NSW National Parks and Wildlife Service

Millewa fish recovery strategy

Restoring and recovering native fish populations in the Millewa Forest

environment.nsw.gov.au

Cover photo: Nine Panel Lagoon. Gabriel Cornell/Arthur Rylah Institute
Other photos: All photographs DPE unless otherwise cited or acknowledged

Authors: Gabriel Cornell, Robin Hale, Bryan Mole, Ivor Stuart (Arthur Rylah Institute), Paul Childs (NDW DPE), Clayton Sharpe, Wil Allen, Brady Cronin (NSW NPWS)

Acknowledgements: The authors would like to thank Meaghan Duncan, Kristy Lawrie, Keisha Eagan, John Conallin, Jimmy Walker, Nick Whiterod and Matt Crawford for their valuable input to the production of this strategy. John Conallin, Nick Whiterod, Sally Hladyz and Ashley Sparrow are also thanked for their feedback on earlier drafts of this document.

Published by:

Environment and Heritage Group
Department of Planning and Environment
Locked Bag 5022, Parramatta NSW 2124
Phone: +61 2 9995 5000 (switchboard)
Phone: 1300 361 967 (Environment and heritage enquiries)
TTY users: phone 133 677, then ask for 1300 361 967
Speak and listen users: phone 1300 555 727, then ask for 1300 361 967
Email: info@environment.nsw.gov.au
Website: www.environment.nsw.gov.au

Report pollution and environmental incidents
Environment Line: 131 555 (NSW only) or info@environment.nsw.gov.au
See also www.environment.nsw.gov.au

ISBN 978-1-923076-70-9
EHG 2023/0287
September 2023

Find out more about your environment at:

www.environment.nsw.gov.au

Contents

List of tables

List of figures

1. Introduction

1.1 Project context

Freshwater ecosystems are under severe threat and in need of conservation and restoration globally (Dudgeon et al. 2006; Vorosmarty et al. 2000). In an Australian context, the Murray–Darling Basin is one of the world's most regulated river basins (Nilsson et al. 2005), and the Murray–Darling is one of the top 10 river systems at environmental risk globally (Wong et al. 2007). In addition to flow regulation, threats to biodiversity in the Murray–Darling Basin include barriers to movement, alien species, habitat loss, cold water pollution, and commercial (past) and recreational fishing (Koehn and 2012; Koehn et al. 2020). Unsurprisingly, Murray–Darling Basin fish populations have suffered significant declines from these threats, and almost half of the species are now listed as threatened under state or national legislation (Lintermans 2007).

The Living Murray program was established to restore the health of the Murray River system with a focus on improving the environmental health of 6 'icon sites' through environmental watering and monitoring. The program is a joint partnership between the Murray–Darling Basin Authority (MDBA), the Australian Government and Basin state governments. The icon sites were selected for their high ecological value and cultural significance. One of the sites is the Barmah–Millewa Forest icon site, which covers 66,600 ha and straddles the Murray and Edward rivers between the towns Tocumwal, Deniliquin and Echuca. The forest and wetland system is reserved as Murray Valley National Park in New South Wales (NSW), and Barmah National Park and Murray River Park in Victoria (Murray–Darling Basin Authority 2012).

The Barmah–Millewa Forest supports the largest river red gum forest (*Eucalyptus camaldulensis*) in Australia and forms the largest and most intact freshwater floodplain system along the Murray River (Murray–Darling Basin Authority 2012). It provides habitat for numerous plant and animal species, and supports colonies of breeding waterbirds. The Barmah–Millewa Forest is listed on the Register of the National Estate in recognition of its importance as part of Australia's heritage and its outstanding natural values. First Nations and the broader Australian communities have significant connections to the Barmah–Millewa Forest. Consequently, the cultural landscape within the icon site reflects both First Nations and European activities (Murray–Darling Basin Authority 2012).

Millewa Forest is a vast, highly complex floodplain wetland ecosystem formed at the confluence of the Edward and the Murray rivers east of the Cadel Fault. It is situated mostly within the Murray Valley National Park, and has international significance under the Ramsar Convention, containing numerous state and nationally listed threatened species. The forest is well known for Murray cod (*Maccullochella peelii*), golden perch (*Macquaria ambigua*) and silver perch (*Bidyanus bidyanus)*, and for its vibrant wetlands, which historically supported a diverse small-bodied fish community.

Like elsewhere across the Murray–Darling Basin, native fish populations in Millewa Forest have severely declined in diversity, distribution and abundance, with many species that were historically found now absent (Sharpe 2014). Healthy native fish populations are intrinsic to the health of the national park and its wetland forest ecosystem; but those fish species that remain face many threats, including reduced connectivity, reduced flooding, loss of seasonal flow components, sedimentation, hypoxic blackwater, invasive species and habitat loss. Hence, a native fish recovery strategy is needed at Millewa Forest to guide the planning and implementation of recovery projects for threatened and locally extinct populations, particularly in wetlands.

1.1.1 Legislative context

The Murray–Darling Basin Authority was established as an independent statutory agency by the enactment of the *Water Act 2007* (Commonwealth). The Living Murray program was initiated by MDBA to deliver environmental water and monitor the ecological health of the river and its anabranch and wetland systems. The Intergovernmental Agreement 2004 (including Australian Capital Territory, NSW, Victoria, South Australia and the Commonwealth) and *The Living Murray business plan* provide the framework for The Living Murray Initiative. This framework includes ongoing government work with community to recover water entitlements that can then be managed to achieve specific ecological outcomes along the river.

NSW National Parks and Wildlife Service (NPWS) is in an agreement with the Australian Government to manage and deliver The Living Murray Initiative for the Millewa Forest component of the Barmah–Millewa Forest icon site within Murray Valley National Park. In NSW, under the *Fisheries Management Act 1994*, native fish, including threatened species, are primarily the responsibility of Department of Primary Industries. Due to the ecological interaction between the floodplain and the river and its anabranches, the Department of Planning and Environment (the department) usually has oversight of native fish management within the Murray Valley National Park. The department's responsibilities are primarily delivered by NPWS and the Biodiversity Conservation and Science Group.

In doing so, the department conforms to the requirements of the Fisheries Management Act, *National Parks and Wildlife Act 1974* (NSW), *Biodiversity Conservation Act 2016* (NSW) and the *Environment Protection and Biodiversity Conservation Act 1999* (Commonwealth). This includes responsibility for obtaining joint Department of Primary Industry approvals for translocations, research licences and other activities in waterways affecting native fish populations. Likewise, auxiliary access and support activities on-park require approval by NPWS. Matters significantly affecting nationally threatened fish require assessment and approval by Commonwealth Department of Climate Change, Energy, the Environment and Water.

1.1.2 Delivering on the strategy

The MDBA's *Barmah–Millewa Forest environmental water management plan* (Murray–Darling Basin Authority 2012) identifies that almost 500 gigalitres (GL) long-term cap equivalent has been recovered through The Living Murray program. This water is being used at 6 national icon sites to improve environmental outcomes. Barmah–Millewa Forest is one of those sites. This native fish recovery strategy anticipates the ongoing delivery of this water and its best use in helping recover and protect the native fish populations within Millewa's wetlands, forest creeks and rivers.

The success of the strategy and its component implementation plans (and work packages) relies on New South Wales and Commonwealth government commitments to protect and restore the ecology of Murray Valley National Park and the Murray floodplain more generally. To realise success, the strategy's implementation plans and work packages need to be achieved off the back of ongoing construction of improved regulators that facilitate safe fish passage, more precise and targeted water delivery, better control and management of sediment, mitigation of hypoxic blackwater, rehabilitation of native aquatic vegetation, management of invasive species, native fish restocking, and practical and adaptable monitoring and review. Because of this changing context, implementation recovery plans for Millewa's native fish habitats will need to be adaptive, 'live' documents nested in the logic and direction of this recovery strategy.

This, of course, relies on many assumptions and condition improvements outside the direct control of NPWS. The Commonwealth's The Living Murray program has 6 icon sites to consider, and priorities for environmental water must be considered along the length of the river. Furthermore, conditions in the area are in many ways not conducive to the persistence of many species. As will be outlined in this strategy, altered wetting and dying and flow regimes are an obvious primary issue. Less obvious issues, such as altered sediment behaviour, changed vegetation communities, and invasive species impacts, are also in play.

The implementation horizon for the strategy is 20 years, and delivery will be staged to meet it as funding opportunities allow. This strategy provides the background and sets the direction for 3 Millewa native fish recovery implementation plans, one for each of Millewa Forest's fish guilds: the channel specialists, the off-channel (wetland) specialists and the generalist fishes. The strategy is intended to provide the conceptual basis and program logic for these plans and their work packages. It has been developed through the following steps:

1. An inception workshop to discuss and finalise the project vision and approach with the Arthur Rylah Institute team and the project steering committee.
2. A series of technical workshops to gather information about Millewa Forest from managers and site experts. Two remote workshops were held, and attendees included: Kristy Lawrie, Clayton Sharpe, Keisha Egan and Brady Cronin (NSW NPWS); Paul Childs and Meghan Duncan (NSW Department of Planning and Environment).
3. A preliminary draft strategy provided to the project steering committee including: a detailed review of the native fish population at Millewa and threats to these fish (based on a literature review and prior meetings with experts), and a draft structure and logic for the strategy.
4. A site visit and technical workshop that was used to guide the identification of recovery actions to be included in site work packages. Attendees (in addition to the project team) included the project steering committee and subject area experts Nick Whiterod (Nature Glenelg Trust), John Conallin (Charles Sturt University), Jimmy Walker (NSW Fisheries) and Matt Crawford (NSW NPWS).
5. A complete draft strategy, for review and feedback by the project steering committee.
6. A final report (this strategy), providing a practical framework and implementation schedule for NPWS to achieve native fish recovery at Millewa Forest and guide the production of the implementation plans and component work packages.
7. Review and progression of the strategy by NPWS to final publication.

This strategy conservatively anticipates similar future The Living Murray program funding and resource availability in recent years for designing and monitoring fish recovery and other so-called 'intervention' programs. However, for the ongoing management of recovered fish stocks and their wetland habitats, NPWS Operations and other stakeholders will need to activate additional or diverted resources to sustain any results in the long term.

An important corollary to this strategy will be a prospectus that sets out investment opportunities and an implementation guide, to assist NPWS in seeking grants and other funding to deliver the strategy.

Adaptation is an essential component; future activities and planning will be based on the learnings of the initial stages and be responsive to emerging information. The final implementation plans and component work packages will further spelt out this. Ideally, monitoring of action outcomes can be afforded by The Living Murray program, noting the program is essentially a monitoring program not a delivery program.

1.1.3 Aims and objectives

The overall **vision** of the strategy is to:

- build native fish populations and recover threatened and locally extinct species in Millewa.

The strategy provides a practical framework, work packages and implementation schedules for NPWS to protect existing populations and recover native fish populations at Millewa Forest. Over a 20-year implementation horizon, the strategy will guide the development of implementation plans and component work packages relating to:

- the delivery of inter-annual environmental flow regimes to optimise movement and migration pathways for native fish spawning and nursery grounds
- the restoration of productivity and trophic processes, and wetland and riparian vegetation communities which support native fish populations
- recovery programs for locally extinct and threatened native fish species
- reduction programs for pests, weeds and other processes threatening native fish and aquatic fauna.

Specific objectives of the strategy are:

- restore annual recruitment and healthy demographics of Murray cod (*Maccullochella peelii*) and trout cod (*Maccullochella macquariensis*)
- provide regular spawning, recruitment and dispersal opportunities for golden perch (*Macquaria ambigua*), silver perch (*Bidyanus bidyanus*), and bony herring (*Nematalosa erebi*) populations, and facilitate population expansion
- increase abundance and distribution of existing small-bodied native fish species, including Murray rainbowfish (*Melanotaenia fluviatilis*), flat-headed gudgeon (*Philypnodon grandiceps*), un-specked hardyhead (*Craterocephalus fulvus*), Australian smelt (*Retropinna semoni*) and carp gudgeon species (*Hypseleotris* spp.), among others
- reintroduce locally extinct native fish species, including southern purple-spotted gudgeon (*Mogurnda adspersa*), river blackfish (*Gadopsis marmoratus*), freshwater catfish (*Tandanus tandanus*), Murray galaxias (*Galaxias rostratus*), olive perchlet (*Ambassis agassizii*) and southern pygmy perch (*Nannoperca australis*); and use these as source populations for further recovery.

1.2 Purpose and structure of this document

The remainder of this document is organised into 3 sections.

Section 2 presents a review of the current and historical status of native fish in Millewa Forest, describes the ecological and habitat requirements of different species, and how they can be broadly classified based on their life history traits (these groupings are used later in the strategy). Conceptual models describe the condition of key habitats required to support fish, which can act as a vision for what the strategy ultimately aims to achieve in terms of improving conditions for native fish. Finally, a summary of the threats to and impacts on fish populations in Millewa Forest is presented, highlighting where the current conditions in the forest may not fully support fishes' requirements, and therefore emphasising where action is warranted. This section synthesises information collated from a review of published and unpublished literature and several workshops with members of the project steering committee, experts and local knowledge holders.

Section 3 presents a logical and strategic approach to fish recovery in Millewa Forest. This incorporates setting aims and objectives, estimates the recovery potential of different fish species, and provides a guide to identify potential management actions and their priority. The prioritisation is based on the likelihood that the action can be successfully implemented; the likely magnitude, timing and certainty associated with ecological responses; and the time and costs involved in planning, implementation and maintenance. This section also highlights key components that will be incorporated into the implementation plans around monitoring, adaptive management, collaboration and coordination with other agencies, communication and evaluation.

Section 4 uses the material from the earlier 2 sections together with staff expertise, workshop outcomes and specialist advice to define the scope of implementation plans for the 3 Millewa fish guilds. These plans will be ‘live’ documents providing up-to-date mitigation methodologies; site, species and action prioritisations; and an outline of the steps to monitor, evaluate and adapt to arising information.

1.3 Embedding restoration ecology theory into fish recovery

Management actions are more likely to succeed when they are based on relevant ecological theory (Lake et al. 2007). Ecological theories underpin this strategy and are used to describe knowledge of fish life history and ecology, and the principles of restoration ecology more generally.

One of the key aspects of restoration projects is to define at the beginning what will constitute a successful outcome. Palmer et al. (2005) propose 5 criteria for measuring success of stream restoration projects from an ecological perspective:

1. the design of restoration projects should be based on a guiding image of what could exist at the site
2. the river’s ecological condition is measurably improved
3. the system must be self-sustaining and only minimal follow-up maintenance is needed
4. no lasting harm should be inflicted by restoration actions
5. pre- and post-monitoring must be completed and data made publicly available.

The development of a guiding image is a critical initial step for the *Millewa fish recovery strategy*. Many restoration projects aim to return sites to historical conditions (e.g., prior to European development) but this may be unrealistic. A more pragmatic approach may aim to move the river/wetland to the least degraded and most ecologically dynamic state possible (Palmer et al. 2005) given the current context (Hobbs et al. 2009) and limitations within the landscape (e.g., the constraints highlighted in Lake et al. 2007). A guiding image helps set these aims; it explicitly outlines what one is aiming for, guides actions required to reach the image and offers a reference target against which monitoring can measure success. The use of conceptual models can also highlight the ecological mechanisms via which actions will lead to their targets (Jansson et al. 2005).

We use the information in this report and conceptual models to outline a guiding image firstly for fish habitats (i.e., how might we ideally expect habitats to look once the strategy has been delivered). For example, in Millewa, an ideal guiding image describes a wetland that has abundant aquatic vegetation, suitable water quality for fish, functioning productivity processes and few or no invasive species. A guiding image for a river would describe a site with optimum levels of woody snags, aquatic vegetation, flows and connectivity.

We then outline a guiding image for the resident fish populations (i.e., what fish assemblages and numbers might be present after the successful delivery of this strategy) based on Millewa Forest's historical community composition and from the goals in this strategy. We then provide context via a deep review of recent fish surveys, investigating the current species diversity, abundance and population structure.

2. Review of native fish in Millewa Forest

2.1 Introduction

A detailed understanding of the target species will greatly inform restoration. To determine what responses to management actions might be possible requires knowledge of the biology, ecology, behaviour and life history of the focal taxa. Broadly speaking, these characteristics mean that fish responses will be related to several factors (Lake et al. 2007):

- The **regional species pool**, which determines which species are available to colonise restored sites. For example, a lack of nearby source populations may mean that fauna fail to colonise restored sites (Sundermann et al. 2011). In many degraded systems, the regional species pool may be very limited and consist of opportunistic, generalist species.
- **Dispersal constraints**, which determine the ability of available species to colonise sites. For example, species that are less mobile or dispersive may be less able to move to restored sites.
- **Habitat constraints**. It is critical that restoration provides the things that animals need to grow, survive and reproduce (Hale et al. 2020). Identifying what kinds of hydrological and physical habitat are required for population persistence, that is critical habitat (Camaclang et al. 2014), means that those types of areas can be protected and enhanced, with the presumption that this will increase fish populations. Understanding the patterns of habitat use by different species and life stages of fish can be a good guide for the restoration of populations (Bond and Lake 2003).
- **Biotic constraints**. Interactions between species, such as predation and competition, can be an important determinant of responses to management actions.

Sharpe and Stuart (2016) outline several practical steps to restore native fish in the region that mirror the steps of Lake et al. (2007):

- review the spatial and temporal distribution of native and exotic fish at Millewa Forest (**understand the species pool**)
- review the factors affecting the colonisation of floodplain and permanent creek, wetland and lake habitats of Millewa Forest, including the movement of various life history stages (**dispersal constraints/threats**)
- review the factors affecting the status of fish communities (**habitat and/or biotic constraints/threats**)
- review the factors affecting spawning and recruitment of fish at Millewa Forest (**habitat and/or biotic constraints/threats**)
- identify major on-ground management opportunities to restore the status and abundance of Millewa Forest native fish communities.

In this section, we discuss the first 3 of the points highlighted by Sharpe and Stuart (2016) by:

- describing the current and historical status of fish in Millewa Forest (Section 2.2)
- summarising current understanding of the requirements of fish in Millewa Forest (Section 2.3)
- describing the habitats within Millewa Forest, and their current condition (Section 2.4)

Section 2.5 then describes the threats that fish in Millewa Forest face.

This information is used in subsequent sections to outline options to mitigate threats and restore fish in Millewa Forest.

2.2 Historical and current status of native fish in Millewa Forest

This section synthesises information on the historical and current status of native fish communities in the flowing channels and off-channel areas of Millewa Forest. Consideration is given to species diversity, abundance and population structure, where such information is available. It is acknowledged that restoring the fish community to pre-European conditions is not the objective, especially given the drastic changes that has since occurred. Nevertheless, information on historical and current populations provides a clear idea of current conditions and changes that have occurred, and can help guide objectives for the strategy.

2.2.1 Historical fish assemblage of Millewa Forest

At least 22 species of native fish likely occurred in the Millewa Forest, based on historical and recent records and predicted occurrences based on likely past distributions of extirpated species (Cadwallader 1977; Leslie 1995; McKinnon 1997; King 2005; Hale and Butcher 2011). Of these, 19 are included as key target species for this strategy (Table 1), with 11 of these species currently considered present in the region. Species were only included if Millewa Forest historically included a significant portion of their range. Transient species that would only occasionally occur in the forest (Hale and Butcher 2011) are not included. These include spangled perch (*Leipotherapon unicolor*), which is mainly distributed in the northern Murray–Darling Basin and rarely occurs in the Murray River (Ellis et al. 2015); short-headed lamprey (*Mordacia mordax*) and short-finned eel (*Anguilla australis*) which transit through Millewa Forest on their migrations; and obscure galaxias (*Galaxias oliros*), which occurs mainly in tributaries or in the main channel in the upper Murray River (Raadik 2014).

Locally extinct native species

Species that would have been recorded in the region but are now absent include: freshwater catfish, river blackfish, Macquarie perch, southern purple-spotted gudgeon, Murray galaxias, Murray hardyhead, southern pygmy perch and olive perchlet. Most of these have not been recorded since at least the 1990s, despite several surveys directly targeting small-bodied wetland specialist fishes (Sharpe and Wilson 2012; Sharpe 2014, 2018). The last record of one such species, southern pygmy perch, was in 2008 (Tonkin and Rourke 2008).

2.2.2 Current status of fish in Millewa Forest

Fish community surveys have been conducted routinely at Millewa Forest since the mid-2000s (Table 1). These provide a picture of the present-day diversity, abundance and population structure of fish in the wetlands, creeks and rivers across Millewa Forest.

Table 1 Number of native fish species recorded in different habitats at Millewa Forest since 2012

Notes: The year the survey was conducted is provided together with the number of sites surveyed in parentheses. Species that were once recorded in the region but are now considered locally extinct are indicated in the last column. Survey methods varied between years and provided an indication of inter-annual variability of occurrence and abundance.
Sources: Sharpe and Wilson (2012), Sharpe (2014, 2018), Whiterod and Gannon (2020) and Raymond et al. (2020).

	Off-channel sites				Flowing channel sites			Considered extant?
Year of survey (no. of sites surveyed)	2012 (39)	2014 (8)	2018 (12)	2020 (11)	2018 (10)	2019 (10)	2020 (10)	
Large-bodied (500–1,000 mm)								
Murray cod	1	1	0	1	66	75	62	Y
Trout cod	0	0	0	0	18	34	24	Y
Medium-bodied (90–500 mm)								
Golden perch	0	0	0	0	43	44	25	Y
Silver perch	0	0	0	0	12	4	3	Y
Bony herring	0	0	0	0	0	1	0	Y
Freshwater catfish	0	0	0	0	0	0	0	N
River blackfish	0	0	0	0	0	0	0	N
Macquarie perch	0	0	0	0	0	0	0	N
Small-bodied (20–90 mm)								
Murray rainbowfish	0	0	0	2	2	579	23	Y
Flat-headed gudgeon	1	24	23	1,840	0	0	0	Y
Dwarf flat-headed gudgeon	0	2	0	3	0	16	0	Y
Un-specked hardyhead	1	27	6	14	1	1,272	691	Y
Australian smelt	176	50	99	385	751	1,546	1,760	Y
Carp gudgeon species	673	31,646	6,416	8,423	118	40	15	Y

	Off-channel sites				Flowing channel sites			Considered extant?
Year of survey (no. of sites surveyed)	2012 (39)	2014 (8)	2018 (12)	2020 (11)	2018 (10)	2019 (10)	2020 (10)	
Purple-spotted gudgeon	0	0	0	0	0	0	0	N
Murray galaxias	0	0	0	0	0	0	0	N
Murray hardyhead	0	0	0	0	0	0	0	N
Southern pygmy perch	0	0	0	0	0	0	0	N
Olive perchlet	0	0	0	0	0	0	0	N

Extant species: off-channel habitats

In Millewa Forest, off-channel habitats (also referred to as wetlands in this strategy) include large floodplains, smaller permanent wetlands and the regulated ephemeral creeks. In general, these habitats are dominated by small-bodied species, especially carp gudgeon species, which are present at most sites surveyed, with numbers varying from a few individuals to tens of thousands of fish (Sharpe 2014). Australian smelt are most abundant in the Murray River channel but are patchily distributed across wetlands and generally recorded in low numbers. Murray rainbowfish and un-specked hardyhead are recorded in wetlands and ephemeral creeks, but at much lower numbers than in main channel habitats. Flat-headed gudgeon are present in low numbers and are patchily distributed but can occur at high densities in individual wetlands. Dwarf flat-headed gudgeon are present although extremely rare.

In summary, the patchy nature of populations is relatively consistent along the Murray valley and at other Living Murray icon sites, and some of the once-common and widespread small-bodied species, such as Australian smelt, Murray rainbowfish, flat-headed gudgeon and un-specked hardyhead, appear to be in long-term population decline (Murray–Darling Basin Authority 2018)

Large-bodied native species make up a much smaller proportion of the fish community in wetlands and ephemeral creek systems than in the main channels. Individual Murray cod are sometimes caught in ephemeral creeks and wetlands (Sharpe and Wilson 2012; Sharpe 2014; Raymond et al. 2020; Whiterod and Gannon 2020). There is currently no evidence for floodplain habitats supporting strong populations of Murray cod and trout cod (Raymond et al. 2020), but these areas can potentially function as nursery habitats. Adult golden perch and silver perch have been recorded repeatedly accessing forest creeks when connected to the Murray River (Koster et al. 2020; Stuart et al. 2020).

Extant species: flowing channel habitats

Compared to the rest of the region, there are relatively high numbers of large-bodied fishes recorded in the main channel habitats at Millewa Forest, including the Murray River, Gulpa Creek and the Edward River. These systems consistently support Murray cod, trout cod, golden perch, silver perch and carp (*Cyprinus carpio*). For Murray cod and trout cod, populations appear stable, albeit fractured as a result of recreational fishing. Likewise for golden perch and silver perch, where adults are present but juveniles are rarely recorded. The demographics of all 4 species are fragmented.

Australian smelt*,* Murray rainbowfish and un-specked hardyhead are present in high numbers in main channel habitats, although the catches of the latter 2 species have varied greatly in recent years. Carp gudgeon species are rare but consistently recorded while bony herring, flat-headed gudgeon and dwarf flat-headed gudgeon (*Philypnodon macrostomus*) are very rarely recorded (Sharpe 2014, 2018; Stuart et al. 2021).

Non-native species

Up to 8 non-native species have been recorded in the central Murray region (King 2005). Carp are ubiquitous and can reach high densities in all habitats. The large, shallow wetland areas around Barmah–Millewa Forest are suitable spawning areas for carp and support large populations (Stuart and Jones 2006, 2002; King et al. 2005).

Eastern gambusia (*Gambusia holbrooki*) are very common and widespread in wetland and ephemeral creek habitats and can reach extremely high densities (MacDonald et al. 2012).

Goldfish (*Carassius auratus*) are widespread, albeit in lower numbers, while oriental weatherloach (*Misgurnus anguilicaudatus*) are common and abundant in wetlands and ephemeral creeks but rare in main channels (Raymond et al. 2020).

Redfin perch (*Perca fluviatilis*) are found in some off-channel habitats and are rare in the main channel (Raymond et al. 2020).

Brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*) and tench (*Tinca tinca*) are occasionally present in the region but are rarely recorded (King 2005).

2.3 Summary of knowledge of fish requirements

2.3.1 Millewa Forest fish traits

The fish in Millewa Forest have a diverse range of biological traits. For example, un-specked hardyhead may produce as few as 20 eggs per female, while bony herring may produce in excess of 800,000. Murray River rainbowfish can reach sexual maturity within 10 months, while Murray cod may take up to 6 years. Some species scatter small eggs among vegetation, while some build nests in wood and protect their young. This diverse range of traits and behaviours means that these species may experience different threats and respond to management interventions in vastly different ways.

To better understand these differences, a summary of species' traits is provided in Table 2. Conceptual models of each species' life history characteristics are detailed in subsequent sections and provided in Appendix A to D.

Table 2 Traits of fish species presently and historically occurring in Millewa Forest

Notes: T = temperature spawning cues, F = flow spawning cues, Age at maturity column – M = males, F = females.
Information from this table comes from a variety of sources including: (Sanger 1986; Winemiller 1992; Allen et al. 2002; Lintermans 2007; Llewellyn 2011, 2014; John D. Koehn et al. 2020; Lyon et al. 2021; Zukowski et al. 2021).

	Spawning frequency	Fecundity	Parental care	Spawning cues	Spawning details	Age at maturity	Life history category	Habitat guild	Diet
Large-bodied									
Murray cod	Circa-annual, single spawning	Moderate (6,000–110,000)	Yes	T	Nest on hard structure in flowing water	4–6 years	Equilibrium	Channel	Carnivorous – insects and fish
Trout cod	Circa-annual, single spawning	Moderate (2,000-14,000)	Yes	T	Nest on hard structure in flowing water	3–5 years	Equilibrium	Channel	Carnivorous – insects, crustaceans and fish
Medium-bodied									
Golden perch	Repeated	Very high (~350,000 up to 700,000)	No	T,F	Eggs scattered in flowing water, eggs and larvae drift long distances	M: 3 years F: 4 years	Periodic	Channel	Carnivorous – insects and fish
Silver perch	Repeated	Very high (up to 500,000)	No	T,F	Eggs scattered in flowing water, eggs and larvae	M: 3 years F: 4–5 years	Periodic	Channel	Omnivorous – insects, crustaceans, algae

	Spawning frequency	Fecundity	Parental care	Spawning cues	Spawning details	Age at maturity	Life history category	Habitat guild	Diet
					drift long distances				
Bony herring	Circa-annual	Very high (33,000–880,000)	No	T	Eggs scattered in still, shallow water	M: 1–2 years F: 2 years	Opportunistic	Generalist	Omnivorous – insects, crustaceans, algae
Freshwater catfish	Circa-annual	Moderate (9,000–60,000)	Yes	T	Nest built in gravel/sand in still/slow flowing waters	3–5 years	Equilibrium	Generalist	Carnivorous – insects, crustaceans, small fish
River blackfish	Circa-annual, single spawning	Low (200–500)	Yes	T	Nest on hard structure such as logs and undercut banks	1–2 years	Equilibrium	Channel	Carnivorous – insects, crustaceans, and fish
Macquarie perch	Circa-annual, single spawning	High (30,000–100,000 eggs/kg female body weight)	No	T	Scattered above riffles, eggs drifting and lodging in riffles and gravel	M: 2 years F: 3 years	Periodic	Channel	Insectivorous – insects and crustaceans

	Spawning frequency	Fecundity	Parental care	Spawning cues	Spawning details	Age at maturity	Life history category	Habitat guild	Diet
Small-bodied									
Murray rainbowfish	Circa-annual, single spawning	Low (35–330)	No	T	Scattered among vegetation; adhesive	10–12 months	Opportunistic	Generalist	Omnivorous – small insects, zooplankton, algae
Flat-headed gudgeon	Protracted repeat spawning	Low (500–900)	Yes	T	Nest on hard structure in still water	Likely ~1 year	Opportunistic	Generalist	Carnivorous – insects, crustaceans, small fish
Dwarf flat-headed gudgeon	Protracted repeat spawning	Likely low	Yes	T	Nest on hard structure in still water	Likely ~1 year	Opportunistic	Generalist	Carnivorous – insects, crustaceans, fish larvae
Un-specked hardyhead	Protracted repeat spawning	Very low (20-100)	No	T	Adhesive demersal eggs scattered	Likely ~1 year	Opportunistic	Generalist	Omnivorous – small insects, plankton, algae
Australian smelt	Protracted repeat spawning	Low (100–1,000)	No	T	Adhesive demersal eggs scattered	Likely ~1 year	Opportunistic	Generalist	Omnivorous – small insects, plankton, algae
Carp gudgeon species	Circa-annual, single spawning	Low (up to 2,000)	No	T	Adhesive deposited on vegetation or structure	Likely ~1 year	Opportunistic	Generalist	Omnivorous – small insects and plankton
Southern purple-spotted gudgeon	Protracted repeat spawning	Low (208–1,300)	Yes	T	Nest on solid structure or	45–49 mm (likely ~1 year)	Opportunistic	Off-channel	Omnivorous – insects, crustaceans,

	Spawning frequency	Fecundity	Parental care	Spawning cues	Spawning details	Age at maturity	Life history category	Habitat guild	Diet
					vegetation in still water				small fish, plant material
Murray galaxias	Circa-annual, single spawning (?)	Low (2,000–7,000)	No	T	Adhesive demersal eggs scattered	~1 year	Opportunistic	Off-channel	Insectivorous – insects and crustaceans
Murray hardyhead	Protracted repeat spawning	Low (200–500)	No	T	Adhesive eggs scattered among vegetation	4–5 months	Opportunistic	Off-channel	Omnivorous – small insects, plankton, algae
Southern pygmy perch	Circa-annual, single spawning	Low (100–4,200)	No	T	Non-adhesive scattered on vegetation in still waters	~1 year	Opportunistic	Off-channel	Insectivorous – small insects and crustaceans
Olive perchlet	Circa-annual, single spawning	Low (400–9,000)	No	T	Adhesive deposited on vegetation or structure	1 year	Opportunistic	Off-channel	Insectivorous – small insects and crustaceans

2.3.2 Models of life history

Spawning and recruitment are key processes in a fish's life history, with the early life stages subject to the greatest mortality rates (Pepin 1993). Hence, understanding and supporting the processes of spawning and recruitment are essential to achieve objectives of building native fish populations, increasing abundance and restoring population demographics.

Fish can be classified along 3 axes of basic life history traits: generation time, fecundity and juvenile survivorship (Winemiller and Rose 1992; Winemiller 2005). Based on demographic data collected from thousands of individuals across many species, Winemiller and Rose (1992) identified 3 common life history strategies (Figure 1):

- **opportunistic** species, with short generation time, low fecundity and low juvenile survivorship (e.g. carp gudgeon species)
- **periodic** species, with long generation time, high fecundity and low juvenile survivorship (e.g. golden perch)
- **equilibrium** species, with long generation time, low fecundity and high juvenile survivorship (e.g. Murray cod).

It is important to note that these are generalisations and not all fishes will fit perfectly into the categories, as highlighted in Figure 1. For example, Murray cod have moderate to high fecundities but are still listed as equilibrium species. In contrast, carp gudgeon species fit opportunistic species characteristics on all 3 axes. Nonetheless, these groupings are useful for predicting how species interact with extrinsic factors (Winemiller 2005), such as disturbance, biotic interactions and spatiotemporal variability of resources (external arrows, Figure 1). In general, these predictions are likely to hold true for Millewa Forest fish species, and thus the life history groupings can thus be used to predict species' responses to threats and restoration activities (Hitt et al. 2020).

Why life history matters for management

Comparing prioritises for equilibrium vs periodic species

A recent study by Lyon et al. (2021), conducted over 19 years in the Murray River, investigated the drivers of 4 species in 2 of these life history categories. They found:

- Local populations of 2 **equilibrium species**, Murray cod and trout cod, were likely driven by local recruitment.
  - Management of these species should focus on **local-scale actions**, such as re-snagging, and water delivery that promotes local juvenile survival and recruitment.
- Local populations of 2 **periodic species**, golden perch and silver perch, were likely driven by immigration.
  - Management of these species should focus on **connectivity of reaches** by constructing fishways and delivering water that triggers migratory movements.
- It is important to consider how and when species responses may occur. Golden perch may respond more quickly and strongly to environmental water delivery, whereas Murray cod responses may be slower and more strongly linked to local conditions.

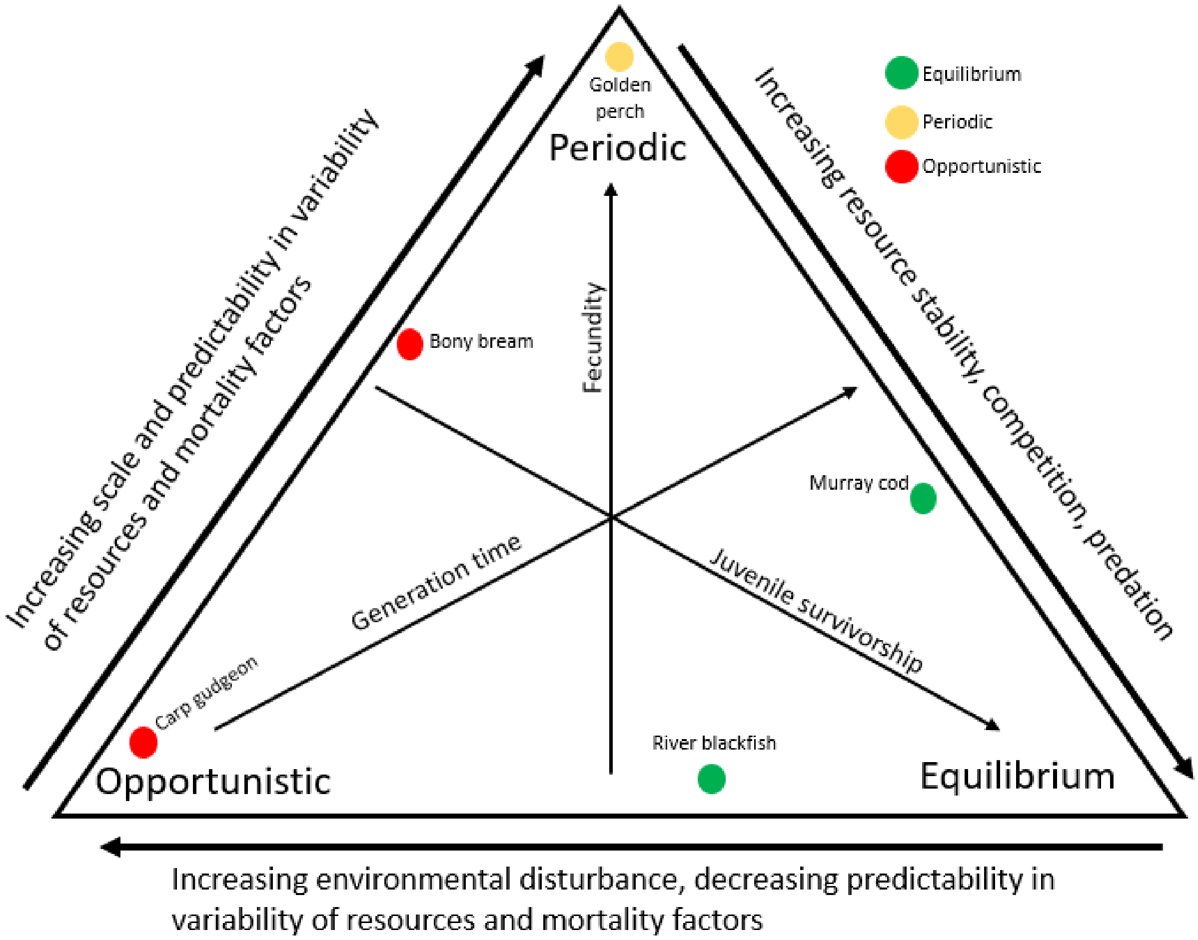

Figure 1 Triangular life history model outlining the axes of demographic parameters (internal arrows) that define the 3 different life history trait groups

Notes: External arrows indicate the environmental parameters that suit different traits' suites of traits (and therefore the different life history group). Several species are included, with their position based on their demographic parameters. This illustrates the fact that not all species fit into a life history group perfectly and can have different combinations of demographic parameters.

