NSW Department of Primary Industries

Fish and Flows in the Southern Murray-Darling Basin

Developing environmental water requirements for native fish outcomes

30 June 2022

Published by the NSW Department of Primary Industries

Title: Fish and Flows in the Southern Murray-Darling Basin

Subtitle: Developing environmental water requirements for native fish outcomes

First published: July 2023

This report should be cited as: Ellis, I., Cheshire, K., Townsend, A., Danaher, K., Lone, R. (2022). Fish and Flows in the Southern Murray-Darling Basin: Developing environmental water requirements for native fish outcomes. NSW Department of Primary Industries, Buronga.

More information

Enquiries regarding the license and use of this document are welcome at the NSW Department of Primary Industries. www.dpi.nsw.gov.au

Acknowledgements

This project was funded by the Murray-Darling Basin Authority (MDBA). NSW Department of Primary Industries Fisheries (NSW DPI Fisheries) Freshwater Environment Branch managed the project including research and report preparation. The NSW DPI Fisheries team would like to thank the following individuals and organisations that have been consulted in the preparation of this document:

Stuart Little and Greg Ringwood (MDBA) for their support throughout this project and their dedication in striving for positive native fish outcomes. Chris Bice, Brenton Zampatti and Qifeng Ye from the South Australian Research and Development Institute (SARDI) and John Koehn, Zeb Tonkin and Wayne Koster, (Arthur Rylah Institute, Victorian Department of Environment, Land, Water and Planning (DEWLP) for contribution to this project. Sam Davis, Luke Pearce, and David Hohnberg (NSW DPI Fisheries) for their contributions and review of drafts. We also recognise with appreciation the various water managers who contributed information used in this report, in particular Iwona Conlan, Sascha Healy, Paula D'Santos, Christina Venebles, Ian Burns, James Dyer, Paul Childs and James Maguire ((NSW DPE EES); Adam McLean, Peter Bridgeman, Andrew Keogh and Sarah Commons (MDBA); Simon Casanelia (Goulburn Broken Catchment Management Authority (CMA); Peter Kelly (formerly Mallee CMA); Linda Broekman (Forestry Corporation of NSW); Scott Jaensch (NSW DPE Water); and Damien McRae, Alana Wilks, Richard Mintern and Irene Wegener at the Commonwealth Environmental Water Office (CEWO).

Australian Government | Murray–Darling Basin Authority

Cover image: Junction of Darling-Baaka and Murray Rivers at Wentworth. I. Ellis. January 2022.

Preamble

In Australia's Murray–Darling Basin (MDB), as in river systems worldwide, altered flow regimes have resulted in substantial negative impacts to native fish communities. The Commonwealth Water Act 2007 established the Murray–Darling Basin Authority (MDBA) and tasked it with the preparation of a Murray–Darling Basin Plan (the "Basin Plan") to provide for the integrated management of the MDB's water resources (Commonwealth of Australia 2012; MDBA 2010).

Managing river health through informed water delivery that targets the protection or re-instatement of natural flow regimes (or key components within natural flow regimes) can contribute to the support and restoration of native fish populations. In recent years the process of restoring more natural flow regimes by augmenting regulated river flows with water for the environment (also referred to as 'environmental flows') has become a key aspect of ecosystem management in the MDB. Effective flow restoration requires an understanding of the relationships between hydrology, life history and population dynamics of river and floodplain biota, which then needs to be linked to management decisions. To manage native fish populations, we therefore need to understand the drivers that support healthy native fish populations and communities, as well as the threats and pressures that may impact them.

To assist with implementation of the Basin Plan, NSW Department of Primary Industries (NSW DPI) Fisheries embarked on a body of work referred to as the 'Fish and Flows' program to review and synthesise our understanding of the requirements of native fish in the MDB.

Initially applied in the Northern MDB (NSW DPI 2015), the principles were transferred to the Southern MDB in a project titled 'Fish and Flows in the Southern Basin: A review of fish and flow relationships in the Southern Murray – Darling Basin conducted in 2015-16. Phase 1 of the project explored the flow conditions that different functional groups of native fish in the Southern MDB need to persist and flourish (Ellis et al. 2016). In Phase 1, a Fish and Flows Management Framework (FFMF) was developed to inform the application of water for the environment to support native fish outcomes in the Southern MDB. The framework informed the development of conceptual flow hydrographs to describe significant flow components which support the varied life -history requirements of the different functional groups of native fish.

