associated with the waters to be stocked and any connected waterways
- identification of the threats posed to the values associated with the proposed translocations
- undertake a preliminary risk assessment with existing information and local knowledge
- documentation of gaps identified and assumptions made during the process
- recommendations for appropriate risk mitigation actions to protect values and reduce threats to these values

The process allowed for a qualitative risk assessment, based on known data or literature and extrapolated to the site. The risk assessment required the determination of a consequence level and likelihood (or probability) rating of each threat causing any impacts to each identified value.

An initial risk workshop was completed on 16 November 2017, with a second workshop completed on 13 December 2017 as part of the overall SDL Fish Management Plan preparation. Attendees are listed below:

Workshop 1 (16 November 2017)

Pam Clunie (DELWP)

Wayne Koster (DELWP)

Jarod Lyon (DELWP)

Ivor Stuart (DELWP)

Tarmo Raadik (DELWP)

Scott Raymond (DELWP)

Zeb Tonkin (DELWP)

Cath Hall (Mallee CMA)

Nick Sheehan (Mallee CMA)

Faith Deans (GHD)

Simon Harrow (GHD)

Workshop 2 (13 December 2017)

John Koehn (DELWP)

Jason Lieschke (DELWP)

Ivor Stuart (DELWP)

Clayton Sharpe (CPS Enviro)

Brenton Zampatti (SARDI)

Cath Hall (Mallee CMA)

Nick Sheehan (Mallee CMA)

Simon Harrow (GHD)

The matrix used to assess risk as part of the Fish Management Plan preparation is presented in Table 34, based on the likelihood and consequence descriptors in Table 35 and Table 36.

Results from the risk assessment process are presented in Table 38. No risks were considered more than moderate post mitigation.

Table 34 Risk assessment matrix

Likelihood	Consequence				
	1-Insignificant	2- Minor	3- Moderate	4- Major	5- Critical/Severe
5-Almost certain	Low	Medium	High	Severe	Severe
4- Likely	Low	Medium	Medium	High	Severe
3- Possible	Low	Low	Medium	High	Severe
2- Unlikely	Low	Low	Low	Medium	High
1 Rare	Low	Low	Low	Medium	High

Table 35 Likelihood ratings for threats to the values of the study area

Likelihood Rating	Descriptor	Definition
5	Near certain	Confident that the threat will occur
4	Highly likely	The threat is expected to occur
3	Likely	The threat is likely to occur
2	Unlikely	The threat is unlikely to occur
1	Highly	Confident that threat will not occur

Table 36 Consequence levels of impacts on the values of the study

Consequence Severity Level	Descriptor	Consequence
5	Critical	Long term impacts at a broad scale
4	Major	Long terms impact at a local scale
3	Moderate	Broad short term impacts
2	Minor	Short term local impacts
1	Insignificant	No impact

Table 37 Hattah Lakes North business case risk assessment

Threat	Description	Likelihood	Consequence	Risk without mitigation	Mitigation	Residual Risk
Low dissolved oxygen (DO) levels	Low dissolved oxygen (DO) concentrations can occur through a variety of processes, including blackwater events, algal and cyanobacterial blooms, high organic matter loadings and stratification. Low DO can cause the death of aquatic fauna and have negative impacts on the health of wetland communities in general. More frequent inundation (i.e. through managed watering events) will reduce the accumulation of organic matter on the floodplain between inundation events.	4	5	High	Planning phase: • monitor antecedent floodplain conditions (i.e. organic matter loads) to assess risk of a hypoxic event occurring. • consider seasonal conditions (e.g. temperature, algae) prior to watering. Operations phase: • commence watering as early as possible to move organic matter off the floodplain while temperatures are low • maintain through-flow where possible in other areas to maximise exchange rates and movement of organic material • monitor DO and water temperature to identify hypoxic areas to inform consequence management (see below). Managing consequences: • ensure dilution of low DO water by managing outflow rates and river flows • delay outflows if river flows are too low • dispose of hypoxic water by pumping to higher wetlands where possible. • agitate water using infrastructure to increase aeration.	Moderate
Poor water quality	Water manipulations may lead to suspension of sediments and/or organic matter causing elevated nutrients, high turbidity	3	3	Moderate	As above.	Low

Threat	Description	Likelihood	Consequence	Risk without mitigation	Mitigation	Residual Risk
	and/or low dissolved oxygen (DO) levels. This may impact reduce food sources and possibly toxic algal blooms upon wetland community health, threatened species, fish and other aquatic fauna communities, and waterbird communities (via impacts). The risk assessment for low DO water is presented above.					
Increased carp populations	Carp will breed in response to both natural and managed floods. High numbers of carp can threaten the health and diversity of wetland vegetation, affecting native fish and other aquatic fauna. This has potential impacts both within the project site and at the reach scale.	5	5	Severe	Tailor watering regimes to provide a competitive advantage for native fish over carp. Dry wetlands that contain large numbers of carp. Manage the drawdown phase to provide triggers for native fish to move off the floodplain and, where possible, strand carp. Additional targeted carp fishdowns, water level manipulations to disrupt the survival of juveniles and the installation of carp cages may all help reduce carp numbers. In addition, future research on carp control may identify new control measures.	Moderate
Managed inundation regimes do not match flow requirements for key species	The delivery of an inappropriate water regime may occur through inadequate knowledge of biotic requirements or conflicting requirements of particular species with	3	3	Moderate	Consider the various requirements of key species/communities when developing operating strategies and planning for watering events. Assess the response of species of concern during and after managed watering events and adjust operational arrangements if required.	Low

Threat	Description	Likelihood	Consequence	Risk without mitigation	Mitigation	Residual Risk
	broader ecological communities. This may lead to adverse ecological outcomes, e.g. failure of waterbird breeding events, lack of spawning response in fish, spawning response but no recruitment.				Update operating strategies to capture new information on the water requirements/ response of key species/communities. Target different taxa at different times (e.g. target vegetation one year and fish the next).	
Stranding and isolation of fish on floodplains	Stranding can occur through sudden changes in water levels and/or new barriers preventing native fish from escaping drying areas during flood recessions. This may result in the death of a portion of the native fish population.	3	3	Moderate	Develop a 'Fish Exit Strategy' to inform regulator operation during the drawdown phase to maintain fish passage for as long as possible and to provide	Low
Barriers to fish and other aquatic fauna movement	Installation of regulators in waterways and wetlands creates barriers to the movement of fish and other aquatic fauna. This can reduce access to feeding and breeding habitat, and limit migration or spawning opportunities.	3	3	Moderate	Determine fish passage requirements and incorporate into regulator design (as in Hames, 2014). Continue to build on knowledge and understanding through current studies relating to fish movement in response to environmental watering and cues.	Low
Sedimentation within the creeks and lakes due to pumping in the sediment loads	Pumping of large volumes due of water with high sediment loads and no outflow may lead to increased sedimentation.	2	3	Low	Knowledge gap – monitor sedimentation, look at paleo work.	Low