Opportunistic life history

Species with an opportunistic life history are usually small, short-lived and reach maturity quickly (Winemiller 2005); and they represent the majority of species in Millewa Forest (Table 2). They are small and underdeveloped upon hatching with a small gape, limited physical development and thus poor swimming capability. Hence, survival of early life stages is highly dependent on having sufficient food resources. Many of these species can spawn multiple times in a season or have extended spawning periods. They exhibit little to no parental care, have high rates of larval mortality and generally have low fecundity. Examples of these species in Millewa Forest are Australian smelt and carp gudgeon species.

Given that they have very low fecundities, it is somewhat counterintuitive that opportunistic species can rapidly achieve very high densities (Winemiller 1992). However, **opportunistic species are well suited to frequent, unpredictable disturbances** (Figure 1) and their short generation time can lead to rapid population growth (e.g. Papas et al. 2021). This means that they are well placed to quickly colonise and exploit newly inundated, productive habitats, such as ephemeral floodplains (Balcombe et al. 2005; Beesley et al. 2012; Balcombe et al. 2015). Those opportunistic species with generalist habitat requirements

(Table 2) and broad physiological tolerances will be even better placed to exploit marginal or ephemeral habitats, hence the ubiquity of species like carp gudgeon species and the non-native eastern gambusia in wetlands and floodplains of the Murray–Darling Basin.

Periodic life history

Periodic species are highly fecund and longer lived but have poor juvenile survivorship (Winemiller 2005). Given their mobility and broadcast spawning, they are well suited to exploit suitable flowing water conditions at larger spatial scales (Figure 1). In the Murray–Darling Basin, golden perch, silver perch and Macquarie perch fit these characteristics. They can have extremely variable inter-annual recruitment which, in a Murray–Darling Basin context, is heavily dependent on the delivery of appropriate flows with adequate temperatures for golden and silver perch (Koster et al. 2017; King et al. 2016) to support spawning, and allow access to nursery habitats (Sharpe 2011; Stuart and Sharpe 2020). For Macquarie perch, it is critical that flow conditions allow access to lotic reaches during spawning runs (Broadhurst et al. 2016; Lintermans 2013). Similar to opportunistic species, the larvae of periodic species tend to hatch quickly and are very small. Their limited larval development at first feeding means that access to nursery sites is essential for successful recruitment (Koster et al. 2017; Arumugam and Geddes 1986; Rowland 1983; Sharpe 2011), and they can have very high rates of early life stage mortality.

Equilibrium life history

Species with an equilibrium life history are larger, take longer to reach sexual maturity and build and defend nests with a high degree of parental care (Winemiller 2005). In the Murray–Darling Basin, these species include Murray cod, trout cod, river blackfish and freshwater catfish. These characteristics mean that equilibrium species are generally better suited to more stable, resource-rich environments. They are also well equipped to deal with the intense competition and predation in locally productive areas (Figure 1), due in part to the high degree of parental investment. However, their lower fecundities and investment in a single batch of eggs each year also leaves them vulnerable to disruption. Nest abandonment by parents, inappropriate variation in river and wetland levels, lack of access to lotic environments during the spring spawning season, sedimentation and predation can lead to the loss of an entire brood.

All 4 equilibrium species in the Murray–Darling Basin can take multiple years to reach maturity (Table 2), with larger females producing more eggs, likely disproportionately so (Barneche et al. 2018). Hence, size selective removal of larger, older fish (e.g. by angling) can have severe impacts on the likelihood of population decline (e.g. Murray cod); (Koehn and Todd 2012). Finally, their requirements for particular types of physical habitat to establish nest sites may mean that the number of spawning adults in a population is limited if there is a limited amount of suitable habitat available (Lyon et al. 2019; Tonkin et al. 2020).

2.3.3 Models of fish movement

Fish may move for a variety of reasons and at vastly different scales. For species that occur or used to occur at Millewa Forest, movement may be to disperse to new areas, to feed, to reproduce and/or to escape disturbance. Understanding and restoring the capacity for movement is a necessary step to support healthy, connected populations in Millewa Forest (Stuart et al. 2020). Understanding scale, patterns and drivers of species' movements can allow predictions of responses to restoration and estimates of effective population size (Radinger and Wolter 2014).

Longitudinal movement

Longitudinal movements (i.e. upstream and downstream in the main channels of rivers) frequently occur in the Murray–Darling Basin, with many species moving as adults and juveniles, in both directions, for spawning and dispersal. In the Millewa Forest region, fish undertake longitudinal movements in the Murray River, Edward River and Gulpa Creek.

Many large-bodied main channel specialist fish are regularly recorded undertaking longitudinal movements in Millewa Forest channels (Stuart et al. 2020, 2021). These may be regular daily movements or to new areas entirely (Koehn and Nicol 2016). Movement is often related to spawning; adult golden perch, silver perch and Murray cod are all observed to move prior to spawning (Koster et al. 2020; O'Connor et al. 2005; Koehn et al. 2009), sometimes over long distances. After their larval drifting phase, juvenile golden and silver perch often disperse upstream through fishways in large numbers (Mallen-Cooper 1999; Baumgartner and Harris 2007), along with bony herring (Baumgartner et al. 2010; Baumgartner and Harris 2007).

Small-bodied fishes have also been recorded undertaking longitudinal movements, sometimes in large numbers (Stuart et al. 2008), although these movements are likely linked to dispersal at the landscape scale and not obligatory spawning movements.

Most habitat generalists and channel specialist species have larvae that may drift downstream in flowing water (Lintermans 2007), with distances varying greatly. Juveniles may then disperse upstream to recruit into adult populations, which may be stimulated by changes in river discharge (e.g. golden and silver perch) and/or rising water temperature. These are also considered longitudinal movements.

Lateral movement

Lateral movement is the movement from main channel to off-channel areas such as creeks and wetlands when they are connected, or the movement onto the floodplain from permanent wetlands during flooding. In the context of Millewa Forest, off-channel areas include large floodplains, smaller permanent wetlands and the regulated ephemeral creeks, such as Toupna Creek. The latter may be periodically connected with the main channel, when these creeks may resemble flowing channel habitat, but draw down to a series of pools when regulators are closed.

Adults of larger-bodied fishes may temporarily access inundated Millewa floodplains or ephemeral creeks when these areas are connected to main channel habitats (Stuart et al. 2020, 2021). These movements are not generally linked to spawning and may be for adult and sub-adult fish to access these highly productive areas for feeding. Fish will leave the floodplain when cued by dropping water levels, but may become stranded if the recession is managed too rapidly (Jones and Stuart 2008). Drifting eggs and larvae may be swept into off-channel areas where they can develop in productive nursery habitats and then return to the main channel areas as juveniles (Sharpe 2011).

Small-bodied generalist species may move back and forth between main channel and off-channel habitats as adults, across a variety of hydrologic conditions (Lyon et al. 2010; Conallin et al. 2011, 2012), or they may drift in as larvae (e.g. Australian smelt; Papas et al. 2021). If they are resident in these areas, they may spawn in productive off-channel areas, with subsequent exit of large numbers of recruits sometimes observed (Papas et al. 2021). There is little information on the movement of off-channel specialist species, although they have been observed using the floodplain for dispersal during large-scale floods (Tonkin et al. 2008), and it is likely that they would have historically used the main channel to some extent for dispersal between different populations.

Movements for spawning and recruitment

Movement within the river is often strongly linked to life history processes, particularly spawning and recruitment. Supporting these movements with management interventions such as fishways or environmental flows can greatly increase larval and juvenile survival, which are the life stages with the greatest mortality. Some species require particular types of physical habitats to spawn, and self-evidently, recruitment is highest at nursery sites where ideal conditions for early life stages are met (Houde 1989).

For periodic species, downstream dispersal to recruitment habitats occurs as drifting eggs, larvae and occasionally fingerlings via flowing riverine habitats. Settlement then occurs in suitable areas such as floodplain wetlands or main channel slack waters for golden and silver perch (Tonkin et al. 2017; Sharpe 2011; Koster et al. 2020; Tonkin et al. 2019; Stuart and Sharpe 2020) or pools downstream of the spawning site for Macquarie perch (Tonkin et al. 2010). Survival of these life stages is often greater in years with increased in-channel flows, riparian zone inundation and overbank flooding, increasing the likelihood that young will encounter suitable nursery areas (Mallen-Cooper and Stuart 2003; Tonkin et al. 2019; Zampatti and Leigh 2013). **The likelihood that a larval fish of periodic species will settle in a suitable nursery area is strongly influenced by riverine hydraulic conditions and connectivity with the main channel.**

For the small-bodied opportunistic species, movement to recruitment habitats occurs as adults move into areas of slow flowing, warmer, nutrient-rich water such as floodplains and main channel slack waters, or remain in these areas if they occupy them as adults (Tonkin et al. 2008; Lyon et al. 2010). **The likelihood that a larval fish of small-bodied opportunistic species will settle in a suitable nursery area is strongly influenced by access for pre-spawning adults.** Juvenile fish may then move out of these nursery areas and presumably join adult populations in the main channel of the river (Papas et al. 2021), especially in the case of generalist species. Many small-bodied opportunistic species may also have larvae or eggs that drift downstream in flowing water. If this occurs, they are likely subject to the same requirements of the periodic species, that they settle in suitable nursery areas. For example, the relatively sedentary flat-headed gudgeon can be collected in very high densities as drifting larvae in the main channel of rivers (Lintermans 2007), and in large numbers in fishways as dispersing juveniles.

For equilibrium species, adults may move to suitable nesting areas, longitudinally within the main channel or into smaller anabranches, or remain where they are and establish nests. Murray cod, trout cod and river blackfish prefer lotic spawning habitats (Stuart et al. 2019) while freshwater catfish prefer lentic (non-flowing) wetlands. Larvae often disperse and settle at sites nearby nests in similar microhabitats to adults (Lyon et al. 2019; Nicol et al. 2004), and dispersal may be via downstream drift or through active swimming, often over relatively short distances (e.g. trout cod); (Koehn et al. 2008). Young-of-year fish may access smaller, anabranch creeks as part of an exploratory phase (Stuart et al. 2020, 2021), and providing access to and from these nursery areas may be important for successful recruitment. **The juvenile equilibrium species often actively disperse to and settle in nursery areas, so proximity of nursery habitats to nesting sites may be an important control on recruitment strength.** Indeed, local-scale recruitment is often an important driver of these species' populations (Lyon et al. 2021).

Fish movements matter for management

- Many fish move upstream and downstream in flowing channels, and improving connectivity can support this process.
- Movements to and among off-channel habitats are important for many small-bodied species and the larvae and juveniles of large-bodied species.
- Periodic species (e.g. golden perch) have drifting larvae, and recruitment is enhanced when these larvae/juveniles can access off-channel nursery habitats such as wetlands or inundated floodplains.
- Adults of opportunistic species (e.g. Australian smelt) may move to and deposit eggs in productive nursery habitats, resulting in enhanced survival and recruitment of larvae.
- Juveniles of equilibrium species (e.g. Murray cod) disperse via drift or active swimming, and will actively seek out nursery habitats as young fish. These may be similar microhabitats to adults or flowing anabranch creeks.

2.3.4 Models of habitat use – fish guilds

Fishes in Millewa Forest can use a variety of different types of hydrological habitat, occurring to a lesser or greater extent in fast-flowing main channels and anabranches, permanent or semi-permanent off-channel areas of still water (e.g. wetlands, billabongs and lagoons), and temporarily inundated floodplains (see Section 2.4). Fish can be grouped into 3 broad guilds based on their associations with different habitats, and areas that they require to complete their life cycles (Baumgartner et al. 2014; Mallen-cooper et al. 2014). These are:

- channel specialists
- off-channel specialists (also called wetland specialists)
- generalist species.

The above designations are not always clear-cut, and channel specialists may temporarily access off-channel areas, and vice versa for off-channel specialists.

Channel specialists are those that require longer areas of flowing water to spawn, and often occupy these areas as adults (Stuart et al. 2019) (e.g. Murray cod and golden perch). They are often associated with areas of complex structural habitat (Koehn and Nicol 2014; Broadhurst et al. 2012; Bond and Lake 2003), although silver perch appear to be more pelagic (Hutchison et al. 2020). Most of the large and medium-bodied fishes at Millewa Forest fall into this category. Adults of channel specialists will temporarily access off-channel areas to feed (Jones and Stuart 2008), and may also spend longer periods in productive off-channel areas as young fish (see 2.3.3 Models of fish movement).

Off-channel specialists (or wetland specialists) are species that specifically prefer wetland areas and obligatorily complete their life cycle entirely within these areas (e.g. southern pygmy perch and southern purple-spotted gudgeon). They may be found in flowing channels but are more common in areas of very low or no flow, such as backwaters. These species are often very strongly associated with areas of complex microhabitat, such as aquatic vegetation and complex woody debris, where they spawn and live (Bond and Lake 2003; Hammer and Wedderburn 2008; Lintermans 2007). They may use temporarily inundated floodplains to feed, disperse and spawn (Tonkin et al. 2008; Stoessel 2010; Ellis and Kavanagh 2014),with higher numbers sometimes recorded in post-flood years (Tonkin et al.

2008). Off-channel specialist species found presently and historically in Millewa Forest are all small-bodied species with opportunistic life histories.

Generalist species can live and breed in a wide variety of hydrological and physical habitat types (e.g. carp gudgeon species and Australian smelt). When connection is provided, they may move between main channel and off-channel areas under varying conditions (Lyon et al. 2010), sometimes in large numbers (Papas et al. 2021). They may benefit from the presence of complex structural habitat, although these associations may not be as strong as for off-channel specialists, and they will readily use areas of open water (Bond and Lake 2003; Hutchison et al. 2020). Most of the generalist species found at Millewa Forest are small-bodied species with opportunistic life histories.

Inter-specific differences in habitat use matter for management

- Understanding inter-specific differences in habitat use can help target management outcomes for different species.
- For specialist fish species, targeted management actions will be needed focused on the narrower range of habitats they use.
- Generalist species may respond to a wider range of management actions based on the broader range of habitats they use.

2.4 Habitats in Millewa Forest

The perennially flowing channels, wetlands and ephemeral creeks discussed in this section are shown in Figure 2. Channel habitats and off-channel habitats (wetlands and ephemeral creeks) are discussed separately (in Sections 2.4.1 and 2.4.2, respectively). These 2 broad habitats are separated for 3 reasons:

they may be in vastly contrasting condition

they will likely respond to management interventions in different ways

the target fish assemblages are likely to be different (although there may be some overlaps).

2.4.1 Channel habitats

Channel habitats at Millewa Forest can be divided broadly into larger main flowing channels and ephemeral forest creeks. They are considered together here as there are similarities in how both types of channel would have historically functioned and how they would likely have supported similar fish communities, but at different scales. If appropriate flow regimes can be restored to these creeks, it is likely that contemporary management of these sites would be similar. Larger, flowing main channel sites include the Murray River, Gulpa Creek and Edward River; while smaller regulated channels include Toupna Creek, Swifts Creek and Bunnydigger Creek (Figure 2).

We present a guiding image of restored Millewa Forest channel habitats in (Figure 3), which is the vision for channels in this strategy and includes:

- **Hydrology** – Diversity of flow, discharge and hydraulic conditions suitable for fish; and connected, flowing forest channels and main channels. Where there are regulating structures, fish are able to pass freely.
- **Vegetation** – Intact riparian zone, and emergent and fringing vegetation in areas of lower flow, supporting fish life history.
- **Water quality** parameters within fishes' tolerances, and the presence of blackwater refugia.
- Dense, connected areas of **woody debris** in main and forest channel.
- Variety of flow conditions, including overbank flooding to support **productivity** processes.

A diverse fish community with sufficient **longitudinal and lateral connectivity** to complete their life history processes.

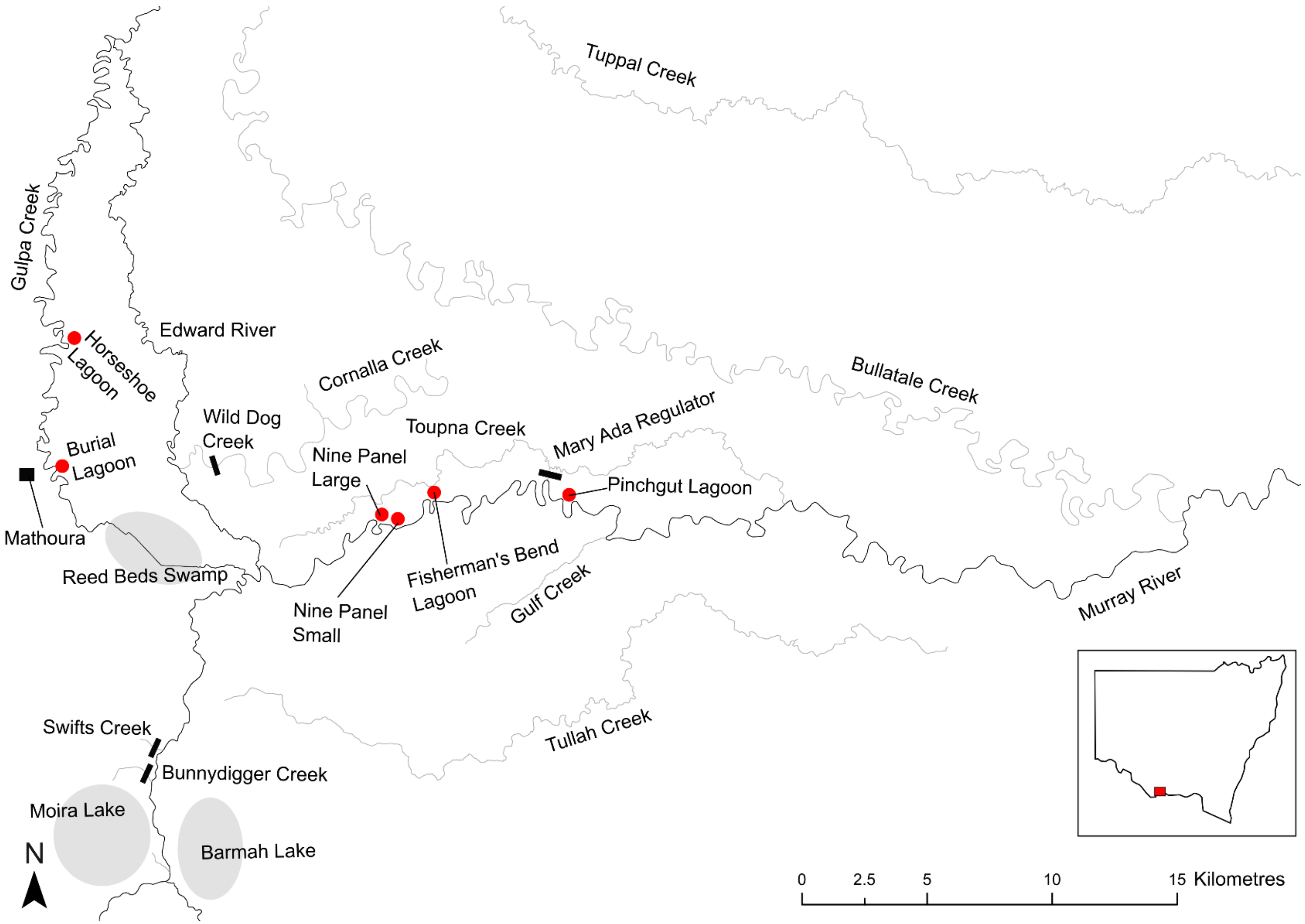

Figure 2 Map of Millewa waterbodies discussed in detail in this strategy

Notes: Main channels are in black, forest channels are in grey, large lakes or floodplains are large grey ovals, permanent wetlands are red circles and instream barriers are short black bars. Mathoura township is denoted with a black square. Some additional sites are included for context, including some channels in Barmah Forest.

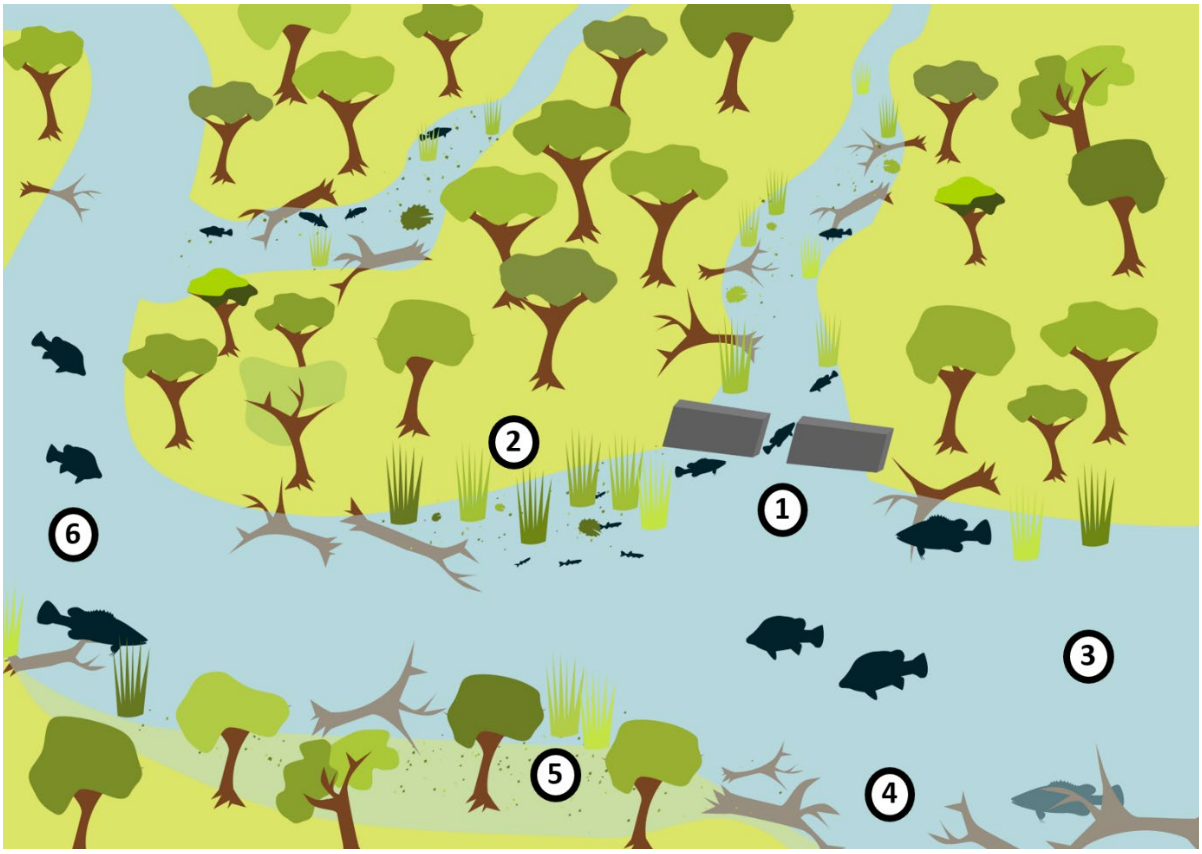

Figure 3 A guiding image for rivers in Millewa Forest, which is the vision for channels in this strategy

Notes: Numbers relate to different habitat aspects of a river, which are described in more detail in the text below. 1: Diversity of flow, discharge and hydraulic conditions suitable for fish, and connected, flowing forest channels and main channels. Where there are regulating structures, fish can pass freely; 2: Intact riparian zone, and emergent and fringing vegetation in areas of lower flow, supporting fish life history; 3: Water quality parameters within fishes' tolerances, and the presence of blackwater refugia; 4: Dense, connected areas of woody debris in main and forest channel; 5: Variety of flow conditions, including overbank flooding to support productivity processes; 6: A diverse fish community with sufficient longitudinal and lateral connectivity to complete their life history processes. The sections below compare this guiding image to the current state of channel habitats in Millewa Forest.

Hydrology

There are several aspects of hydrology in-channel habitats that are considered relevant for restoring native fish at Millewa Forest. At the meso (large) and micro (small) scale, the depth and hydrodynamic diversity of flow supports fishes with different flow-habitat requirements. For example, turbulence and micro-scale flow diversity around instream structures such as snags and rock bars is preferred by species such trout cod, Murray cod and golden perch (Koehn and Nicol 2014). In contrast, species such as freshwater catfish and a variety of small-bodied generalist species will occupy slower flowing, shallower parts of channel habitats.

Diversity of pool and run areas within a reach (and connection between these areas) can support channel specialists' movements and life history processes at the meso-scale (Stuart et al. 2019); and hydrological connection with anabranches, creeks and floodplains supports lateral movement between these areas and main channels. Deeper pools can be important refuges during low or no-flow conditions, particularly in smaller forest creeks and anabranches. For species that spawn in flowing channels and/or whose spawning is triggered by flow cues, appropriate seasonal hydrographs are essential to initiate spawning and support nesting and larval survival.

A survey mapping depth and hydrodynamic profiles of representative reaches at Millewa Forest found that the Murray River and Edward Creek had good diversity of depth and hydrodynamics, whereas Gulpa Creek was much shallower and generally slower flowing for most of its length, likely impacting the carrying capacity of channel specialist species (Kitchingman et al. 2020). There are several creeks in Millewa Forest such as Toupna, Cornella, Winters and Wild Dog, that are connected to main channels by regulators (Figure 2). When opened, these and other forest creeks have high hydrodynamic diversity (Sharpe 2018). When regulators are closed, the forest creeks dry down and cease to flow, often to a series of disconnected pools and therefore are ephemeral, or 'seasonally flowing'.

Vegetation

Aquatic vegetation in flowing channel habitats is a key element supporting several species of fish, providing resources such as food, shelter and nesting sites. Small-bodied generalist species such as Australian smelt and Murray River rainbowfish spawn on and among aquatic vegetation, and juveniles of large-bodied channel specialists have been shown to occupy vegetated areas rather than unvegetated substrates (Hutchison et al. 2020).

Water quality

Water quality parameters in flowing channels can fluctuate widely with seasonality and flow conditions. Many channel specialist species have limited tolerance for poor water quality. Blackwater events are a key threat to adults and cold water pollution has severe impacts on spawning and recruitment success (Koehn et al. 2020). (Small et al. 2014) found that juveniles of channel species are vulnerable to low dissolved oxygen conditions, with 50% mortality for Murray cod at 1.58 mg O_2/L (oxygen per litre), golden perch at 0.85 mg O_2/L and silver perch at 1.04 mg O_2/L.

Water quality in the Murray River downstream of Yarrawonga is generally 'good', based on monitoring data between 2010 and 2015 (NSW Department of Planning 2020). Water quality data are not readily available for other channels in Millewa Forest, upper Edward River and Gulpa Creek. However, given that these waterways are fed by this stretch of the Murray River it is likely that they share similar water quality parameters. Promisingly, point measurements taken in autumn 2020 at Toupna Creek found conditions suitable for native fishes (Whiterod and Gannon 2020). However, it should be noted that point measurements have somewhat limited utility as water quality (particularly temperature and dissolved oxygen) can fluctuate widely through the seasons.

Hypoxic blackwater events occur in aquatic systems when a large amount of terrestrial organic carbon is washed into aquatic environments, giving the water a brown or black appearance. This carbon can be rapidly decomposed by microbes, a process which also uses oxygen available in the water, sometimes resulting in extremely low levels of dissolved oxygen (King et al. 2012). Blackwater events from large floods and inundation of the floodplain occur with some regularity through the middle and lower Murray River, with recent hypoxic events in 2010 to 2011 and 2016 (NSW Department of Planning 2020). The stretch of the Murray River downstream of Yarrawonga to the Barmah Choke has little return flow from the floodplain and is, therefore, less at risk of blackwater because there is little high nutrient, low dissolved oxygen water returning to the river from the floodplain. However, fish are still impacted in the region, particularly large-bodied native species. For example, Raymond et al. (2020) recorded lower catches of Murray cod, golden perch and trout cod for several years after a severe blackwater event that impacted the Yarrawonga–Barmah reach of the Murray in 2010 to 2011. In contrast, the channel fish community appeared resilient to the 2016 to 2017 blackwater event. It is likely that Edward River, Gulpa Creek and smaller forest creeks are at risk from blackwater events given their greater levels of connection with the floodplain at elevated flows.

Woody habitat

Large, complex woody structure is a key habitat factor in large lowland channels of the Murray–Darling Basin. Many channel specialist species use these areas for a number of life history functions (Tonkin et al. 2020), and small-bodied generalist species can benefit from the increased structural complexity. Woody structures can create micro-scale flow diversity and provide surfaces for attachment of algae, periphyton and invertebrates, enhancing local productivity and creating areas for recruitment of channel specialist species (Humphries et al. 2020).

Many of the lowland rivers of south-east Australia were de-snagged following European arrival (Erskine and Webb 2003). In the Millewa Forest region, a recent survey of the larger channels around Millewa found that the density of instream wood in the Murray River (and Edward River) approximated likely natural densities (Kitchingman et al. 2020). However, there were some areas with longer distances between areas of good density, demonstrating reduced connectivity of habitat patches. In contrast, Gulpa Creek had low densities of woody structure with poor connectivity between patches. Immediately downstream of Millewa Forest, instream woody structure density is considered to be depauperate due to historic de-snagging (Leslie 1995). There have been fewer surveys in smaller forest creeks, although surveys in Wild Dog, Tootalong, Aluminy, Winters, Aratula and Toupna creeks revealed relatively good levels of woody structure (~10–40 % coverage) (Sharpe and Wilson 2012; Whiterod and Gannon 2020).

Productivity

Throughout this document, we use the term ‘productivity’ as a descriptor of the amount of food available for fishes. For riverine species, the amount of food available is a strong driver of recruitment success (Humphries et al. 2002). Food availability is a function of nutrients available in the system and food web function (how that energy is transferred between trophic levels). In riverine systems, these nutrients may flow in from upstream, or be made available through local processes within the river channel (e.g. photosynthesis or decomposition), inputs from the riparian zone or from inundated floodplains. In flowing channels, retention and concentration of nutrients (and subsequent algae and zooplankton) occurs more often in areas of slow flowing water, such as eddies and slack waters, or on inundated floodplains (Humphries et al. 2002). High productivity in a flowing reach is therefore a combination of inputs of nutrients and retention of nutrients so they are available to consumers. In the Murray–Darling Basin, this is often clearly seen when floodplains are inundated, resulting in greater recruitment of channel specialist species when compared to years that flows remain in the channel (King et al. 2009, 2010).

Productivity in the main channels around Millewa Forest likely has high variability and is difficult to quantify, with relevant empirical studies unable to be found. In lieu of this, the factors that make up productivity in a reach can be assessed, that is, inputs and retention. In the larger reaches around Millewa Forest there is limited macrophyte coverage and, although the river has national park forests on either side at Millewa, the broader landscape and the reaches upstream have undergone extensive modification and clearing, meaning that inputs from the riparian zone are likely to be reduced relative to pre-European levels. Retention is increased by the presence of instream structures, so the good density of woody debris in the Murray and Edward rivers would contribute to retention of (potentially nutrient-rich) water. Perhaps the most significant factor for productivity in the study reach is floodplain connection and return flows into the main channel after flooding. In the Murray

River, this is likely to be reduced relative to historic levels – the river is heavily regulated, with fewer floodplain connection events (Figure 4) and, as discussed above, there are few return flows to this section of the river. In contrast, the forest creeks and Edward River and Gulpa Creek are more directly connected to the floodplain and are therefore well placed to benefit from inputs of nutrients from the floodplain in flood years. Outside of these high-flow events, the disconnected nature of the forest creeks means limited nutrient inputs from upstream – this is borne out by the limited survey data available, where Sharpe (2018) found very low zooplankton densities in 2 sites of Toupna Creek.

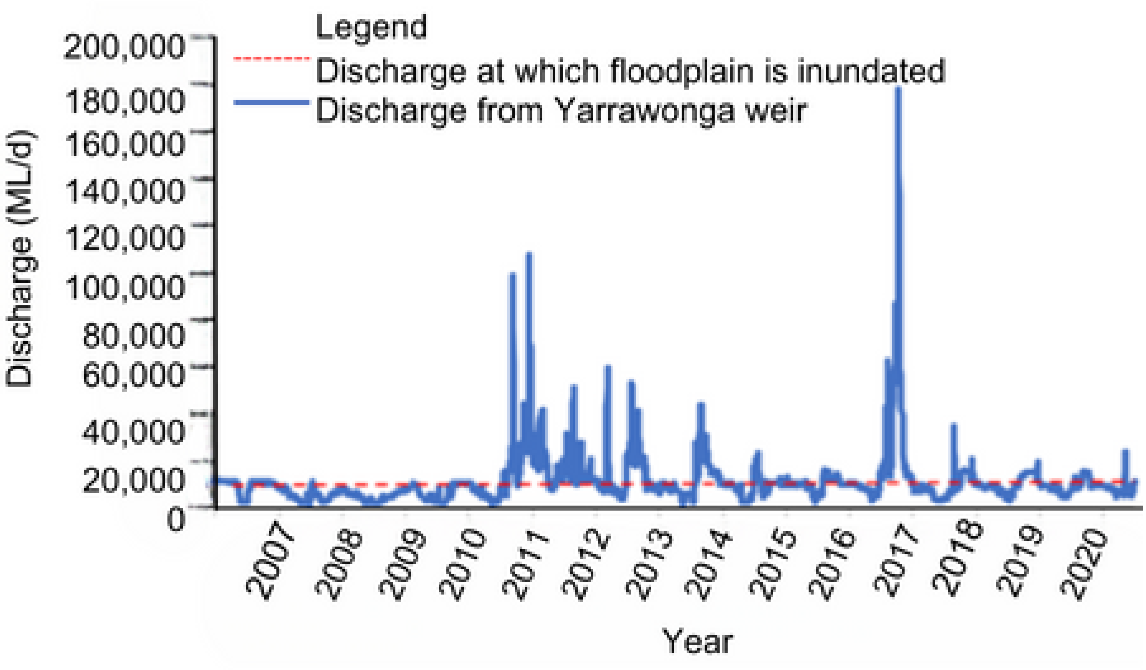

Figure 4 **Average daily flows (megalitres per day) downstream of Yarrawonga Weir from 2006 to 2020 (gauge #409025). The red line indicates the discharge at which the floodplain is inundated. Source: Raymond et al. (2020)**

General observations of main channels at Millewa Forest

- There are consistent in-channel flows in main channels during the irrigation season.
- Forest creeks are periodically connected and drawn down to pools, or sometimes dry completely when disconnected.
- There is reduced lateral connectivity relative to natural levels.
- Hydraulic and depth diversity exist in Murray and Edward rivers, less so in Gulpa Creek.
- Little aquatic vegetation exists in main channels or forest creeks.
- Water quality is generally good, and within the physiological tolerances of native fishes.
- Murray River at Millewa is impacted by blackwater events but is more resilient than other areas of the Murray River downstream where water returns from the forest.
- Edward River, Gulpa Creek and forest creeks are likely impacted by blackwater events when they occur.
- Density of instream woody structure approximates natural levels in the Murray and Edward rivers, less so in Gulpa Creek.
- Relatively long distances exist between areas of dense woody structure in some reaches of all main channels.
- Woody structure in forest creeks is under-quantified but likely approximating natural densities.
- There has been little direct measurement of productivity, but it is likely driven primarily by lateral connection and floodplain inundation.