This report represents Phase 2 of the Southern MDB project, in which we translate key flow components from the FFMF into fish-specific Environmental Water Requirements (EWRs) targeting native fish outcomes at representative gauging locations (Hydrologic Indicator Sites) in the valleys of the Southern Connected MDB. River systems included in this work include the Murray, Lower Darling-Baaka, Lachlan, Murrumbidgee and Goulburn-Broken). Where possible, we have sought to ensure broad consistency with EWR's developed by state agencies in NSW, SA and VIC charged with developing Long Term Watering Plans for (LTWP) as components of each Basin States Basin Plan commitments. Water managers can refer to the recommended EWRs when planning and prioritising water delivery to achieve (or generate) hydrograph components that enhance native fish outcomes.

The outputs in this report are intended to guide the delivery of water and protection of flows by agencies with water for the environment management responsibilities in the implementation of the Basin Plan. These outputs may support outcomes related to the Basin-Wide Watering Strategy (BWS), and the objective and targets developed as part of state Long Term Watering Plans (LTWPs) and Water Resource Plans (WRPs).

The EWRs we present herein are based on the best available scientific understanding of the life-history requirements for fish at the time of writing, are not designed to be a comprehensive or prescriptive 'recipe'. They are aspirational to guide flow planning processes, and not constrained by management and operational elements such as volume of held or planned water for the environment, physical constraints, rivers operations or third-party impacts. EWR's.

Responsible water management and the prioritisation of flow components within and between systems (both spatially and temporally) will require coordinated efforts by water managers across both the Southern and Northern MDB as well as sustained consultation with expert fish ecologists.

The principles and outputs we present here are already being utilised in the adaptive management of flow and environmental water in various catchments throughout the Southern MDB.

Table of Contents

Background

The importance of flow and hydraulic variability

Water is fundamental to fish; however, the interaction of the movement of water within and between waterbodies (i.e., flow) also has a major influence on their life history and population processes. Different species of fish have particular habitat, food and lifecycle needs linked to the availability of water and the way it flows in the landscape.

Flow produces hydrodynamic (and hence habitat) diversity, which in turn supports a range of different species and life-history stages with varied requirements and preferences. Flow variability also promotes the exchange of nutrients and productivity in aquatic ecosystems and provides connectivity between aquatic habitats (e.g., rivers and floodplain habitats, valleys or reaches within a valley). The biological rhythms of fish may be linked to flow so that opportunities for spawning, growth and dispersal are synchronised (Baumgartner et al. 2014). For example, survival of eggs and larvae may also be dependent on flow to transport them to suitable nursery habitat, or to maintain habitat while the eggs hatch and larvae develop.

In short, flow and the physical characteristics of flowing water (hydraulics) influence fish life cycles and hence their survival and persistence (Koehn et al 2020a; Mallen-Cooper and Zampatti 2018). Assuming all water will have positive outcomes for all fish is simplistic.

In river systems worldwide, the alteration of flow regimes has resulted in a range of negative impacts to fish communities. Historically, diversity and variability in flowing conditions (particularly hydraulics) was a natural feature of the Murray-Darling Basin (MDB) to which fish and other aquatic biota have adapted over millennia (Mallen-Cooper and Zampatti 2018). Human influences and the exploitation of freshwater resources have substantially altered flow regimes throughout much of the MDB in less than 150 years (see Koehn et al 2020a).

The resulting impacts to native fish include:

- reduced flow variability and hydraulic complexity
- loss of extensive stretches of perennial flowing (lotic) habitat
- shifts in seasonal flow patterns
- reduced incidence and duration of small to medium floods
- loss or alterations to habitat and refugia
- permanent inundation of some areas
- altered connectivity both longitudinally and laterally between rivers and their floodplains.

Regulatory structures can also prevent or impair the movements of fish (Baumgartner et al. 2014) and cold-water releases from larger dams severely impact the breeding cycles of native fish in downstream reaches (Lugg and Copeland 2014). Unsurprisingly, many native fish species in the MDB have suffered a decline in their abundance and distribution, with some now absent throughout much of their former range.

Flow management and water for the environment

Managing river health through the protection or re-instatement of natural (or near-natural) flow regimes or flow components can be an effective way to support native fish and help restore or recover their populations. In recent years the process of restoring more natural flow regimes, augmented by the delivery of water for the environment (or environmental flows) has become a key aspect of ecosystem management in the MDB (Arthington 2012; Koehn et al. 2014b; Mallen-Cooper and Zampatti 2015c; Stuart and Sharpe 2017; Koehn et al 2020a). Environmental flows are a relatively new management action in Australia, and as such our ecological knowledge is still evolving, particularly regarding how different fish species may be affected by flows, including natural events, water for the environment and other water management actions.

Furthermore, managing water flows for consumptive and agricultural use whilst considering flow restoration for environmental purposes can be challenging and may lead to conflict (e.g., over water buybacks and environmental water management) (Arthington 2012; Koehn et al. 2014b). Water managers may also be limited in returning large volumes of water to mimic natural flooding cycles due to either insufficient water availability, or due to physical and operational constraints that govern the volume and timing of regulated water delivery through the river system (MDBA 2013).