Threat	Description	Likelihood	Consequence	Risk without mitigation	Mitigation	Residual Risk
Mortality of entrained fish in pumps	Excludes large bodied individuals – not breeding size fish, breeding delayed Pressure impacts Difficult to quantify the impacts Removing fish from the channel (unknown level of impact)	5	3	High	Pump intake position. Pumping strategy (day/night). Mesh on intakes. Monitoring/research to inform strategy.	Moderate
Mis-matching fish/waterbird breeding cues/recruitment and general ecological requirements	Inappropriate water regime created by operating the structure out of sync with the fish/waterbirds breeding cues or recruitment requirements.	4	3 1yr 5 >yr	Moderate (for one year) High (for more than one year)	Develop a detailed operations plan - establish regional and temporal context. Monitoring program. Manage stakeholder expectations (including competing stakeholders) Might target veg in one year but be unseasonal for fish.NB Waterholders require objectives to be set beforehand and will review/approve them.	Low
Inability to discharge poor quality water (in-channel and floodplain)	Resultant inappropriate watering regime (if we can't release and have to hold water levels high for too long).	2	5	Moderate	Dilution flows. Good relationships. Local disposal (e.g. from Oatey's to Chalka creek).	Low
Inaccurate water quantity or regime delivered	Design issues. Modelling assumptions. Pipe invert levels incorrectly located Capacity of structures incorrect. Inadequate provision for monitoring and measurements of flows. Inadequate capacity to regulate flows.	2	5	Moderate	Model water usage – calibrate and/or confirm models / expectations / operations plan. Planning and co-ordination – Document and approval of measurement strategy for inflows and outflows (Operations Plan). Water metering and monitoring. Need to have adequate water measurement and reporting to meet accounting requirements. VEWH has developed a state-wide approach to accounting at sites.	Moderate

Threat	Description	Likelihood	Consequence	Risk without mitigation	Mitigation	Residual Risk
	Inadequate event planning. Lakes filled by natural flooding followed by waterings.				Gauge boards installed. Provision for future upgrades or refinements to structures.	

Table 38 Potential risks from actions proposed in Fish Management Plan

Value	Threats	Likelihood	Consequence	Risk	Rationale	Possible Treatments	L	C	Residual Risk
Ramsar values (Refer to Ecological Character Description for Hattah Lakes)	Permanent wetlands support the establishment of invasive plant and animal species.	5	3	High	• Perennial inundation provides habitat for invasive spp. incl. carp and gambusia • Stable water levels provide opportunities for invasive spp. incl. carp and gambusia	• Manage water levels with permanent regime to support native species and interrupt invasive species breeding cycles. • Rotate target wetlands over the long term to remove invasive species • Install mechanical exclusion devices when filling wetlands • Develop carp management plan for Hattah system • Introduce carp herpes virus	5	2	Med
	Permanent wetlands reduce wetland diversity.	1	3	Low	• Hattah Lakes is a diverse wetland system that can be managed to achieve multiple ecological objectives	• Rotate management of permanent wetlands to maintain a diverse system	1	2	Low
	Permanent wetlands interrupts wetting drying cycles leading to reduced wetland productivity.	1	3	Low	• Hattah Lakes is a diverse wetland system that can be managed to achieve multiple ecological objectives	• Rotate management of permanent wetlands to maintain a diverse system			Low
	Stocked species introduce diseases and pathogens	1	4	Med.	• Species stocked will be sourced from accredited hatcheries • If disease is present it can have major consequences	• Ensure all stocked species are sourced from quality accredited hatcheries. • Monitor and adapt	1	2	Low

Value	Threats	Likelihood	Consequence	Risk	Rationale	Possible Treatments	L	C	Residual Risk
	into native populations.								
	Hydrological manipulation induces adverse salinity impacts	1	2	Low	• The Hattah floodplain and groundwater system is not a salinity "hotspot" and does not contribute to increased salinity in the Murray River. • Filling and drying wetlands can induce salt accumulation if flushing does not occur	• Ensure target wetlands are able to be flushed on a cyclical basis (naturally or artificially)			Low
	Hydrological manipulation induces adverse water quality outcomes.	2	2	Low	• Deoxygenation may occur when filling wetlands that are not often watered. • This can lead to mortalities in aquatic species.	• Ensure target wetlands are able to be flushed on a cyclical basis (naturally or artificially) • Identify biodiversity hotspots that may be affected			Low
	Translocation of weeds	3	2	Low	• Weed translocation is possible but will be restricted to areas where hydrological management occurs	• Monitor and adapt			Low
Listed flora and fauna species	Altered hydrological regime - wetlands supports the establishment of invasive plant and animal species.	5	3	High	• Perennial inundation provides habitat for invasive spp. incl. carp and gambusia • Stable water levels provide opportunities for invasive spp. incl. carp and gambusia	• Manage water levels with permanent regime to support native species and interrupt invasive species breeding cycles. • Rotate target wetlands over the long term to remove invasive species • Install mechanical exclusion devices when filling wetlands • Develop carp management plan for Hattah system	5	2	Med

Value	Threats	Likelihood	Consequence	Risk	Rationale	Possible Treatments	L	C	Residual Risk
						• Introduce carp herpes virus			
	Permanent wetlands may impact upon habitat for other listed species (birds, reptiles etc…)	1	3	Low	• Some species may occupy dried wetlands during some part of their lifecycle and may be impacted by permanent wetting.	• Monitor and adapt			Low
	Permanent wetlands interrupt wetting drying cycles leading to reduced wetland productivity.	1	3	Low	• Hattah Lakes is a diverse wetland system that can be managed to achieve multiple ecological objectives	• Rotate management of permanent wetlands to maintain a diverse system			Low
	Stocked species introduce diseases and pathogens into native populations.	1	4	Med	• Species stocked will be sourced from accredited hatcheries • If disease is present it can have major consequences	• Ensure all stocked species are sourced from quality accredited hatcheries.	1	2	Low
Fish populations in the Hattah Lakes system	Limited genetic diversity across stocked species (wetland specialists)	2	3	Low	• Sources of wetland generalists for stocking are limited and may carry similar genetic character. This may lead to inbreeding depression in populations	• Source target species from multiple hatcheries. • Identify genetic variability within sourced species • Establish alternative sources of target species			Low
	Limited genetic diversity	1	2	Low	• Golden perch larvae and fingerlings can be sourced	• Source target species from multiple hatcheries.			Low