2.4.2 Off-channel habitats – wetlands and ephemeral creeks

The number, size, type and condition of off-channel habitats in Millewa Forest can vary significantly based on river flows. Keogh (2012) modelled an estimate of 2,170 ha inundated at 8,000 megalitres (ML)/day downstream of Yarrawonga and 27,294 ha inundated at flood flows of 65,000 ML/day. Much of the information presented here is focused on sites that hold water at lower flows, mainly smaller permanent wetlands and some larger lake areas. Many of the sites are small, permanent or semi-permanent wetlands close to main channels, with some larger floodplain sites. These sites have been identified in previous reports (Sharpe and Wilson 2012; Sharpe 2014, 2018; Whiterod and Gannon 2020) as high priority locations for the reintroduction of small-bodied wetland specialist fish. A list of these sites is included in Table 3. Other sites, higher in the landscape, form an important part of an ephemeral wetland matrix, but limited information is available on such sites (except for Sharpe and Wilson 2012).

A guiding image of a restored wetland is presented in Figure 5, which is the vision for wetlands in the strategy:

- **Hydrology** – occasional hydrological connectivity with main channels to facilitate fish movement and periodic inundation of terrestrial habitats for productivity (and water level variation)
- **Vegetation** – dense emergent, submerged and fringing vegetation support various aspects of fishes' life history, providing shelter, shade and basal productivity
- **Water quality** – water quality parameters within the tolerance ranges of native fishes
- **Woody debris** – woody structure of various sizes to provide shelter and nest sites
- **Productivity** – nutrients available in the system
- **Invasive fish** – few to no invasive fish and a diverse community of native fishes, including small-bodied wetland specialists and generalists.

The sections below compare this guiding image to the current state of off-channel habitats in Millewa Forest.

Hydrology

Hydrological connection between off-channel and main channel habitats facilitates movement of wetland specialist fish between sites, access to productive nursery areas for larvae and juveniles of large-bodied species, and supports metapopulation processes and gene flow. Connection also facilitates movement between main channels and productive wetland areas for generalist species. When the floodplain is inundated, ephemeral wetlands can be highly productive sites as terrestrial resources such as carbon and nutrients are mobilised. If these sites are connected with others before they dry, this productivity (as nutrients, zooplankton or locally spawned fish) can be returned to the broader wetland system. For permanent wetlands, sufficient connection (surface or subsurface) is also needed to maintain surface water permanently for wetland specialist species, although some fluctuation in water level can increase basal productivity and promote fringing aquatic vegetation growth.

There are several wetlands at Millewa Forest that have water permanence, with likely hyporheic (groundwater) connection and some with surface connection to main channels via ephemeral creeks (Sharpe 2014; Whiterod and Gannon 2020; Sharpe 2018). For wetlands maintained by subsurface flows, it is unclear how much water levels fluctuate in concert with flows in adjacent and connected main channels. For wetlands that are dependent on surface water connection, inundation is limited to higher flows and floods. Larger overbank floods also inundate ephemeral floodplain wetlands, although it is unclear how often this occurs and how long different wetlands hold water. However, the presence of submerged aquatic plants at some sites surveyed by Sharpe and Wilson (2012) indicates that inundation can occur for months. Regardless, it is clear that the floodplain is inundated less often than under natural conditions, partly owing to the regulated nature of the Murray River (Bren 2005) and downstream constraints limiting the amount of environmental water that can be delivered to Millewa Forest (Kahan et al. 2020).

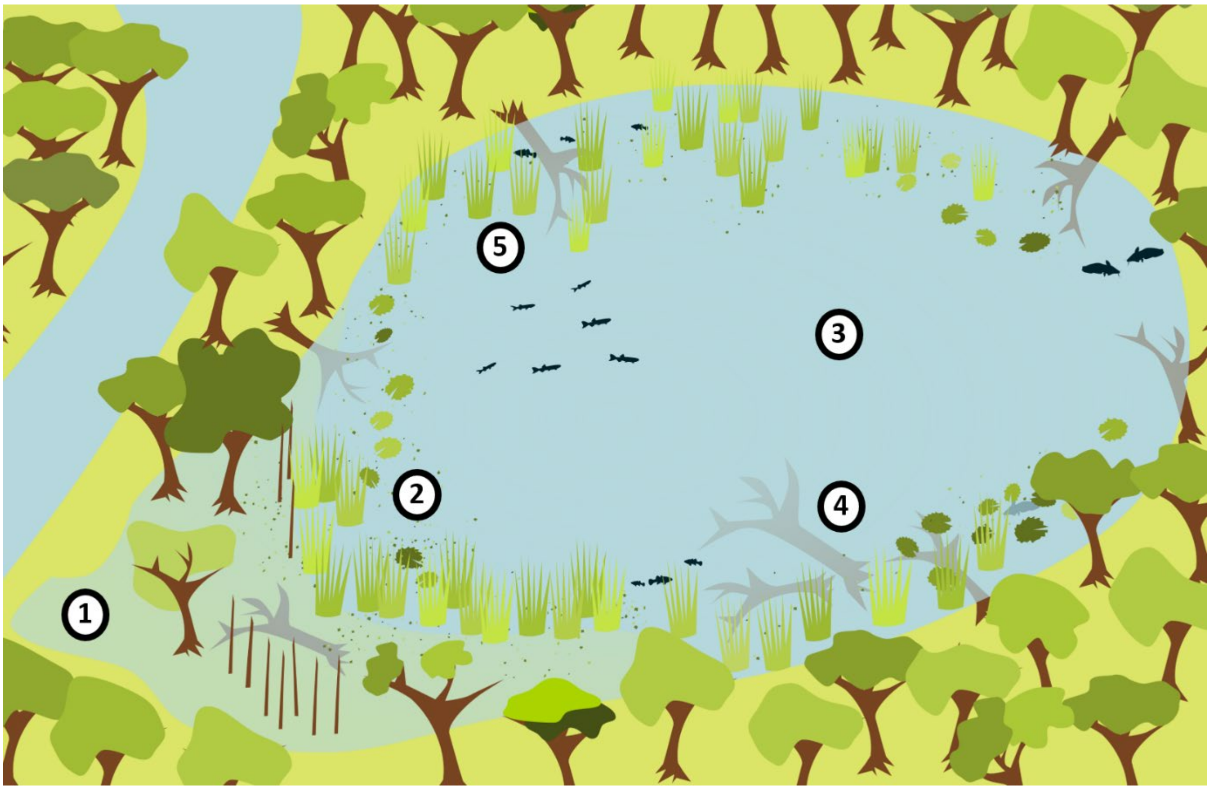

Figure 5 **A guiding image for wetlands in Millewa Forest, which is the vision for wetlands in the strategy**

Notes: Numbers relate to different habitat aspects of a wetland, which are described in more detail in the text below. 1: Occasional hydrological connectivity with main channels to facilitate fish movement and periodic inundation of terrestrial habitats for productivity (and water level variation); 2: Dense emergent, submerged and fringing vegetation support various aspects of fishes' life history, providing shelter, shade and basal productivity; 3: Water quality parameters within the tolerance ranges of native fishes; 4: Woody structure of various sizes to provide shelter and nest sites; 5: Few to no invasive fish and a diverse community of native fishes, including small-bodied wetland specialists and generalists.

Vegetation

Vegetation can provide a range of benefits for wetland-dependent fishes. It provides shelter and spawning sites and may be an important source of autochthonous carbon for basal productivity, particularly if there are limited external inputs. There is evidence that many wetlands in south-east Australia have undergone a change from macrophyte dominated to phytoplankton dominated since European arrival (Gell and Reid 2014), suggesting that current levels of vegetation are lower than historically. During flooding, dense terrestrial vegetation on the floodplain can support booms in primary productivity (Junk et al. 1989).

Figure 6 A permanent lagoon with dense fringing emergent and submerged aquatic vegetation (left) and a smaller ephemeral wetland in Millewa Forest with aquatic vegetation present (from Sharpe and Wilson 2012)

Emergent vegetation at permanent wetlands in Millewa Forest is present in moderate to high densities, typically as a fringing ring around the edge of wetlands consisting of *Typha* spp., *Juncus* spp. and common reed (*Phragmites australis*). Critically, submerged aquatic vegetation is either absent from most of the wetlands surveyed or present in only very low densities (Whiterod and Gannon 2020). Vegetation coverage at larger wetlands is variable, with Whiterod and Gannon (2020) recording 0–20% coverage at Moira Lake and 60% at Reed Beds Swamp South. Small, ephemeral forest wetlands appear to have varying levels of vegetation cover. Sharpe and Wilson (2012) found some sites with dense cover of *Triglochin* spp. and *Myriophyllum* spp., for example, while others had no aquatic vegetation at all.

As these sites are situated in the forest, there is dense terrestrial vegetation surrounding many of the wetlands for which there is survey data (Whiterod and Gannon 2020).

Water quality

Wetland water quality parameters can vary widely, particularly as the wetlands contract to small pools during summer. The tolerances of wetland fishes to poor water quality varies, although most are adapted to poor water quality and are generally resilient (Zukowski et al. 2021). Dissolved oxygen concentration is one of the key drivers to the survival of native fish. Laboratory studies have shown that Australian smelt can tolerate dissolved oxygen concentrations down to 1.4 mg O_2/L, Murray galaxias 1 mg O_2/L, while southern pygmy perch and carp gudgeon species are tolerant of concentrations down to 0.59 mg O_2/L and 0.5 mg O_2/L, respectively. Many wetland species can tolerate a wide range of temperatures (John D Koehn et al. 2020), and carp gudgeon species and southern pygmy perch have been found to be tolerant of high levels of leachate (Mcmaster and Bond 2008), which can be toxic to some species.

Point measurements in Millewa Forest wetlands revealed water quality conditions with low salinity (46–111 microsiemens per centimetre [µS/cm]), relatively clear water, good levels of dissolved oxygen (6–92 mg O_2/L) and cool temperatures (Whiterod and Gannon 2020). It should be noted that point measurements have somewhat limited utility as water quality can fluctuate widely through the seasons.

Blackwater events occur with some regularity through the middle and lower Murray–Darling Basin, with recent hypoxic events at Millewa in 2010–11 and 2016 (NSW Department of Planning 2020). Although there are clear impacts on the fish populations in some areas (King et al. 2012), particularly in the Edward–Wakool system in 2010–11 ((Thiem et al. 2017), the impact and extent of these events in Millewa Forest is still somewhat unclear, especially on the floodplain. Despite this uncertainty, it is highly likely that sites on the floodplain of Millewa Forest are at risk of blackwater during extended flooding and large-scale inundation. Impact will depend on flooding duration and extent and local conditions, but the area of floodplain that can be inundated (Figure 7, from Keogh 2012) makes these impacts potentially severe. In contrast, many of the smaller permanent wetlands may be lower risk. Models predict that they will not be inundated even during very large flows (Figure 7), and they are thus less likely to be impacted in small to moderate blackwater events and may have a shorter water residence time.

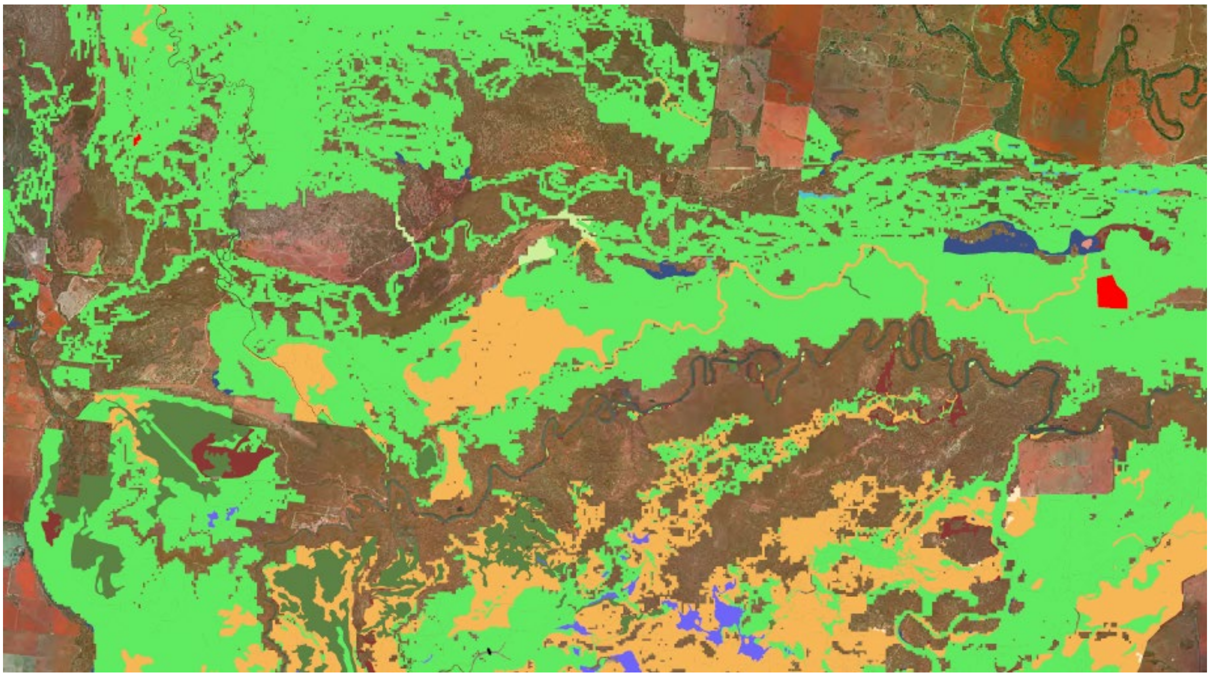

Figure 7 Modelled extent of inundation across Barmah–Millewa Forest at 65,000 ML/day downstream of Yarrawonga (Keogh 2012)

Notes: The Murray River runs through the middle of the map, with little floodplain inundation on either side. Many of the small permanent wetlands prioritised in this strategy occur in this area. Different colours represent different vegetation communities that are inundated, and no colours (i.e. where Landsat background is visible) indicate areas where inundation is not predicted.

Woody debris - snags

The amount of naturally occurring snags in a wetland varies (Figure 8), depending on location, rate of decomposition and rates of input. However, higher amounts are beneficial; snags can provide shelter and spawning surfaces for egg-laying species, and support productivity processes by providing surfaces for periphyton growth and invertebrates upon which many small-bodied species feed (Crook and Robertson 1999).

Figure 8 Two forest wetlands demonstrating varying densities of woody debris cover

Current levels of snag loadings at wetlands in Millewa Forest range from relatively low densities to high densities, generally with a coverage of 5–20% (Whiterod and Gannon 2020). At larger floodplain wetlands such as Moira Lake and Reed Beds Swamp, survey results indicate low cover of 0–5% (Whiterod and Gannon 2020). Ephemeral forest wetlands surveyed by Sharpe and Wilson (2012) had moderate cover of snags, usually around 10–30%.

Productivity

Wetlands can be highly productive, particularly when previously dry areas are inundated and nutrients from terrestrial production are released (Junk et al. 1989; Kobayashi et al. 2013). Ephemeral semi-aquatic plants can quickly colonise the exposed littoral zone and, when inundated, decay and mobilise terrestrial nutrients (Figure 9). This mobilisation of nutrients can be rapid, reflected by increased growth of bacteria and phytoplankton within days (Kobayashi et al. 2009), quickly increasing the growth of other planktonic organisms (Kobayashi et al. 2015). This burst of productivity following flooding is often reflected in the stomach contents of fishes that readily feed on terrestrially derived resources when they become available (Balcombe et al. 2015, 2005). In more permanent water bodies with less water level fluctuation, local decomposition of algae and aquatic macrophytes can be the main source of nutrients (Varner et al. 2018; Bertilsson and Jones 2003).

Zooplankton is an important food source for many fish species, either for younger life history stages (e.g. larvae) for larger-bodied species, or throughout the life cycle for small-bodied planktivorous fish such as southern pygmy perch, Australian smelt and Murray hardyhead. In consideration of this, Sharpe (2018) examined zooplankton densities at Millewa Forest wetlands, applying a surrogate minimum density (number of animals per litre) required to support such species. At most wetland sites zooplankton density was lower than required (~500/L), possibly indicating low levels of productivity at sites sampled (Sharpe 2018).

Figure 9 Two states of a larger permanent wetland on the Murray River. Left illustrates a drawn-down state, where the regulator was closed and terrestrial plants were quick to grow in the exposed littoral mud. Right is the wetland after the regulator was opened and the plants were inundated, quickly decaying and mobilising the terrestrial production.

Invasive fish species

While invasive species are not strictly part of the habitat, they are an important consideration when selecting wetlands for rehabilitation as they can feasibly be excluded from isolated wetlands; ideally, they would be absent or present only in low numbers. Carp are estimated to have impacts in wetlands and lakes with biomass above 80–100 kg/ha (Brown and Gilligan 2014; Vilizzi et al. 2014), and can be excluded from entering wetlands and physical removal can keep numbers down (Pinto et al. 2005). However, carp screens are likely not a practical option in Millewa. Redfin perch are voracious predators with severe impacts on small-bodied, wetland specialist species (Lintermans 2007), and physical removal can reduce their impacts (Closs et al. 2001).

Entirely excluding species such as gambusia or oriental weatherloach is not practical. Gambusia are a small, highly invasive fish that impact small native species through aggressive fin nipping and competition for food (MacDonald et al. 2012). The impact of oriental weatherloach is understudied in south-east Australia, but it likely competes for food and consumes eggs of native species (Keller and Lake 2007). Both gambusia and weatherloach are ubiquitous, and due to their small size, exclusion via screens is not practical, and complete elimination from wetlands is very difficult.

All wetlands recently surveyed in Millewa Forest have had invasive species detected, sometimes in high densities (Sharpe and Wilson 2012; Sharpe 2014). These numbers may fluctuate, and the exact level of impact that invasive fishes are having at these sites is still somewhat unclear. Promisingly, neither Nine Panel Lagoon (large) nor Nine Panel Lagoon (small) have had carp or redfin detected in recent surveys.

General observations of wetlands in Millewa Forest

- There are many large wetland sites with good water permanence and limited connectivity with main channels, providing opportunities for rehabilitation.
- Some sites with dense emergent vegetation exist.
- There is little to no submerged aquatic vegetation at any sites.
- Water quality is within the range required for wetland species.
- There are varying densities of submerged woody habitat.
- Productivity is low.
- Invasive species are present, but at low numbers at some sites.
- Blackwater events will impact forest wetlands, but the extent of this impact is unclear.

Table 3 Habitat conditions at permanent wetlands in Millewa Forest

Notes: Habitat elements are graded on a scale from 0 to 5, with 0 = absent and 5 = very high density. Water quality measurements are scored as within the tolerance range of wetlands fishes or not. Invasive fish species: C = carp, EG = eastern gambusia, WL = oriental weatherloach, RF = redfin perch, GF = goldfish. A dash indicates that empirical data could not be found in the literature.
Sources: 1 = Sharpe 2014; 2 = Whiterod and Gannon 2020; 3 = Sharpe 2018.

Location	Hydrology	Submerged vegetation	Emergent vegetation	Water quality within the tolerance ranges of native species?	Complex woody habitat	Productivity (no. zooplankton per litre)	Invasive fish
Nine Panel (large)[1,2,3]	Permanent water likely maintained by subsurface flow, no direct connection	0	3	Yes	3	757.87	EG
Nine Panel (small)[1,3]	Permanent water likely maintained by subsurface flow, no direct connection	0	4	Yes	2	177.33	EG, WL
Burial Lagoon[1,2,3]	Permanent water maintained by overland flow, possibly by subsurface flow	1	3	Yes	3	323.24	C, GF, EG, WL
Fishermans Bend Lagoon[1,2,3]	Permanent water likely maintained by subsurface flow, no direct connection	0	3	Yes	3	339.18	C, RF, EG, WL
Horseshoe Lagoon[1]	Regulator present; will dry if disconnected	0	4	-	3	-	C, RF, GF

Location	Hydrology	Submerged vegetation	Emergent vegetation	Water quality within the tolerance ranges of native species?	Complex woody habitat	Productivity (no. zooplankton per litre)	Invasive fish
Pinchgut Lagoon[2,3]	Fed by regulator on Pinchgut Creek and possibly subsurface flow	0	2	Yes	3	103.56	C, RF, GF, WL, RF
Reed Beds South[2,3]	Larger shallow floodplain, inundated by overbank flows from Gulpa Creek cutting	0	5	Yes	1	3.23	C, EG, WL
Moira Lake[3]	Large lake, inundated via regulated creek channels	-	-	-	-	175.44	C, EG, GF, WL

2.5 Threatening processes

In the previous sections we outlined key aspects of the ecology, habitat requirements and life history of the Millewa Forest fish species. We also outlined a guiding image of what kinds of channel and off-channel habitats would best support these processes and compared this information to the current state of these habitats in Millewa Forest. In this section, we use the knowledge of fishes' requirements and the differences between the ideal and current habitat state to identify impacts on fish. We also outline other threats associated with the decline of habitat quality and native fish species. Where there may not be direct empirical information on a threat's impact, we can infer impacts by identifying the environmental impacts of the threat and matching this to the requirements of a species. Clarifying impacts and threats enables an assessment and prioritisation of mitigation options and subsequent recovery potential, which forms the basis of this *Millewa fish recovery strategy*.

There are myriad threats to freshwater ecosystems. Broadly, these can be grouped into flow modification, habitat degradation, over-exploitation, water pollution and invasive species (Dudgeon et al. 2006). However, within these broad groups there are many types of threats. For example, Koehn et al. (2020) have identified 22 more specific threats relevant to the Murray–Darling Basin. Here, we use a modified subset of this list to explain threats to the fishes and habitats of Millewa Forest, including:

- barriers to movement
- alterations to flow
- loss and degradation of habitat
- invasive species
- blackwater events.

For practicability, we group some similar threats that have related impacts and management responses. We also omit some threats that are unlikely to be directly impacting Millewa Forest fishes, such as cold water pollution, loss to pumps, or those where management actions are outside the scope of this strategy, such as illegal harvest.

The impacts of climate change will affect the fishes of Millewa Forest, and indeed the whole Murray–Darling Basin (Chessman 2013). Modelling predicts hotter, drier scenarios in the southern Basin, with less overall rainfall, large reductions in winter rainfall and more intense droughts by 2030 (Zhang et al. 2020). While the exact impacts of climate change are difficult to predict at the scale of Millewa Forest, it is highly likely that the existing flow-related challenges will increase as flows are reduced and temperatures increase. This strategy can be revised and updated as the impacts of climate change emerge more clearly.

2.5.1 Barriers to movement

All fish species need to move to some degree for spawning, recruitment and dispersal. The scale and direction of a fish's movement varies depending on life stage and species. Therefore, the impacts of barriers to movement can also vary. There may be sub-lethal effects, such as slower growth rates, because fish cannot access productive floodplain areas; or more serious impacts, such as interrupted spawning migrations or death of larvae when they cannot reach nursery habitats. The spatial arrangement of barriers and the scale of movement will also influence whether barriers impact fish; fish with movements over small scales, wholly between 2 barriers, are less impacted than those whose movements are longer or in areas with many barriers. Barriers may interrupt movements within the main channel, or movement from main channels to off-channel areas, or movements among different off-channel areas.

Main channels

Longitudinal connectivity in the Murray River in the Millewa Forest reach is intact, with no major instream barriers immediately affecting fish movement. The regulators at the Edward and Gulpa offtakes on the Murray River both have fishways that effectively facilitate directional movement to and from the Murray River (Stuart et al. 2020).

There are still several barriers on channels in Millewa Forest that impede fish movement. The crossing on Wild Dog Creek may act as a barrier to fish movement, affecting movement between Edward River and Toupna and Cornalla creeks, but this is yet to be confirmed. Towards the downstream end of the system, Stevens Weir on Edward River may impact larger-scale connectivity within the Edward–Wakool system. The fishway on Edward River is designed to provide excellent upstream fish passage but has high operational requirements and may not always facilitate upstream passage. This may be particularly important for silver perch migrations, which are anecdotally reported to spawn between Stevens Weir and Deniliquin (Stuart et al. 2020). The weir and weir pool at Stevens Weir also likely impede downstream fish movement. A similar process may be occurring at Torrumbarry Weir, where the undershot gates likely kill high numbers of drifting eggs and larvae, particularly those of golden and silver perch. The large Torrumbarry Weir pool may also be impacting the survival and recruitment of eggs and larvae from these 2 species that spawn around Millewa, but this is yet to be demonstrated.

Forest channels

In general, there is limited capacity for fish to move between the main channels and forest creeks around Millewa Forest, except during overbank floods. A key example of this is the lack of connectivity between Toupna Creek, a large forest creek network, and the Murray River. The main connection between these 2 systems is at Mary Ada Regulator, which has no fishway and is known to impede movement of fishes moving in either direction. It is likely that the poor connectivity between main channels and forest creeks resulting from the Mary Ada Regulator has impacts for many species that would otherwise access these areas, but a key impact may be on juveniles of large-bodied species undertaking exploratory movements. For example, juvenile Murray cod and golden perch were unable to move into Toupna Creek from the Murray (Stuart et al. 2020), and trout cod have been observed accumulated below the regulator (Raymond et al. 2020), unable to move to the Murray River. Toupna Creek appears to be a major pathway for fish to enter and exit the forest (Stuart et al. 2020). In addition, many of the smaller secondary regulators that connect Toupna Creek and the Murray River (e.g. Pinch Gut, Nestrons and Nine Panel) likely prevent much fish movement. Similarly, the regulators on forest creeks around the Moira Lake system, such as at Swifts and Bunnydigger creeks, can prevent fish returning to the Murray River if closed too quickly without adequate flow signalling for fish to leave.

Off-channel habitats

More information is required to assess the barriers to fish movement at off-channel habitats. For smaller wetlands that have regulators, fish passage would be completely cut off when they are closed. Depending on the channel morphology, there may be a good degree of connection with channels when the regulators are open. At small wetlands, water levels within the wetland would quickly match those of the channel, providing fish passage. This kind of connection is likely to be used by small-bodied generalist species that move between wetlands and channels. Due to the more incised, steeper channel present at the larger Moira Creek Regulator, fish passage may still be impeded when regulators are open. At sites where there does not appear to be a direct connection with channels, such as Fishermans Bend and Nine Panel lagoons, connection may be more dependent on flow conditions (see Section 2.5.2 ‘Alterations to flow’ below).

Barriers to fish movement in Millewa Forest

- There is a good degree of movement within and between the 3 large main river channels facilitated by fishways.
- Many forest creek regulators lack fishways and impede bi-directional movement.
- There are limited connections with small permanent floodplain wetlands, influenced by flow conditions.
- 'Exploring' sub-adults of large-bodied species are likely to be heavily impacted by barriers.
- Large barriers on the Edward and Murray rivers downstream of Millewa Forest are likely to impact golden and silver perch around Millewa.
- More information is needed to assess fish passage from and to small permanent wetlands, important for small-bodied generalist fishes.

2.5.2 Alterations to flow

There are several elements of flow that will influence fish at different scales. Broadly, these are:

- discharge – the amount of water moving through a system
- hydraulics – the finer-scale movement of water
- hydrodynamic diversity – the diversity of cross-sectional flow in a system, with slower and faster flowing zones such as runs or pools (Mallen-Cooper and Zampatti 2018).

Across the Murray–Darling Basin, a heavily regulated basin, there are several flow-related threats to fishes (Koehn et al. 2020). Here, the flow-related threats to fish in the Millewa Forest region are discussed, outlining where they interact with habitat, hydrological and life history requirements of different fish species.

Altered flow variation

Seasonal and spatial variation in river flow support the life history processes of many large-bodied native species, with changes in river discharge and associated hydraulic conditions cuing movement and spawning. For example, Murray cod and trout cod recruitment and spawning can be best supported by a spring water level rise with no major drops, the presence of faster-flowing hydraulics and elevated winter base flows (Figure 10; Sharpe and Stuart 2016; Stuart et al. 2019; Tonkin et al. 2020). Silver and golden perch movement is also strongly influenced by increased discharge during the spawning season (Koster et al. 2020), and, given that local populations are often dependent on immigration, it is essential to support this life history process though delivery of appropriate changes in flow conditions.

While the main channels around Millewa Forest retain surface flow throughout the year, current flow seasonality and magnitude is significantly different from pre-regulation conditions (Figure 11). As a result, the flow conditions do not always suit large-bodied species. For example, in 2019, the Murray River and Gulpa Creek both exhibited sharp drops in water level during the spawning season (Figure 12), although Edward River generally exhibits more stable spring flows without sharp drops in flow, which are more suitable for Murray cod (Figure 13) (Stuart et al. 2020).

As discussed above, many of the forest creeks are highly regulated and fish are sometimes trapped behind barriers. The altered flow regime in these creeks may mean that ‘exploring’ fish lack the cues to exit before regulators are closed, for example at Swifts and Bunnydigger creeks. An altered hydrograph in these creeks, with a slower descending limb, may be sufficient to cue fish to leave.

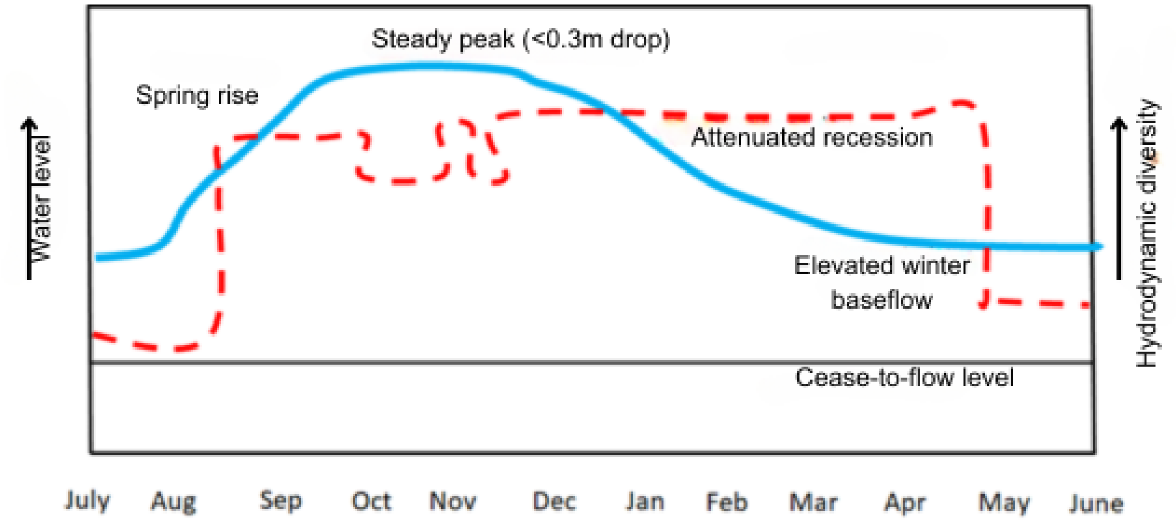

Figure 10 Conceptual hydrographs showing an ideal (solid blue line) and actual 2019 (dotted red line) flows for the Murray River and Gulpa Creek (from Stuart et al. 2020)

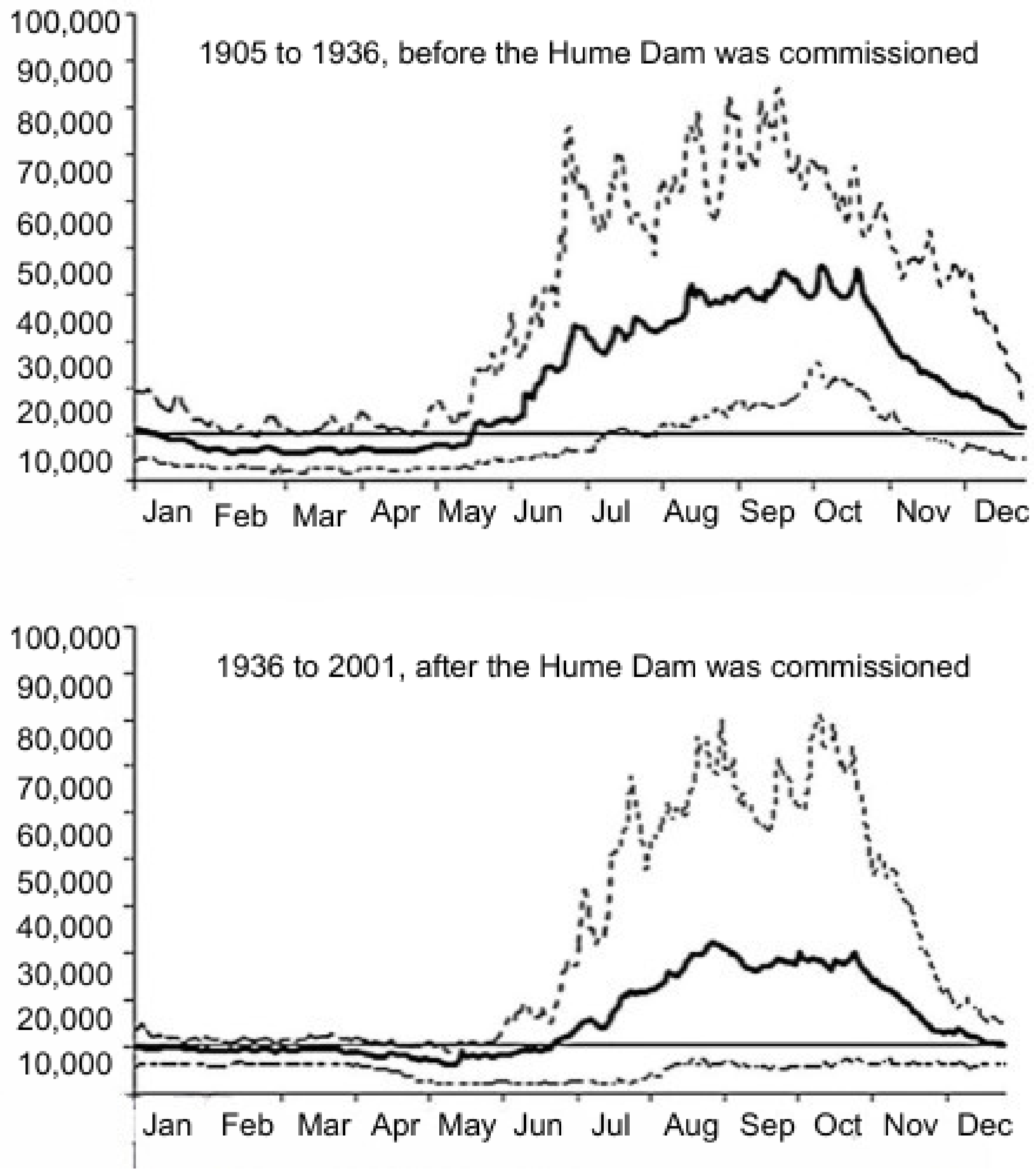

Figure 11 **Mean daily discharge (black line in ML/day) at Yarrawonga Weir before (between 1905 and 1936; top chart) and after (between 1936 and 2001; bottom chart) the commissioning of Hume Dam (from Vivian et al. 2014). Dotted lines represent the 10th and 90th percentiles**

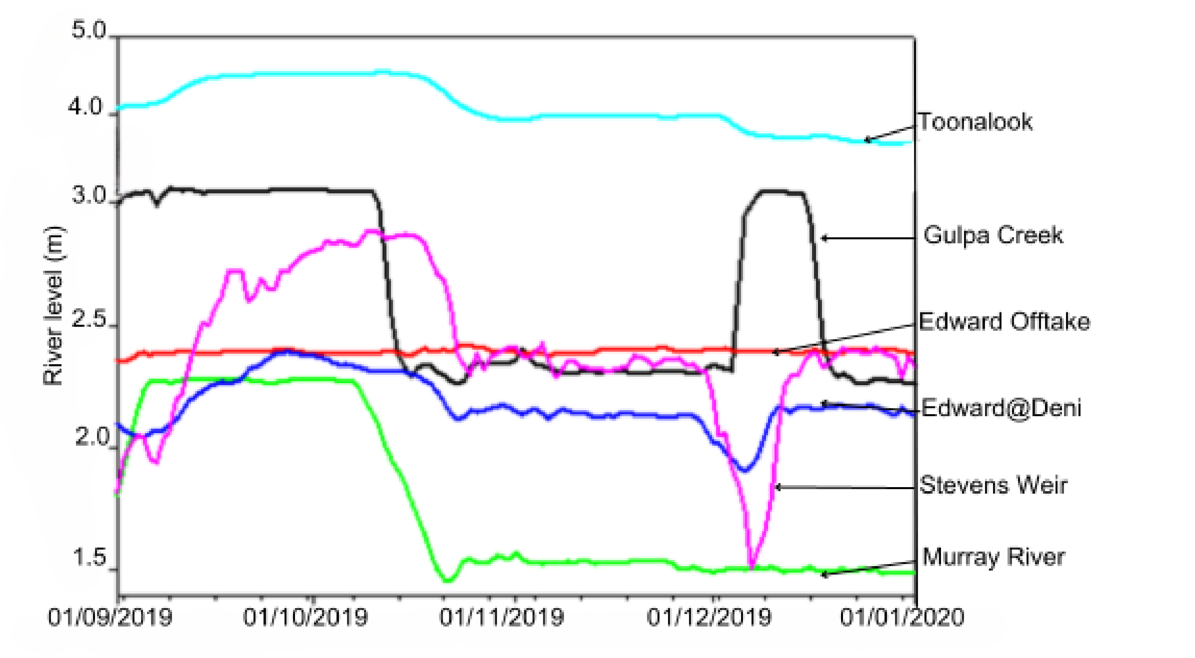

Figure 12 **Water level (m) from September 2019 to January 2020 at several gauge sites. This time period approximates the spawning season for Murray cod and trout cod (from Stuart et al. 2020)**