Managed flows can also potentially contribute to negative outcomes such as increased recruitment of non-native fishes (Stuart and Jones 2006; Beesley et al. 2012), hypoxic blackwater events (King et al. 2012) or sedimentation (Lyon and O'Connor 2008). Infrastructure constructed to facilitate environmental watering could themselves infer unexpected outcomes. For example, regulators which artificially inundate floodplains by backing up water rather than delivery of a downstream pulse of floodwater, could also lead to negative impacts (e.g. increases in residency times, reduction in hydraulic variability, fish passage obstruction and proliferation of non-native species) (Koehn et al. 2014b; Baumgartner et al. 2014).

The need to maximise environmental benefits and minimise risks of unwanted outcomes has increased expectations for science to underpin and justify water management and the delivery of environmental flows (Arthington et al. 2006; Beasley et al. 2011; Koehn et al. 2014b; Koehn et al 2020a). Effective flow management therefore requires an understanding of relationships between hydrology, life history and population dynamics of biota. Flows need to be managed at spatial scales that match the life cycles of fish, with consideration of volume and timing (hydrology) as well as the physical characteristics of flowing water (hydraulics) (Mallen-Cooper and Zampatti 2018).

Complementary measures

To effectively manage riverine and floodplain fish populations we need to understand the drivers that support healthy fish populations and communities, and the threats and pressures impacting them. Flow regulation and changes to the natural flow regime are only one of the threats implicated in the decline of native fish in the MDB. A range of external influences also impact the health of rivers and wetlands and therefore the status of fish communities.

These include:

- riparian and instream habitat degradation
- reduced water quality
- barriers which impede fish movement
- loss of fish through irrigation diversions and pumping
- competition and/or predation by non-native species
- exploitation through fishing activities
- disease
- loss of genetic integrity and fitness
- climate change.

The potential for achieving long-term ecological outcomes through management of flow and water for the environment will be increased by undertaking parallel complementary measures that also address these threats.

The Murray-Darling Basin Plan and environmental water requirements

The Commonwealth Water Act 2007 established the Murray – Darling Basin Authority (MDBA) and tasked it with the preparation of a Murray – Darling Basin Plan ("Basin Plan") to provide for the integrated management of the MDB's water resources (Commonwealth of Australia 2012; MDBA 2010). The Basin Plan required the development of an Environmental Watering Plan (EWP) to ensure that the size, timing and nature of flows (and coordination of flows) will maximise benefits to the environment. The intent is for the EWP to protect, enhance and nourish the rivers, wetlands, and floodplains of the MDB together with their plants and animals including native fish and other aquatic biota. At a local scale LTWPs and WRPs (see Chapter 8 and Chapter 10 of the Basin Plan) will drive and inform environmental watering to ensure consistency in the implementation of the Basin Plan and EWPs across the MDB.

In developing the Basin Plan, the MDBA used an indicator site method to assess the environmental water needs of the MDB and determine a proposed Environmentally Sustainable Level of Take (ESLT) (MDBA 2011b). This included assessments of Environmental Water Requirements (EWRs) for major themes (waterbirds, vegetation, fish and ecosystem functions) at key Hydrologic Indicator Sites (HIS) across the MDB (see MDBA 2011b).

EWRs were integral in developing an assessment framework for the Basin Plan using the best science available at the time (2009), and to provide a common language between the themes, and between environmental outcomes and hydrology.

The original Basin Plan EWRs primarily addressed the requirements of vegetation and waterbirds, which are often longer in duration or vary seasonally from those required by fish and other within-channel biota. Consequently, consideration of flow-ecology relationships for fish was limited. Where they were presented, site-specific flow indicators for fish were expressed in general terms and focused on providing key fish species with greater access to habitats by wetting benches, riverbanks and in-stream habitat, as well as facilitating opportunities for native fish migration and recruitment (MDBA 2011b).

There was a general assumption that in meeting the floodplain requirements for other biota, the in-channel flows required to support ecosystem functions, fish and other riverine biota would be catered for. It is important to note that in many cases flow indicators of a higher magnitude will meet the requirement for lower events, but only if they are delivered in line with natural processes (e.g. not using works and measures to artificially inundate floodplains).

Furthermore, the EWRs originally developed to inform Basin Plan development do not reflect newer (post-2009) scientific advancements. The Basin-Wide Environmental Watering Strategy (BWS) (MDBA 2014a) does incorporate more recent information regarding the responses of fish to flows. Given Basin and State-wide LTWPs and WRPs currently being developed are required to “have regard” to the objectives of the BWS, the Basin Plan EWRs also require revision to reflect best available science if they are to be used to support Basin Plan implementation.