Value	Threats	Likelihood	Consequence	Risk	Rationale	Possible Treatments	L	C	Residual Risk
	across stocked species (Golden Perch)				from a variety of public and private hatcheries	• Identify genetic variability within sourced species • Establish alternative sources of target species			
	Permanent wetlands support the establishment of invasive plant and animal species which may outcompete native species	5	3	High	• Perennial inundation provides habitat for invasive spp. incl. carp and gambusia • Stable water levels provide competitive advantages for invasive spp. incl. carp and gambusia	• Manage water levels with permanent regime to support native species and interrupt invasive species breeding cycles. • Rotate target wetlands over the long term to remove invasive species • Install mechanical exclusion devices when filling wetlands • Develop carp management plan for Hattah system • Introduce carp herpes virus	5	2	Med
	Permanent wetlands interrupt wetting drying cycles leading to reduced wetland productivity.	3	2	Low	• Hattah Lakes is a diverse wetland system that can be managed to achieve multiple ecological objectives	• Rotate management of permanent wetlands to maintain a diverse system			Low
	Wetland generalist fish species displace wetland specialists (including	1	1	Low	• Very few wetland specialists exist in the Hattah system	• Acceptable			Low

Value	Threats	Likelihood	Consequence	Risk	Rationale	Possible Treatments	L	C	Residual Risk
	listed species).								
	Stocked (wetland specialist, freshwater catfish) species prey upon extant species (in permanent wetlands or Chalka Creek)	5	2	Low	• Catfish will prey upon extant species but the species present are not threatened and naturally co-exist with catfish	• Acceptable			Low
	Stocked (golden perch) species prey upon extant species. (Kramer and Bitterang)	1	1	Low	• No other fish species occur in these areas.	• Acceptable			Low
	Stocked species introduce diseases and pathogens into native populations.	1	4	Med	• Species stocked will be sourced from accredited hatcheries • If disease is present it can have major consequences	• Ensure all stocked species are sourced from quality accredited hatcheries.	1	2	Low

16. Monitoring recommendations

The following broad monitoring recommendations are provided in addition to the current condition monitoring and intervention monitoring programs taking place for the site.

Table 39 Monitoring recommendations

Gap	Recommendation
Species composition, use of off-stream habitats, variability across site	Current monitoring programs conducted under TLM include fish surveys for some of the lakes within the site. Data collected to date has been from a short period of time (post 2005) and includes mostly drought years and response to pumping. An understanding of fish population dynamics in the site will improve over time with current monitoring.
Golden perch stocking and recruitment event	Specific monitoring program to evaluate successional plankton processes and fish recruitment and survival/exit
Murray cod, silver perch, golden perch and catfish hydrograph requirements	Flow-event monitoring is crucial to identify the specific components of the hydrograph (shape, timing, frequency, duration, height, discharge, velocity) that influence population dynamics.
Flow monitoring in the Murray/Darling system that could provide potential silver perch and golden perch movements for the site.	Landscape scale planning and monitoring is required to maximise silver perch outcomes, such as providing Victorian re-colonisation flows after high flows in the lower Murray/Darling systems (Sharpe et al. 2015)
Silver perch recruitment links to flows.	Improve knowledge of recruitment links to flows (intervention and monitoring).
Reintroduction of small-bodied fish	Monitor status of reintroduced populations
Golden perch food requirements prior to stocking program.	Monitor zooplankton diversity and abundance, particularly in high priority lakes that may be considered for a golden perch stocking trial. This is likely to be Lake Kramen.
Pumped inundations of lakes trap and strand native fish.	Real-time fish monitoring of pumped inundations to plan availability of required resources to rescue stranded fish.
Non-native fish species. carp and gambusia establish in grow-out wetlands and compromise habitat for golden perch recruits.	Ongoing low-level (e.g. annual) monitoring to assess carp populations with active management of non-native fish species.

17. Conclusion

Hattah Lakes is an extensive complex of lakes and floodplain set within the Hattah–Kulkyne National Park and the Murray–Kulkyne Regional Park. Twelve of the lakes are listed as internationally important wetland systems under the Ramsar Convention on Wetlands of International significance (the Ramsar Convention), primarily for their value as waterbird habitat and importance in maintaining regional biodiversity. The values that relate to the Ramsar criteria which relate to fish and need to be considered in any management actions are:

- Threatened fish species - Murray cod (*Maccullochella peelii),* silver perch (*Bidyanus bidyanus), and* flat-headed galaxias (*Galaxias rostratus)*
- importance for fish breeding and
- important nursery area for native fish

The general impact of river regulation has been to reduce peak flows, change the seasonality of flows and increase minimum flows. The condition of ecological values has declined in response to altered flow regimes. Aquatic habitat is available much less frequently and for shorter periods than under natural unregulated conditions. This decline has been exacerbated by drought and the lakes are less able to provide refuge during extended dry periods and less able to support local populations of aquatic fauna. Up to 10 species of native freshwater fish inhabit the Hattah Lakes, with these dominated by the small-bodied generalist species that have flexible life-history strategies regarding flow conditions.

Watering the Hattah Lakes via environmental pumps has allowed the establishment of a fish community of both valuable native and unwanted exotic species in this system of shallow productive wetlands. Furthermore, during reconnection with the Murray River, native and exotic fish transported to, and raised in, the lakes chose to move back from the lake habitats towards the river. The environmental watering clearly allows the Hattah Lakes to provide some functionality as a nursery-environment for a range of small-bodied generalist species found within the southern MDB.

This fish management plan has therefore focussed on these major opportunities for the Hattah Lakes:

1. Evaluate the current condition of fish communities at Hattah that could serve as a population source.
2. Develop a series of permanent wetlands with a modified filling and top-up hydrology which contain optimum habitat characteristics and where water delivery can be easily to support reintroduced and local fish populations. Preliminary wetlands are Bulla, Arawak, and Brokie because they are small, terminal and at a low elevation so that there are maximum filling options. Chalka Creek could also be managed as a permanent refuge habitat.
3. Recovery of small-bodied wetland generalist fish species in permanent wetlands because these have declined locally. These include unspecked hardyhead, flat-headed gudgeons, carp gudgeons, Australian smelt and Murray-Darling rainbowfish.
4. Threatened species translocation of small-bodied fish species, potentially including unspecked hardyhead, Australian smelt, flat-headed gudgeons and Murray-Darling rainbowfish. There is potential to expand this approach to include several threatened species (e.g. southern pygmy perch and flat-headed galaxias (and the medium-bodied freshwater catfish) where permanent wetlands can be re-established.