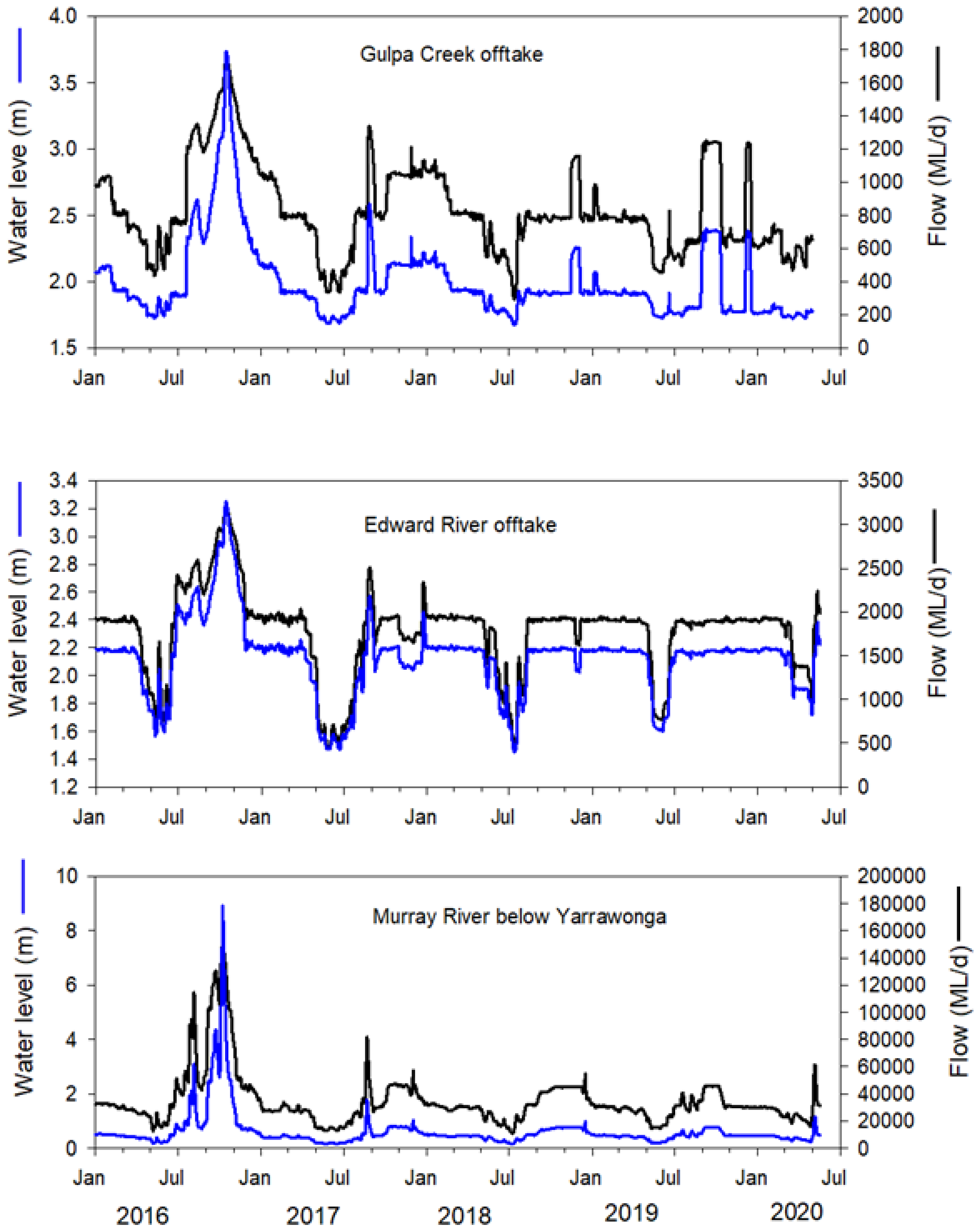

Figure 13 **Water level (m, black line) and flow discharge (ML/day, blue line) from January 2016 to May 2020 at (from top to bottom) Gulpa Creek Offtake, Edward River Offtake and the Murray River downstream of Yarrawonga (from Stuart et al. 2020)**

Reduced hydrodynamic diversity

The turbulence and micro-scale flow diversity around instream structure in deeper, faster water support channel specialist fishes' life history processes (Stuart et al. 2019), and these areas are often where species like trout cod, Murray cod and golden perch are commonly found (Koehn and Nicol 2014). Where these areas are lacking, there are concomitant impacts on large-bodied channel specialist fishes.

In general, there is good hydrodynamic diversity through much of the Murray and Edward rivers, and within the Barmah–Millewa reach of the Murray River, with long sections of flowing water. The presence of natural densities of instream woody structure through these areas makes it likely that there is a good degree of micro-scale flow diversity where these structures interact with the flow. In contrast, the middle and lower reaches of Gulpa Creek have long sections of slower, shallower water (Kitchingman et al. 2020), with less instream woody structure. This may be in part due to sedimentation in the lower reaches of Gulpa Creek, and may contribute to poor densities of large-bodied fishes in these areas (Raymond et al. 2020; Stuart et al. 2020).

Altered flooding

Regulation of the Murray River has altered its flow regime, particularly by reducing the magnitude of the average annual floods and increasing low-flow volumes (Maheshwari et al. 1995). Bren (2005) demonstrates this altered flow regime at Tocumwal, with implications for Millewa Forest (Figure 14). The figure shows that after the construction of Lake Hume, the magnitude and frequency of large floods in spring-winter have been reduced and small-scale summer flooding has increased (Bren 2005). As a result, wetlands close to the river have more water for longer periods and experience less draw down, while the broader floodplain is inundated less frequently, reducing the mosaic of ephemeral wetlands present, impacting connectivity between these sites, and disrupting productivity processes.

Constraints on flow delivery also mean that there are limits to the amount of environmental water that can be delivered to Millewa Forest to alleviate these issues. Currently, a maximum of 22,000 ML/day can be delivered through the stretch of the Murray River at Millewa Forest without large-scale flooding occurring, although this may be increased to up to 50,000 ML/day under the *Constraints management strategy* (Kahan et al. 2020).

Inundation of previously dry areas is often an important source of basal productivity, mobilising terrestrially derived nutrients and supporting high densities of zooplankton (Kobayashi et al. 2013). This process can occur when wetlands draw down, exposing sediments, and are then re-wet; or when large areas of terrestrial vegetation are inundated. The return of this water to channels can also support the survival of young native fish, and ephemeral floodplains can be readily exploited by small-bodied generalist fishes (Balcombe et al. 2015, 2005). Reduced overbank flooding in Millewa Forest is highly likely to have disrupted these important basal productivity processes. For small wetlands close to the Murray River, the combination of permanent water from elevated summer flows and limited large-scale overbank flooding may explain their limited primary productivity and hence poor zooplankton densities (Sharpe 2018). The fine-scale degree of wetting/drying is unclear for many wetlands in Millewa Forest, so it is unclear to what degree these processes are supported or not by current flow regimes (Sharpe 2018).

Many sites in Millewa Forest require overbank flows for hydrological connection, as they are either higher in the landscape than the rest of the floodplain, or lack a direct connecting channel (e.g. some small wetlands), and hence fish dispersal to and from these sites is likely to be severely limited.

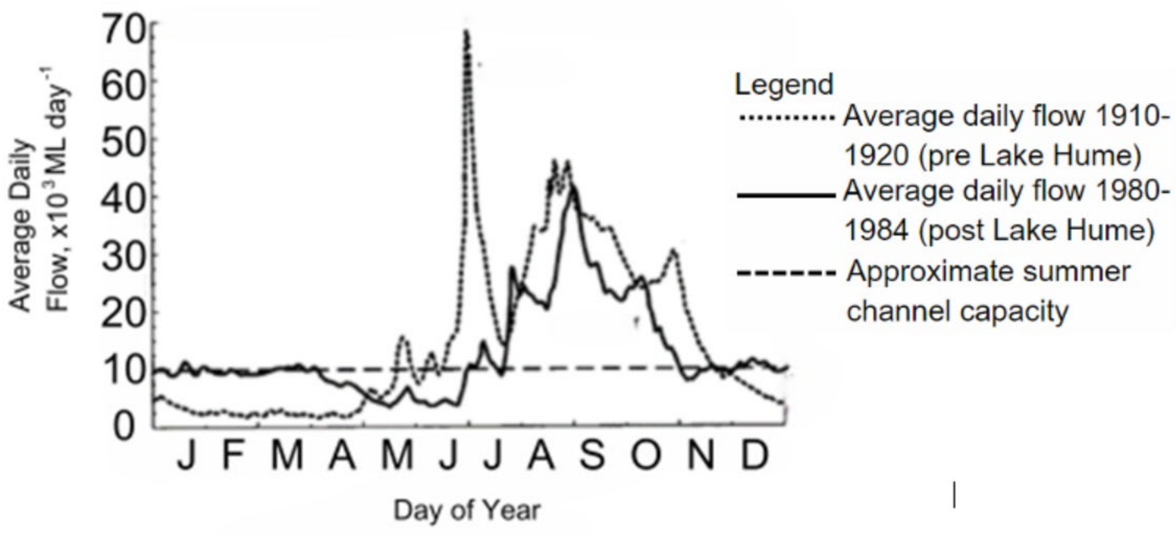

Figure 14 Average daily flow (x 10^3 ML/day) in the Murray River at Tocumwal for a pre-Lake Hume period (1910–1920) and a post-Lake Hume period (1980–1984). The approximate channel capacity of the Narrows (10,000 ML/day) is also shown (Bren 2005).

Loss of small forest wetlands

The small, permanent forest wetlands in Millewa Forest are important sites for the potential reintroduction of small-bodied specialist fishes (Sharpe 2014; Whiterod and Gannon 2020), providing essential habitat for these wetland specialist species throughout their entire life histories. It is highly likely that the loss of permanent water across the forest (and poor water quality at remaining sites) from the altered flow regime (Figure 14) led to the extirpation of wetland specialist species. Some of these permanent wetlands are regulated and watered through channels (Table 3), others are likely to only be inundated with overbank flooding in very high flows (Figure 7). At these sites, hyporheic flows are likely to support surface water permanence. Although they appear to remain full for much of the year, water permanence at these sites is uncertain, with some likely to have dried during the Millennium Drought while others likely retained surface water (e.g. Fishermans Bend and Nine Panel Bend; Sharpe 2014). More information about how these sites are connected with main channels is needed to fully assess the risk of these sites drying.

In addition to these permanent wetland sites, there are many other small ephemeral wetlands in the forest system (Sharpe and Wilson 2012) that likely hold water for shorter periods. Historically, these wetlands would have been periodically connected during overbank flows, allowing the metapopulation of small wetland specialist fishes to move between sites and allowing generalist fishes access to these productive wetland habitats. In drier periods they may have lost all surface water, but the interval between dry periods would have been long enough that fish would have contributed to metapopulation persistence. With current regulation of flow and reduced frequency of larger floodplain inundation, these sites would dry completely more frequently than under historical conditions. If this occurs before they are reconnected in another large flood, all fish would be lost, and these sites would not fully function as part of the floodplain metapopulation. More data are required to uncover the current wetting/drying cycles of these small ephemeral floodplain wetlands.

Loss of forest creek flowing habitats

The extensive forest creek network in Millewa Forest is heavily regulated, with physical barriers to movement, as discussed in the preceding section. In addition, the altered hydrology likely has impacts on the resident fish population; when disconnected, forest creeks cease to flow, contracting to a series of pools. These hydrological conditions are less suitable for large-bodied fishes, which will use flowing forest creeks (e.g. Murray cod); (Koehn 2009) or anabranch systems (e.g. trout cod); (Koehn and Harrington 2006), particularly as juveniles. In addition, as creeks draw down, complex physical habitat may also be exposed, reducing the amount of instream structure available for fish. Currently, large-bodied fishes are rarely caught in Toupna Creek and other creeks within Millewa Forest (Sharpe and Wilson 2012; Sharpe 2014, 2018; Whiterod and Gannon 2020), reflecting their largely lentic, disconnected hydrology.

Flow-related impacts on fish in Millewa Forest

- Inappropriate flows in the Murray River and Gulpa Creek may have impacted Murray cod and trout cod spawning and recruitment.
- Flow pulses to attract silver and golden perch to the Millewa Forest region are rarely delivered.
- Fish can be trapped in forest creeks as flow is rapidly cut and they are not cued to leave.
- The middle and lower reaches of Gulpa Creek lack hydraulic diversity.
- Fewer large flows in Millewa Forest may be disrupting fish dispersal and productivity processes.
- Reduced overbank flooding in the region may be impacting silver and golden perch recruitment.
- Water permanence at small permanent wetland habitats is uncertain.
- Regulation of flows to forest creeks results in these habitats becoming unsuitable for large-bodied fishes.

2.5.3 Loss and degradation of habitat

The current state of flowing channel and off-channel habitats in Millewa Forest is discussed in detail in the Section 2.4 ‘Habitats in Millewa Forest’. Here, we briefly highlight threats to aspects of these habitats and outline how they are likely impacting fish populations in Millewa Forest.

Woody debris

As many large-bodied channel fishes occupy and nest in areas with woody debris (Koehn and Nicol 2014), reduced wood densities will have impacts on abundance on these fish. Woody debris supports many fish species by creating eddies to provide velocity refuges for fish, as well as providing hard surfaces for periphyton and algae. Mapping by Kitchingman et al. (2020) revealed that Gulpa Creek had low densities of woody debris, with a low degree of connectivity between patches. In general, the Murray and Edward rivers had good woody debris density, although some areas had low connectivity between patches. Patchy distribution of woody debris will impact fish dispersal between these areas, which is likely to most heavily impact trout cod (Koehn and Nicol 2016). Forest creeks have good densities of woody debris, although this is variable (Sharpe and Wilson 2012). Anecdotal evidence suggests that snag density is low in the smaller creeks around Moira Lake, although more detailed surveys are needed to confirm this. Immediately downstream of Millewa Forest, instream woody structure density in the Murray River is considered to be depauperate due to historic de-snagging (Leslie 1995).

Vegetation

Many small-bodied fish species are strongly associated with aquatic vegetation, and it can also provide important nursery areas for larger fish species. Riparian vegetation provides shading and inputs of woody debris, and both aquatic and riparian vegetation provide carbon inputs which support basal productivity. In both the main channels and forest channels around Millewa Forest, there is very little fringing aquatic vegetation, meaning that these important nursery sites are lacking, and this life history process is not well supported. Riparian vegetation cover is patchy in some parts of the main channels, but coverage is relatively good in the forest channels.

A concerning characteristic of Millewa Forest's permanent wetlands is the effective absence of any submerged vegetation, although many sites have good coverage of fringing emergent vegetation. It is unclear if these 2 vegetation types provide different habitat niches for small-bodied wetland specialist fishes (Hutchison et al. 2020), but the lack of submerged vegetation warrants investigation. Many ephemeral wetlands in Millewa Forest appear to have good coverage of submerged aquatic vegetation when they are inundated (Sharpe and Wilson 2012).

Sediment and sedimentation

Massive channel changes, particularly during the gold mining era, are still playing out for the Murray River and its floodplain. Sedimentation of wetlands from accelerated bank collapse caused by high-running summer irrigation supply is ongoing and is the source of most sediment in the river, which has profound biological, chemical and physical consequences for habitats. The potential impacts of sedimentation are important considerations for fish recovery.

Sediment deposition can smother large woody debris and kill vegetation, impacting the availability of these elements in a system. There are reports that sedimentation has been occurring since the 1930s (King 2005), it is ongoing in the main channel of the Murray River (Paul Childs, pers. comm.), and there is a large sand slug at the downstream end of Gulpa Creek which may be impacting flow speeds through the middle reaches of the system. At Moira Lake there has been ongoing deposition, resulting in a loss of the deeper water areas (Sharpe 2018; Whiterod and Gannon 2020) that could have historically supported populations of golden and silver perch (King 2005)).

Figure 15 The bare banks of a small ephemeral floodplain wetland in Barmah Forest

Loss and degradation of habitat in Millewa Forest

- Gulpa Creek has a low density of woody habitat, with poor connectivity between patches.
- Murray River has poor connectivity between patches of woody debris in some areas.
- There is a low density of instream woody habitat in the Murray River below Millewa.
- There is poor density of aquatic vegetation in main channels and forest creeks.
- Many wetland sites lack submerged aquatic vegetation.
- Gulpa Creek has been impacted by sediment deposition.
- Sediment deposition is an ongoing concern in the Murray River and at Moira Lake.

2.5.4 Invasive species

The impacts from invasive fish are a key threat to the native fishes of Millewa Forest. The 5 most common species are carp, gambusia, redfin perch, goldfish and oriental weatherloach. These 5 species were also ranked as the most threatening across the Murray–Darling Basin (Clunie et al. 2002).

Carp are powerful invaders that can compete for food, damage submerged vegetation and increase turbidity (Koehn 2004). The large, shallow wetland areas around Barmah–Millewa Forest are suitable spawning areas and can produce large numbers of recruits (Stuart and Jones 2006). At Millewa Forest these sites likely include Moira Lake and Reed Beds Swamp, with large numbers of young carp sometimes caught entering The Cutting from Reed Beds. Carp have been recorded in many of the small permanent wetland sites (Sharpe 2018; Whiterod and Gannon 2020) but, encouragingly, they were absent in recent surveys at Nine Panel Lagoon (large and small).

Gambusia are ubiquitous, small-bodied fish that can occur in high numbers in wetlands (Raymond et al. 2020). They impact small-bodied native fish through competition for similar resources and by aggressive fin nipping, and have been shown to impact the body condition of small native fish and the overall assemblage structure of wetlands when they reach high densities (MacDonald et al. 2012).

Redfin perch are rare in Millewa Forest wetlands and in the main channels. However, they are aggressive piscivores, and can have severe impacts on small-bodied native fishes (e.g. Murray galaxias); (McNeil 2004). Their presence at small permanent wetlands is a clear impediment to the reintroduction of threatened wetland specialist fishes. They have been recorded at some of these wetlands, but not all (Table 3). They are also the main host for the epizootic haematopoietic necrosis virus, which can affect several native fishes (Lintermans 2007).

Oriental weatherloach and goldfish are present through Millewa Forest, though in lower numbers and their impacts are likely to be less severe than the 3 other common invasive species. Goldfish will have a similar type of impact to carp due to a similar feeding biology. The direct impacts of oriental weatherloach in the Murray–Darling Basin are understudied, although they are likely to include competition for food and predation on eggs (Keller and Lake 2007).

Hard-hooved mammals, such as pigs and deer, can severely degrade wetlands. Wallowing and defecation may severely impact water quality (Doupé et al. 2009), particularly of smaller sites. They can directly graze on fringing emergent and submerged vegetation or may destroy these habitats through trampling or foraging (Doupé et al. 2010).

Invasive species in Millewa Forest

- Carp are a pervasive threat in Millewa Forest and impact native fish, fish habitats and water quality.
- Gambusia are widespread and aggressive, impacting small-bodied native fishes.
- Redfin perch are a key predatory threat to small-bodied wetland specialist fishes that may be reintroduced.
- Hard-hooved mammals can severely impact wetland soil, plants and water quality.

Figure 16 The impact of pugging at a small ephemeral wetland in Barmah Forest. Note the very turbid water, even though no carp were caught at this wetland over several surveys

2.5.5 Blackwater events

Blackwater events occur with some regularity through the middle and lower Murray–Darling Basin, with recent hypoxic events at Millewa in 2010–11 and 2016 (NSW Department of Planning 2020). However, the extent and impact of these events is not yet fully understood. The Murray River around Millewa Forest has several distributaries (branches off the main stem that don't directly return) and is also downstream of a large impoundment. Hence, this section of the Murray is relatively resistant to the impact of blackwater events, with sites at Picnic Point and Barmah Choke identified as potential refugia during a low-flow event in 2010–11 (King et al. 2012). The degree and extent of impact a blackwater event has depends on the nature of the flood, but areas that receive water from the floodplain, and the floodplain itself, are likely to be impacted. Forest creeks and wetlands and Gulpa Creek and Edward River are likely to be severely impacted by blackwater events.

Blackwater in Millewa Forest

- The Murray River around Millewa Forest is somewhat resistant to the impacts of blackwater.
- Downstream of the Millewa Forest, when water returns to the river, there is evidence of severe impacts and fish deaths during blackwater events.
- It is likely that sites on the floodplain of the forest are heavily impacted during blackwater events.

2.5.6 Synthesis of threats

Clarifying impacts and threats allows us to assess and prioritise mitigation options and subsequent recovery potential of species and habitats. In Table 4, we provide a synthesis of the threats, sites and species likely affected at those sites. While not all locations within Millewa Forest are included in the table, the current list includes all major sites for which there is information available, and it is assumed that many other sites will have similar threats and impacts, and the information contained here is thus transferrable.

Information in the table is based on the information on threats in this section and the analysis of the current habitat state at Millewa Forest in the preceding section. The list of impacted species at each site is informed in 2 ways:

- from direct surveys and experiments in Millewa Forest, for example, the effect of forest creek regulators on large-bodied fishes (Stuart et al. 2020)
- by using knowledge about a species' life history, ecological and habitat requirements and assessing whether a threat would impact those requirements.

The latter source is especially useful for understudied or rare species, such as those small-bodied wetland specialists that are currently absent from the forest. It should also be acknowledged that many species may access a variety of these sites, but they are only considered if a site is likely to form a core part of their habitat.

Table 4 Summary of the threats affecting fish at sites in Millewa Forest

Notes: Cell colour relates to the severity of the threat impact at a site and is a function of the state of the threat at that site and the likely impact that it is having on fish. For example, vegetation in the Murray River is largely absent, yet the severity is rated as ‘moderate’ because this is likely to only be having a moderate impact on main channel fishes. Threat level: red = high, yellow = moderate, green = low. A blank cell means that a threat either does not occur at a site or has very little, if any, impact. Species impacted are noted in the cell, listed in order of descending level of threat impacts. While most threats will impact all species present at a site to some degree, only those that will have key life history processes or habitat requirement impacted are listed.
Species: MC = Murray cod, TC = trout cod, GP = golden perch, SP = silver perch, BH = bony herring, FC = freshwater catfish, RB = river blackfish, MP = Macquarie perch, SBG = small-bodied generalist species, SBS = small-bodied wetland specialist species.

	Barriers	Flow					Habitat degradation			Invasive species		Blackwater
Main channel sites		Altered flow variation	Reduced hydraulic diversity	Reduced flooding	Loss of flowing forest creeks	Loss of wetland surface water	Woody debris	Vegetation	Sedimentation	Fish	Mammals	
Murray River	SP, GP, MC (Moderate)	MC, TC, SP, GC (High)	MC, TC (Moderate)	SP, GP (Low)	-	-	MC, TC, RB, GP, SP, SBG (Moderate)	SP, GP, MC, TC, SBG, FC (Moderate)	MC, TC, RB, GP, SP, BH, FC (Moderate)	MC, TC, RB, MP, BH (Low)	SP, GP, MC, TC, SBG, FC (Low)	MC, TC, SP, GP, BH, FC, MP, RB, SBG (Moderate)
Edward River	SP, GP, MC (Moderate)	MC, TC, SP, GC (High)	MC, TC (Moderate)	SP, GP (Low)	-	-	MC, TC, RB, GP, SP, SBG (Moderate)	SP, GP, MC, TC, SBG, FC (Moderate)	MC, TC, RB, GP, SP, BH, FC (Low)	MC, TC, RB, MP, BH (Low)	SP, GP, MC, TC, SBG, FC (Low)	MC, TC, SP, GP, BH, FC, MP, RB, SBG (High)
Gulpa Creek	SP, GP, MC, TC (Low)	MC, TC, SP, GC (High)	MC, TC (High)	SP, GP (Low)	-	-	MC, TC, RB, GP, SP, SBG (High)	SP, GP, MC, TC, SBG, FC (Low)	MC, TC, RB, GP, SP, BH, FC (High)	MC, TC, RB, MP, BH (Low)	SP, GP, MC, TC, SBG, FC (Low)	MC, TC, SP, GP, BH, FC, MP, RB, SBG (High)

Main channel sites	Barriers	Flow: Altered flow variation	Flow: Reduced hydraulic diversity	Flow: Reduced flooding	Flow: Loss of flowing forest creeks	Flow: Loss of wetland surface water	Habitat degradation: Woody debris	Habitat degradation: Vegetation	Habitat degradation: Sedimentation	Invasive species: Fish	Invasive species: Mammals	Blackwater
Toupna Creek	MC, TC (High)	MC, TC (Moderate)	MC, TC, RB, MP (High)	SP, GP, SBS, SBG (Moderate)	MC, TC, RB, MP, FC, SBG, SBS (High)	-	MC, TC, RB, SBG (Low)	MC, TC, SBG, FC (Moderate)	MC, TC, RB, BH, FC, MP (Low)	MC, TC, SBG, FC, MP, RB (Moderate)	MC, TC, SBG, FC (Low)	MC, TC, BH, RB, MP, FC, SBG (High)
Swifts Creek	MC, TC (High)	MC, TC (Moderate)	MC, TC, RB, MP (High)	SP, GP, SBS, SBG (Moderate)	MC, TC, RB, MP, FC, SBG, SBS (High)	-	MC, TC, RB, SBG (Low)	MC, TC, SBG, FC (Moderate)	MC, TC, RB, BH, FC, MP (Low)	MC, TC, SBG, FC, MP, RB (Moderate)	MC, TC, SBG, FC (Low)	MC, TC, BH, RB, MP, FC, SBG (High)
Bunnydigger Creek	MC, TC (High)	MC, TC (Moderate)	MC, TC, RB, MP (High)	SP, GP, SBS, SBG (Moderate)	MC, TC, RB, MP, FC, SBG, SBS (High)	-	MC, TC, RB, SBG (Low)	MC, TC, SBG, FC (Moderate)	MC, TC, RB, BH, FC, MP (Low)	MC, TC, SBG, FC, MP, RB (Moderate)	MC, TC, SBG, FC (Low)	MC, TC, BH, RB, MP, FC, SBG (High)
Wild Dog Creek	MC, TC, GP, SP (Moderate)	MC, TC (Moderate)	MC, TC, RB, MP (Moderate)	SP, GP, SBS, SBG (Moderate)	MC, TC, RB, MP, FC, SBG, SBS (Low)	-	MC, TC, RB, SBG (Low)	SP, GP, MC, TC, SBG, FC (Moderate)	MC, TC, RB, BH, FC, MP (Low)	MC, TC, SBG, FC, MP, RB (Moderate)	SP, GP, MC, TC, SBG, FC (Low)	MC, TC, BH, RB, MP, FC, SBG (High)
Moira Lake	SP, GP, BH, SBG (High)	-	-	SP, GP, SBG, BH, SBS (High)	-	SP, GP, SBG, BH, SBS (Moderate)	BH, SBS, SBG (Moderate)	SP, GP, SBG, SBS (High)	SP, GP, BH, FC, SBG, SBS (High)	SP, GP, BH, FC, SBG, SBS (High)	SP, GP, SBG, SBS (Low)	SP, GP, BH, SBG, SBS (High)

	Barriers	Flow					Habitat degradation			Invasive species		Blackwater
Main channel sites		Altered flow variation	Reduced hydraulic diversity	Reduced flooding	Loss of flowing forest creeks	Loss of wetland surface water	Woody debris	Vegetation	Sedimentation	Fish	Mammals	
Reed Beds Swamp	-	-		SP, GP, SBG, BH, SBS (High)	-	SP, GP, SBG, BH, SBS (Moderate)	BH, SBS, SBG (Moderate)	SP, GP, SBG, SBS (Low)	-	SBG, SBS (High)	SP, GP, SBG, SBS (Low)	SP, GP, BH, SBG, SBS (High)
Fishermans Bend Lagoon	-	-		SBS, SBG, FC (High)	-	SBS, SBG (High)	SBG, SBS (Low)	SBS, FC, SBG (High)	-	SBS, SBG (High)	SBS, FC, SBG (Moderate)	SBS, FC, SBG (High)
Nine Panel Lagoon (large)	-	-		SBS, SBG, FC (High)	-	SBS, SBG (High)	SBG, SBS (Low)	SBS, FC, SBG (High)	-	SBS, SBG (High)	SBS, FC, SBG (Moderate)	SBS, FC, SBG (High)
Nine Panel Lagoon (small)	-	-		SBS, SBG, FC (High)	-	SBS, SBG (High)	SBG, SBS (Low)	SBS, FC, SBG (High)	-	SBS, SBG (High)	SBS, FC, SBG (Moderate)	SBS, FC, SBG (High)
Horseshoe Lagoon	SBS, SBG, FC (Moderate)	-		SBS, SBG, FC (Moderate)	-	SBS, SBG (High)	SBG, SBS (Low)	SBS, FC, SBG (High)	-	SBS, SBG (High)	SBS, FC, SBG (Moderate)	SBS, FC, SBG (High)
Burial Lagoon	-	-		SBS, SBG, FC (Moderate)	-	SBS, SBG (High)	SBG, SBS (Low)	SBS, FC, SBG (High)	-	SBS, SBG (High) (High)	SBS, FC, SBG (Moderate)	SBS, FC, SBG (High)
Pinchgut Lagoon	-	-		SBS, SBG, FC (High)	-	SBS, SBG (High)	SBG, SBS (Low)	SBS, FC, SBG (High)	-	SBS, SBG (High)	SBS, FC, SBG (Moderate)	SBS, FC, SBG (High)

	Barriers	Flow					Habitat degradation			Invasive species		Blackwater
Main channel sites		Altered flow variation	Reduced hydraulic diversity	Reduced flooding	Loss of flowing forest creeks	Loss of wetland surface water	Woody debris	Vegetation	Sedimentation	Fish	Mammals	
Ephemeral forest wetlands	-	-		SBS, SBG, FC (High)	-	SBS, SBG (High)	SBG, SBS (Low)	SBS, SBG (Moderate)	-	SBS, SBG (High)	SBS, SBG (Moderate)	SBS, SBG (High)

3. Structure and logic of the recovery strategy

3.1 Introduction

This section outlines a structure and underlying logic for the *Millewa fish recovery strategy*. It draws on the information presented in the preceding section about the life history and ecology of fishes, and the condition of and threats to the remnant habitats.

The strategy represents a risk/reward-based approach to choosing recovery actions that optimise the use of the current The Living Murray program rewatering regime, local geomorphologies, and the regulator network. Recovery will be sought in 2 potentially overlapping phases. The objectives of the first phase will be to build on the immediate ecological outcomes of the ongoing Living Murray rewatering and the controls and manipulations available via the existing regulator network. A second phase would involve planning for recovery actions that would become available when the current regulator construction and improvement program is complete.

3.2 Overall structure

The structure of the strategy follows a similar process to the flow chart for recovery actions outlined in the *Gunbower fish recovery plan* (Mallen-Cooper et al. 2014), with some modifications to define monitoring and adaptive management and to ensure the ‘no action’ base-case scenario is considered (Figure 17).

The first step is to summarise knowledge to generate a guiding model for recovery, identify threat impact, and determine likely recovery pathways for fish. This step has been completed in Section 2, where we presented conceptual models of fish ecology, and summarised and synthesised information on the condition of habitats and the threats to these habitats.

In this section we outline steps, and outline other key considerations, such as likelihood of achievement, the inter-dependencies of proposed actions and the spatial and temporal contexts that shape the recovery possibilities. Another aspect is developing and implementing a communication strategy and exploring possibilities for embedding collaboration and coordination with other agencies into the strategy. The scope of this strategy was to outline many of the key principles that underpin these steps and considerations, with the intention they will be refined through further consultation.

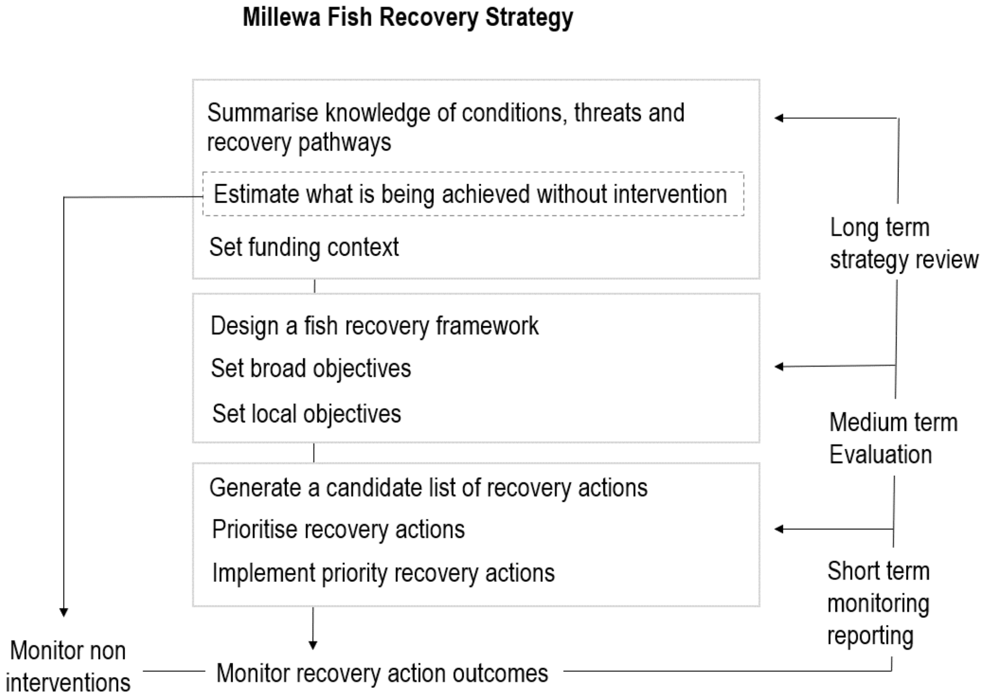

Figure 17 Key steps involved in the *Millewa fish recovery strategy* (modified from Mallen-Cooper et al. 2014)

3.3 Setting aims and objectives

It is critical to set clear objectives and aims to guide the strategy and its implementation plans.

The overarching **vision** for the strategy is to:

- build native fish populations and recover threatened and locally extinct species.

The **aims** of the strategy are to guide the type of recovery action to be developed and implemented to achieve this vision. The aims are:

- restore the ecological connectivity of rivers, forest creeks and wetlands
- guide the delivery of inter-annual environmental flow regimes to facilitate movement and migration pathways to native fish spawning and nursery grounds
- restore productivity and trophic processes, and wetland and riparian vegetation communities to support native fish populations
- guide recovery programs for locally extinct and threatened native fish species.
- reduce the impact of pests, weeds and other processes threatening native fish communities at Millewa Forest.

The **objectives** of the strategy define actions that are needed to meet the aims for target fish species. The objectives are to:

- restore annual recruitment and healthy demographics for Murray cod and trout cod populations
- provide regular spawning, recruitment and dispersal opportunities for golden perch, silver perch and bony herring populations, and facilitate population expansion

- increase abundance and distribution of existing small-bodied native fish species, including Murray rainbowfish, flat-headed gudgeon, un-specked hardyhead, Australian smelt and carp gudgeon species, among others
- reintroduce locally extinct native fish species, including southern purple-spotted gudgeon, river blackfish, freshwater catfish, Murray galaxias, olive perchlet and southern pygmy perch; and use these as source populations for further recovery.