As part of this project it was proposed that the original EWRs be reviewed and fish specific EWRs (which reflect the flow requirements of native fish throughout the Southern MDB as well as the broad objectives of the BWS) be developed. These EWRs will support the MDBA and managers of water for the environment to systematically develop annual watering priorities and will contribute to future reviews of Basin Plan implementation. Revision of EWRs across key sites in the Southern MDB will also support the MDB States in the development of LTWPs, WRPs and annual priorities to reflect the objectives of the BWS. Additionally, this review will inform the development of coordinated multi-site watering opportunities.

Recent scientific advances

Improvements to native fish populations in the MDB will not be achieved without continued concerted management efforts and the incorporation of recently generated knowledge (Koehn et al 2014a). In Phase 1 of this project we undertook a review of the information available regarding the flow requirements of fish in the Southern MDB (see Ellis et al 2016). In the review we noted that advancements in our understanding had been made since the Basin Plan was drafted in 2009. Key advances in our understanding of fish and flow relationships include:

- The linkages between flow requirements and the different life history stages of fish species.
- The spatio-temporal scales at which habitat and population processes occur (e.g. annual processes occurring within localised habitats compared to processes which occur over 100’s or 1000’s of km spanning multiple years).

- The importance of hydrodynamic complexity in supporting life cycles and diversity within fish communities (i.e. how the distribution and change in flow velocity, depth and turbulence support species reliant on flowing habitats such as Murray Cod, Golden Perch, and Macquarie Perch).
- How hydrological variability influences riverine productivity, which in-turn promotes food and breeding opportunities fishes (i.e. the links between flow, growth, body condition and recruitment success).
- The importance of unobstructed connectivity (between channels and floodplains, and between locations and catchments) and translucency of flows (i.e. progression of flood related cues and productivity) to fish condition, recruitment, movement and population dynamics.
- The influence of antecedent hydrology on fish assemblages, and hence the importance of sequential flows in supporting healthy populations (e.g. growth, body condition and recruitment success).
- How floods and instream Flow Pulses, or Freshes, may augment recruitment for certain species (i.e. frequent Overbank flooding interspersed with within-channel increases in discharge may result in more successful spawning and recruitment, and hence more robust population structure).
- Negative outcomes may arise from managed flow regimes (e.g. increased risk of non-native fish recruitment, nest abandonment or disruption for nesting species, hypoxic blackwater events and sedimentation).
- Due to the extent of water and land use in the MDB there is a need for complementary actions in addition to the delivery of optimised flow regimes to achieve meaningful outcomes for native fish.
- Key physical and operational constraints currently limit our capacity to deliver the flows necessary to ensure broad scale native fish requirements are met.
- The importance of habitat features which are needed by many fish species (such as snags and rocks, in-stream and emergent vegetation, refuge pools in dry periods, and in-steam benches).
- Population models will allow predictively assessment of how populations of different species may be affected by flow modification or new/increasing threats, and thus inform water management so that the benefits to fish populations can be maximised.

Project objectives

Phase 1: Review of fish and flow relationships in Southern MDB catchments

To assist with the implementation of the Basin Plan, NSW Department of Primary Industries (NSW DPI) Fisheries embarked on a body of work referred to as the ‘Fish and Flows’ program to review and synthesise our understanding of the requirements of native fish in the MDB (NSW DPI 2015). A Fish and Flows Management Framework (FFMF) was developed to inform the application of ‘water environment’ to support native fish outcomes, initially in the rivers of the Northern Murray-Darling Basin (steps 1-4 in Figure 1).

This framework was then used in Phase 1 of this project, ‘Fish and Flows in the Southern Basin’, in producing a synthesis of information regarding the relationships between fish and flow in the Southern MDB (see Ellis et al. 2016).

Phase 2: Developing EWRs in the Southern MDB

This report represents Phase 2 of the ‘Fish and Flows in Southern Basin’ project, in which the FFMF is used to develop conceptual hydrographs and accompanying fish-specific flow recommendations (EWRs) targeting fish outcomes in the Murray, Lower Darling, Lachlan, Murrumbidgee and Goulburn-Broken river systems of the Southern Connected MDB.

These fish specific EWRs are intended to support the management of water such that the needs of native fish are considered. EWRs are expressed as a set of flow indicators representing key components of the flow regime relevant to the known biological requirements of fish (flow magnitude/threshold or volume, duration, seasonality and frequency).

The EWRs we present herein reflect the objectives of the EWP (Chapter 8 of Basin Plan), the BWS and best available science regarding fish-flow relationships at the time of writing. We have endeavoured to ensure consistency between EWR's presented here and those in the recently completed NSW Long Term Watering Plans and South Australian long term flow aspirations.