5. Stocking selected wetlands with golden perch larvae that have conditions suitable for recruitment.

The preparation of this Fish Management Plan included a risk assessment to protect aquatic values of the Hattah Lakes from potential threats posed to them. This identified several risks to native fish communities, which, for the most part could be mitigated by management actions. The main risk that could only be partially mitigated was the potential for invasive species such as carp and gambusia to proliferate in the wetlands.

In summary, the Hattah Fish Management Plan provides a strategic and practical way forward in recovering local small-bodied native fish with potential future extension to threatened species.

18. References

Anderson, J.R., Morison, A.K., and Ray, D.J. (1992a). Age and growth of Murray cod*,* *Maccullochella peelii* (Perciformes: Percichthyidae), in the lower Murray-Darling Basin, Australia, from thin-sectioned otoliths. *Marine and Freshwater Research* **43(5)**, 983-1013.

Anderson, J.R., Morison, A.K. and Ray, D.J. (1992b). Validation of the use of thin-sectioned otoliths for determining the age and growth of golden perch, *Macquaria ambigua*, in the lower MDB. *Marine and Freshwater Research* **43**, 1103-1128.

Arumugam, P. T. and Geddes, M. C. (1987). Feeding and growth of golden perch larvae and fry (*Macquaria ambigua*)*.* Transactions of the Royal Society South Australia **111**, 59-65.

Australian Ecosystems (2013). Hattah North and Belsar-Yungera Islands Flora Census. Report for the Mallee CMA.

Baumgartner, L. J. (2007). Diet and feeding habits of predatory fishes upstream and downstream of a low-level weir. *Journal of Fish Biology* **70(3)**, 879-894.

Baumgartner, L., Reynoldson, N., and Gilligan, D. (2006). Mortality of larval Murray cod (*Maccullochella peelii peelii*) and golden perch (*Macquaria ambigua*) associated with passage through two types of low-head weirs. *Marine and Freshwater Research* **57(2)**, 187-191.

Baumgartner, L., Zampatti, B., Jones, M., Stuart, I. and Mallen-Cooper, M. (2014a). Fish passage in the Murray-Darling Basin: not just an uphill battle. *Ecological Management and Restoration* **15**, 28-39.

Baumgartner, L.J., Conallin, J., Wooden, I., Campbell, B., Gee, R., Robinson, W.A. and Mallen-Cooper, M. (2014b). Using flow guilds of freshwater fish in an adaptive management framework to simplify environmental flow delivery for semi-arid riverine systems. *Fish and Fisheries* **15**: 410-427

Bicknell, T. (2017). Tar-Ru's native nursery trial. FISH. Fisheries Research & Development Corporation News. 25(3) September 2017. pp 32-33.

Boys, C., Baumgartner, L., Robinson, W., Giddings, G. and Lay, C. (2010). Protecting migrating fish at in-stream structures: downstream mortality at weirs and screening water diversions. 2010 Native Fish Forum — Abstracts. Murray-Darling Basin Authority, Canberra. Online at: http://www.mdba.gov.au/system/files/NFS-2010-fish-forum-abstracts_Final.pdf Accessed: 8 November 2011.

Brown, P., Huntley, S., Ellis, I., Henderson, M., and Lampard, B. (2015). Movement of fish eggs and larvae through the Hattah Lakes environmental pumps. Final Report prepared for the Mallee Catchment Management Authority by The Murray-Darling Freshwater Research Centre and La Trobe University, MDFRC Publication 50/2015 January, 36pp.

Butcher, R. and Hale, J. (2011). Ecological Character Description for Hattah-Kulkyne Lakes Ramsar site. Report to the Department of Sustainability, Environment, Water, Population and Communities, Canberra (DSEWPaC).

Cadwallader, P. and Backhouse, G.N. (1983). A Guide to the Freshwater Fish of Victoria. Government Printer, Melbourne.

Close, A. (1990). The impact of man on the natural flow. In: Mackay, N. and Eastburn, D. (Eds.) *The Murray*, pp. 61-77. The Murray Darling Basin Commission, Canberra.

Clunie, P. E. and Koehn, J. D. (2001a). Silver Perch: A Recovery Plan. Final report for project R8002 to Murray-Darling Basin Commission: Canberra. Department of Natural Resources and Environment, Victoria.

Clunie, P. E. and Koehn, J. D. (2001b). Freshwater Catfish: A Recovery Plan. Final report for project R8002 to Murray-Darling Basin Commission: Canberra. Department of Natural Resources and Environment, Victoria.

Crook, D.A. (2004). Is the home range concept compatible with the movements of two species of lowland river fish? *Journal of Animal Ecology* **73**, 353-366.

Crook, D.A., Robertson, A., King, A.J. and Humphries, P. (2001). The influence of spatial scale and habitat arrangement on diel patterns of habitat use by two lowland river fishes. *Oecologia* **129**, 525-533.

Crook, D.A., O'Mahony, D.J., Gillanders, B.M., Munro, A.R., Sanger, A.C., Thurstan, S. and Baumgartner, L.J., (2016). Contribution of stocked fish to riverine populations of golden perch (*Macquaria ambigua*) in the Murray–Darling Basin, Australia. *Marine and Freshwater Research*, ***67***, 1401-1409.

DELWP (2017). MapshareVic database. Viewed 28 November 2017. http://mapshare.maps.vic.gov.au/MapShareVic/index.html?viewer=MapShareVic.PublicSite&locale=en-AU

DSEWPC (2012). Limits of acceptable change – Fact Sheet http://www.environment.gov.au/system/files/resources/4b6b222f-bb51-4f1e-893a-c49ffc82f346/files/acceptable-change-factsheet.pdf.

DSE (2013). Advisory list of threatened vertebrate fauna in Victoria. Department of Sustainability and Environment, Victoria.

Ebner, B.C. (2006). Murray cod an apex predator in the Murray River, Australia. *Ecology Freshwater Fish* **15**, 510–520.