The objectives will be achieved by establishing work packages for wetland, creek and river reach rehabilitation and recovery as part of the strategy's 3 implementation plans – one for each guild (off-channel, channel and generalists). When conditions are suitable, reintroductions would be undertaken for those species that are currently extinct from the region. Reintroductions would be piloted following the identification of those best and most easily improved habitats; those which can be protected into the future from stochastic events and unnatural changes.

3.4 A strategy to define actions and sites

The aims and objectives of the strategy provide a broad overview of what it is seeking to achieve. However, the implementation plans ultimately need to outline specific tasks and priority actions to meet these at the scale of individual locations/habitat types within Millewa Forest. To identify priority tasks and actions, it is important to consider a wide range of factors that relate to the following:

- Ecological responses, such as what is the relative population improvement likely to occur in response to different management actions?
- Logistical factors, such as what are the costs involved in the implementation and ongoing maintenance of different management actions?
- Social and cultural factors, such as what locations or target species might be most important to Traditional Owners or stakeholder groups such as landholders or recreational fishers?

In identifying and prioritising specific actions, the steering committee will incorporate and consider this range of factors, and how they might interact. A useful way of incorporating multiple criteria in a decision-making process is undertaking a multi-criteria analysis. Multi-criteria analyses are an established method of finding optimal solutions based on multiple, differing decision factors and incorporating decision-maker's perspectives and priorities (Mateo 2012). Such an analysis is well suited to environmental governance and management (Herman et al. 2007) and can consider eco-social perspectives (Mendoza and Prabhu 2005) as well as ecological and cost-based factors.

As a preliminary exercise, we undertook an evaluation and prioritisation of management actions to mitigate threats for fish in the Millewa region. An extract for the off-channel wetlands is presented in Table 5, with the full list of habitat types, their threats and potential mitigations is included in Appendix E. In the analysis we considered the following criteria:

- degree of certainty that actions (see column 1 in Table 5) can be successfully implemented
- likely ecological responses to the action in relation to magnitude (i.e. size of response), timeframe of response, and level of certainty of response
- time and costs involved in planning, implementation and maintenance.

It is important to understand that in complex and interjoined aquatic systems, different decision-makers could come up with different but still practical approaches to site and recovery action selection. As the implementation plans are developed, candidate projects (work packages) will be ranked. These ranks may change over time as new information and funding opportunities arise or the distribution and nature of threats changes. Ultimately the projects selected will need to fit local, regional and national circumstances and the budgets available. Stakeholder engagement will be maintained throughout the development and selection process.

We have provided our scores for the off-channel wetlands example (and in Appendix E, the ecological response components for all threats) based on the literature review and expert knowledge.

Incorporating stakeholder knowledge and priorities is an important step in the development and finalisation of the implementation plans. Tabled stakeholder priorities on actions, locations and species will be sought from NPWS staff, Traditional Owners and recreational fishers. This information can be updated into the 'live' Section 4, and recovery action and site prioritisation can be redone incorporating this wider information.

Table 5 Multi-criteria analysis to prioritise mitigation of threats identified for the permanent wetlands that are identified in the strategy

Notes: Full table of all sites is included in Appendix E. Scores are from 1 (red) (low priority: high cost, long implementation time and weaker ecological response) to 3 (green) (high priority: lower cost, shorter implementation, and stronger ecological response). The certainty an action will be successfully implemented refers to the success of implementation of an action, not whether it will successfully restore fish population. The magnitude of ecological response refers to a predicted increase in target fish populations, and the certainty of ecological response refers to the certainty of this prediction. Target species are: FC = freshwater catfish, SBG = small-bodied generalist species, SBS = small-bodied wetland specialist species.

Action	Detail	Target spp.	Certainty action will be successfully implemented	Ecological response to action			Planning		Implementation		Maintenance
				Magnitude	Timeframe	Certainty	Time	Cost	Time	Cost	Cost
Threatened fish translocations	Develop and implement threatened fish translocation plan	SBS, FC	Moderate	3	Moderate	High	2	3	2	2	2
Improve flooding regime	Investigate and implement flooding regime to maximise productivity and aquatic vegetation and facilitate dispersal of SBG/FC	SBS, SBG, FC	Low	2	Moderate	Moderate	3	2	2	2	2
Ensure surface water security	Investigate hydrology of wetland and develop drought management plan to maintain surface water	SBS, SBG	Moderate	3	Moderate	High	3	3	2	2	2
Restore aquatic vegetation	Investigate causes of degraded vegetation and implement solutions	SBS, SBG	Moderate	3	Moderate	Moderate	2	2	3	3	3
Invasive fish management	Undertake control measures, targeting elimination of carp and redfin	SBS, SBG	High	3	Immediate	High	3	3	3	2	2

Action	Detail	Target spp.	Certainty action will be successfully implemented	Ecological response to action			Planning		Implementation		Maintenance
				Magnitude	Timeframe	Certainty	Time	Cost	Time	Cost	Cost
Invasive mammal management	Investigate impact of hard-hooved mammals on littoral zone, undertake exclusion if necessary, explicitly include small wetlands in mammal management plans	SBS, SBG	High	1	Moderate	Moderate	3	3	2	2	2
Blackwater management	Develop blackwater management plan, investigating flows at which wetlands are likely to be impacted	SBS, SBG, FC	Moderate	1	Moderate	Moderate	2	3	2	2	2

3.5 Actions needed to meet objectives

As the strategy's implementation plans are delivered in the future, a list of priority actions will emerge from the multi-criteria analysis process. Once these have been identified, work packages within the relevant implementation plan would be developed. These will include methods, resources and scheduling the highest priority actions.

In the multi-criteria analysis, we identified what should be done to overcome a threat. How that is done may be quite involved; some actions may have multiple elements, for which the knowledge of and the relationships between may not yet be understood. For example, an action to 'restore appropriate flow variation' needs to consider typical hydrographs over several seasons and many species requirements and their biological responses. In contrast, the steps and methods required to undertake other actions may be simple and evident from the action itself. For example, re-snagging in the Murray River involves the placement of snags in the river at already known priority sites.

It is anticipated that recommended actions will include (but not be limited to):

- restoring aquatic vegetation communities and structural habitats such as snags
- restoring critical elements of flow regimes
- restoring connectivity among obligate habitats such as breeding and nursery areas
- promoting productivity processes and invertebrate communities
- minimising hypoxic blackwater disturbances and reducing the impacts of invasive pests and weeds, including invasive fish and hard-hooved introduced herbivores.

3.6 Final selection of target species, recovery actions and project sites

The site-specific nature of the multi-criteria analysis enables candidate sites to be matched to candidate actions and then prioritised. Ultimately, it may be beneficial to include a mix of actions and sites, from those that are likely to achieve more immediate results for a smaller number of species, through to longer-term actions that may be more expensive or have less certainty but have the potential to achieve larger ecological outcomes. The delivery teams will need to decide on this prioritisation, drawing on expertise should that be required.

NPWS proposes a policy that every species in Millewa Forest targeted by this strategy should ultimately have at least one recovery action designed and implemented for it, despite any noted difficulties in achieving recovery. This policy will be an important consideration in balancing what actions are undertaken, where, and for which target species.

It is also important to consider any other current external or departmental conservation programs, where they overlap with the strategy, or where there are gaps that the current strategy can fill. Some of the larger projects with intervention sites in Millewa Forest, such as The Living Murray, the Sustainable Diversion Limits and the Reconnecting River Country programs will benefit many of the fish identified in this strategy, particularly large-bodied fish. In addition, large-bodied fish spawning and recruitment has many reach-scale considerations that require collaboration and management actions outside of the forest scale. For example, an area that is not covered by existing programs is the targeted restoration of wetlands for the reintroduction of threatened wetland specialist fishes. Hence, supporting these actions is a high priority for this strategy.

3.7 Approach to monitoring

Monitoring must be a critical component of the strategy, its implementation plans, work packages and recovery actions. This is to evaluate biological responses and demonstrate that the investments have led to desirable outcomes. Effective monitoring programs have several key characteristics (Lindenmayer and Likens 2010):

- good and evolving questions
- use of conceptual models
- well-developed partnerships, ideally between people with different but complementary skills
- strong and dedicated leadership
- ongoing funding
- frequent use of data
- scientific productivity
- maintenance of data integrity and calibration of field techniques.

In comparison, monitoring programs that fail generally have some of the following characteristics (Lindenmayer and Likens 2010):

- poorly thought out and undefined questions
- poor experimental design
- monitor too many things poorly instead of fewer things well
- failure to agree on what entities to monitor
- scientific disengagement from monitoring programs
- poor data management, or loss of integrity of long-term data record
- lack of funding
- loss of key personnel.

It is important that monitoring for the *Millewa fish recovery strategy* is designed to meet the upper (and avoid the lower list) of dot points. Monitoring should be tied to the expected timing of the ecological responses and be undertaken for the time required to achieve statistical certainty. For example, it might be possible to quantify short-term movement of fish in response to environmental flows, but a longer-term perspective will be needed to determine if recruitment events in response to environmental flows, reintroductions or pest management ultimately lead to increased population sizes and persistence.

Ideally, recovery actions will be planned at sites that already receive monitoring under The Living Murray program, but depending on site geography, additional monitoring under that program may need to be sought.

3.8 Adaptive management

While monitoring is important to evaluate responses, it will ideally support an adaptive management process. Adaptive management, or ‘learning by doing’ is critical, and will allow the *Millewa fish recovery strategy* to evolve through time as:

- greater knowledge is gathered about which management actions have succeeded or failed and why – such information can help to improve outcomes from future efforts because even properly monitored unsuccessful projects can still provide useful information
- knowledge gaps are identified and addressed.

Adaptive management is an iterative process (Figure 17) whereby monitoring and research outputs are used to evaluate and refine the conceptual inputs collected at the start of the project, potentially leading to changes in how different objectives and recovery actions are prioritised, implemented and assessed through time. Additional steps include:

- updating conceptual models
- identifying knowledge gaps and using these to guide investments in targeted research/monitoring.

Adaptation requirements will be part of the fish recovery program's design. Actions and techniques need to be undertaken for long enough and across a large enough area to confirm any observations that suggest the strategy and/or its delivery program need adjustment.

3.8.1 Collaboration and coordination

Projects conducted under the broad umbrella of the strategy will present a range of opportunities for collaboration and coordination with other agencies, including universities and research institutions. These research opportunities could be linked to knowledge gaps and monitoring objectives and provide information to inform the assessment of recovery actions and to guide refining management as the strategy progresses. The expansion of this strategy to include Barmah Forest, in collaboration with the Goulburn Broken Catchment Management Authority, would be beneficial. Acknowledging that the 2 sides of the river are inextricably linked is important as management actions have a greater chance of success if they can be coordinated across the whole of the Barmah–Millewa Forest.

It is critical that the strategy links with other work being undertaken under other strategies and plans, such as native fish recovery strategies, national recovery plans for focal species, and basin-wide environmental watering strategies. For example, the Tri-state Murray NRM Alliance is working on fish recovery in the Mid Murray and could serve as a forum for communication and collaboration.

3.8.2 Communication strategy

A communications strategy is important to ensure (Mallen-Cooper et al. 2014):

- stakeholders are engaged
- funding agencies are kept informed of process
- project support grows
- findings are disseminated to ensure wider uptake
- project profile is maintained to attract future funding and good staff
- institutions are attracted to cooperative projects.

Establishing a communications and engagement strategy is outside the scope of this strategy but would involve:

- Identifying stakeholders and funding sources, including creating strategic links. Stakeholders would include community groups, Traditional Owners, shires, recreational fishing groups, catchment management authorities, bulk water deliverers, Murray–Darling Basin Authority, government departments, research institutions and universities.
- Serious and meaningful engagement with Traditional Owners to garner support for the strategy, incorporate traditional Aboriginal knowledge as appropriate, foster opportunities for Aboriginal groups to be involved in project delivery where suitable, and to respect/strengthen cultural connections and practices. This engagement would also ensure that Traditional Owner aspirations for native fish recovery in the Millewa Forest

are an important component of the project, and more specifically that cultural significance (i.e., outputs and knowledge from the Millewa Forest Aboriginal Waterway Assessment) is considered as part of the assessment and prioritisation of prospective sites for management actions.

- Conference presentations to communicate the findings of the work to relevant professional networks, including those with a scientific focus (e.g., Australian Society for Fish Biology, Australian Freshwater Sciences Society) and management focus (e.g., Australian Stream Management Conference, River Symposium).

3.8.3 Program evaluation and review

The strategy has a 20-year implementation horizon and will require a range of actions to meet its broad vision and specific objectives. Given this long timeframe and broad scope, it is critical that the strategy is periodically evaluated to review the objectives and progress towards these, and to adjust both objectives and approaches where necessary. We would recommend that this evaluation and review has 3 components:

- A **technical working group** with responsibility for designing, undertaking and assessing management interventions. This group would consist of relevant subject matter experts (especially fish and wetland ecologists), NPWS staff and potentially representatives from any other organisations involved in on-ground delivery. This group would meet (virtually or in-person) as needed, but probably quite frequently during the early stages.
- A broader **project steering committee**, including representatives from the technical working group plus Traditional Owners and other stakeholders. This group may meet less frequently (perhaps annually).
- An **expert review panel**, consisting of independent scientists. This group would review the project periodically throughout the project (perhaps triennially).

4. Implementation plans

4.1 Introduction

The strategy's final implementation plans will consist of work packages, each with detailed actions (and costings) for the steps required to recover and retain fish in Millewa Forest at individual sites or groups of sites.

In this section, we provide draft implementation plans, and identify relevant recovery actions for inclusion from the multi-criteria analysis for each fish guild: off-channel specialists, channel specialists and generalist fishes.

These draft plans are the result of a review of historic data and projects. Additionally, the development of the off-channel specialist plan (Section 4.2) involved a site visit and a workshop involving experts. It is anticipated that the work packages in the final implementation plans will be informed by a unique but similar processes.

The draft implementation plans also identify conceptual knowledge gaps and gaps in information, where more detail may be needed to undertake management actions. The defined information gaps and lists of required actions will guide NPWS, funding bodies and delivery partners in deciding which projects to seek grants for and deliver, and in what order. A project prospectus will be developed by the department in 2023 to support such application processes.

The list of candidate actions forming a work package is based on knowledge and informed opinion at the time of publication. A 3-year review cycle is proposed for the plan, so that new research, action outcomes and other emerging information can be used to update departmental priorities, program design and the program prospectus.

The level of detail and structure of each implementation plan will vary based on the state of knowledge for each set of actions, the complexity of the situation and the amount of effort that NPWS and other agencies may have already put into implementing the actions. For example, wetland rehabilitation for off-channel specialist species is a high priority, is likely to involve a complicated set of actions, and has not been the focus of much previous work. Therefore, more detail is provided for this work package than for instream habitat rehabilitation for channel specialist species, which is more straightforward and for which improvement actions have been delivered (e.g. pulse provision and re-snagging) and monitored in some areas of the Murray River.

The potential difficulty or expense of an action is considered from a first principles perspective for prioritisation in this strategy (i.e. see rankings in Table 6 in relation to planning, implementation and maintenance and different actions). A work package is required to properly cost different candidate options as well as detail the required steps.

To guide the development of the implementation plans and their work packages, a case study for a high priority wetland has been included in Section 4.2.5. This example work package, for Nine Panel Lagoon (large), was developed based on a technical workshop held in May 2022 and provides a detailed, site-based action plan to restore a single wetland. Following on from this, additional implementation plans for wetland specialists will be developed in 2023 consisting of other work packages, which, in association with the program prospectus, can be used to develop project proposals and funding bids.

4.2 Draft Implementation plan 1 – Off-channel specialist fishes

A key goal of the strategy is to reintroduce locally extinct species including southern purple-spotted gudgeon, Murray galaxias and southern pygmy perch, and use these as source populations for further recovery. The ultimate vision for these species is to create connected Millewa-wide populations, with fishes dispersing between permanent and ephemeral sites, fishes occurring in flowing and wetland habitats and accessing the floodplain during floods. Resilience during drought is also key, and it is essential that these fishes have access to sufficient refuge habitat during such times. To achieve this vision, the short-term goal is to create several self-sustaining populations in small, isolated, permanent wetlands that are resilient to drought and other disturbances.

Given these species' limited dispersal capacity/distribution and current scarcity in the Mid Murray region, it will be necessary to improve existing habitat conditions and then reintroduce target species via restocking to support this goal. There are 6 candidate wetlands earmarked for initial reintroductions, based on data from initial surveys by Sharpe (2014, 2018) and Whiterod and Gannon (2020), and discussion with the project steering committee. These candidate sites are:

- Nine Panel (large)
- Nine Panel (small)
- Burial Lagoon
- Fishermans Bend Lagoon
- Horseshoe Lagoon
- Pinchgut Lagoon.

These sites are considered suitable because initial observations suggest they have relatively permanent water, threats have been or can be reduced, and their smaller size makes it practicable to apply targeted management interventions.

The 2 other off-channel wetlands that were identified as high priority locations for the reintroduction of small-bodied wetland specialist fish (see Table 3) – Moira Lake and Reed Beds Swamp – are larger with more complex mechanisms for water delivery. As such, they were included in the multi-criteria analysis but are not considered part of the detailed reintroduction plan presented here. They should, however, form part of the longer-term vision for wetland specialist species in Millewa Forest.

Before reintroductions can occur, it is necessary to ensure that prospective sites will be suitable for fish, by providing conditions that meet their ecological and biological requirements. Therefore, planning is needed to identify and mitigate the threats that caused initial extirpations as well as actions to improve other habitat elements that off-channel specialist fish require. We apply the following logic in this implementation plan specifically because these elements should be considered before reintroductions can occur (represented diagrammatically in Figure 18):

- identify the **habitat requirements** to support the target species
- characterise current state of habitat components at target locations
- identify where a lack of information constrains rehabilitation actions **and gather information** to fill that information need
- undertake required restoration actions
- these results are tabulated for each candidate site (or group of sites) as prioritised lists of related rehabilitation actions.

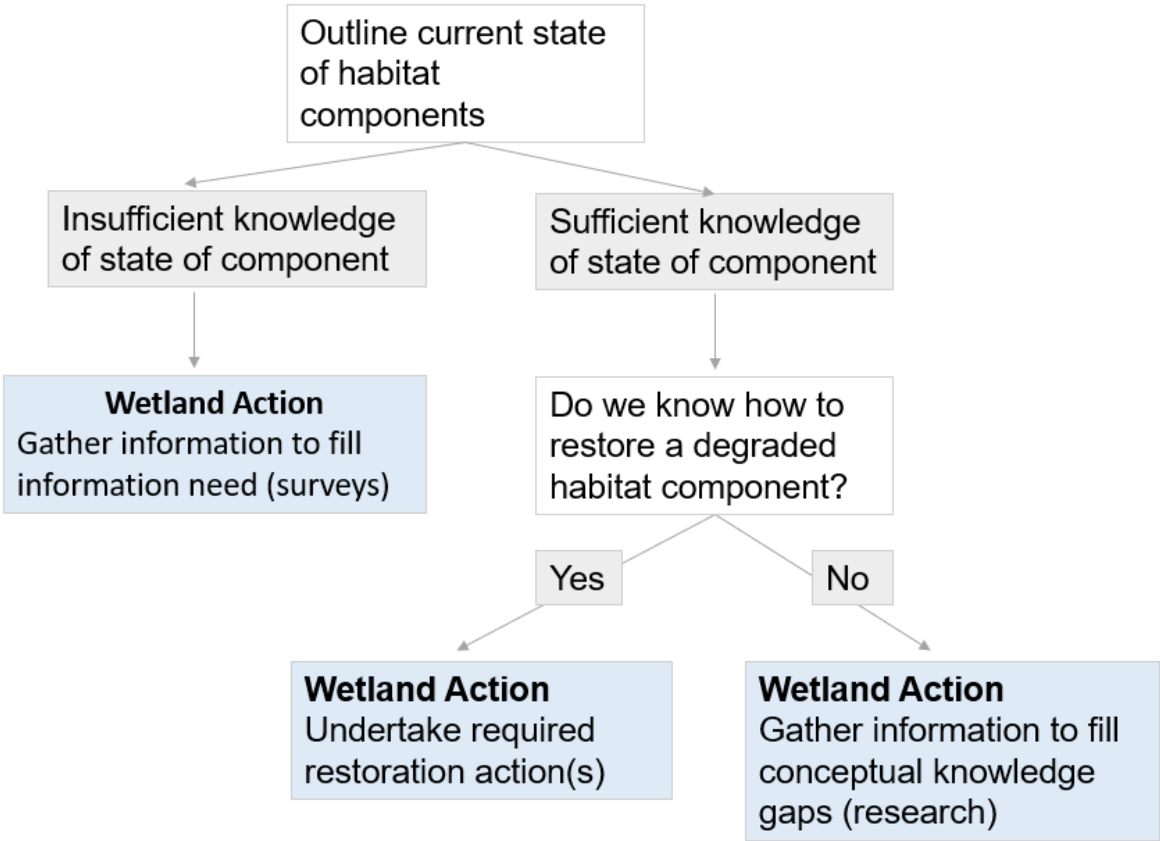

Figure 18 Flow diagram for deciding what actions will be needed at a location to restore it for the target species

Note: Blue boxes represent sets of actions that can be undertaken at a wetland and are summarised in this implementation plan.

4.2.1 Habitat requirements

The initial starting point is to identify the key habitat components required to support target fish species at a site, based on our understanding of what constitutes a healthy wetland, and the target species' ecology. We used the conceptual model (Figure 5) in Section 2, which outlines 6 broad habitat components for fish: hydrology, aquatic vegetation, water quality, productivity, physical habitat and invasive species. These broad themes are listed in column one of Table 6. To quantify these habitat components, each one is further broken down into several specific, measurable aspects that small-bodied fish require to survive and reproduce. These are summarised in the second column of Table 6.

4.2.2 Gather information

It is important to assess whether there is sufficient current information to proceed with management actions. If information about a habitat component's state is insufficient, it is recommended that more information is gathered (e.g., through surveys) before sites are selected for wetland rehabilitation and fish recovery operations. If there is a lack of knowledge about how to restore a habitat component, it is recommended that more information is gathered (i.e., research) before restoration actions are attempted. The third column in Table 6 highlights the adequacy of the currently available information for each habitat aspect of the selected Millewa wetlands.

4.2.3 Habitat conditions

For each wetland, the current state of each known habitat component is outlined in Table 7. Where a component is not sufficient to support target species, we provide actions to restore that component.

Where feasible, ephemeral floodplain wetlands and forest creeks can be included in the above actions to better understand the current state of the forest and support NPWS's broader floodplain management. Candidate sites could be those visited by Sharpe and Wilson (2012) and Whiterod and Gannon (2020).

Table 6 Habitat requirements for small-bodied wetland specialist fish in the Mid Murray region and a summary of the standard of information on these requirements in the Millewa Forest region

Note: Colours reflect the amount, quality and reliability of the currently available information (green = high, yellow = moderate, red = low).

Habitat component	Requirements for off-channel specialist fishes	Standard of information available for candidate wetlands (see Table 3for details of each wetland)
Hydrology	Permanent water	Basic observational evidence of water permanence for 5 of the 6 wetlands.
	Sufficient depth	Maximum depth measurements exist for 5 of the 6 wetlands, from one snapshot in April.
	Water level variability to support vegetation and productivity (influenced by flows and wetland bathymetry)	No data available on finer-scale water level variability. No finer-scale bathymetry data available.
	Periodic connection with river/floodplain for dispersal	For wetlands lacking regulators, degree and type of connection with floodplain unclear.
	Protected from blackwater events	Likelihood and magnitude of blackwater impact on sites unclear.
Vegetation	Presence of dense submerged and emergent vegetation (providing shelter, nest sites and supporting basal productivity)	Single time series surveys from each of 2012, 2014 and 2020 provide rough estimates of per cent cover. Not all sites covered by all surveys, but where sites were repeatedly surveyed, there is concordance, although conditions may have changed since last surveys.
Water quality	Within tolerance ranges of target species	One point measurement of pH, conductivity, temperature, dissolved oxygen and transparency taken in autumn 2020 at 5 of the 6 wetlands.
Productivity	Sufficient to support macroinvertebrates (food) at high enough densities for target fishes	One point measurement of zooplankton density taken in autumn 2018 at 5 of the 6 wetlands.
	Sufficient to support algae, periphyton and biofilms (food) at high enough density for target fishes	No data available on other forms of productivity at any wetlands.
Physical habitat	Sufficient woody structure/rock to provide shelter, nesting sites and surface for attachment of periphyton (productivity)	All sites have estimates of woody habitat coverage, which is unlikely to have changed.

Habitat component	Requirements for off-channel specialist fishes	Standard of information available for candidate wetlands (see Table 3for details of each wetland)
Invasive species	Few or no invasive species	All sites have fish surveys. May have changed since last surveys, or surveys did not detect all species present. Little information exists about impact of invasive terrestrial herbivores.
	Low to moderate levels of small native fish (particularly carp gudgeon species) which may compete for resources or larger predatory species	All sites have fish surveys. May have changed since last surveys, or surveys did not detect all species present.

Table 7 Habitat conditions at the candidate permanent wetlands in Millewa Forest

Notes: Vegetation and woody habitat are graded on a scale from 0 to 5, with 0 = absent and 5 = very high density. Water quality measurements are scored as within the tolerance range of wetlands fishes or not. Invasive fish species: C = carp, EG = eastern gambusia, WL = oriental weatherloach, RF = redfin perch, GF = goldfish. A dash indicates that empirical data could not be found in the literature. Coloured cells indicate a relative condition, with green = favourable, yellow = moderately favourable and red = unfavourable. Table modified from Table 3 in Section 2.
Sources: 1 = Sharpe 2014; 2 = Whiterod and Gannon 2020; 3 = Sharpe 2018.

Habitat element	Nine Panel (large)[1,2,3]	Nine Panel (small)[1,3]	Burial Lagoon[1,2,3]	Fishermans Bend Lagoon[1,2,3]	Horseshoe Lagoon[1]	Pinchgut Lagoon[2,3]
Hydrology	Permanent water likely maintained by subsurface flow, no direct connection	Permanent water likely maintained by subsurface flow, no direct connection	Permanent water maintained by overland flow and possibly by subsurface flow	Permanent water likely maintained by subsurface flow, no direct connection	Regulator present; will dry if disconnected	Fed by regulator on Pinchgut Creek and possibly subsurface flow
Submerged vegetation	0	0	1	0	0	0
Emergent vegetation	3	4	3	3	4	2
Water quality within the tolerance ranges of native species?	Yes	Yes	Yes	Yes	-	Yes
Complex woody habitat	3	2	3	3	3	3
Productivity (no. zooplankton per litre)	757.87	177.33	323.24	339.18	-	103.56
Invasive fish	EG	EG, WL	C, GF, EG, WL	C, RF, EG, WL	C, RF, GF	C, RF, GF, WL, RF

4.2.4 Priority actions

We summarise the candidate actions for wetlands in Millewa Forest across the 6 habitat components and provide a ranking of their relative priority in Table 8. This allows readers to look across the 6 candidate wetlands and assess which actions are likely to be most needed. In the following sections, we discuss candidate actions in more detail. These actions are grouped by habitat component as there is considerable overlap between the habitat condition (and required actions) at each site. Where there are differences between sites, these are highlighted in the table and discussed in the text. It is anticipated that the implementation of many of these actions will require detailed planning, including budgeting and consultation with NPWS staff and subject area experts.

The purpose of this section is to consider what actions are the highest priority when looking across the 6 candidate wetlands. From this broad overview considering threats and actions across wetlands, we then provide a case study of a work package that outlines in more detail how these actions could be applied at Nine Panel Lagoon.

Hydrology

Gathering information

The highest priority action is to better understand hydrology across all candidate wetlands and more specifically to confirm water permanence, and thus the wetlands' ability to support fish for extended periods. This can be done through historical imagery, particularly around the Millennium Drought, supported by interviews with long-term agency staff, and utilising the Murray Wetland Working Group Database Atlas.

Installing depth loggers is a moderate priority action and will provide details of annual and inter-annual water level fluctuations across all candidate wetlands. This information provides evidence to support vegetation and productivity management. Hydrological connection modelling (commence-to-fill levels) for the 4 wetlands that do not have a direct connection (see Table 7) is also a moderate priority, as it supports the management of connected populations of fishes.

Bathymetric surveys at all wetlands are a low priority action, but would support hydrological models and fine-scale vegetation management at the site scale, including providing information on where wetlands will be connected, what is the size of a drought refuge pool, and what areas are the best for littoral vegetation.

An additional consideration may be to integrate knowledge from the NSW Reconnecting River Country Program. The NSW Government has implemented the program to consider physical, policy and operational constraints that limit the flow of river systems (including connections between rivers and their adjacent floodplains and wetlands), and how these can be best managed. Stochastic population modelling has been used to predict likely fish responses to different hydrological scenarios, and these models are constructed incorporating flow-productivity and flow-blackwater processes. Results are not yet available, but will be useful to help understand blackwater risk, and how fish respond to changes in hydrology.

Restoring habitat

Securing the ability to deliver water to wetlands during drought (when required) is a high priority management action. This is to prevent the loss of surface water or extended periods of adverse water quality, and the resultant extirpation of reintroduced fishes. It is anticipated that this will require pumping from adjacent channels.

A moderate priority management action is increasing littoral zone fluctuations at all wetlands. This will directly support vegetation management and productivity. The targeted degree fluctuation will be heavily informed by the information gained from the depth loggers. How this fluctuation is implemented will also depend on the wetland and type of fluctuation required; water may be pumped in or out of wetlands to fill or draw them down, or regulators may be opened at Horseshoe and Pinchgut lagoons.

A lower priority will be to periodically connect wetlands with the floodplain to enable immigration and emigration of wetland specialist species. How and when wetland connection is established will be informed by hydrological connection modelling and is likely to be easier at Horseshoe and Pinchgut lagoons, which have direct connections with the main channels.

Vegetation

Gathering information

Understanding the reasons for poor coverage of submerged vegetation is a high priority at all wetlands. To fill this knowledge gap, it is likely that experimental tests will be required, such as exclusion of carp and terrestrial herbivores, and collecting information about the state of seed banks and the water regime. Wetland cores may provide information about historical vegetation communities, but the resolution of these data may be too coarse to reconstruct recent communities. Consultation with wetland vegetation experts will be required.

Undertaking follow-up surveys of vegetation is a moderate priority at all wetlands. Updated surveys of wetland vegetation will better support prioritisation and understanding of current conditions and seasonal fluctuation. Some of the currently available information is from 2012, and conditions may have changed since. However, repeated surveys revealing low coverage mean that this may not be completely necessary. Methods such as aerial mapping will allow for rigorous comparisons through time and measurement of change after rehabilitation actions. Undertaking multiple surveys throughout the year will identify potential seasonal fluctuations in vegetation quality.

Restoring habitat

Identifying and ameliorating the causes of low plant coverage is a high priority, as this is a very important habitat component for small-bodied fish. Consulting with wetland vegetation rehabilitation specialists is highly recommended. If the reasons for the lack of submerged vegetation are unclear, NPWS could attempt replanting at a trial wetland to see if it works; the reasons for poor vegetation coverage may be legacy effects and no longer present. If this is the case, planting is likely to recover vegetation. A candidate wetland for replanting is Nine Panel Lagoon (small), given its small size and lack of invasive carp and redfin in 2 recent surveys.

Water quality

Gathering information

Updating the existing water quality data is a high priority. Although water quality parameters appear to currently be within tolerance ranges (from one snapshot measurement), it is important to update this information at different times of the year (especially warmer months), particularly for Horseshoe Lagoon, which the current data do not cover. In addition, much of the existing data are from autumn; data from the summer months are most important, as this is when it is most likely that water quality will exceed acceptable temperature and dissolved oxygen ranges. Gathering this information would enable better site prioritisation for fish reintroductions. In the first instance, updating the water quality data may be done by regular wetland visits by an NPWS staff member. However, if temperature and dissolved oxygen (and water depth) loggers were installed, these would provide very high-resolution data, across the diel range. It is envisioned that this would be done at all 6 candidate wetlands. Given the value of this type of information and the ease of collection, it is a higher priority than repeated spot measurements.

When there are several seasons of high-resolution water quality data available (i.e. from data loggers), a moderate priority would be to construct a water quality risk model. Such a tool would use real-time data (e.g. ambient temperature, river height) to predict water quality and water depth. This model would be used by NPWS staff to assess when site visits would be prudent to assess on-ground conditions and, if necessary, implement interventions.

Restoring habitat

If water quality exceeds target parameters, intervention will be required. The highest priority intervention would be to pump water into wetlands, increasing depth, creating thermal refuges and increasing surface area to increase dissolved oxygen. There are a number of steps required to undertake this action, including assessing feasibility, securing the right to pump water during drought, and planning for the required infrastructure and funds. If pumping is not feasible, a secondary option is undertaking emergency fish removal when water quality conditions deteriorate. This action is less desirable as it is highly disruptive to fishes. It also has a number of steps, including licensing, establishing budgets, seeking service providers, finding fish and housing rescued fish, either in off-site aquaria or in permanent water bodies such as farm dams, and also determining when conditions are suitable for fish to be returned to wetlands.

Productivity

Gathering information

A high priority is updated zooplankton surveys across all sites, which are used here as a proxy for wetland productivity. While information has been collected on pelagic zooplankton densities at 5 of the 6 wetlands (Sharpe 2018), this was a single sample. Given that zooplankton densities within a wetland can fluctuate greatly in space and time (Papas et al. 2021), more detailed surveys are needed to assess the likely amount of food available for fish. Indeed, given the density-dependent nature of predator–prey relationships, merely assessing the number of prey items may be insufficient. These surveys should be coupled with surveys of other forms of productivity – terrestrial inputs, algal growth and associated benthic microorganisms and macroinvertebrates – as they also form part of the diet of many of the target species.

If these updated surveys confirm that food availability is likely to limit fish survival, understanding the reasons for this is a high priority. Experiments are one way to do this, where an action is implemented, and changes assessed against unmanipulated controls. These actions may include increasing littoral zone fluctuations, planting of large amounts of vegetation, and/or artificially increasing terrestrial inputs (placing leaf litter into the water). Each of these 3 actions targets a different productivity process, and results will provide insight into possible restoration methods.

A lower priority action is to define target productivity levels. Sharpe (2014) relates zooplankton densities relative to the requirements of juvenile golden perch, of which only Nine Panel (large) was sufficient. However, more work is required to fully define what is sufficient zooplankton/periphyton density for the wetland specialist fishes. There appears to be little information available in the literature on this, so it may be necessary to undertake expert elicitation or laboratory trials. This is a lower priority as it may be possible to provide sufficient levels of productivity (assessed by fish-health surveys), without knowing exactly what these levels are.

Restoring habitat

Actions to restore productivity are contingent on filling the information need on reasons for low productivity.

Physical habitat

Gathering information

Future surveys of the physical habitat would provide up-to-date information for wetland prioritisation. However, it is unlikely that much has changed since Whiterod and Gannon (2020), and all sites had relatively similar levels of physical habitat cover. Hence, more surveys are a low priority, but could be undertaken at the same time as vegetation surveys for very little extra effort.

Restoring habitat

Although cover was moderate at most wetlands in recent surveys (Table 7), increasing the amount of physical habitat is a low priority; except at Nine Panel (small) where coverage was low. The resources provided by physical habitat are also provided by emergent vegetation (of which many wetlands had good coverage) and by submerged vegetation (which is a high priority for restoration). However, increasing the amount of physical habitat may provide resources for wetland specialist fishes if there is a lag in increasing vegetation, or if it is not possible at some wetlands. Rock and woody debris can be used, and structures with small interstitial spaces would be more suitable for the target species than large, open structures.

Invasive species

Gathering information

Assessing the impact of terrestrial herbivores (particularly invasive deer and pigs) at all 6 candidate wetlands is a high priority. Current information about these impacts is not well understood, and more information would assist in site prioritisation, as well as inform the need for management actions. Potential methods include visual assessments for pugging and grazing, camera traps and exclosure fencing. Initial interviews with long-term NPWS staff familiar with the area may assist in prioritising the sites to be surveyed, and the methods used. Data from these surveys may also provide insight into the current state of aquatic vegetation.

A moderate priority is to update the existing fish surveys. Although they were fairly comprehensive, conditions may have changed, and imperfect detection may have missed some species. Using eDNA may be useful to rapidly detect the presence of invasive species, particularly carp and redfin perch (the 2 species likely to have the biggest direct impact on reintroduced wetland specialist species).