The Fish and Flows Management – Southern MDB

1. Review the **flow-related history attributes** of fish species in the Southern MDB (habitat, reproduction, movement, growth and condition).
2. Assign Soutehrn MDB fish species into **Functional Groups** based on shared flow-related attributes to simplify the flwo requirements for fish.
3. Describe important or **Ecologically Significant Components (ESC)** of the in-steam flow regime for functional groupa of fish (i.e. Base Flows, small and large within-channel 'fresh' flows, Bank Full and Overbank flows).
4. Develop **Conceptual Flow Hydrographs** which incorporate the ecologically significant components of the flow regime required by each functional group of fish (and life history stages within).
5. Review historic data sets and modelled outputs to determine **flow threshold** estimates for significant flow components at representative gauging sites (Hydraulic Indicator Sites, or HIS) in the Southern MDB (magnitude/threshold, duration, seasonality and frequency).
6. Develop recommended **EWRs** (including flow magnitude, duration, seasonality and return interval) at key HIS which describes the ESCs required by fish within a reach.

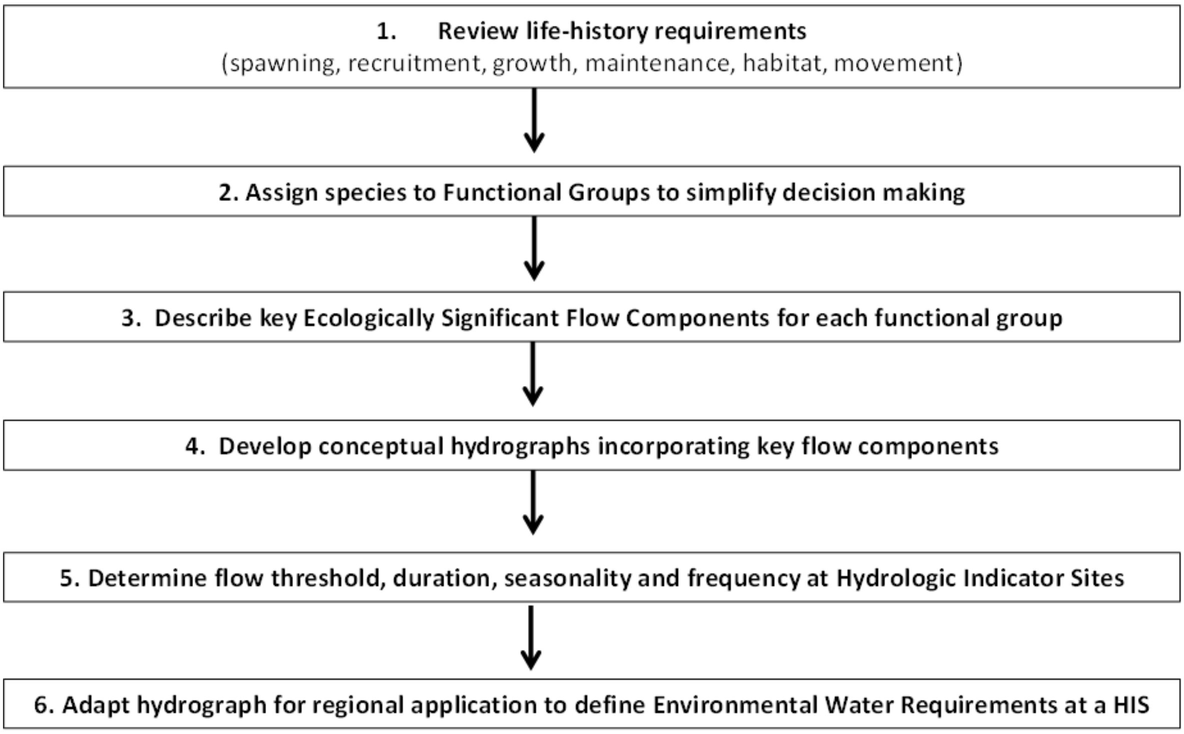

Figure 1. The Fish and Flows Management Framework produced to assist with the development of watering strategies that support native fish outcomes.

The Fish and Flows Management Framework presented here and the outputs it generates are being incorporated into the delivery of water in various catchments of the Southern MDB. Appropriate monitoring will continue to inform evaluation of Basin Plan implementation over coming years.