Ebner, B.C., Scholtz, O. and Gawne, B. (2009). Golden perch *Macquaria ambigua* are flexible spawners in the Darling River, Australia. *New Zealand Journal of Marine and Freshwater Research* **43**, 571-578.

Ecological Associates (2007a). Feasibility investigation of options for the Hattah Lakes: final report. Mallee Catchment Management Authority, Mildura, Victoria.

Ecological Associates (2007b). Values and threats report: investigation of options for the delivery of environmental flows to Dry lakes, Lake Boolca and adjacent floodplain. Mallee Catchment Management Authority, Mildura, Victoria.

Ecological Associates (2014). SDL Rationale and Outcomes. Ecological Associates report AL040-1D. Report for the Mallee CMA.

Ecological Associates (2015). Environmental Water Management Plan for the Murray River at the Lock 15 Weir Pool – System Characterisation. Ecological Associates report AL043-2-B prepared for Mallee Catchment Management Authority, Irymple.

Ellis, I. and Pyke, L. (2010). Assessment of fish movement to and from Margooya Lagoon upon re-connection to the Murray River.

Ellis, I. and Wood, D. (2011). Assessment of the fish community in Lake Kramen (north-west Victoria) upon re-inundation after a 17 year dry spell. Final Report prepared for the Mallee Catchment Management Authority by The Murray-Darling Freshwater Research Centre, MDFRC Publication 18/2011, June, 9pp.

Ellis, I. (2016). Lock 8 Wetland 780 Fish Nursery Project on Tar-Ru Land. NSW Department of Primary Industries - Fisheries, Buronga.

EPA and MDFRC (2008). Implications of pumping and ponding water on water quality and the development of diverse aquatic ecosystems - Intervention monitoring of the Hattah Lakes Icon

Site 2006/07. Report to the Murray-Darling Basin Commission. Environmental Protection Agency Victoria and Murray-Darling Freshwater Research Centre.

Ferguson, G. and Ye, Q. (2012). 2012 Stock assessment of golden perch for PIRSA Stock Assessment of Golden perch (*Macquaria ambigua*) Fishery Stock Assessment Report to PIRSA Fisheries and Aquaculture.

Fluvial Systems (2014). Spells analysis of modelled flow for the Murray River from Swan Hill to the South Australian Border. Irymple, Victoria: Fluvial Systems report to the Mallee Catchment Management Authority, 2014.

Forbes, J., Watts, R. J., Robinson, W. A., Baumgartner, L. J., McGuffie, P., Cameron, L. M., and Crook, D. A. (2016). Assessment of stocking effectiveness for Murray cod (*Maccullochella peelii*) and golden perch (*Macquaria ambigua*) in rivers and impoundments of south-eastern Australia. *Marine and Freshwater Research* **67(10)**, 1410-1419.

Gehrke, P.C. (1992). Enhancing recruitment of native fish in inland environments by accessing alienated floodplain habitats. *Proceedings of the Bureau of Rural Resources*. 1992.

Gippel, C.J. (2014). Spells analysis of modelled flow for the Murray River from Swan Hill to the South Australia Border. Fluvial Systems Pty Ltd, Stockton. Mallee CMA November.

Greenfield, A. (2013). Hattah Watering Guide. Irymple, Victoria: Mallee Catchment Management Authority.

GHD (2012). Hattah Lakes Water Management Options Investigations – Part B – Concept Development and Design. GHD report prepared for Mallee Catchment Management Authority, Irymple.

GHD (2014). SDL Offsets - Fauna Survey Hattah North and Belsar-Yungera. Irymple, Victoria. Report for the Mallee CMA.

Gilligan, D., Jess, L., McLean, G., Asmus, M., Wooden, I., Hartwell, D., McGregor, C., Stuart, I., Vey, A., Jefferies, M. and Lewis, B. (2010). Identifying and implementing targeted carp control options for the Lower Lachlan Catchment. *Fisheries Final Report Series*, (118).

Hammer M. and Wedderburn S. (2008). The threatened Murray hardyhead: natural history and captive rearing. Fishes of Sahul **22**: 390–399.

Hammer, M., Wedderburn, S. and Van Weenen, J. (2009). Action plan for South Australian freshwater fishes.

Hammer, M., Barnes, T., Piller, L. and Sortino, D. (2012). Reintroduction plan for the purple spotted gudgeon in the southern Murray–Darling Basin. *MDBA Publication*, (45/12).

Harris, J.H. and Gehrke, P.C. (1994). Modelling the relationship between streamflow and population recruitment to manage freshwater fisheries. Aust. Fish. **6**: 28–30.

Henderson M, Campbell C, Johns C, Sharpe C, Kattel G, Wallace T (2010a) 'The Living Murray Condition Monitoring at Lindsay, Mulcra and Wallpolla Islands 2008/09.' Report prepared for the Department of Sustainability and Environment by The Murray-Darling Freshwater Research Centre, Mildura.

Henderson M, Walters S, Wood D, Chapman D, Sharpe C, Vilizzi L, Campbell C, Johns C and McCarthy B (2010b) The Living Murray Condition Monitoring at Lindsay, Mulcra and Wallpolla Islands 2009/10. Draft Report prepared for the Department of Sustainability and Environment by The Murray-Darling Freshwater Research Centre, MDFRC Publication 28/2010, July, 316 pp.

Henderson, M., Wood, D., Cranston, G., Hayward, G., Campbell, C., Johns, C. and Vilizzi, L. (2012). The Living Murray Condition Monitoring at Hattah Lakes 2011/12: Part A – Main Report

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

Henderson, M., Freestone, F., Wood, D., Cranston, G., Campbell, C., Vlamis, T. and Vilizzi, L. (2013). The Living Murray Condition Monitoring at Hattah Lakes 2012–13: Part A – Main Report. Final Report prepared for the Mallee Catchment Management Authority by The Murray-Darling Freshwater Research Centre, MDFRC.

Henderson, M., Freestone, F., Vlamis, T., Cranston, G., Huntley, S., Campbell, C. and Brown, P. (2014). The Living Murray Condition Monitoring at Hattah Lakes 2013–14: Part A – Main Report. Final Report prepared for the Mallee Catchment Management Authority by The Murray-Darling Freshwater Research Centre, MDFRC.

Humphries, P. (2005). Spawning time and early life history of Murray cod, *Maccullochella peelii* (Mitchell) in an Australian river. *Environmental Biology of Fishes* ***72*(4)**, 393-407.

Jacobs (2016). Hattah North SDL, Detailed Design report. Jacobs report prepared for Goulburn-Murray Water, July 2016.