Restoring habitat

It is a high priority for candidate wetlands to be free from invasive fish, particularly redfin perch and carp, or for these species to be present in very low numbers. The site-by-site prioritisation for management of redfin perch and carp in Table 8 is based on the current understanding of the presence of these species. As these species appear to be absent from Nine Panel (large and small), these sites are a lower priority for elimination or management. At Horseshoe Lagoon, drying and rewetting in winter or through a carp screen to eliminate invasive species is a higher priority given its hydrological connection and the presence of a regulator. At Burial Lagoon, Fishermans Bend Lagoon and Pinchgut Lagoon, drying would likely require pumping to dry, which may be logistically more difficult and expensive. Hence, managing carp and redfin by mechanical removal is a higher priority at these sites.

Fencing wetlands to prevent access by herbivores is a low priority given the current uncertainty of their impacts, the likely cost and the impact on amenity and other non-target species.

Reintroducing threatened species

Threatened small-bodied fishes can be reintroduced to wetlands in Millewa Forest once threats to these fish have been mitigated. We anticipate that this will initially be within a small number of wetlands as a pilot study, but moving towards the overall goal of recreating self-sustaining populations of threatened fish throughout Millewa Forest.

There are several steps to consider when reintroducing species. These have been outlined in several publications, both around translocations in general (IUCN/SSC 2013) and for fish more specifically (Zukowski et al. 2021).

The details of these steps will be context-dependent, but, broadly, include:

- Set translocation objectives.
- Establish commitment timeframe and exit strategy. Not all translocations proceed according to plan, so it is important to have a defensible basis for discontinuing if this is the case, based on clear indicators of lack of success, tolerable limits of their duration, or if undesirable/unacceptable consequences have occurred (IUCN/SSC 2013).
- Identify which species will be selected to be the focus of translocations. Formal prioritisation tools can be used, such as the Project Prioritisation Protocol (Joseph et al. 2009), which considers criteria such as the level of endangerment of the species, metrics describing the value of the species (e.g., evolutionary distinctness, ecological importance, social value), costs of management, and likelihood that management may succeed. In some instances, selection of species may follow a less structured process and be driven by meeting a smaller set of criteria, especially availability of individuals for translocations.
- Identify the population size and genetic diversity required at the wetland to support a viable population. This can be done by population modelling.
- Identify if there are sufficient fish in the wild to support collections for translocations. If so, then identify source populations – based on criteria such as genetic structure, for environmental matching, or to maximise adaptation potential. This can be done by surveys, captive breeding and coordinating with existing programs (e.g., Tri-State Alliance, North Central Catchment Management Authority). Ensure appropriate genetic management guidelines are followed.
- If sufficient fish are not available to provide individuals for translocations, investigate options for source fish from captive breeding programs.
- Ensure relevant permits and permissions are obtained; in New South Wales this requires at least a review of environmental factors and a permit from NSW Fisheries Management. Cross-border movement of threatened fish (e.g., southern pygmy perch from Victoria) may require extra permissions and permits.
- Genetic management, to preserve gene flow among populations and genetic diversity.
- Identifying potential sites, especially understanding the drivers of local extirpation and how these can be mitigated. Site suitability can be assessed using pre-existing guides (e.g., Whiterod 2019).
- Assessing potential for, and then undertaking, site enhancement, such as improving water quality and emergent and submergent vegetation, ensuring the presence of macroinvertebrates, and absence of introduced or other predators/competitors.

- Develop an emergency intervention plan to manage disturbances. This could include the potential for fish rescues and translocations to other locations (e.g., other wetlands or captive facilities).
- Ensure capture, transport and release are undertaken correctly to minimise fish stress. This can be done by using contractors with experience in fish translocation and following established guidelines (e.g., Zukowski et al. 2021).
- Determine the most appropriate release strategy, including timing (spring/early summer, and late summer/autumn are likely to be best; Zukowski et al. 2021), and how releases are spread over time (e.g., a single large vs several small releases). The latter decisions can be guided by population modelling (Todd and Lintermans 2015), especially to consider the need for repeated reintroductions to bolster population size, increase genetic diversity and increase the chance of successful establishment.
- Consider biosecurity and disease risks. Ongoing inspections of fish are needed, and fish presenting in poor health should be quarantined/treated.
- Monitor and evaluate success with follow-up surveys of release sites, looking for:
    - short-term survival of released fish (weeks)
    - long-term survival of released fish (months)
    - evidence of reproduction (months to years).
- If fish come from multiple sources, genetic assessments of source fish and then fish that are bred after translocations can determine the relative contribution of genetic material from different sources into the reintroduced population.

Table 8 Priority of actions to restore 6 candidate wetlands for off-channel (wetland) specialist fishes

Note: 1 (green) = highest priority, 2 (yellow) = moderate priority, 3 (red) = lower priority.

Habitat component	Action type	Action	Location					
			Nine Panel (large)	Nine Panel (small)	Burial Lagoon	Fishermans Bend Lagoon	Horseshoe Lagoon	Pinchgut Lagoon
Hydrology	Gather information	Confirm water permanence	1	1	1	1	1	1
Hydrology	Gather information	Install depth loggers	2	2	2	2	2	2
Hydrology	Gather information	Bathymetric surveys	3	3	3	3	3	3
Hydrology	Gather information	Hydrological connection modelling	2	2	2	2	3	3
Hydrology	Restore habitat	Secure water delivery during drought	1	1	1	1	1	1
Hydrology	Restore habitat	Connect with floodplain	3	3	3	3	3	3
Hydrology	Restore habitat	Increase littoral zone fluctuations	2	2	2	2	2	2
Vegetation	Gather information	Update surveys of vegetation cover	2	2	2	2	2	2
Vegetation	Gather information	Investigate drivers of lack of submerged vegetation	1	1	1	1	1	1
Vegetation	Restore habitat	Identify and implement actions for submerged vegetation recovery	1	1	1	1	1	1
Water quality	Gather information	Update existing water quality surveys	1	1	1	1	1	1
Water quality	Gather information	Install temperature and dissolved oxygen loggers	2	2	2	2	2	2

Habitat component	Action type	Action	Location					
			Nine Panel (large)	Nine Panel (small)	Burial Lagoon	Fishermans Bend Lagoon	Horseshoe Lagoon	Pinchgut Lagoon
Water quality	Gather information	Create model to predict poor water quality events	2	2	2	2	2	2
Water quality	Restore habitat	Deliver water during drought	1	1	1	1	1	1
Water quality	Restore habitat	Undertake fish rescues during drought	2	2	2	2	2	2
Productivity	Gather information	Update zooplankton surveys	1	1	1	1	1	1
Productivity	Gather information	Undertake surveys of other forms of productivity	1	1	1	1	1	1
Productivity	Gather information	Define target productivity levels	3	3	3	3	3	3
Productivity	Gather information	Investigate reasons for prospective low productivity and methods to increase it	2	1	1	1	1	1
Productivity	Restore habitat	Implement actions to increase productivity	2	1	1	1	1	1
Physical habitat	Gather information	Update surveys of physical habitat	3	3	3	3	3	3
Physical habitat	Restore habitat	Increase amount of physical habitat	3	2	3	3	3	3
Invasive species	Gather information	Assess invasive herbivore impacts	1	1	1	1	1	1
Invasive species	Gather information	Update fish survey data	2	2	2	2	2	2
Invasive species	Restore habitat	Eliminate carp and redfin by drying and rewetting	3	3	2	2	1	2

Habitat component	Action type	Action	Location					
			Nine Panel (large)	Nine Panel (small)	Burial Lagoon	Fishermans Bend Lagoon	Horseshoe Lagoon	Pinchgut Lagoon
Invasive species	Restore habitat	Manage carp and redfin perch numbers by mechanical removal	3	3	1	1	2	1
Invasive species	Restore habitat	Fence wetlands from herbivores	3	3	3	3	3	3

4.2.5 Wetland rehabilitation work package for Nine Panel Lagoon

On 24 and 25 May 2022, NPWS hosted a field visit and technical workshop to discuss and detail actions required to rehabilitate the small, permanent wetlands in Millewa Forest.

Attendees were Nick Whiterod (Aquasave Glenelg Trust); John Conallin (Charles Sturt University); Paul Childs (NSW DPE); Wil Allen, Clayton Sharpe, Brady Cronin and Matthew Crawford (NSW NPWS); Jimmy Walker (NSW Fisheries); Ivor Stuart (Charles Sturt University); Rob Hale, Gabriel Cornell and Bryan Mole (Arthur Rylah Institute).

The group visited potential wetlands for fish translocations, and across the 2 days discussed a range of issues, including:

- the current habitat conditions at each wetland, especially the aspects that are required for fish which may be absent
- how to prioritise which wetlands to select for initial rehabilitation works, and ultimately fish releases
- what actions are likely to be required to rehabilitate wetlands for fish
- what order rehabilitation actions should be undertaken – there was consensus from the group that ensuring hydrological conditions are suitable, and will remain so in the future, was the highest priority initially, and from there other actions (e.g., revegetation, managing invasive species) could be undertaken concurrently
- how to implement wetland rehabilitation actions, that is, what the specific steps involved are, and what are the key considerations (e.g., logistics, costs, inter-dependencies between actions)
- key considerations around fish translocations (i.e., those outlined above) in the context of wetlands in Millewa Forest.

The group selected Nine Panel Lagoon (large) as a high priority site to use as a case study to work through implementation of rehabilitation actions in more detail, and develop a case study work package.

Nine Panel Lagoon is a small wetland (approximately 2.8 ha) on Millewa River Road. At the nearest point it is 50 m from the Murray River. This site was selected because:

- a site visit confirmed the presence of a dense ring of fringing vegetation, including *Juncus ingens*, *Typha* spp., and some scattered *Cycnogeton procerum* with little other aquatic vegetation
- previous data (Table 8) have indicated that it likely has permanent water, lacks carp, has some emergent vegetation and wood, and the highest zooplankton densities across the 6 candidate wetlands.

Below we present the steps and key considerations that would be involved in better understanding the habitat conditions at Nine Panel (where required), improving these where necessary, and ultimately releasing fish into this site.

Figure 19 Nine Panel Lagoon (Gabriel Cornell/Arthur Rylah Institute)

Hydrology

Understand current hydrology and water permanence

For Nine Panel Lagoon, there is currently very little information available about the degree and seasonality of water level fluctuation, the hyporheic connection with the Murray River, or water permanence during dry spells. From observation and anecdotal evidence, the water level is thought to be relatively stable and permanent, maintained by subsurface flows from the Murray River. However, confirming if this is the case is a high priority for Nine Panel Lagoon, along with gaining a better understanding of the drivers behind the lagoon's water levels. Filling this knowledge gap will support hydrological management and vegetation management, and the following actions were discussed as high priorities at the workshop:

- Install a depth logger in the lagoon to obtain high-resolution data on water level fluctuations
  - Nine Panel Lagoon could be incorporated into the existing network of depth loggers in the Millewa Forest. Ultimately, depth data from this logger could be used to construct a model to identify drivers of water level and the strength and direction of potential relationships with environmental conditions. Recommended predictor variables include Murray River discharge (ML/day below Yarrawonga), mean monthly evaporation, and mean monthly precipitation.
- Undertake detailed investigations of historical imagery
  - If available, high-resolution historical imagery could be used to investigate the extent of surface water during dry periods. If water was present during the Millennium Drought, it is likely that the lagoon will retain water under most future scenarios within the time frame of this strategy.
- Observe water level change during pumping to empty wetland
  - If water is pumped out of the wetland for vegetation management, invasive species management or planting activities, the rate of refill will provide direct evidence of the hyporheic connection with the Murray River.

Secure water during drought

The highest priority identified by workshop attendees to support fish populations at Nine Panel Lagoon is ensuring long-term water permanence. Anecdotal evidence suggests that the water level is maintained for long periods of time, and the above investigations will provide more details. However, a recommendation from the workshop was that the investigations proposed above are coupled with the development of an emergency response plan for the worst-case scenario of no or very low surface water under future conditions. In this case, pumping from the Murray River is the recommended response. To facilitate this, we outline the logistical and preparatory work required for a rapid response, as well as the steps involved in such a response. Pre-emptively outlining actions and undertaking all necessary planning will allow for rapid action when required.

This outline was developed based on input from workshop attendees, and broadly involves the following steps (discussed in more detail below):

- plan and prepare to secure surface water
- monitor water levels and water quality and assess against trigger points
- implement water delivery plan if trigger points reached.

These steps are outlined in more detail below (and presented diagrammatically in Figure 20).

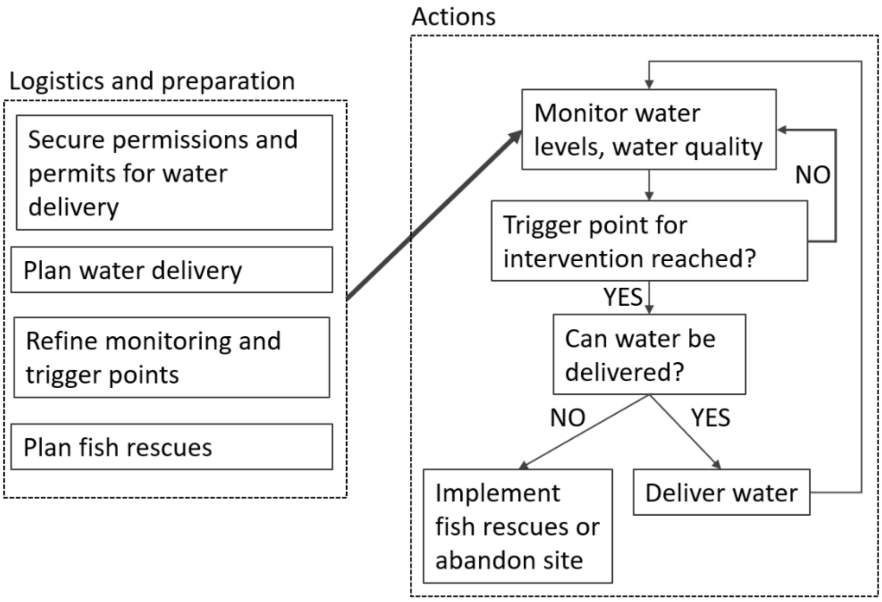

Figure 20 Flow of logic to prepare for, and implement, a drought action plan to support threatened fishes at Nine Panel Lagoon

Step 1: Plan and prepare to secure surface water

Step 1A: Secure the necessary permits and permissions to pump water.

NPWS to:

- obtain a water access licence
- generate memorandum of understanding with the department for water allocation during period of critical need
- ensure compliance with the Natural Resources Access Regulator
- undertake a review of environmental factors for the placement of a pump in Millewa Forest

- investigate and fulfil any other regulatory requirements for pumping water from the Murray River to Nine Panel Lagoon.

Step 1B: Plan the water delivery

NPWS to plan the logistics of pumping water into Nine Panel Lagoon. Steps involved include:

- identify the water provider
- scope site for placement of pump and pipe (likely south end of wetland – shortest distance from river but has nearby road access)
- identify contractor to undertake pumping.

Additional considerations include the volume required and the frequency of watering. As Nine Panel is less than 3 ha when full, and if it is an average of 1 m deep, the total volume required to fill would be less than 30 ML. However, this volume may vary depending on subsurface flows, and water may seep out of the wetland, which may also increase the required frequency for watering. This is currently an unknown factor.

Step 1C: Plan monitoring program and trigger points

A prospective monitoring plan and trigger points are outlined in Figure 21, but these can be further refined by NPWS.

Step 1D: Plan for fish rescue

NPWS to plan for potential removal of fish if surface water cannot be secured or delivered. Steps involved include:

- identify potential surrogate sites that will hold water (permanent water sites in the forest, farm dams or aquaria)
- identify contractors or NPWS staff to undertake removal
- identify rescue methods (likely fyke netting and/or electrofishing)
- identify trigger points for return of fish to wetlands once surface water returns
- outline the conditions under which rescues would not occur (suitable refuge sites could not be secured, or likelihood of success too low, or costs outweigh benefits).

Step 2: Monitor water levels and water quality and assess against trigger points

The frequency, type and importance of monitoring will vary depending on prevailing conditions, separated into 3 distinct stages. Figure 21 outlines the type of monitoring suggested at each stage before the water delivery plan is implemented.

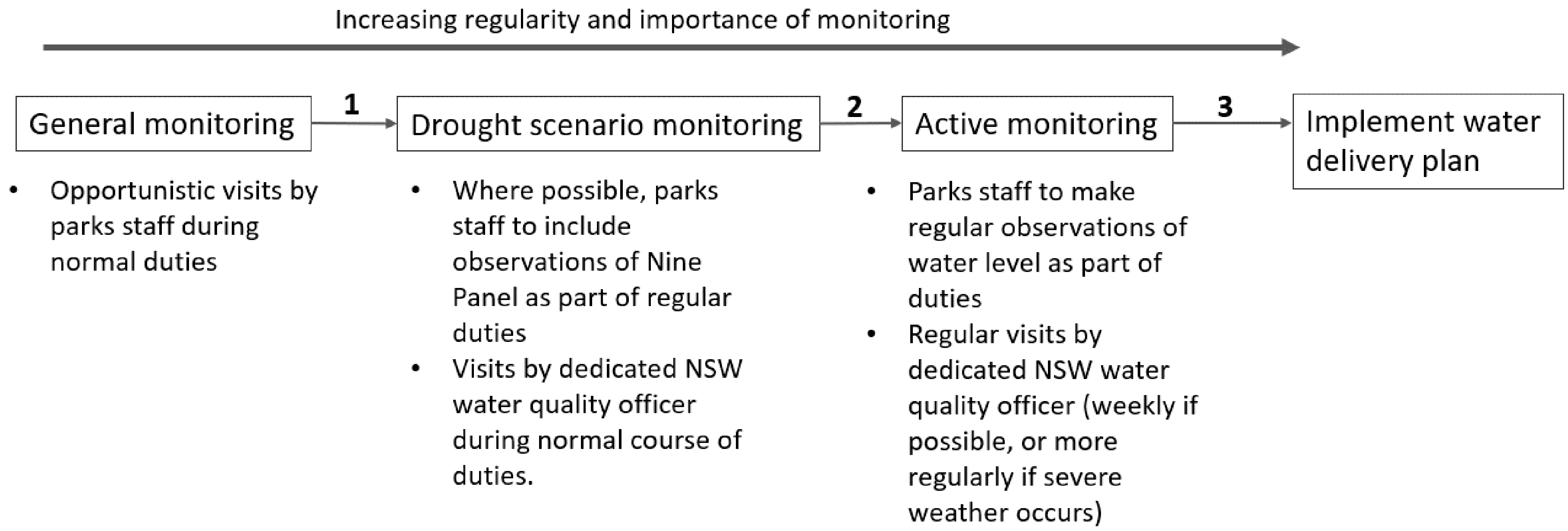

Figure 21 Description of monitoring of water level and water quality at Nine Panel Lagoon (numbers indicate trigger points for increased level of action)

There are 3 **trigger points** for elevating the type of action (labelled in Figure 21). The details of these trigger points may be refined in future, but prospective details include:

- Move from general monitoring to drought scenario monitoring when the Millewa region is in a drought/dry phase and/or when Murray River discharge is severely reduced for an extended period.
- Move from drought monitoring to active monitoring when there is a rapid and notable reduction in water level, and/or when water temperatures approach 30°C (upper limit suggested by commercial growers for keeping southern pygmy perch in aquaria), and/or when dissolved oxygen approaches 2 ppm (parts per million; point of hypoxic distress for southern pygmy perch (McNeil and Closs 2007)); and/or when there are signs of algal blooms.
- Move from active monitoring to implementing the water delivery plan when water level is very low (approximately 0.2 m deep) and wetland area is severely reduced, and/or when there are signs of fish distress or death (pygmy perch or non-target species), and/or when water temperatures regularly exceed 30°C, and/or when dissolved oxygen is below 0.5 ppm (point of severe hypoxic distress for pygmy perch (MCNEIL and CLOSS 2007)).

Step 3: Implement water delivery plan if trigger points reached

When the trigger point for intervention is reached, deliver water to the wetland, if possible. It may not be possible to deliver water for several reasons, but most likely because water is not available to be delivered, or conditions are so severe that prior agreements cannot be honoured by providers. Conditions may also be so severe that water pumped into the wetland drains back to the Murray via the hyporheic connection.

If the water delivery plan cannot be implemented, then implement fish rescues, or abandon the site.

Vegetation

At the workshop, a realistic, achievable vision for Nine Panel Lagoon's plant community was discussed as being a dense, structurally diverse group of plants, covering the shallower edges of the lagoon and providing cover and food for fish. Because the water level at Nine Panel Lagoon appears to be relatively stable, the most appropriate plant community to try and establish would be one suited for conditions where the position of the littoral zone stays consistent. If pumping water becomes a viable option in the future and more variability in water level occurs, a wider range of species may be considered (especially those that require such variability) in the future.

Workshop attendees concluded that a detailed re-survey is not required before planting occurs as there is clearly an overall lack of submerged vegetation. While the reasons for this remain unclear, it is suspected that there was a severe impact on the plant populations during the Millennium Drought, and that some aquatic species have not subsequently recolonised. Relatively stable and consistently high water levels since the break of drought, and the lack of propagules from a surface connection with the Murray River, may be preventing the re-colonisation of aquatics in deeper water. Planting species that are not reliant on water level draw down may help to overcome this. However, it is important to note that no replanting attempt is guaranteed to be successful, and repeated planting may be required.

There are several steps involved in planting Nine Panel Lagoon. Broadly, these are:

- map planting zones
- confirm plant lists
- plant and maintain wetlands.

These steps are outlined in more detail below (and presented diagrammatically in Figure 22).

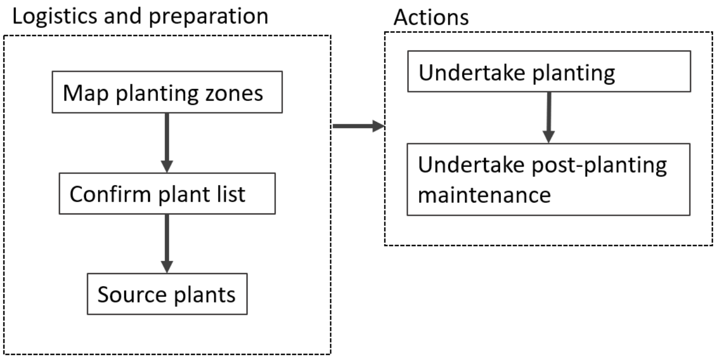

Figure 22 Broad outline of steps involved in planting Nine Panel Lagoon

Step 1: Map planting zones

To ensure plants are placed at the correct depth, it is necessary to understand the bathymetry and water depth of Nine Panel Lagoon. For the purposes of planting, this can be relatively coarse, delineating zones at 0–200 mm deep, 200–400 mm deep and 400+ mm deep. This may be done by wading around the edge of the lagoon and placing wooden stakes at regular intervals at 200 mm deep and at 400 mm deep. The distance of each stake from the bank will allow a coarse planting zone map to be produced. For demonstration purposes, we have produced a theoretical example in Figure 23. It is possible that the existing band of *Juncus ingens* and *Typha* spp. at the wetland edge already occupy most of the available 0–400 mm deep water. If this proves to be the case following investigation of the wetland bathymetry, the following planting suggestions may require modification.

Figure 23 **Aerial view of Nine Panel Lagoon (large) with theoretical plant depth zones indicated**

Step 2: Confirm plant list

A list of candidate plant species for each depth zone is presented in Table 9. The final selection of species will depend on availability at the time of works. The suggested plants are regionally indigenous species that may provide suitable habitat for target fish species. They are also present or likely to be present in Millewa Forest. These have been selected to create favourable fine-scale, dense habitat for small fishes and invertebrates, with a variety of growth forms and a mix of submerged and emergent species. All species selected perform well in constructed wetland situations with relatively stable water levels. Although *Cycnogeton procerum* requires shallow water levels or exposed mud for significant seedling recruitment, once planted and fully established it should persist in deeper water for longer periods of time.

Species already present at Nine Panel Lagoon include dense stands of *Typha* spp. and *Juncus ingens* in the shallow edges, and some sparse *Cycnogeton* spp. plants. Selected plants will complement those already present.

Table 9 List of potential plants to be planted in Nine Panel Lagoon, and the approximate number of plants required per planting clump

Species	Notes	No. of plants per square metre
0–200 mm depth		
Eleocharis acuta	Rhizomatous aquatic sedge. Grows in moist fringing margins, between 0–200 mm depth, and will also tolerate dry periods.	4
Myriophyllum papillosum	Partially submerged aquatic herb with robust upright emergent stems. Roots at the nodes, which can facilitate the formation of large floating mats.	4
200–400 mm		
Eleocharis sphacelata	Rhizomatous, aquatic, emergent sedge. Plant at upper end of zone; will handle some fluctuation and lowering of water level.	4
Cycnogeton procerum (previously Triglochin)	Partially submerged, tuber-bearing aquatic herb. Requires shallow water or exposure of substrate to facilitate significant recruitment from seed.	6
Potamogeton cripsus	Fully submerged aquatic herb. Dense leaves provide fine structural habitat.	4
Vallisneria australis	Fully submerged aquatic herb. Can grow in deep water but requires good light penetration/low turbidity. Plant at lower end of zone and may spread deeper if conditions suitable.	4
Open water rafting species		
Myriophyllum papillosum	Can float, growing unrooted, may raft out from shallower planted position.	4
Potamogeton cheesmanii	Submerged plant with oval floating leaves. Long, narrow stems may extend up to water surface in deeper water when rooted in shallower areas.	4

Step 3: Plant and maintain wetlands

There are several steps and considerations involved in planting. These include:

- **Permits:** NPWS to investigate and arrange the permits required to plant in a national park and/or the requirements for transplanting from within the park itself.
- **Sourcing plants:** Plants can be purchased from commercial growers. It is likely that growers will need at least a season's notice to fulfil an order. Finding local growers will reduce transport costs and associated plant health issues from driving long distances. Plants sourced from NSW growers may incur fewer permitting considerations. Transplanting from established wild populations in Millewa Forest is also an option; this will require finding appropriate source sites with sufficient density of plants but has the advantage of ensuring local provenance and adaptation to local conditions. Care must be taken with both translocated plants and commercially sourced plants that undesirable species are not inadvertently introduced. It is important to ensure all plants are regionally indigenous and of local provenance.
- **Planting *Cycnogeton*:** If it is not possible to lower water levels for planting, then *Cycnogeton procerum* should have had sufficient nursery growing time to allow development of large rhizomes/tubers, and preferably be grown in a similar water depth to the planting site (Table 9). However, if it is possible to lower water levels for a significant period, then *Cycnogeton* present a low-cost opportunity in Millewa Forest, where seeds may be collected from established local populations (e.g., Gulpa Creek), then direct seeded in large quantities in Nine Panel Lagoon, while the wetland is drawn down. This is a novel and untested approach, but is relatively low effort and low cost and could be undertaken by NPWS staff under the guidance of an experience practitioner. If successful, subsequent periodic draw down of the wetland could be undertaken to bolster the *Cycnogeton* population at Nine Panel Lagoon. This approach would not require any planting of *Cycnogeton*. If *Cycnogeton* are to be translocated, plants should be mature and have well-developed rhizomes and tubers. It is essential that *Cycnogeton procerum* are netted immediately after planting.
- **Planting *Eleocharis sphacelata*:** Although this is a regionally indigenous species, there do not appear to be many records of *E. sphacelata* from within Millewa itself. For this reason, it is recommended that *Cycnogeton procerum* be preferentially used for the proposed plantings at Nine Panel Lagoon. At the recent workshop, *E. sphacelata* was presented as a possible alternative to *C. procerum*, however, this step should only be taken after confirming how widely distributed *E. sphacelata* is within Millewa Forest. It should also be noted that in certain situations, particularly smaller shallow wetlands with permanent water, *E. sphacelata* can completely cover the entire wetland.
- **Water level when planting:** Plants will have the best chance of establishment if planted in a drawn-down wetland (via pumping) with shallow water levels. As plants establish, water levels can slowly be allowed to increase. If pumping to draw down is not feasible, older and more established plants should be used to give them the best chance of surviving when planted underwater. A consideration of drawing the wetland down in summer is that this may facilitate further expansion into the wetland of the *Juncus ingens* and *Typha* spp. currently at the margins of the wetland.
- **Timing of planting:** Plants have the best chance of establishment if planted in summer when water levels are low and water temperatures are not too cold.
- **Planting groups and costs:** Plants should be planted in groups of the same species placed together. The number of plants per group and the area occupied by the group will vary by species (see Table 9), but rough cost estimates are for $1–2 per plant, with approximately 4–6 plants per square metre required within each depth zone. Planting in groups also make subsequent netting to protect the plantings from herbivory more achievable. Actual costs to plant Nine Panel Lagoon will depend on the area of the planting zone and exact costs per plant.

- **Plant half a wetland:** If funding is limited, it may be possible to only plant a portion of the wetland. This does not have to fully cover a particular area of the wetland (although it could be if that is seen as desirable), it could be just half the total area with dense groups scattered throughout the wetland. If this occurs, planting could preferentially happen in the portion of the wetland that has the larger area of littoral zone with a gentle slope, giving plants more space to spread and colonise – in the hypothetical Figure 23, this would be the south-west edge of the wetland.
- **Netting:** To protect newly planted plants from uprooting and intense herbivory by birds, groups of plants need to have nets placed over them for up to 12 months or until they are established and resilient.
- **Ongoing maintenance:** Successful establishment of plants will be supported by ongoing post-planting maintenance. This may include infill planting (replacing losses), supplementary planting (adding more species, or extending planting area), weeding and removal or replacement of netting. The exact requirements and level of effort will vary, and consultation with an experienced practitioner is recommended to identify required maintenance. Once plants are established, it is anticipated that this maintenance will decrease.
- **Exclusion of carp:** For successful establishment of plants, it is essential that the impact of carp is mitigated. Recent surveys at Nine Panel Lagoon have not uncovered any carp, so they are likely present in low numbers, if at all, which is encouraging. However, it is recommended that carp numbers be controlled, if possible, to give plants the best chance to establish. When plants are established in good densities, they will be more resilient to the impact of low numbers of carp.
- **Expert advice:** While much of the preparatory and planning work can be done by NPWS staff, it is recommended that experienced practitioners are consulted when undertaking the planting itself. Expert direction on exactly where to plant in the littoral zone, how to plant different species, clump density, netting arrangement and ongoing maintenance methods will give plants the best chance to successfully establish. Parks staff may work under an expert's direction, or a professional planting crew can be engaged.

Water quality

Existing surveys of Nine Panel Lagoon indicate water quality is within acceptable ranges for southern pygmy perch and other small-bodied wetland specialist species, but this is only based on point readings and does not capture diel and seasonal changes. However, given general observations, it is likely that the annual range of water quality will support the target species under normal environmental conditions. Water quality may be of a concern during drought periods, and water quality monitoring is incorporated into the management of surface water and triggers for water delivery, outlined in Figure 21.

Install water quality loggers

To obtain high-resolution temperature and dissolved oxygen readings across multiple years, loggers could be installed in Nine Panel Lagoon. If a water depth logger is installed, it should be a model that includes temperature readings (e.g., HOBO U20L ~$700). Dissolved oxygen will require a separate logger (e.g., HOBO U26-001 ~$3,000). Loggers will require staff to visit the wetland and download data, so they will not provide an early warning of potential poor water quality. However, with several years of data, models could be produced to predict the conditions (e.g., extended heatwaves or low Murray River flows) under which water quality may crash. These data may help to refine the water quality triggers outlined in Figure 21.

Productivity

Defining, and subsequently measuring, a ‘productive’ wetland is complex and species-specific. The single measurement of zooplankton densities at Nine Panel Lagoon indicate it had sufficient zooplankton to support golden perch juveniles (Sharpe 2018). The zooplankton density required by southern pygmy perch and other small-bodied wetland specialists remains unknown. Given this current understanding of Nine Panel Lagoon and the target species, there are no recommended actions to directly increase or measure productivity. However, it is anticipated that the recommended vegetation planting will increase in situ productivity (carbon and nitrogen available as plant matter – autochthonous productivity), providing food for macroinvertebrates and microorganisms.

Increase terrestrial inputs

If NPWS wanted to directly boost the productivity of Nine Panel Lagoon, a possible action may be the placement of terrestrial plant matter into the lagoon. This could take the form of cleared river red gum saplings or other plant material produced during park maintenance. As this organic matter decays, it would increase the nutrients available for basal productivity in the wetland (this allochthonous productivity effectively increases the carbon and nitrogen budget of the wetland). It also directly supports invertebrates that consume plant litter, and the fine structure of leaves and branches would provide surface for biofilm growth and shelter for small fish and macroinvertebrates. Experiments from a sediment-smothered lowland stream in Victoria have demonstrated that increasing the amount of coarse particulate organic matter can dramatically increase the diversity and abundance of invertebrates (Lancaster and Downes 2021) and native fish (Cornell et al. 2022), including southern pygmy perch. While this is a different context and remains to be tested in wetlands, it provides a useful example that supplementing organic matter can result in positive invertebrate and fish responses.

Physical habitat

There are currently moderate amounts of woody habitat present in Nine Panel Lagoon. The resources provided for small fish by hard structures are likely to be better provided by vegetation and, as such, no actions to increase physical structure are recommended at this stage.

Invasive species

Current survey data at Nine Panel Lagoon indicate that redfin perch and carp are absent or present in low abundances. Given this, workshop attendees concluded that reintroductions could take place with little or no expected impact from invasive fish. In addition, there is little evidence of impacts from pigs or deer, but this has not been systematically surveyed.

Update fish surveys

To confirm the current fish community, updated fish population surveys could be undertaken. Boat-mounted electrofishing may better survey the deeper sections of the wetland than the backpack electrofishing previously undertaken. Alternatively, mesh nets could be used to target large-bodied fishes specifically. eDNA methods may also be used.

Dry and refill wetland

If Nine Panel Lagoon can be pumped dry, doing so would eliminate all fish and present a blank slate, allowing for a highly curated fish community to be created. As refilling likely occurs via subsurface flow from the Murray River, the fish species present would only be those that are translocated there.

Pumping the wetland dry could be coordinated with vegetation planting, as plants would benefit from being planted in exposed substrate.

There are several steps involved in coordinating such an action, including permitting, identifying pump pathways, and engaging contractors to undertake the work. The feasibility of drying the wetland completely remains unclear as the degree of subsurface connection with the Murray River is still uncertain.

Off-target impacts on other aquatic fauna, such as turtles and frogs, must also be considered and planned for.

Undertake ongoing management

If carp and/or redfin perch are found to be present, and they cannot be eliminated by wetland drying, then periodic mechanical removal (e.g. by electrofishing or mesh nets) is recommended to ensure their numbers remain low.

Camera traps

Placement of camera traps at strategic points around the wetland would allow the frequency of visitation by large herbivores to be assessed.

Fish reintroduction

Selection of species and sourcing of fish

The ultimate objectives of fish translocations would be to maximise biodiversity and establish populations that could be used as sources populations for future translocations at other locations. The recommendation from the technical workshop was to initially start with southern pygmy perch or southern purple-spotted gudgeon as the focal species, and to consider a wider range of species once populations of these 2 species have been successfully established.

Individuals of both species are likely to be available for approximately $2/fish from hatcheries.

Permits and approvals

The permitting and approval process is likely to take up to 6 months. A review of environmental factors is required as part of translocation permits, and an AQUIS Biosecurity process will need to be followed if fish are moved into New South Wales from other states.

Fish transportation and release

Fish transportation and release should follow the guidelines outlined in Zukowski et al. (2021).

Release strategy

Recommendations from technical experts at the workshop were that up to 1,000 to 2,000 fish of each species may be needed, and that multi-year releases should occur for up to 5 years. If more specific details are required, then population modelling could be undertaken to explore the predicted outcomes of different release strategies (e.g., numbers of fish, single large vs several smaller releases, life cycle stage to be released). Similar modelling has been undertaken for some species to guide translocations in Victoria (e.g., Macquarie perch; Todd and Lintermans 2015).

Monitoring

Ideally, releases will initially happen at sites that are being monitored in The Living Murray program. This will allow some overlap in monitoring effort, but additional monitoring is likely to be required at release sites – both in terms of monitoring frequency (probably several times/year in the first year or 2) and what variables are monitored (e.g., to measure population size but also other variables like recruitment success).

4.3 Draft Implementation plan 2 – Channel specialist fishes

A key goal of the strategy is to facilitate the annual recruitment and persistence of populations of Murray cod and trout cod, and regular spawning, recruitment and dispersal opportunities and expansion of golden perch and silver perch populations. All of these species are large-bodied predators, requiring flowing water to live and reproduce.