The approach presented in this report has already been useful in assisting agencies with environmental water management responsibilities in the implementation of the Basin Plan (including the BWS and the development of LTWPs). By helping to define what can be achieved for native fish with improved hydrological regimes, it is anticipated that implementation of Fish-specific EWRs will continue to contribute to the achievement of overarching Basin Plan outcomes for native fish, including:

- No loss of species
- Increased distribution and abundance of short-lived species relative to levels prior to Basin Plan monitoring
- Improved population structure of moderate and long-lived species driven by sufficient frequency and magnitude of recruitment events
- Increased prevalence and or extent of occurrence (range) for key species driven by increased site prevalence and dispersal and establishment in additional locations.

Limitations

Competing needs in a working MDB

Given the life histories of different biota (i.e. fish, waterbirds, and vegetation) are adapted to historical flow regimes, the conceptual hydrographs and fish-specific EWRs we present in this report are generally based on natural or 'historic' flow regimes for Southern MDB river systems. EWRs represent ideal flow conditions to maximise the opportunities for targeted native fish outcomes in a highly modified system. However, we acknowledge that natural flowing systems were historically more dynamic than is likely to be achieved under current or future river operations. Thus, to improve these populations, it may be necessary to implement flow regimes that do not necessarily reflect 'natural conditions' but seek to balance the impact of river regulation in a working MDB. The EWRs we present were developed in consultation with environmental water managers and key stakeholders to identify flexibility (where appropriate) in the descriptive parameters (e.g., magnitude above a threshold or seasonality). The fish specific EWRs we present should be read in conjunction with information regarding the holistic environmental water requirements of a site or environmental asses (i.e., to achieve multiple ecological targets for the site where appropriate).

Existing infrastructure

Whilst the EWRs we present here will inform the delivery of flows for native fish outcomes, in many cases they will not automatically produce the connectivity or hydrodynamic diversity required to support certain native fish requirements (due to existing infrastructure). For example, weirs create slow flowing weir pools and which exhibit reduced hydraulic complexity compared to pre-river regulation. Integrating eco-hydraulics into river rehabilitation has been identified as a priority for flow management in the MDB (Mallen-Cooper and Zampatti 2018, Koehn et al. 2020a). This may be achieved in some reaches through temporary removal or lowering weir levels, in conjunction with managed flow deliveries.

Flow constraints

The conceptual hydrographs and EWRs we present do not directly consider management and operational elements such as constraints, rivers operations or third-party impacts. We expect these EWRs to become less aspirational and more realistic in coming years as the Reconnecting River Country program (RRC) is implemented to address flow delivery constraints in the southern MDB (https://www.industry.nsw.gov.au/water/plans-programs/sdlam/reconnecting-river-country-program).

Coordinated management

Most of the streams in the Southern MDB are connected and therefore interdependent. To be most effective, manipulation of the flow regime targeting fish objectives should aim to achieve cumulative benefits through coordination of flows within and across catchments. This report provides conceptual hydrographs and EWRs that support water managers in achieving regional fish outcomes and encourages collaboration with neighbouring regions to contribute to temporal and longitudinal water delivery, which promotes connectivity between adjoining catchments (to provide cumulative benefits for native fish).

Specifically, the MDBA's "Towards a Southern Connected Basin Project" (TSCBP) (Stuart and Sharpe 2017) was conducted in parallel to this project. For continuity we have ensured key themes and concepts presented in the TSCBP align with, and are reflected in, the application of the FFMF described in this report. The alignment between these two projects provides an important information base, already demonstrated to support connectivity and multi-site watering.

The outputs in this report do not represent comprehensive 'recipes' and are by no means prescriptive. Natural variation in flow magnitude, timing and duration across a catchment will inevitably necessitate 'adaptation' of the flow components and EWRs to suit different or specific geographic locations and objectives.

Responsible water management and the prioritisation of flow components within and between systems (both spatially and temporally) will require coordinated efforts by water managers across both the Southern and Northern MDB as well as sustained consultation with expert Fish Ecologists. Adaptive management is a central pillar in environmental management, meaning that the suite of EWRs proposed in this document and the details within each EWR will most likely require revision over time. Monitoring outcomes associated with targeted flow management events will contribute to this refinement, and hence the attainment of positive outcomes for native fish.

Project operation, mechanisms and processes

DPI Fisheries staff from the Freshwater Environment Branch managed the project, including desktop research and analysis to develop and refine conceptual hydrographs and EWRs for Southern MDB HIS sites. DPI Fisheries sourced modelling data and other supporting information from the MDBA and other relevant agencies and sought input on the development of conceptual hydrographs and EWRs from expert Fish and Freshwater Ecologists, Water and Fisheries Managers in the Commonwealth, NSW, Victoria and South Australia and key stakeholders including recreational anglers and First Nations people and communities (through the Murray Lower Darling Rivers Indigenous Nations, or MLDRIN). Input was provided in the form of comments on draft reports and verbal communications.