Jones, M.J. and Stuart, I.G. (2007). Movements and habitat use of common carp (*Cyprinus carpio*) and Murray cod (*Maccullochella peelii peelii*) juveniles in a large lowland Australian river. *Ecology of Freshwater Fish*, ***16*(2)**, 210-220.

Jones, M.J. and Stuart, I. G. (2008). Regulated floodplains – a trap for unwary fish. *Fisheries Management and Ecology* **15,** 71–79.

Kaye, J. and Sharpe, C. (2009). Lindsay Mullaroo instream habitat mapping and assessment. Water Technology report to Mallee CMA.

Keenan, C., Watts, R. and Serafini, L. (1996). Population genetics of golden perch, silver perch and eel-tailed catfish within the Murray-Darling Basin. Pages 17-25 *in* J.R. Banes and R. Lehane (eds.) Proceedings 1995 Riverine Environment Research Forum. Murray-Darling Basin Committee, Canberra, Australia.

Keller, R.P. and Lake, P.S., (2007). Potential impacts of a recent and rapidly spreading coloniser of Australian freshwaters: oriental weatherloach (*Misgurnus anguillicaudatus*). *Ecology of Freshwater Fish* **16(2)**,124-132.

King, A.J., Crook, D.A., Koster, W.M., Mahoney, J., and Tonkin, Z. (2005). Comparison of larval fish drift in the lower-Goulburn and mid-Murray Rivers. *Environmental Management and Restoration* **6(2),** 136-138.

King, A.J. and O'Connor, J.P. (2007) Native fish entrapment in irrigation systems: A step towards understanding the significance of the problem. *Ecological Management and Restoration* **8(1),** 32-37.

King, A.J., Tonkin, Z. and Mahoney, J. (2007). Assessing the effectiveness of environmental flows on fish recruitment in Barmah-Millewa Forest. Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Heidelberg, Victoria.

King, A., Tonkin, Z., and Mahoney, J. (2009a). Environmental flow enhances native fish spawning and recruitment in the Murray River, Australia. *River Research and Applications* **25** 1205-1218.

King, A.J., Ramsey, D., Baumgartner, L., Humphries, P., Jones, M., Koehn, J., Lyon, J., Mallen-Cooper, M., Meredith, S., Vilizzi, L., Ye, Q. and Zampatti, B. (2009b). *Environmental requirements for managing successful fish recruitment in the Murray River Valley – Review of existing knowledge*, Arthur Rylah Institute for Environmental Research Technical Report Series No. 197, Department of Sustainability and Environment, Heidelberg.

Koehn, J. D. (2004). Carp (*Cyprinus carpio*) as a powerful invader in Australian waterways. Freshwater Biology, **49**: 882–894.

Koehn, J. (2009). Multi-scale habitat selection by Murray cod *Maccullochella peelii peelii* in two lowland rivers. *Journal of Fish Biology* **75(1)**, 113-129.

Koehn, J.D., and O'Connor, W.G. (1990). *Biological Information for Management of Native Freshwater Fish in Victoria*. Department of Conservation and Environment, Freshwater Fish Management Branch, Arthur Rylah Institute for Environmental Research. Government Printer, Melbourne.

Koehn, J. and Harrington, D. (2005). Collection and distribution of the early life stages of the Murray cod (*Maccullochella peelii peelii*) in a regulated river. *Australian Journal of Zoology* **53(3)**, 137-144.

Koehn, J., McKenzie, J., O'Mahony, D., Nicol, S., O'Connor, J., and O'Connor, W. (2009). Movements of Murray cod (*Maccullochella peelii peelii*) in a large Australian lowland river. *Ecology of Freshwater Fish* **18(4)**, 594-602.

Koehn, J., Stuart, I., Bamford, H., Bice, C., Hodges, K., Jackson, P., Lieschke, J., Lovett, S., Mallen-Cooper, M., Raadik, T., Thiem, J., Todd, C., Tonkin, Z. and Zampatti, B. (2014). Quantifiable Environmental Outcomes for Fish. Arthur Rylah Institute for Environmental Research Unpublished Client Report for the Murray Darling Basin Authority, Department of Environment and Primary Industries, Heidelberg, Victoria.

Koehn, J.D., Todd, C.R., Zampatti, B.P., Stuart, I.G., Conallin, A., Thwaites, L. and Ye, Q., (2017). Using a population model to inform the management of river flows and invasive carp (*Cyprinus carpio*). *Environmental Management* pp.1-11.DOI 10.1007/s00267-017-0855-y.

Koster, W.M., Dawson, D.R., O'Mahony, D.J., Moloney, P.D. and Crook, D.A. (2014). Timing, frequency and environmental conditions associated with mainstem-tributary movements by a lowland river fish, golden perch (*Macquaria ambigua*). PLoS ONE 9 (5).

Lake, J.S. (1967). Rearing experiments with five species of Australian freshwater fishes. I. Inducement to spawning. Australian Journal of Marine and Freshwater Research **18:** 137–153.

Langdon, J.S. (1989). Experimental transmission and pathogenicity of epizootic haematopoietic necrosis virus (EHNV) in redfin perch, *Perca fluviatilis* L., and 11 other teleosts. *Journal of Fish Diseases* **12:** 295–310.

Leigh, S.J. and Zampatti, B.P. (2011). Movement and spawning of Murray cod, *Maccullochella peelii* and golden perch *Macquaria ambigua* in response to a small-scale flow manipulation in the Chowilla anabranch system. SARDI report.

Leigh, S.J. and Zampatti, B.P. (2013). Movement and mortality of Murray cod, *Maccullochella peelii*, during overbank flows in the lower Murray River, Australia. *Australian Journal of Zoology* **6**, 160-169.

Lintermans, M. (2007). Fishes of the Murray-Darling Basin: An introductory guide. Murray-Darling Basin Commission, Canberra.

Lloyd, L.N. and Walker, K.F. (1986). Distribution and conservation status of small freshwater fish in the River Murray, South Australia. *Transactions of the Royal Society of South Australia* (Australia).

Lucas M. C., Baras E., Thom T. J., Duncan A. and Slavik O. (2001) Migration of Freshwater Fishes. Blackwell Science Ltd, London, UK.

Lyon, J., Stuart, I., Ramsey, D. and O'Mahony, J. (2010). The effect of water level on lateral movements of fish between river and off-channel habitats and implications for management. *Marine and Freshwater Research* **61**, 271-278.