In Table 10 we outline the candidate actions to support the goals for channel specialist species and provide a relative ranking of their priority. Unlike the preceding section on off-channel wetland specialist species, the discussion of this section is arranged by site. This is because there are considerable differences between the condition (and required actions) for each site, compared with the preceding section where conditions/actions were quite comparable across wetlands (refer to Table 8). In particular, the main channels (Murray River, Gulpa Creek, Edward River) differ from the forest channels (Toupna Creek, Swifts Creek, Bunnydigger Creek, Wild Dog Creek). It is envisioned that the main channels will support the persistence and spawning of larger individuals and provide the conditions for spawning. In contrast, actions for the forest channels are designed to support the survival and growth of young fish, as well as facilitate temporary foraging movements by adults. There are more forest channels in Millewa Forest than just those named here; these sites emerged as high priority from the initial workshops with NPWS staff. The challenges faced at these sites, and actions to overcome them, are likely to be similar at the other smaller forest channels not named explicitly here.

The channel specialist species targeted here are already present in the Millewa Forest region, and many of the actions to support these species are already being undertaken or considered. Hence, there are fewer suggested actions than for the off-channel wetland specialist species.

4.3.1 Murray River

A moderate priority in the Murray River is to understand and mitigate the impact of Torrumbarry Weir on the downstream passage of fish, particularly eggs and larvae of golden and silver perch. It is likely that there is severe mortality from barotrauma as fish pass through the undershot gates, or as underdeveloped eggs settle in the weir pool. This is a moderate priority for action because mitigating this large barrier is beyond the scope of this strategy, but if it is overcome it will likely go a long way to improving recruitment of fish spawned in the Millewa region. NPWS could support Mid Murray initiatives to address the impact of Torrumbarry Weir through lobbying for funding or through logistical support for on-ground efforts.

Increasing woody debris density and connectivity in the Murray River is a moderate priority. While largely sufficient around Millewa Forest, increasing connectivity between patches in areas where this is low will support local dispersal, particularly for trout cod. Immediately downstream of Millewa Forest, density and connectivity is lower; while outside the spatial scope of this strategy, placing woody debris in this region will support channel specialist fishes by expanding the amount of available habitat.

There is an opportunity to increase the consistency of the spawning and recruitment hydrograph for channel specialist fishes in the Murray River (i.e., attraction and spawning pulses for perches and with elevated, stable spawning flows for cods). This is a moderate priority, as these flows are being delivered in most (but not all) years, and these are longer-lived species that are not reliant on annual spawning for populations persistence.

A moderate priority for the Murray River is to deliver flow to forest creek distributaries to provide habitat for young fish (particularly Murray cod and trout cod), and occasional foraging habitat for adult fish. There is a high potential for increased population sizes of target species through this action. However, it is a moderate priority for the Murray River but a high priority for Toupna Creek, Swifts Creek and Bunnydigger Creek (Table 10). There may be small adjustments that can be made to the delivery of water in the Murray River, but the focus point for this action will be regulator settings of the forest creeks, working within the existing hydrological regime of the Murray River.

Although aquatic vegetation supports juveniles of channel specialist species, the likely scale of actions required to make a tangible difference makes aquatic vegetation restoration a lower priority at this stage.

4.3.2 Edward River

A moderate consideration for Edward River is the delivery of sufficient flows through the Edward River Offtake to hydrologically connect its multiple distributaries. As with the Murray River, the focus for this action is the operation of each distributary's regulator, but the flow regime in Edward River will have some impact on the flow in these smaller forest creeks. The appropriate flow regime to create semi-permanent flow in the creeks will be informed by the ongoing fish movement work currently occurring in Millewa Forest.

Overall, Edward River is currently a relatively low priority for action. The flow regime generally aligns with the spawning and recruitment requirements for large-bodied channel specialist fish, and there is a good degree of hydrological diversity to support flow-dependent adult fish. The fishway at Edward River Offtake appears to pass fish sufficiently. However, it is important to consider the conditions of Edward River as part of this strategy as it forms a major waterway in Millewa Forest.

As for the Murray River, restoring in-channel vegetation is a low priority for Edward River.

4.3.3 Gulpa Creek

Gulpa Creek requires some attention to create sufficient conditions for large-bodied channel specialist fishes.

A high priority is the placement of large structural habitat, as there are long sections with low density of woody debris.

In addition, the flow regime through the spawning season is not ideal to support spawning and recruitment of channel specialist fish; restoring appropriate conditions is a high priority. Changing the discharge to implement an earlier spring rise, reaching a higher maximum discharge, and attenuating the discharge recession (Figure 10) will better support the conditions for Murray cod and trout cod spawning and recruitment.

Increasing local-scale hydraulic diversity of Gulpa Creek is another high priority, particularly in the lower and middle reaches. This will create better conditions for adult channel specialist fishes. To determine the most appropriate methods to do so, a detailed site-based scoping exercise is recommended. Options include the placement of hard structures (which will scour sediment, disrupt laminar flow, and increase local-scale hydrodynamic diversity), the delivery of elevated flows through the Gulpa Creek Offtake, or even dredging and sediment removal.

Table 10 Priority of actions to restore channels for channel specialist fishes (primarily Murray cod, trout cod, golden perch and silver perch)

Note: 1 (green) = highest priority, 2 (yellow) = moderate priority, 3 (red) = lower priority, NA = actions not relevant for a particular location.

Habitat component	Action type	Action	Location					
			Murray River	Edward River	Gulpa Creek	Toupna Creek	Swifts Creek and Bunnydigger Creek	Wild Dog Creek
Connectivity	Restore habitat	Mitigate barriers to fish passage	2	NA	NA	1	1	2
Physical habitat	Restore habitat	Increase density of local patches of structural habitat and increase connectivity between habitat patches	2	3	1	3	3	3
Hydrology	Restore habitat	Implement hydrograph with attraction pulses for perches and with elevated, stable spawning flows for cods	2	3	1	NA	NA	NA
Hydrology	Restore habitat	Restore local hydraulic diversity and flow permanence	3	3	1	1	2	NA
Hydrology	Restore habitat	Implement appropriate flow variation to facilitate movement of fish between forest creeks and main channels	2	2	3	1	1	3
Vegetation	Gather information	Update surveys of littoral and submerged vegetation cover	3	3	3	1	1	1
Vegetation	Restore habitat	Identify and implement actions for submerged vegetation recovery	3	3	3	1	1	1

4.3.4 Toupna Creek

A key priority for Toupna Creek is to mitigate the barriers that prevent bi-directional movement of large-bodied fishes. In particular, this would involve upgrades to the Mary Ada Regulator, but other smaller regulators, such as Nine Panel and Neston's should also be considered, pending the results of the ongoing fish movement studies in Millewa Forest. Bi-directional movement will also be supported by seasonal flow variation – in particular, larger fish may need to be cued to leave small forest creeks by slow recession of flow. The appropriate flow regime will be informed by the ongoing fish movement work currently occurring in Millewa Forest.

Securing the capacity to deliver semi-permanent flowing water (supporting resident fish and enhancing the growth of juveniles) is also a high priority to support a permanent population of flow-dependent species in Toupna Creek.

To create optimal conditions for the growth and survival of juvenile channel specialist fish, enhancing aquatic vegetation in the creek is a high priority. Exact actions and locations will be informed by updated surveys of the existing vegetation condition in the creek, which are also a high priority.

Habitat in Toupna Creek could be further enhanced by placement of woody debris. However, given the current high density of woody debris in the creek, this is a lower priority action.

4.3.5 Swifts Creek and Bunnydigger Creek

A high priority is facilitating bi-directional movement for channel specialist fishes between the Murray River and the Moira Lake creeks system. Scoping regulator upgrades for the addition of fishways is a high priority, and then delivering flows to facilitate fish passage. Prior to modification, flows can be delivered that cue fish to leave before regulators are closed, including a slower decline of the discharge rate.

To support the growth and survival of juvenile channel specialist fish, enhancing aquatic vegetation in the creek system is a high priority. Exact actions and locations will be informed by updated surveys of the existing vegetation condition in the creek, which are also a high priority.

Restoring hydraulic diversity and flow permanence is a moderate priority, as Swifts Creek and Bunnydigger Creek currently receive a moderate amount of inflow from the Murray River.

4.3.6 Wild Dog Creek

To support juvenile fish that move into Wild Dog Creek, enhancing littoral and submerged vegetation is a high priority. When, where and how this is done will be informed by updated vegetation surveys, which are also a high priority.

Investigating the potential impact of the crossing on Wild Dog Creek on fish passage is a moderate priority, as is mediating this barrier if it is found to be impacting the ability of exploring juvenile fish to access forest creeks such as Toupna Creek and Cornalla Creek.

4.4 Draft Implementation plan 3 – Generalist fishes

One of the goals of the strategy is increased abundance and distribution of existing small-bodied native fish species, including Murray rainbowfish, flat-headed gudgeon, un-specked hardyhead, Australian smelt and carp gudgeon species, as well as expanded populations of bony herring. All of these species are generalists, with opportunistic life histories, so they can live in a variety of habitat types and are well placed to take advantage of ephemeral or marginal habitats.

In Table 11, we outline the candidate actions to support generalist species in Millewa Forest and provide a relative ranking of their priority. The sites considered here include Moira Lake, Reed Beds Swamp and smaller ephemeral wetlands that are periodically inundated. We do not identify specific locations for the ephemeral forest wetlands, as limited information is available in the literature on their location and conditions (although Sharpe and Wilson [2012] provide several examples).

Table 11 Priority of actions to restore floodplains and lakes for generalist species

Note: 1 (green) = highest priority, 2 (yellow) = moderate priority, 3 (red) = lower priority.

Habitat component	Action type	Action	Location		
			Moira Lake	Reed Beds Swamp	Ephemeral forest wetlands
Hydrology	Restore habitat/ gather information	Identify flooding regime that will maximise productivity, support submerged vegetation and facilitate fish access to wetland habitats	1	1	1
Invasive species	Restore habitat	Undertake targeted carp control to minimise spawning of carp on the floodplain	1	1	1
Invasive species	Gather information	Investigate impact of hard-hooved mammals on floodplain	3	2	1

4.4.1 Moira Lake

A high priority for Moira Lake is to identify the watering regime that will best support productivity, vegetation and connectivity relevant for small-bodied fishes, and to incorporate these considerations into the existing watering strategy. This requires more information on the watering regime at Moira Lake that will maximise benefits for small-bodied generalist fishes. It is acknowledged that these goals may compete with existing watering goals, such as waterbird breeding. However, explicitly including actions for generalist fishes means that all potential benefits of watering can be considered.

Managing carp is a high priority, as the large, shallow floodplain areas have the potential to support large carp breeding events, which will affect Moira Lake and Millewa Forest more generally. This is a complex issue, and may involve mechanical removal of large spawning aggregations, or altering timing of water delivery to avoid large areas of shallow, warm water during carp spawning season.

The current level of impact of hard-hooved invasive mammals is unclear. Given the large size of the lake and relative water permanence in areas, impacts are likely to be less concentrated and hence investigating these impacts is a low priority.

It should be noted that Moira Lake has the potential to act as a nursery site for young golden and silver perch if eggs and larvae drift in from the Murray River via Swifts and Bunnydigger regulators. Factors that will support small-bodied generalist fish, such as increased productivity, will also support perch recruitment. Hence, if it is observed that eggs and larvae are likely to be present, actions to restore Moira Lake may increase in priority.

4.4.2 Reed Beds Swamp

Reed Beds Swamp has the potential to be a highly productive floodplain area, supporting the short-term spawning and growth of opportunistic small-bodied generalist fishes. If water is delivered during the spawning season (late spring and summer), inundating previously dry areas, the resultant increase in productivity will likely support recruitment of large numbers of these fishes. If these areas are again connected with more permanent water bodies (such as The Cutting), then the recently spawned fish will have the chance to emigrate before Reed Beds Swamp dries again. Utilising this area as an ephemeral nursery has the potential to greatly increase the abundance and distribution of the target species. Implementing such a watering regime is a high priority, but should be considered alongside other goals, such as native vegetation and waterbirds.

Controlling carp in Reed Beds Swamp is a high priority to prevent increases in numbers due to spawning events. Actions may include trapping or screening at water entry points; restricted watering season or area to avoid large, shallow areas of warm water during carp spawning season; or mechanical removal of spawning aggregations of fish.

As with Moira Lake, the current level of impact of hard-hooved invasive mammals at Reed Beds Swamp is unclear. Understanding their impacts here is a moderate priority, given the large area and likely diffusion of impact, but the ephemeral nature of the floodplain makes it vulnerable to disturbance.

4.4.3 Ephemeral floodplain wetlands

To maximise the spawning and recruitment of generalist fishes on the broader floodplain of Millewa Forest, a high priority is management of floodplain inundation. Enacting a flood regime that maximises local productivity, enhances vegetation growth, facilitates access to these habitats and retains surface water at smaller wetlands on the floodplain through the breeding season will provide generalist, opportunistic fish with habitat to breed. If these sites are inundated again before they dry, the young fish will be able to return to more permanent habitats, increasing the abundance and distribution of these species. An advantage of this mechanism is that floodplain inundation can be opportunistic, in years when conditions are suitable, and fish will be able to quickly colonise the newly available habitat. The areas that can be inundated may increase or change under future relaxed constraints scenarios.

Coupled with wide floodplain inundation, carp management is a high priority, as flooded forest areas are ideal for carp spawning. Targeted carp removal may be effective at floodplain sites once they have retracted to pools, as these areas are smaller and more tractable to electrofish or net.

Understanding and, if necessary, mitigating the impacts of herbivores on these smaller floodplain wetlands is a high priority. As many of the ephemeral wetlands are relatively small, they may be subject to high levels of activity as animals congregate for water. The concentrated activity could damage vegetation and reduce the water quality.

Appendices

Appendix A: Conceptual model for golden perch

Source: The model below is a direct quote/extract from Sharpe and Stuart (2018).

Golden perch, 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 lifespan of 25 years and commonly reach 600 mm long.

Habitat use

- 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
- Diverse aquatic habitats are important to provide shelter and a productive food web, especially so these fish can feed in winter.
- Main river habitats are used for feeding and are also an important refuge and overwintering habitat.
- Habitat generalists often associated with physical habitat ('snags'), drop offs and deep water (Crook et al., 2001).
- 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

- The species is an opportunistic carnivore. The diet of adults consists mainly of shrimps, yabbies, small fish and benthic aquatic insect larvae (Baumgartner 2007).
- Juveniles consume more of the smaller items such as aquatic insect larvae and microcrustaceans (Lintermans 2007).

Spawning

- Long-lived, show variable growth and females are highly fecund, they display no parental care (Anderson et al., 1992b; Mallen-Cooper and Stuart, 2003).
- Spawning occurs in spring and early summer (October-February; >17oC; King et al., 2009a).
- A 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).
- Eggs 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).
- Fish spawn during 1-in-1 year bank full flows that have variability (e.g. 0.15 m/24 h) and during overbank flows.
- Eggs hatch after 1-2 days and larvae may drift for 10-12 days. Drift aids dispersal from spawning areas to feeding and nursery areas. Much of this drift is along the main river channel (i.e. 300 km drift distance), and larvae are likely to settle along the channel margins.

- Larval passage through undershot 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).
- There is no evidence that golden perch directly use ephemeral floodplains for spawning in the Murray system.
- 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 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

- Recruitment occurs during within-channel flows and especially during overbank flows when floodplains are inundated increasing productivity and larval survival (Mallen-Cooper and Stuart, 2003; Ye et al., 2008; Ebner et al., 2009; Zampatti and Leigh, 2013; Sharpe and Stuart 2018).
- Recent research indicates that the juvenile population, in the lower Murray and at least upstream to Torrumbarry, can be dominated by cohorts 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).
- 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 juveniles and adults from downstream and connectivity with the Victorian Murray.
- There is no evidence for enhanced recruitment from deliberate creation of 'slackwaters'.
- Young fish settle into off-stream floodplain or littoral riverine nursery habitats.
- 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).
- 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).
- 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).
- 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

- 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).

- 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).
- Movement is strongly cued by rising/falling flow and water temperature with much less migration in stable flow and in winter.
- Also move downstream in spring, summer and autumn (O'Connor et al., 2005).
- Thousands of immature golden perch and silver perch, that are one year and older, migrate upstream, responding to increased flow (e.g. +0.15m/24h) and these migrate into early autumn.
- 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.
- Juveniles make staged re-colonisation migrations, responding to a flow in a movement pulse and then stopping during stable flows.
- 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).
- A greater proportion of the fish population migrates during major overbank 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

- 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.
- 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.
- Spawning flows can be 1-in-1 year bankfull style events, with strong variability, and should be based on the natural hydrograph.
- Prioritising ‘slackwater’ habitats for larvae in these tributaries is highly unlikely to result in enhanced recruitment.
- 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).
- 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.
- Weir pool lowering can also be used in conjunction with environmental flows to maximise hydraulic diversity over large spatial scales (Ye et al., 2008).
- 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).
- 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.

Implications for flow monitoring

- 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.
- 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

- Loss of connectivity to floodplain nursery habitats
- River regulation and diversion restricts juvenile and adult movement, prevents dispersal and recolonisation of extensive stretches of river and increases risk of localised extinction and fragmentation
- Weirs may trap eggs and early larvae causing them to settle and die (Baumgartner et al., 2014a)
- Undershot weirs kill >90% of larvae (Boys et al., 2010)
- Thermal issues will limit spawning below weirs and possibly increase larvae survivorship
- Loss of off-channel floodplain nursery habitats
- Impoundment of riverine flowing water habitats
- Knowledge and data limitations
- Implementation of catchment scale flow planning to recover populations
- Impact of weir pools on egg/larvae survivorship
- 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).

Appendix B: Conceptual models for Murray cod

Source: The model below is a direct quote/extract from Sharpe and Stuart (2018)

Murray cod 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).

Habitat use

- Prefer permanent flowing river reaches and creeks with hydraulic complexity/diversity.
- Require woody debris (snags), debris piles and bank side vegetation (Koehn and Harrington 2005).
- 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).
- 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.
- 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

- Diet changes with age with the typical adult diet consisting of spiny crayfish, yabbies and shrimps (National Murray Cod Recovery Team 2010)
- 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*)].
- Less common animals found in the diet include ducks, cormorants, grebes, tortoises, water dragons, snakes, mice, frogs and mussels (Rowland, 1996).
- 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 begin to feed on aquatic insects (King, 2005).

Spawning

- Occurs annually during October, November and December each year (Humphries, 2005; Koehn and Harrington, 2005), occurs during base flows and during river rises (King et al., 2009a; Ye et al., 2008).
- Display complex pre-spawning courtship behaviour (during winter and spring) and females may spawn with more than one male.
- Females lay their eggs into nests. The male guards the nest for up to 2 weeks while the eggs hatch. Juveniles leave the nest and move into littoral or snag habitats.
- Despite often being classified as a 'flow independent spawner' Murray cod do require permanent flowing water for optimal recruitment ((Sharpe and Stuart 2016).
- Can spawn and recruit during low stable flows, rising flows and floods.

- Floods are not necessary for spawning but in some cases, appear to enhance subsequent recruitment (King et al., 2009a).
- 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).
- Mature late (3-5 years) and at a reasonably large size (>600 mm long) but females have relatively low egg numbers (fecundity).
- 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).
- Where riverine stocking occurs there can be significant augmentation of natural populations (Forbes et al., 2016).

Movement and migration

- May move large distances (e.g. up to 120 km) but are usually only a few kilometres (e.g. commonly up to 30 km), (Leigh and Zampatti, 2011; 2013).
- 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).
- 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).
- 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

- A specific Murray cod hydrograph should be implemented where population recovery is required (Sharpe and Stuart 2016, 2018).
- Flowing riverine sites can be considered ecological priorities for Murray cod recovery
- Application of the Murray cod hydrograph, especially high winter base flows, is required on an annual basis (Sharpe and Stuart 2016, 2018).

Implications for flow monitoring

- 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

- Lack of flowing water habitats with a high 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 high dams (Mallen-Cooper and Zampatti 2017).
- Loss of permanent flows when rivers and anabranches are de-watered during winter.
- In many regulated rivers and anabranches (e.g. Gunbower Creek, Gulpa Creek, Edward River, Mullaroo Creek) there are 2 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 2016).

Knowledge and data limitations

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

Appendix C: Conceptual model - wetland specialists

Source: The model below is a direct quote/extract from Stuart (2020)

Application to: southern pygmy perch, flat-headed galaxias, southern purple- spotted gudgeon and olive perchlet.

Movement

- 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.
- During a floodplain inundation event, these fish appear to be 'first colonisers' of newly inundated wetlands.
- 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.

Hydrology

- Wetland specialist fish naturally inhabit the full mosaic of wetland types across a floodplain landscape but these are generally slow flowing habitats.
- During annual flows that reconnect wetlands, or during small (e.g. 25,000 ML/d), medium (e.g. 35-40,000 ML/d) and large flood events (e.g. >40,000 ML/d) fish move among wetlands, even colonising temporary habitats.
- At Cameron's Creek, under natural conditions, overbank flows (e.g. 30,000 ML/d) would have occurred in >80% of years with a long mean duration (e.g. >100 days); (Gippel 2014).
- 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.

Physical habitat

- Wetland specialists are often found in small shallow ephemeral floodplain wetlands which flood regularly and have intact riparian canopy.
- Wetland specialists have broad physical habitat requirements and can be found among fine woody debris, leaf litter and branches, aquatic macrophytes and open water. Some species, such as southern purple-spotted gudgeons, have specific habitat requirements and are usually associated with macrophytes; hence re- establishing complex macrophytes is likely to be highly advantageous for recovery (Hammer et al. 2012).

Water quality

- 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 2007; Tonkin et al. 2008).

- Generally, there are population declines with increasing salinity, with the notable exception of Murray hardyhead.

Spawning and recruitment

- Low fecundity (usually < 2000 eggs per female)
- Spawn adhesive eggs on floodplain vegetation or non-adhesive demersal scatter, depending on the species.

Food

- Appear to require flooding of new floodplain habitats and productivity boom with a variety of food organisms (e.g. Invertebrates, zooplankton and shrimp).
- Do not thrive in permanent weirpool low-productivity style wetlands.

Threats

- The decline of wetland specialists is directly linked to reduced floodplain inundation frequency and duration where fish move among habitats (Wedderburn et al. 2017).
- 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).
- Changes to hydrology have reduced diversity and accessibility of wetland habitats (King et al. 2007).
- Returning one component of environmental flows cannot re-establish wetland specialists and a specific hydrograph is required at high priority sites.
- Impacts of invasive fish, especially carp, redfin perch and gambusia (Tonkin et al. 2008; Macdonald et al. 2012).
- 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.
- Loss of remnant wetland specialist populations during the Millennium drought, for example, southern pygmy perch at Barmah.

Appendix D: Conceptual model - wetland generalists

Source: The model below is a direct quote/extract from Stuart (2020)

Application to: carp gudgeon, flat-headed gudgeon, dwarf flat-headed gudgeon, un-specked hardyhead, Australian smelt and Murray rainbowfish.

Movement

- Wetland generalists move among Murray River main channel habitat and floodplains, usually in spring and summer, when wetlands become available as the river rises (Stuart et al. 2008; Lyon et al. 2010).
- Generalists tend to move on low regulated flows with relatively little riverine movement during high flows and floods.

Preferred habitats

- Generalist fish species tolerate a wide range of environmental conditions, have a flexible life history, and
- generally are highly fecund and small-bodied, and spawn over a protracted period independent of flow cues.
- The greatest diversity of generalist species usually inhabit 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).
- Australian smelt and un-specked hardyhead school in mid water, but also utilise some structural habitat such as plants and wood.

Physical habitat

- Prefer floodplains with complex and diverse macrophyte assemblages, usually prefer slow flowing habitats.

Hydrology

- Generalists inhabit a variety of wetland types but these are generally slow flowing habitats.
- Fish move at low regulated flows, often suffer severe population declines during major floods but usually recover quickly where connectivity is adequate.
- Resilient to low flows and floods.

Threats

- Impacts of invasive fish, especially carp, redfin and gambusia (Macdonald 2012; Tonkin 2014).
- Drying of wetlands with diverse macrophytes and small-bodied fish assemblages.
- Strong regular variations in wetland water levels.
- Loss of wetland macrophytes.
- Loss of connectivity to main channel habitats for regular exchange of fish and nutrients.

Water quality

- 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).

Food

- Appear to require flooding of new floodplain habitats and productivity boom with a variety of food organisms (e.g. Invertebrates, zooplankton and shrimp).
- Thrive in permanent weirpool low-productivity style wetlands.

Management implications of the conceptual models

- The short-term priority for Cameron Creek is to maintain the existing macrophyte and small-bodied generalist fish communities which are a valuable source population asset at the broader Gunbower Icon site scale.
- It is one of the rare areas in the MDB where flow regime favours native fish over alien species. There is a very low overall abundance of carp with few new recruits
- To maintain the wetland generalists, the priority focus area for active management is the upper Cameron's Creek and lagoons with Black Charlie Lagoon also likely to support these fish.
- It is strongly recommended to Implement a hydrological regime that supports self-sustaining wetland generalist populations, which is summarised in Tables 2 and 3.
- Baggott's Swamp and floodplain habitats should be restored as an ephemeral wetland to support relatively smaller sink populations of wetland generalists, most likely the more tolerant species such as carp gudgeons.
- Wetland specialists are highly unlikely to recolonise Cameron's Creek in the absence of restocking intervention, followed by implementation of a specific dispersal hydrograph. There are significant uncertainties with this model and hydrology and re-establishment of wetland specialists has a risk of failure until evaluations of other reintroductions (e.g. Barmah) are complete. Success can be greatly enhanced by ensuring the flow regime supports the various habitat requirements of wetland specialise species (macrophytes, slow flowing water and connectivity out of Baggots Swamp – if this is to be ephemerally dried).

Appendix E: Multi-criteria analysis to prioritise mitigation of regional threats to native aquatic fish identified in the strategy

Table 12 Multi-criteria analysis to prioritise mitigation of regional threats to native aquatic fish identified in the strategy

Notes: Named sites are included where there was sufficient information to assess threats; it is anticipated that threats will be similar at other unnamed sites within the same habitat type. Scores are from 1 (red) (low priority: high cost, long implementation time and weaker ecological response) to 3 (green) (high priority: lower cost, shorter implementation, and stronger ecological response). The certainty and action will be successfully implemented refers to the success of implementation of an action, not whether it will successfully restore fish population. The magnitude of ecological response refers to a predicted increase in target fish populations, and the certainty of ecological response refers to the certainty of this prediction. Target species are: MC = Murray cod, TC = trout cod, GP = golden perch, SP = silver perch, BH = bony herring, FC = freshwater catfish, RB = river blackfish, MP = Macquarie perch, SBG = small-bodied generalist species, SBS = small-bodied wetland specialist species.

Location	Action	Details	Target spp.	Certainty action will be successfully implemented	Ecological response to action			Planning		Implementation		Maintenance
					Magnitude	Timeframe	Certainty	Time	Cost	Time	Cost	Cost
Main channels												
Murray River	Mitigate barriers below Millewa Reach	Understand and mitigate impacts of Torrumbarry Weir on fish leaving and entering the Middle Murray	GP, SP, MC	High	2	Immediate	Moderate	2	2	2	1	3
	Restore appropriate flow variation	Implement hydrograph with attraction pulses for perches and with elevated, stable spawning flows for cods	MC, TC, SP, GP	High	2	Short	High	3	3	3	1	2
	Re-snagging	Increase connectivity between patches of woody debris around Millewa Forest	MC, TC, RB, SP, GP, SBG	High	2	Short	High	2	3	2	2	3

Location	Action	Details	Target spp.	Certainty action will be successfully implemented	Ecological response to action			Planning		Implementation		Maintenance
					Magnitude	Timeframe	Certainty	Time	Cost	Time	Cost	Cost
	Re-snagging	Increase density and connectivity of woody debris downstream of Millewa Forest	MC, TC, RB, SP, GP, SBG	High	3	Short	High	2	2	1	1	3
	Sedimentation management	Understand and mitigate process of sediment delivery, map and mitigate impacts in-channel	MC, TC, RB, GP, SP, BH, FC	Low	1	Moderate	Low	1	1	2	1	1
	Floodplain access	Identify large floodplain wetlands downstream of Millewa as possible nursery sites for SP/GP, and coordinate access	GP, SP	High	3	Short	Low	3	3	2	2	2
	Blackwater management	Develop blackwater management plan, maintain main channel refugia	MC, TC, SP, GP, BH, FC, MP, RB, SBG	Moderate	1	Moderate	High	2	3	2	2	2
Edward River	Mitigate barriers below Millewa Reach	Understand and mitigate impacts of Stevens Weir on fish leaving and entering the Millewa Forest region	GP, SP, MC	High	2	Immediate	Moderate	2	2	3	3	3
	Restore appropriate flow variation	Implement hydrograph with attraction pulses for perches and with elevated, stable spawning flows for cods	MC, TC, SP, GP	High	2	Short	High	3	3	3	2	2

Location	Action	Details	Target spp.	Certainty action will be successfully implemented	Ecological response to action			Planning		Implementation		Maintenance
					Magnitude	Timeframe	Certainty	Time	Cost	Time	Cost	Cost
	Blackwater management	Develop blackwater management plan, maintain connection with Murray channel refugia	MC, TC, SP, GP, BH, FC, MP, RB, SBG	Moderate	2	Moderate	Low	2	3	2	2	2
Gulpa Creek	Restore appropriate flow variation	Implement hydrograph with attraction pulses for perches and with elevated, stable spawning flows for cods	MC, TC, SP, GP	High	2	Short	High	3	3	3	2	2
	Restore hydraulic diversity	Investigate causes of slower middle reach flows, deliver altered flows if necessary, place woody debris to disrupt laminar flow	MC, TC, SP, GP	High	2	Immediate	Moderate	2	2	3	3	3
	Re-snagging	Increase density and connectivity of woody debris	MC, TC, RB, SP, GP, SBG	High	3	Short	High	3	3	2	1	3
	Blackwater management	Develop blackwater management plan, maintain connection with Murray channel refugia	MC, TC, SP, GP, BH, FC, MP, RB, SBG	Moderate	2	Moderate	Low	2	3	2	2	2
Forest creek channels												
Toupna Creek	Mitigate barriers at regulators	Mitigate the impeded connectivity with Murray River and creek,	MC, TC	High	3	Immediate	High	3	3	2	1	2

Location	Action	Details	Target spp.	Certainty action will be successfully implemented	Ecological response to action			Planning		Implementation		Maintenance
					Magnitude	Timeframe	Certainty	Time	Cost	Time	Cost	Cost
		especially Mary Ada Regulator										
	Implement appropriate flow variation	Deliver flows that will cue exploring main channel specialist fishes to leave if regulators are to be closed	MC, TC	High	2	Immediate	High	3	3	3	3	3
	Restore hydraulic diversity of creek	Deliver flows to create and maintain hydraulically diverse reaches within Toupna Creek	MC, TC, RB, MP	High	2	Short	High	3	3	3	2	2
	Restore flowing water in creek	Deliver flows to create and maintain water levels and flowing water in creek	MC, TC, RB, MP, FC, SBG, SBS	High	3	Short	High	3	3	3	2	2
	Restore aquatic vegetation	Investigate causes of degraded vegetation and implement solutions (likely restored water levels)	MC, TC, RB, MP, FC, SBG, SBS	Low	1	Moderate	Low	2	2	2	2	3
	Blackwater management	Develop blackwater management plan, maintain connection with Murray channel refugia	MC, TC, BH, FC, MP, RB, SBG, SBS	Moderate	2	Moderate	Low	2	3	2	2	2
	Mitigate barriers at regulators	Mitigate the impeded connectivity with Murray	MC, TC, SP, GP	High	3	Immediate	High	3	3	2	2	2

Location	Action	Details	Target spp.	Certainty action will be successfully implemented	Ecological response to action			Planning		Implementation		Maintenance
					Magnitude	Timeframe	Certainty	Time	Cost	Time	Cost	Cost
Swifts Creek, Bunnydigger Creek		River and creek regulators										
	Implement appropriate flow variation	Deliver flows that will cue main channel specialist fishes to leave if regulators are to be closed	MC, TC, SP, GP	High	2	Immediate	High	3	3	3	2	3
	Restore hydraulic diversity of creek	Deliver flows to create and maintain hydraulically diverse reaches within creeks	MC, TC, SP, GP, RB, MP	High	2	Short	High	3	3	3	2	3
	Restore flowing water in creek	Deliver flows to create and maintain water levels and flowing water in creeks	MC, TC, SP, GP, RB, MP, FC, SBG	High	3	Short	High	3	3	3	2	3
	Restore aquatic vegetation	Investigate causes of degraded vegetation and implement solutions (likely restored water levels)	MC, TC, SP, GP, RB, MP, FC, SBG	Low	1	Moderate	Low	2	2	2	2	3
	Blackwater management	Develop blackwater management plan, maintain connection with Murray channel refugia	MC, TC, SP, GP, RB, MP, FC, SBG	Moderate	2	Moderate	Low	2	3	2	2	2
Wild Dog Creek	Mitigate barrier	Investigate the degree of impingement of fish passage at Clay Island Road crossing and mitigate if necessary	MC, TC, SP, GP	High	2	Immediate	High	2	2	2	2	3

Location	Action	Details	Target spp.	Certainty action will be successfully implemented	Ecological response to action			Planning		Implementation		Maintenance
					Magnitude	Timeframe	Certainty	Time	Cost	Time	Cost	Cost
	Restore aquatic vegetation	Investigate causes of degraded vegetation and implement solutions (likely restored water levels)	MC, TC, SP, GP, RB, MP, FC, SBG	Low	1	Moderate	Low	2	2	2	2	3
	Blackwater management	Develop blackwater management plan, maintain connection with Murray channel refugia if possible	MC, TC, SP, GP, RB, MP, FC, SBG	Moderate	2	Moderate	Low	2	3	2	2	2
	Threatened fish translocations	Develop and implement threatened fish translocation plan	FC, RB, MP	Moderate	3	Moderate	High	2	2	2	3	2
Off-channel sites												
Moira Lake	Mitigate barriers at regulators	Mitigate the impeded connectivity with Murray River and creeks around Moira Lake	SP, GP, FC, BH, SBG	High	3	Immediate	Moderate	2	2	2	1	2
	Improve flooding regime	Investigate and implement flooding regime to maximise productivity and facilitate access of larval SP/GP	SP, GP, FC, BH, SBG, SBS	Moderate	3	Short	Low	2	2	2	2	2
	Restore aquatic vegetation	Investigate causes of degraded vegetation and implement solutions (likely restored water level fluctuations)	SP, GP, FC, BH, SBG, SBS	Low	1	Moderate	Low	2	2	2	2	3

Location	Action	Details	Target spp.	Certainty action will be successfully implemented	Ecological response to action			Planning		Implementation		Maintenance
					Magnitude	Timeframe	Certainty	Time	Cost	Time	Cost	Cost
	Sedimentation management	Understand and mitigate process of sediment delivery, map and mitigate impacts in wetland	SP, GP, FC, BH, SBG, SBS	Low	3	Moderate	Low	2	2	2	2	1
	Undertake targeted carp control	Control carp, particularly during spawning season, to reduce number of carp produced at Moira Lake	All	Moderate	3	Short	Low	3	3	2	2	2
	Blackwater management	Develop blackwater management plan, maintain connection with Murray channel refugia if possible	SP, GP, FC, BH, SBG	Moderate	2	Moderate	Low	2	3	2	2	2
Reed Beds Swamp	Improve flooding regime	Investigate and implement flooding regime to maximise productivity and facilitate access of larval SP/GP	SP, GP, FC, BH, SBG, SBS	High	3	Short	Low	3	3	2	2	2
	Undertake targeted carp control	Control carp, particularly during spawning season, to reduce number of carp produced at Reed Beds	SP, GP, FC, BH, SBG, SBS	Moderate	3	Short	Low	3	3	2	2	2
	Blackwater management	Develop blackwater management plan, maintain connection with Murray channel refugia if possible	SP, GP, FC, BH, SBG	Moderate	2	Moderate	Low	2	3	2	2	2

Location	Action	Details	Target spp.	Certainty action will be successfully implemented	Ecological response to action			Planning		Implementation		Maintenance
					Magnitude	Timeframe	Certainty	Time	Cost	Time	Cost	Cost
Permanent forest wetlands	Threatened fish translocations	Develop and implement threatened fish translocation plan	SBS, FC	Moderate	3	Moderate	High	2	3	2	2	2
	Improve flooding regime	Investigate and implement flooding regime to maximise productivity and aquatic vegetation and facilitate dispersal of SBG/FC	SBS, SBG, FC	Low	2	Moderate	Moderate	3	2	2	s	2
	Ensure surface water security	Investigate hydrology of wetland and develop drought management plan to maintain surface water	SBS, SBG	Moderate	3	Moderate	High	3	3	2	2	2
	Restore aquatic vegetation	Investigate causes of degraded vegetation and implement solutions	SBS, SBG	Moderate	3	Moderate	Moderate	2	2	3	3	3
	Invasive fish management	Undertake control measures, targeting elimination of Carp and Redfin	SBS, SBG	High	3	Immediate	High	3	3	3	2	2
	Invasive mammal management	Investigate impact of hard-hooved mammals on littoral zone, undertake exclusion if necessary, explicitly include small wetlands in mammal management plans	SBS, SBG	High	1	Moderate	Moderate	3	3	2	2	2

Location	Action	Details	Target spp.	Certainty action will be successfully implemented	Ecological response to action			Planning		Implementation		Maintenance
					Magnitude	Timeframe	Certainty	Time	Cost	Time	Cost	Cost
	Blackwater management	Develop blackwater management plan, investigating flows at which wetlands are likely to be impacted	SBS, SBG, FC	Moderate	1	Moderate	Moderate	2	3	2	2	2
Horseshoe Lagoon	Mitigate barrier at regulator	Mitigate impeded connectivity with Murray River	SBG, FC	Moderate	2	Short	Low	3	3	2	1	2
Ephemeral forest wetlands	Improve flooding regime	Investigate and implement flooding regime to maximise productivity and aquatic vegetation and facilitate opportunistic use of ephemeral wetlands	SBG, BH, FC, SBS	Moderate	2	Moderate	Moderate	2	2	2	1	2
	Alter water delivery	Investigate (and implement if possible) new areas to be inundated under relaxed constraints scenarios	SBG, BH, FC, SBS	Moderate	3	Moderate	High	3	3	3	3	3
	Invasive fish management	Undertake targeted control measures to prevent large carp spawning events in ephemeral wetlands	All	Moderate	3	Short	Low	2	2	3	2	2
	Invasive mammal management	Investigate impact of hard-hooved mammals on wetlands, undertake exclusion if necessary,	SBG, BH, FC, SBS	Low	1	Moderate	Low	3	3	2	2	2

Location	Action	Details	Target spp.	Certainty action will be successfully implemented	Ecological response to action			Planning		Implementation		Maintenance
					Magnitude	Timeframe	Certainty	Time	Cost	Time	Cost	Cost
		explicitly include floodplain impacts in mammal management plans										
	Blackwater management	Develop blackwater management plan, investigating potential impacts of ephemeral floodplain inundation and relaxed constraints	All	Moderate	3	Moderate	High	2	3	2	2	2

5. References

Allen GR, Midgley SH and Allen M (2002) ‘Field guide to freshwater fishes of Australia’, *Choice Reviews Online*, 40(03):40-1545-40–1545, doi:10.5860/CHOICE.40-1545.