Draft progress reports were submitted to the MDBA in 2017 and 2018. The MDBA agreed to an extension of the final report deliverable dates to allow for consideration of new and emerging knowledge on fish and flows and due to changes to broader Basin Plan implementation deadlines. Completion of this report was delayed allowing EWRs to be developed in line with Long Term Watering Plans for the southern MDB.

The Southern Murray-Darling Basin

The MDB experiences average annual inflows of 32,800 GL, although this number has ranged from 7,000 GL (in 2006) to 118,000 GL (in 1956) due to variable climatic conditions. The Southern MDB covers approximately 40% of the MDB and is comprised of the Murray River and tributaries in New South Wales (NSW), Victoria and South Australia (SA), and the Lower Darling Baaka River (LDBR) from just upstream of the Menindee Lakes (Figure 2).

The Murray River catchment drains the southern rivers of the MDB and generally carries around 50% of the MDB's average annual inflow, most of which originates in the Goulburn, Murrumbidgee and Upper Murray Rivers. By comparison, the upper Darling-Baaka River and its tributaries contribute around 42% of total inflows in the MDB (MDBA 2010). Tributaries in NSW include the LDBR (downstream of Menindee Lakes), the Great Darling Anabranch and the Murrumbidgee River. The Edward and Wakool rivers are a major effluent system in NSW that re-enter the Murray River upstream of Euston. The Lachlan River connects with the Southern MDB (i.e., the Murrumbidgee River) although this is relatively infrequent. Major Victorian tributaries of the Southern MDB include the Ovens, Campaspe, Goulburn, Loddon and Avoca Rivers. Several smaller catchments in the Mount Lofty Ranges drain to the lower Murray in South Australia including the Marne, Bremer and Finniss Rivers.

The topography of the Southern MDB ranges from steep to gently undulating hills, low relief floodplains and flat plains (CSIRO 2008a). Much of the Murray River and its major tributaries are low gradient rivers, which has led to the formation of complex systems of effluent creeks in the lower reaches of many rivers in the MDB (MDBA 2011a). Historically the rivers of the Southern MDB incorporated widespread reaches of perennial lotic habitat and seasonal Flow Pulses (usually in Spring) which increased hydrodynamic complexity and connectivity (Mallen-Cooper and Zampatti 2018).

The Southern MDB generally receives higher and less variable rainfall than the Northern MDB, with wetter winters (as compared to wet summer-autumn in the north). Southern MDB catchments are generally more regulated than the Northern MDB, and as a result have less variable flow, especially during summer and early autumn (NSW DPI 2015). River regulation and increasing extraction over the last century have resulted in many reaches now being characterised by less flow variability and slower flow velocities (MDBC 2006).