Lyon, J., Kearns, J., Bird, T., Tonkin, Z, O'Mahony, J., Nicol, S., Hackett, G., Raymond, S., Todd, C. and Kitchingman, A. (2014). Monitoring of Resnagging between Lake Hume and Yarrawonga: Final Report 2014. Arthur Rylah Institute for Environmental Research Unpublished Client Report for the Murray-Darling Basin Authority, The Living Murray Program, Department of Environment and Primary Industries, Heidelberg, Victoria.

Macdonald, J. I, Tonkin, Z., Ramsey, D., Kaus, A., King, A. and Crook, D. (2012) Do invasive eastern gambusia (*Gambusia holbrooki*) shape wetland fish assemblage structure in south-eastern Australia?. Marine and Freshwater Research 63, 659 (2012).

Mallee CMA (2014). Sustainable Diversion Limit Adjustment, Phase 2 Assessment. Supply Measure Business Case: Hattah Lakes North Floodplain Management Project. December 2014.

Mallen-Cooper, M. (1999). Developing fishways for non-salmonid fishes; a case study from the Murray River in Australia. In 'Innovations in Fish Passage Technology'. (Ed. M. Odeh.) pp. 173-195. (American Fisheries Society: Bethesda, Maryland.)

Mallen-Cooper M., Stuart, I.G., Hides-Pearson, F. and Harris, J.H. (1995). Fish migration in the Murray River and assessment of the Torrumbarry fishway. Final report for Natural Resources Management Strategy Project. NSW Fisheries, Sydney, Australia.

Mallen-Cooper M. and Brand D. M. (2007). Non salmonids in a salmonid fishway: what do 50 years of data tell us about past and future fish passage? *Fisheries Management and Ecology* **14**, 319–332.

Mallen-Cooper, M., and Stuart, I. (2003). Age, growth and non-flood recruitment of two potamodromous fishes in a large semi-arid/temperate river system. *River Research and Applications* **19**, 697-719.

Mallen-Cooper, M., Stuart, I.G., Sharpe, C. (2013). A Sustainable Irrigation – Native Fish Recovery Plan; A New Partnership for Working Rivers. Report prepared for the North Central Catchment Management Authority.

Mallen-Cooper, M., and Zampatti, B. (2015a). Background paper: use of life-history conceptual models of fish in flow management in the Murray-Darling Basin. Murray-Darling Basin Authority, Canberra.

Mallen-Cooper, M., and Zampatti, B.P. (2015b). Background Paper: The Natural Flow Paradigm and managing flows in the Murray-Darling Basin. Report prepared for the Murray-Darling Basin Authority. 37 p.

Mallen-Cooper, M. and Zampatti, B.P. (2017). History, hydrology and hydraulics: rethinking the ecological management of large rivers. *Ecohydrology*.

McCarthy, B., Tucker, M., Campbell, C., Henderson, M., Vilizzi, L., Wallace, T., Walters, S. (2008). The Living Murray Condition Monitoring of Hattah Lakes 2007/08. Report No. 7/2008. The Murray-Darling Freshwater Research Centre, Mildura.

McNeil D. G. and Closs G. P. (2007). Behavioural responses of a south-east Australian floodplain fish community to gradual hypoxia. Freshwater Biology **52**: 412–420.

McNeil, D.G., Wilson, P., Hartwell, D. and Pellizari, M. (2008). Olive Perchlet (Ambassis agassizii) in the Lachlan River: Population status and sustainability in the Lake Brewster region. A Report submitted to the Lachlan Catchment Management Authority. 66 pp.

NSW DPI (2006). Silver perch (*Bidyanus bidyanus*) NSW Recovery Plan. Fisheries Management Branch, NSW Department of Primary Industries. Port Nelson, NSW.

MDBA (2012a). Hattah Lakes Environmental Water Management Plan. Report by the Murray Darling Basin Authority, February 2012.

MDBA (2012b). Assessment of environmental water requirements for the proposed Basin Plan: Hattah Lakes. Report by MDBA, 2012.

MDBA (2014). Basin-wide environmental watering strategy. Published by Murray-Darling basin Authority. MDBA Publication No 20/14. 24 November 2014.

MDBA (2016). Operating Plan. Hattah Lakes Environmental Works and Measures Program. Post commissioning update v2 Update. March 2016

MDBA (2017) Murray River Lock and Weir Information (2017)

https://www.mdba.gov.au/river-information/running-river-murray/weirs-locks

Meredith, S., and Beesley, L. (eds.) (2009). Watering floodplain wetlands in the Murray–Darling Basin to benefit fish: a discussion with managers. Arthur Rylah Institute for Environmental Research Technical Report Series No. 189. Department of Sustainability and Environment, Heidelberg, Victoria

Merrick, J.R. (1996). Freshwater grunters or perches, Family Terapontidae. Chapter 26. Silver perch. Pp. 164-166 in: Freshwater fishes of south-eastern Australia. [Ed. McDowall R.]. Reed Books, NSW.

Merrick, J.R. and Schmida, G.E. (1984). Australian freshwater fishes: biology and management. Griffin Press Ltd., South Australia. 409 p. NSW Department of Primary Industries. (2006). Silver perch *Bidyanus bidyanus*: NSW Recovery Plan. Port Stephens NSW.

National Murray Cod Recovery Team (2010). Background and Implementation Information for the National Recovery Plan for the Murray Cod *Maccullochella peelii peelii.* Department of Sustainability and Environment, Melbourne.

NSW DPI (2006). Silver perch (*Bidyanus bidyanus*) NSW Recovery Plan. Fisheries Management Branch, NSW Department of Primary Industries. Port Nelson, NSW.

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

O'Connor, J., Mallen-Cooper, M. and Stuart, I. (2015). Performance, operation and maintenance guidelines for fishways and fish passage works. Arthur Rylah Institute for Environmental Research Technical Report No. 262 for the Water and Catchments Group, Department of Environment, Land, Water. Arthur Rylah Institute.

Raymond, S., Duncan, M., Robinson, W. and Tonkin, Z. (2014). Barmah-Millewa Fish Condition Monitoring: 2006 to 2014. Arthur Rylah Institute for Environmental Research Unpublished Client Report for the Murray Darling Basin Authority. Department of Environment and Primary Industries, Heidelberg, Victoria.

Reynolds, L.F., (1983). Migration patterns of five fish species in the Murray-Darling River system. *Marine and Freshwater Research*, **34(6)**, 857-871.

Rowland, S. J. (1983). Spawning of the Australian freshwater fish Murray cod, Maccullochella peeli (Mitchell), in earthen ponds. *Journal of Fish Biology*, *23*(5), 525-534.