Arumugam PT and Geddes MC (1986) ‘Feeding and growth of golden perch larvae and fry (Macquaria ambigua Richardson).’, *Transactions of the Royal Society of South Australia*.

Balcombe SR, Bunn SE, McKenzie-Smith FJ and Davies PM (2005) ‘Variability of fish diets between dry and flood periods in an arid zone floodplain river’, *Journal of Fish Biology*, 67(6):1552–1567, doi:10.1111/j.1095-8649.2005.00858.x.

Balcombe SR, Turschwell MP, Arthington AH and Fellows CS (2015) ‘Is fish biomass in dryland river waterholes fuelled by benthic primary production after major overland flooding?’, *Journal of Arid Environments*, 116:71–76, doi:10.1016/j.jaridenv.2015.01.020.

Barneche DR, Robertson DR, White CR and Marshall DJ (2018) ‘Fish reproductive-energy output increases disproportionately with body size’, *Science*, 360(6389):642 LP – 645, doi:10.1126/science.aao6868.

Baumgartner LJ, Boys CA, Stuart IG and Zampatti BP (2010) ‘Evaluating migratory fish behaviour and fishway performance: testing a combined assessment methodology’, *Australian Journal of Zoology*, 58(3):154–164.

Baumgartner LJ, Conallin J, Wooden I, Campbell B, Gee R, Robinson WA and Mallen-Cooper M (2014) ‘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(3):410–427, doi:10.1111/faf.12023.

Baumgartner LJ and Harris JH (2007) ‘Passage of non-salmonid fish through a Deelder lock on a lowland river’, *River Research and Applications*, 23(10):1058–1069, doi:https://doi.org/10.1002/rra.1032.

Beesley L, King AJ, Amtstaetter F, Koehn JD, Gawne B, Price A, Nielsen DL, Vilizzi L and Meredith SN (2012) ‘Does flooding affect spatiotemporal variation of fish assemblages in temperate floodplain wetlands?’, *Freshwater Biology*, 57(11):2230–2246, doi:10.1111/j.1365-2427.2012.02865.x.

Bertilsson S and Jones JB (2003) ‘Supply of Dissolved Organic Matter to Aquatic Ecosystems: Autochthonous Sources’, in SEG Findlay and RLBT-AE Sinsabaugh (eds) *Aquatic Ecology*, Academic Press, Burlington, doi:https://doi.org/10.1016/B978-012256371-3/50002-0.

Bond N and Lake PS (2003) ‘Characterizing fish-habitat associations in streams as the first step in ecological restoration’, *Austral Ecology*, 28:611–621.

Bren LJ (2005) The changing hydrology of the Barmah-Millewa Forests and its effect on vegetation, Royal Society of Victoria; 1998.

Broadhurst B, Clear R, Fulton C and Lintermans M (2016) ‘Enlarged cotter reservoir ecological monitoring program: technical report 2016’, *University of Canberra, Canberra*.

Broadhurst BT, Ebner BC and Clear RC (2012) ‘A rock-ramp fishway expands nursery grounds of the endangered Macquarie perch (*Macquaria australasica*)’, *Australian Journal of Zoology*, 60(2):91–100.

Brown P and Gilligan D (2014) ‘Optimising an integrated pest-management strategy for a spatially structured population of common carp (Cyprinus carpio) using meta-population modelling’, *Marine and Freshwater Research*, 65(6):538–550.

Cadwallader PL (1977) *JO Langtry's 1949-50 Murray River investigations*, Fisheries and Wildlife Division, Victoria.

Camaclang AE, Maron M, Martin TG and Possingham HP (2014) 'Current practices in the identification of critical habitat for threatened species', *Conservation Biology*, 29(2):482–492, doi:10.1111/cobi.12428.

Chessman BC (2013) 'Identifying species at risk from climate change: Traits predict the drought vulnerability of freshwater fishes', *Biological Conservation*, 160:40–49, doi:10.1016/j.biocon.2012.12.032.

Closs GP, Ludgate B and Goldsmith RJ (2001) 'Controlling European perch (Perca fluviatilis): lessons from an experimental removal', in *Proceedings of the workshop: Managing invasive freshwater fish in New Zealand*.

Clunie P, Stuart I, Jones M, Crowther D, Schreiber S, McKay S, O'Connor J, McLaren D, Weiss J and Gunasekera L (2002) 'A risk assessment of the impacts of pest species in the riverine environment in the Murray-Darling Basin', *Report prepared for the Murray Darling Basin Commission, Strategic Investigations and Riverine Program, Project*, 2006.

Conallin AJ, Hillyard KA, Walker KF, Gillanders BM and Smith BB (2011) 'Offstream movements of fish during drought in a regulated lowland river', *River Research and Applications*, 27(10):1237–1252, doi:10.1002/rra.1419.

Conallin AJ, Smith BB, Thwaites LA, Walker KF and Gillanders BM (2012) 'Environmental Water Allocations in regulated lowland rivers may encourage offstream movements and spawning by common carp, Cyprinus carpio: implications for wetland rehabilitation', *Marine and Freshwater Research*, 63(10):865, doi:10.1071/MF12044.

Cornell GL, Hale R, Morrongiello JR and Downes BJ (2022) 'Experimental increases in detritus boost abundances of small-bodied fish in a sand-affected stream', *Freshwater Biology*, 67(4):742–755.

Crook DA and Robertson AI (1999) 'Relationships between riverine fish and woody debris: implications for lowland rivers', *Marine and Freshwater Research*, 50(8):941–953.

Doupé RG, Mitchell J, Knott MJ, Davis AM and Lymbery AJ (2010) 'Efficacy of exclusion fencing to protect ephemeral floodplain lagoon habitats from feral pigs (Sus scrofa)', *Wetlands Ecology and Management*, 18(1):69–78.

Doupé RG, Schaffer J, Knott MJ and Dicky PW (2009) 'A description of freshwater turtle habitat destruction by feral pigs in tropical north eastern Australia', *Herpetological Conservation and Biology*, 4:331–339.

Dudgeon D, Arthington AH, Gessner MO, Kawabata Z-I, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard A-H, Soto D, Stiassny MLJ and Sullivan CA (2006) 'Freshwater biodiversity: importance, threats, status and conservation challenges', *Biological reviews*, 81(2):163–182.

Ellis I and Kavanagh M (2014) *A review of the biology and status of the endangered Murray hardyhead: streamlining recovery processes*, Report for Murray–Darling Basin Authority. Murray Darling Freshwater Research Centre.

Ellis I, Whiterod N, Linklater D, Bogenhuber D, Brown P and Gilligan D (2015) 'Spangled perch (Leiopotherapon unicolor) in the southern Murray Darling Basi: Flood dispersal and short-term persistence outside its core range', *Austral Ecology*, 40(5):591–600.

Erskine WD and Webb AA (2003) 'Desnagging to resnagging: new directions in river rehabilitation in southeastern Australia', *River Research and Applications*, 19(3):233–249, doi:10.1002/rra.750.

Gell P and Reid M (2014) 'Assessing change in floodplain wetland condition in the Murray Darling Basin, Australia', *Anthropocene*, 8:39–45, doi:https://doi.org/10.1016/j.ancene.2014.12.002.

Hale J and Butcher R (2011) Ecological Character Description for the Barmah Forest Ramsar Site, Canberra.

Hale R, Blumstein DT, Mac Nally R and Swearer SE (2020) 'Harnessing knowledge of animal behavior to improve habitat restoration outcomes', *Ecosphere*, 11(4):e03104, doi:10.1002/ecs2.3104.

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

Hitt NP, Rogers KM, Kelly ZA, Henesy J and Mullican JE (2020) 'Fish life history trends indicate increasing flow stochasticity in an unregulated river', *Ecosphere*, 11(2):e03026.

Hobbs RJ, Higgs E and Harris JA (2009) 'Novel ecosystems: implications for conservation and restoration', *Trends in ecology & evolution*, 24(11):599–605.

Houde ED (1989) 'Subtleties and episodes in the early life of fishes', *Journal of Fish Biology*, 35:29–38.

Humphries P, King A, Mccasker N, Kopf RK, Stoffels R, Zampatti B and Price A (2020) 'Riverscape recruitment: a conceptual synthesis of drivers of fish recruitment in rivers', *Canadian Journal of Fisheries and Aquatic Sciences*, 77:213–225.

Humphries P, Serafini LG and King AJ (2002) 'River regulation and fish larvae: variation through space and time', *Freshwater Biology*, 47(7):1307–1331, doi:10.1046/j.1365-2427.2002.00871.x.

Hutchison M, Norris A and Nixon D (2020) 'Habitat preferences and habitat restoration options for small-bodied and juvenile fish species in the northern Murray–Darling Basin', *Ecological Management & Restoration*, 21(1):51–57, doi:https://doi.org/10.1111/emr.12394.

IUCN/SSC (2013) *Guidelines for Reintroductions and Other Conservation Translocations*, Gland, https://portals.iucn.org/library/efiles/documents/2013-009.pdf, accessed 14 August 2023.

Jansson R, Backx H, Boulton AJ, Dixon M, Dudgeon D, Hughes FMR, Nakamura K, Stanley EH and Tockner K (2005) 'Stating mechanisms and refining criteria for ecologically successful river restoration: a comment on Palmer et al. (2005)', *Journal of Applied Ecology*, 42(2):218–222, doi:10.1111/j.1365-2664.2005.01022.x.

Jones M and Stuart I (2008) 'Regulated floodplains – a trap for unwary fish', *Fisheries Management and Ecology*, 15(1):71–79, doi:https://doi.org/10.1111/j.1365-2400.2007.00580.x.

JOSEPH LN, MALONEY RF and POSSINGHAM HP (2009) 'Optimal Allocation of Resources among Threatened Species: a Project Prioritization Protocol', *Conservation Biology*, 23(2):328–338, doi:10.1111/j.1523-1739.2008.01124.x.

Junk WJ, Bayley PB and Sparks RE (1989) 'The Flood Pulse Concept in River-Floodplain Systems', in *Canadian Special Publication of Fisheries and Aquatic Sciences*.

Kahan G, Colloff M and Pittock J (2020) 'Using an ecosystem services approach to re-frame the management of flow constraints in a major regulated river basin', *Australasian Journal of Water Resources*1–12, doi:10.1080/13241583.2020.1832723.

Keller RP and Lake PS (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, doi:10.1111/j.1600-0633.2006.00204.x.

Keogh A (2012) Barmah-Millewa Flood Maps, Hydrodynamic modelling 8,000 - 65,000 Ml/d, Report for Murray–Darling Basin Authority.

King AJ (2005) ‘Fish and the Barmah-Millewa Forest: history, status and management challenges’, *PROCEEDINGS-ROYAL SOCIETY OF VICTORIA*, 117(1):117.

King AJ, Crook DA, Koster WM, Mahoney J and Tonkin Z (2005) ‘Comparison of larval fish drift in the Lower Goulburn and mid-Murray Rivers’, *Ecological Management & Restoration*, 6(2):136–139, doi:https://doi.org/10.1111/j.1442-8903.2005.230-3.x.

King AJ, Gwinn DC, Tonkin Z, Mahoney J, Raymond S and Beesley L (2016) ‘Using abiotic drivers of fish spawning to inform environmental flow management’, *Journal of Applied Ecology*, 53(1):34–43, doi:https://doi.org/10.1111/1365-2664.12542.

King AJ, Tonkin Z and Lieshcke J (2012) ‘Short-term effects of a prolonged blackwater event on aquatic fauna in the Murray River, Australia: considerations for future events’, *Marine and Freshwater Research*, 63(7):576–586.

King AJ, Tonkin Z and Mahoney J (2009) ‘Environmental flow enhances native fish spawning and recruitment in the Murray River, Australia’, *River Research and Applications*, 25(10):1205–1218, doi:https://doi.org/10.1002/rra.1209.

King AJ, Ward KA, O’Connor P, Green D, Tonkin Z and Mahoney J (2010) ‘Adaptive management of an environmental watering event to enhance native fish spawning and recruitment’, *Freshwater Biology*, 55(1):17–31, doi:10.1111/j.1365-2427.2009.02178.x.

Kitchingman A, Stuart I and Sharpe C (2020) *Habitat mapping to inform the recovery of large bodied native fish in Millewa Forest*, Report prepared for National Parks and Wildlife Service NSW, Arthur Rylah Institute.

Kobayashi T, Ralph TJ, Ryder DS and Hunter SJ (2013) ‘Gross primary productivity of phytoplankton and planktonic respiration in inland floodplain wetlands of southeast Australia : habitat-dependent patterns and regulating processes’, , 2:833–843, doi:10.1007/s11284-013-1065-6.

Kobayashi T, Ralph TJ, Ryder DS, Hunter SJ, Shiel RJ and Segers H (2015) ‘Spatial dissimilarities in plankton structure and function during flood pulses in a semi-arid floodplain wetland system’, 19–31, doi:10.1007/s10750-014-2119-7.

Kobayashi T, Ryder DS, Gordon G, Shannon I, Ingleton T, Carpenter M and Jacobs S (2009) ‘Short-term response of nutrients, carbon and planktonic microbial communities to floodplain wetland inundation’, *Aquatic Ecology*, 43:843–858, doi:10.1007/s10452-008-9219-2.

Koehn J and Lintermans M (2012) ‘A strategy to rehabilitate fishes of the Murray-Darling Basin, south-eastern Australia’, *Endangered Species Research*, 16(2):165–181, doi:10.3354/esr00398.

Koehn JD (2004) ‘Carp (Cyprinus carpio) as a powerful invader in Australian waterways’, *Freshwater Biology*, 49(7):882–894, doi:https://doi.org/10.1111/j.1365-2427.2004.01232.x.

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

Koehn JD and Harrington DJ (2006) ‘Environmental conditions and timing for the spawning of Murray cod (Maccullochella peelii peelii) and the endangered trout cod (M. macquariensis) in southeastern Australian rivers’, *River Research and Applications*, 22(3):327–342, doi:https://doi.org/10.1002/rra.897.

Koehn JD, McKenzie JA, O’mahony DJ, Nicol SJ, O’connor JP and O’connor WG (2009) ‘Movements of Murray cod (Maccullochella peelii peelii) in a large Australian lowland river’, *Ecology of Freshwater Fish*, 18(4):594–602.

Koehn JD and Nicol SJ (2014) ‘Comparative habitat use by large riverine fishes’, *Marine and Freshwater Research*, 65(2):164–174.

Koehn JD and Nicol SJ (2016) ‘Comparative movements of four large fish species in a lowland river’, *Journal of Fish Biology*, 88(4):1350–1368.

Koehn JD, Nicol SJ, McKenzie JA, Lieschke JA, Lyon JP and Pomorin K (2008) ‘Spatial ecology of an endangered native Australian Percichthyid fish, the trout cod Maccullochella macquariensis’, *Endangered Species Research*, 4(1–2):219–225.

Koehn John D, Raymond SM, Stuart I, Todd CR, Balcombe SR, Zampatti BP, Bamford H, Ingram BA, Bice CM, Burndred K, Butler G, Baumgartner L, Clunie P, Ellis I, Forbes JP, Hutchison M, Koster WM, Lintermans M, Lyon JP, Mallen-Cooper M, McLellan M, Pearce L, Ryall J, Sharpe C, Stoessel DJ, Thiem JD, Tonkin Z, Townsend A and Ye Q (2020) ‘A compendium of ecological knowledge for restoration of freshwater fishes in Australia’s Murray–Darling Basin’, *Marine and Freshwater Research*, 71(11):1391–1463.

Koehn John D., Raymond SM, Stuart I, Todd CR, Balcombe SR, Zampatti BP, Bamford H, Ingram BA, Bice CM, Burndred K, Butler G, Baumgartner L, Clunie P, Ellis I, Forbes JP, Hutchison M, Koster WM, Lintermans M, Lyon JP, Mallen-Cooper M, McLellan M, Pearce L, Ryall J, Sharpe C, Stoessel DJ, Thiem JD, Tonkin Z, Townsend A and Ye Q (2020) ‘A compendium of ecological knowledge for restoration of freshwater fishes in Australia’s Murray–Darling Basin’, *Marine and Freshwater Research*, 71(11):1391–1463, doi:10.1071/MF20127.

Koehn JD and Todd CR (2012) ‘Balancing conservation and recreational fishery objectives for a threatened fish species, the Murray cod, Maccullochella peelii’, *Fisheries Management and Ecology*, 19(5):410–425.

Koster WM, Dawson DR, Liu C, Moloney PD, Crook DA and Thomson JR (2017) ‘Influence of streamflow on spawning-related movements of golden perch Macquaria ambigua in south-eastern Australia’, *Journal of Fish Biology*, 90(1):93–108, doi:https://doi.org/10.1111/jfb.13160.

Koster WM, Fanson B, Stuart I and Dawson D (2020) ‘Environmental influences on migration patterns and pathways of a threatened potamodromous fish in a regulated lowland river network’, , (July):1–12, doi:10.1002/eco.2260.

Lancaster J and Downes BJ (2021) ‘Multiyear resource enrichment creates persistently higher species diversity in a landscape-scale field experiment’, *Ecology*, 102(9), doi:10.1002/ecy.3451.

Leslie DJ (1995) Moira Lake: a case study of the deterioration of a River Murray natural resource, University of Melbourne.

Lindenmayer DB and Likens GE (2010) ‘The science and application of ecological monitoring’, *Biological Conservation*, 143(6):1317–1328, doi:10.1016/j.biocon.2010.02.013.

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

Lintermans M (2013) ‘The rise and fall of a translocated population of the endangered Macquarie perch, Macquaria australasica, in south-eastern Australia’, *Marine and Freshwater Research*, 64(9):838, doi:10.1071/MF12270.

Llewellyn L (2011) ‘Observations on the breeding biology of Ambassis agassizii Steindachner, 1867 (Teleostei: Ambassidae) from the Murray Darling Basin in New South Wales’, *Australian Zoologist*, 34(4):476–498, doi:10.7882/AZ.2008.026.

Llewellyn LC (2014) ‘Breeding biology, and egg and larval development of Galaxias rostratus Klunzinger, the Murray Jollytail from inland New South Wales’, *Australian Zoologist*, 33(2):141–165, doi:10.7882/AZ.2005.011.

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(3):271, doi:10.1071/MF08246.

Lyon JP, Bird T, Tonkin Z, Raymond S, Sharley J and Hale R (2021) 'Does life history mediate discharge as a driver of multi-decadal changes in populations of freshwater fish?', *Ecological Applications*, n/a(n/a):e02430, doi:https://doi.org/10.1002/eap.2430.

Lyon JP, Bird TJ, Kearns J, Nicol S, Tonkin Z, Todd CR, O'Mahony J, Hackett G, Raymond S, Lieschke J, Kitchingman A and Bradshaw CJA (2019) 'Increased population size of fish in a lowland river following restoration of structural habitat', *Ecological Applications*, 29(4):e01882, doi:https://doi.org/10.1002/eap.1882.

MacDonald JI, Tonkin ZD, Ramsey DSL, Kaus AK, King AK and Crook DA (2012) 'Do invasive eastern gambusia (Gambusia holbrooki) shape wetland fish assemblage structure in south-eastern Australia?', *Marine and Freshwater Research*, 63(8):659–671, doi:10.1071/MF12019.

Maheshwari BL, Walker KF and McMahon TA (1995) 'Effects of regulation on the flow regime of the River Murray, Australia', *Regulated Rivers: Research & Management*, 10(1):15–38.

Mallen-Cooper M (1999) 'Developing fishways for nonsalmonid fishes: a case study from the Murray River in Australia', *Innovations in fish passage technology*, 173.

Mallen-cooper M, Stuart I and Sharpe C (2014) The Native Fish Recovery Plan – Gunbower and Lower Loddon.

Mallen-Cooper M and Stuart IG (2003) 'Age, growth and non-flood recruitment of two potamodromous fishes in a large semi-arid/temperate river system', *River Research and Applications*, 19(7):697–719, doi:https://doi.org/10.1002/rra.714.

Mallen-Cooper M and Zampatti BP (2018) 'History, hydrology and hydraulics: Rethinking the ecological management of large rivers', *Ecohydrology*, 11(5):e1965, doi:10.1002/eco.1965.

Mateo JRSC (2012) 'Multi-Criteria Analysis', Springer Science & Business Media, doi:10.1007/978-1-4471-2346-0_2.

McKinnon LJ (1997) Monitoring of fish aspects of the flooding of Barmah Forest, Murray-Darling Basin Commission.

Mcmaster D and Bond N (2008) 'A field and experimental study on the tolerances of fish to Eucalyptus camaldulensis leachate and low dissolved oxygen concentrations', *Marine and Freshwater Research*, 59:177–185, doi:10.1071/MF07140.

McNeil DG (2004) 'Ecophysiology and behaviour of Ovens River floodplain fish: hypoxia tolerance and the role of the physicochemical environment in structuring Australian billabong fish communities'.

MCNEIL DG and CLOSS GP (2007) 'Behavioural responses of a south-east Australian floodplain fish community to gradual hypoxia', *Freshwater Biology*, 52(3):412–420, doi:10.1111/j.1365-2427.2006.01705.x.

Mendoza GA and Prabhu R (2005) 'Combining participatory modeling and multi-criteria analysis for community-based forest management', *Forest Ecology and Management*, 207(1–2):145–156, doi:10.1016/j.foreco.2004.10.024.

Murray Darling Basin Authority (2012) Barmah-Millewa Forest Environmental Water Management Plan, Canberra.

Murray-Darling Basin Authority (2018) *Icon site condition: The Living Murray*, Canberra, https://apo.org.au/node/143276, accessed 14 August 2023.

Nicol SJ, Lieschke JA, Lyon JP and Koehn JD (2004) ‘Observations on the distribution and abundance of carp and native fish, and their responses to a habitat restoration trial in the Murray River, Australia’, *New Zealand Journal of Marine and Freshwater Research*, 38(3):541–551, doi:10.1080/00288330.2004.9517259.

Nilsson C, Reidy CA, Dynesius M and Revenga C (2005) ‘Fragmentation and flow regulation of the world’s large river systems’, *Science*, 308(5720):405–408, doi:https://doi.org/10.1126/science.1107887.

NSW Department of Planning I and E (2020) *Water quality technical report for the Murray Lower Darling surface water resource plan area (SW8)* , https://apo.org.au/node/257731, accessed 14 August 2023.

O’Connor JP, O’Mahony DJ and O’Mahony JM (2005) ‘Movements of Macquaria ambigua, in the Murray River, south-eastern Australia’, *Journal of Fish Biology*, 66(2):392–403.

Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, Carr J, Clayton S, Dahm CN, Follstad Shah J, Galat DL, Loss SG, Goodwin P, Hart DD, Hasset B, Jenkinson R, Kondolf GM, Lave R, Meyer JL, O’Donnell TK, Pagano L and Sudduth E (2005) ‘Standards for ecologically successful river restoration’, *Journal of Applied Ecology*, 42(2):208–217, doi:10.1111/j.1365-2664.2005.01004.x.

Papas P, Hale R, Amtstaetter F, Clunie P, Rogers D, Brown G, Brooks J, Cornell G, Stamation K and Downe J (2021) *Wetland monitoring and assessment program for environmental water: stage 3 final report*, Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, https://www.ari.vic.gov.au/__data/assets/pdf_file/0027/517806/WetMAP-Stage-3-Synthesis-Report.pdf, accessed 14 August 2023.

Pepin P (1993) ‘An Appraisal of the Size-Dependent Mortality Hypothesis for Larval Fish: Comparison of a Multispecies Study with an Empirical Review’, *Canadian Journal of Fisheries and Aquatic Sciences*, 50(10):2166–2174, doi:10.1139/f93-242.

Pinto L, Chandrasena N, Pera J, Hawkins P, Eccles D and Sim R (2005) ‘Managing invasive carp (Cyprinus carpio L.) for habitat enhancement at Botany Wetlands, Australia’, *Aquatic Conservation: Marine and Freshwater Ecosystems*, 15(5):447–462.

Raadik TA (2014) ‘Fifteen from one: a revision of the Galaxias olidus Günther, 1866 complex (Teleostei, Galaxiidae) in south-eastern Australia recognises three previously described taxa and describes 12 new species’, *Zootaxa*, 3898(18):1–198, doi:10.11646/zootaxa.3898.1.1.

Radinger J and Wolter C (2014) ‘Patterns and predictors of fish dispersal in rivers’, *Fish and Fisheries*, 15(3):456–473, doi:https://doi.org/10.1111/faf.12028.

Raymond S, Duncan M, Tonkin Z and Robinson W (2020) *Barmah-Millewa Fish Condition Monitoring: 2020*, Report prepared for the Murray–Darling Basin Authority. Arthur Rylah Institute.

Rowland SJ (1983) ‘The hormone-induced ovulation and spawning of the Australian freshwater fish golden perch, Macquaria ambigua (Richardson) (Percichthyidae)’, *Aquaculture*, 35:221–238, doi:https://doi.org/10.1016/0044-8486(83)90093-5.

Sanger A (1986) *The evolution and ecology of the Gadopsis marmoratus complex*, Doctor of Philosophy thesis, University of Melbourne.

Sharpe C (2014) *Millewa Forest Fish Surveys 2014*, Summary of findings report for NSW National Parks and Wildlife Service, CPS Enviro P/L.

Sharpe C (2018) *Restoring Large bodied fish populations at Millewa Forest*, Report for NSW National Parks and Wildlife Service, CPS Enviro P/L.

Sharpe C and Stuart I (2016) *Background concepts to the restoration of diverse native fish communities at Barmah-Millewa Forest*, Report for NSW National Parks and Wildlife Service, https://ramond.aquaticecohub.com.au/uploads/5bnwXa9GJzL67PgSAtjwUiP5XAyHnZi4BOIHJP0x.pdf, accessed 14 August 2023.

Sharpe C and Stuart I (2018) *Environmental flows in the Darling River to support native fish populations 2016-17*, Report for Commonwealth Environmental Water Office, CPS Enviro, https://www.agriculture.gov.au/sites/default/files/documents/environmental-flows-darling-river-fish-2016-17.pdf, accessed 14 August 2023.

Sharpe C and Wilson E (2012) Fish surveys at 39 sites throughout Millewa Forest, NSW, with focus on the distribution of Southern pygmy perch (Nannoperca australis). May/June 2012, Report for NSW Office of Environment and Heritage, CPS Enviro P/L.

Sharpe CP (2011) ‘Spawning and recruitment ecology of golden perch (Macquaria ambigua Richardson 1845) in the Murray and Darling Rivers’.

Small K, Kopf RK, Watts RJ and Howitt J (2014) ‘Hypoxia, blackwater and fish kills: experimental lethal oxygen thresholds in juvenile predatory lowland river fishes’, *PLoS One*, 9(4):e94524.

Stoessel D (2010) ‘Review of Murray Hardyhead (Craterocephalus fluviatilis) biology and ecology, and the environmental data for two key populations in the Kerang region’, *Unpublished report*, (2010/30).

Stuart I and Jones M (2002) Ecology and Management of Common Carp in the Barmah-Millewa Forest: Final Report of the Point Source Management of Carp Project to Agriculture Fisheries & Forestry Australia, Arthur Rylah Institute for Environmental Research.

Stuart I, Jones M and Sharpe C (2021) *Millewa Forest TLM Intervention Monitoring Large-bodied fish surveys 2021: Summary of findings*, Report for NSW National Parks and Wildlife Services, Arthur Rylah Institute.

Stuart I, Sharpe C and Childs P (2020) *Recovery of large-bodied fish in Millewa Forest*, Report for NSW National Parks and Wildlife Services, Arthur Rylah Institute.

Stuart I, Sharpe C, Stanislawski K, Parker A and Mallen-Cooper M (2019) ‘From an irrigation system to an ecological asset: adding environmental flows establishes recovery of a threatened fish species’, *Marine and Freshwater Research*, 70(9):1295–1306.

Stuart IG, Baumgartner LJ and Zampatti BP (2008) ‘Lock gates improve passage of small-bodied fish and crustaceans in a low gradient vertical-slot fishway’, *Fisheries Management and Ecology*, 15(3):241–248.

Stuart IG and Jones M (2006) ‘Large, regulated forest floodplain is an ideal recruitment zone for non-native common carp (Cyprinus carpio L.)’, *Marine and Freshwater Research*, 57(3):333–347.

Stuart IG and Sharpe CP (2020) ‘Riverine spawning, long distance larval drift, and floodplain recruitment of a pelagophilic fish: A case study of golden perch (Macquaria ambigua) in the arid Darling River, Australia’, *Aquatic Conservation: Marine and Freshwater Ecosystems*, 30(4):675–690.

Sundermann A, Stoll S and Haase P (2011) ‘River restoration success depends on the species pool of the immediate surroundings’, *Ecological Applications*, 21(6):1962–1971.

Thiem JD, Wooden IJ, Baumgartner LJ, Butler GL, Forbes JP and Conallin J (2017) ‘Recovery from a fish kill in a semi-arid Australian river: Can stocking augment natural recruitment processes?’, *Austral Ecology*, 42(2):218–226.

Tonkin Z, King AJ 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 and Restoration*, 9(3):196–201, doi:10.1111/j.1442-8903.2008.00418.x.

Tonkin Z, Kitchingman A, Fanson B, Lyon J, Ayres R, Sharley J, Koster WM, O'Mahony J, Hackett G and Reich P (2020) 'Quantifying links between instream woody habitat and freshwater fish species in south-eastern Australia to inform waterway restoration', *Aquatic Conservation: Marine and Freshwater Ecosystems*, 30(7):1385–1396.

Tonkin Z, Lyon J and Pickworth A (2010) 'Spawning behaviour of the endangered Macquarie perch Macquaria australasica in an upland Australian river.', *Ecological Management & Restoration*, 11(3):223–226.

Tonkin Z and Rourke M (2008) 'Barmah–Millewa fish condition monitoring–2008 annual summary and refuge habitat report', Report to the Murray–Darling Basin Commission, Canberra. Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Melbourne.

Tonkin Z, Stuart I, Kitchingman A, Jones M, Thiem J, Zampatti B, Hackett G, Koster W and Koehn J (2017) *The effects of flow on silver perch population dynamics in the Murray River*, Arthur Rylah Institute for Environmental Research, Department of Environment ….

Tonkin Z, Stuart I, Kitchingman A, Thiem JD, Zampatti B, Hackett G, Koster W, Koehn J, Morrongiello J, Mallen-Cooper M and Lyon J (2019) 'Hydrology and water temperature influence recruitment dynamics of the threatened silver perch *Bidyanus bidyanus* in a regulated lowland river', *Marine and Freshwater Research*, 70(9):1333–1344.

Varner RK, Horruitiner CD, Palace MW, Wik M and Johnson JE (2018) 'Autochthonous carbon from submerged aquatic vegetation fuels methane production in lake sediments', in *AGU Fall Meeting Abstracts*.

Vilizzi L, Thwaites LA, Smith BB, Nicol JM and Madden CP (2014) 'Ecological effects of common carp (Cyprinus carpio) in a semi-arid floodplain wetland', *Marine and Freshwater Research*, 65(9):802–817.

Vivian LM, Godfree RC, Colloff MJ, Mayence CE and Marshall DJ (2014) 'Wetland plant growth under contrasting water regimes associated with river regulation and drought: implications for environmental water management', *Plant Ecology*, 215:997–1011.

Vorosmarty CJ, Green P, Salisbury J and Lammers RB (2000) 'Global water resources: vulnerability from climate change and population growth', *science*, 289(5477):284–288.

Whiterod N (2019) A translocation strategy to ensure the long-term future of threatened small-bodied freshwater fishes in the South Australian section of the Murray–Darling Basin, Report to Natural Resources, South Australian Murray–Darling Basin and the Riverine Recovery Project. Aquasave–Nature Glenelg River Trust.

Whiterod N and Gannon R (2020) TLM Condition Monitoring, small-bodied fish 2019–20: the status of fish and turtle communities across Millewa Forest.

Winemiller KO (1992) 'Life-History Strategies and the Effectiveness of Sexual Selection', *Oikos*, 63(2):318–327, doi:10.2307/3545395.

Winemiller KO (2005) 'Life history strategies, population regulation, and implications for fisheries management', *Canadian Journal of Fisheries and Aquatic Sciences*, 62(4):872–885, doi:10.1139/f05-040.

Winemiller KO and Rose KA (1992) 'Patterns of life-history diversification in North American fishes: implications for population regulation', *Canadian Journal of Fisheries and Aquatic Sciences*, 49(10):2196–2218.

Wong CM, Williams CE, Pittock J, Collier U and Schelle P (2007) *World's top 10 rivers at risk. Gland, Switzerland: WWF International*, https://www.researchgate.net/publication/23778568_World%27s_Top_10_Rivers_at_Risk, accessed 14 August 2023.

Zampatti BP and Leigh SJ (2013) ‘Within-channel flows promote spawning and recruitment of golden perch, *Macquaria ambigua ambigua* – implications for environmental flow management in the River Murray, Australia’, *Marine and Freshwater Research*, 64(7):618–630.

Zampatti BP, Wilson PJ, Baumgartner LJ, Koster WM, Livore JP, McCasker NG, Thiem JD, Tonkin Z and Ye Q (2015) Reproduction and recruitment of golden perch (Macquaria ambigua ambigua) in the southern Murray-Darling Basin in 2013-2014: an exploration of river-scale response, connectivity and population dynamics, SARDI Aquatic Sciences.

Zhang L, Zheng H, Teng J, Chiew F and Post D (2020) *Plausible hydroclimate futures for the Murray–Darling Basin*, Report for Murray-Darling Basin Authority, CSIRO, doi:https://doi.org/10.25919/samv-ey93.

Zukowski S, Whiterod N, Ellis I, Gilligan D, Kerezsy A, Lamin C, Lintermans M, Mueller S, Raadik TA and Stoessel D (2021) *Conservation translocation handbook for New South Wales threatened freshwater fishes*, Report to New South Wales Department of Primary Industries Fisheries. Aquasave–Nature Glenelg Trust, https://www.freshwateranglers.com.au/wp-content/uploads/2021/04/Zukowskietal-2021-NSW-conservation-translocation-handbook-FINAL.pdf, accessed 14 August 2023.