Rowland, S.J. (1995). The silver perch and its potential for aquaculture. Pp. 9-11 in: Proceedings of Silver Perch Aquaculture Workshops, Grafton and Narrandera, April 1994. NSW Fisheries.

Rowland, S.J. (1996). Development of techniques for the large-scale rearing of the larvae of the Australian freshwater fish golden perch, *Macquaria ambigua* (Richardson, 1845). *Marine and Freshwater Research*, ***47*(2)**, 233-242.

Rowland, S.J. (2009). Review of Aquaculture research and development of the Australian freshwater fish silver perch, *Bidyanus bidyanus*. *Journal of the World Aquaculture Society* **40(3):** 291-323.

Saddlier, S., O'Mahony, J. and Ramsey, D. (2008). Protection and enhancement of Murray cod populations. Arthur Rylah Institute for Environmental Research Technical Report Series No. 172. Department of Sustainability and Environment, Heidelberg, Victoria.

Sharpe, C. (2011). Fish surveys in Gunbower Creek downstream of Koondrook Weir in association with Environmental Flows, December 2011. pp. 15.

Sharpe C. P. and Vilizzi L. (2011) Fish. In: Walters S. ed. The Living Murray Condition Monitoring at Hattah Lakes 2009/10. Final Report prepared for the Department of Sustainability and Environment by The Murray-Darling Freshwater Research Centre, MDFRC Publication 27/2010, May, 265pp.

Sharpe, C. and Stuart, I. (2015). Optimising flow in Gunbower Creek to enhance spawning opportunities for Murray cod. Final Report to North Central Catchment Management Authority by CPS Enviro and Kingfisher Research P/L.

Sharpe, C. and Stuart, I. (2018). Environmental flows in the Darling River to support native fish populations. CPS Enviro report to The Commonwealth Environmental Water Office.

Sharpe, C., Stuart, I. and Mallen-Cooper, M. (2015). Monitoring of fish spawning in response to variable flow releases in the lower Darling River 2013/14. A summary of findings report to MDBA by CPS Enviro.

Sharpe C, Stuart, I., Stanislawski, K and Parker, A. (2016). The Gunbower Forest Fish Exit Strategy; Implementation and Monitoring. A technical report for the North Central Catchment Management Authority by CPS Enviro P/L.

SKM (2004). Hattah Lakes Water Management Plan: background report. Mallee Catchment Management Authority, Mildura, Victoria.

SKM (2006). Hydraulic modelling of the Hattah Lakes, final report. Mallee Catchment Management Authority, Mildura, Victoria.

Smith, B.B., Conallin, A. and Vilizzi, L. (2009). Regional patterns in the distribution, diversity and relative abundance of wetland fishes of the River Murray, South Australia. *Transactions of the Royal Society of South Australia* **133**: 339-360.

Stuart, I. (2013). A carp management plan for Hattah Lakes. Kingfisher Research report to Mallee CMA.

Stuart, I., Baumgartner, L. and Zampatti, B. (2008). Can a low slope fishway provide passage for a lowland river fish community? *Marine and Freshwater Research* **59**, 332-346.

Stuart, I. and Sharpe, C. (2015). Golden Perch tagging and potential for colonisation of Gunbower Creek. CPS Enviro and Kingfisher Research P/L report for North Central CMA.

Stuart, I. and Sharpe, C. (2017). Towards a Southern Connected Basin Plan: connecting rivers to recover native fish communities. Kingfisher Research and CPS Enviro report to the Murray-Darling Basin Authority.

Stuart, I., Sharpe, C., Stanislawski, K., Parker, A. and Mallen-Cooper (2018). Recovery of a large-bodied threatened fish species in a highly regulated river system: a case study managing flow and hydrodynamics. Manuscript in preparation.

Thiem, J. D., Wooden, I. J., Baumgartner, L. J., Butler, G. L., Forbes, J. P., and Conallin, J. (2017). Recovery from a fish kill in a semi-arid Australian river: Can stocking augment natural recruitment processes? *Austral Ecology* **42**, 218-226.

Tonkin, Z., King, A.J. and Mahoney, J. (2008). Effects of flooding on recruitment and dispersal of the southern pygmy perch (*Nannoperca australis*) at a Murray River floodplain wetland. *Ecological Management & Restoration*, ***9*(3)**, 196-201.

Tonkin, Z., Ramsey, D. S. L., Macdonald, J., Crook, D., King, A. J., and Kaus, A. (2014). Does localized control of invasive eastern gambusia (Poeciliidae: *Gambusia holbrooki*) increase population growth of generalist wetland fishes? *Austral Ecology* **39**: 355–366.

Tonkin, Z., Stuart, I., Kitchingman, A., Jones, M., Thiem, J., Zampatti, B., Hackett, G., Koster, W. and Koehn, J. (2017). A review of the effects of flow on silver perch population dynamics in the Murray River. Unpublished Client Report for the Murray Darling Basin Authority March 2017. Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Vilizzi, L., McCarthy, B. J., Scholz, O., Sharpe, C. P., & Wood, D. B. (2013). Managed and natural inundation: benefits for conservation of native fish in a semi-arid wetland system. *Aquatic Conservation: Marine and Freshwater Ecosystems* **23(1)**, 37-50.

Wedderburn, S.D., Hammer, M.P., Bice, C.M., Lloyd, L.N., Whiterod, N.S. and Zampatti, B.P. (2017). Flow regulation simplifies a lowland fish assemblage in the Lower Murray River, South Australia. *Transactions of the Royal Society of South Australia* **141***:*169-192.

Ye, Q., Cheshire, K. and Fleer, D. (2008). Recruitment of golden perch and selected large-bodied fish species following the weir pool manipulation in the Murray River, South Australia. SARDI Aquatic Sciences report.

Zampatti, B.P. and Leigh, S.J. (2013). Within-channel flows promote spawning and recruitment of golden perch, *Macquaria ambigua ambigua*–implications for environmental flow management in the Murray River, Australia. Marine and Freshwater Research **64**, 618-630.

Zampatti, B.P., Wilson, P.J., Baumgartner, L., Koster, W., Livore, J.P., McCasker, N., Thiem, J., Tonkin, Z. and Ye, Q. (2015). Reproduction and recruitment of golden perch (*Macquaria ambigua*) in the southern Murray-Darling Basin in 2013-14: an exploration of river-scale response, connectivity and population dynamics. SARDI Research Report Series No. 820. 61 pp.