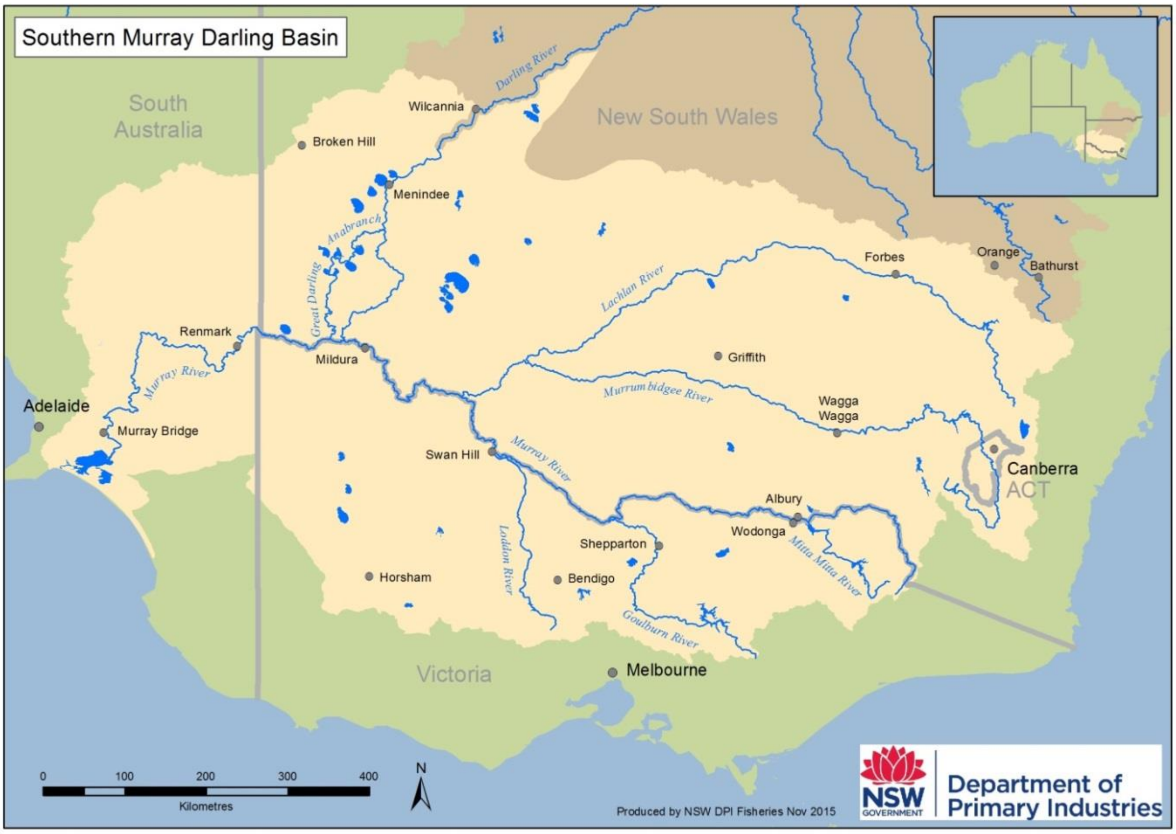

Figure 2. Major streams in the Southern connected MDB catchment.

Fish in the MDB

The MDB has over 46 species of native fish (the number is increasing with ongoing genetic investigations) and ten non-native invasive species (Lintermans 2007). Of these, 27 native species and eight non-native species occur or are expected to occur in the Southern MDB (see Appendix A: Fish of the Southern MDB, Table A1 and Table A2). The Southern MDB contains different fish assemblages in upland, midland and lowland zones. Additional species are found only in the Lower Murray and estuarine habitats at the terminus of the MDB in South Australian (including Small-mouthed Hardyhead, Yarra Pygmy Perch, Western Blue-spot Goby, Lagoon Goby, Black Bream and Mulloway). Not included in Tables A1 and A2 are those species found only in the upper Victorian reaches of the Southern MDB (Barred Galaxias). Non-native species with a limited presence in the NSW MDB (i.e., little to no self-sustaining populations) including Atlantic Salmon, Brook Char and Roach have also been excluded.

Since European settlement in the MDB, human development and use of freshwater resources has contributed to a substantial decline in native fish number (MDBC 2004; Koehn and Lintermans 2012; Koehn et al. 2020a). This decline is attributed to cumulative threats and stressors including flow regulation, habitat degradation, poor water quality (cold-water pollution, sedimentation, blue-green algal impacts, hypoxic blackwater, salinity, pollutants etc.), barriers which impede fish passage, exploitation (commercial and recreational fishing), entrainment though irrigation diversions, competition and/or predation by non-native species, and disease.

Twenty-six of the of the MDB's 46 native fish species are listed as threatened, either at federal or state and territory levels (Lintermans 2007). At least ten of these have been recorded in the Southern MDB (and other states) (see Appendix A). Furthermore, the aquatic ecological communities of the lowland Murray River are listed as an Endangered Ecological Community (EEC) in NSW (NSW DPI 2007a). Areas covered by the EEC include the Lower Murray downstream of Hume Weir, the Murrumbidgee downstream of Burrinjuck Dam, Billabong, Yanco and Columbo Creeks and their tributaries, Frenchman's Creek, Edward and Wakool Rivers and their tributaries, Rufus River and Lake Victoria. The Lower Darling catchment from Mungindi to the convergence with the Murray is also listed as an EEC (NSW DPI 2007b).

Status of fish communities in the MDB

The Sustainable Rivers Audit (SRA) was a comprehensive Basin-wide comparison of the status of biological communities (groups of species) first completed in 2008 (Davies et al. 2008). A second round of the SRA (SRA2) assessed the status of the fish community throughout most valleys in the Southern MDB to be in a ’poor ‘to ’extremely poor ‘condition (see Davies et al. 2012). Fish communities in heavily regulated sections of the central and upper Murray and Murrumbidgee catchments were particularly impacted, being classed as either ‘very poor’ or ‘extremely poor’.

More recently, the ‘NSW Fish Community Status Project’ undertaken by DPI Fisheries consolidated and analysed fish data collected over twenty years of biological surveys and spatial distribution models (NSW DPI 2016a). The project provides de-lineation and spatial recognition of the condition of fish communities and threatened species across NSW derived from the three condition indicators of ‘Expectedness’, ‘Nativeness’ and ‘Recruitment’. The ‘Expectedness’ indicator represents the proportion of native species that are now found within a reach, compared to that which was historically expected based on expert opinion. The ‘Nativeness’ indicator represents the proportion of native versus non-native fishes within the reach (based on biomass, abundance and number of species), and the ‘Recruitment’ indicator represents the recent reproductive activity of the native fish community. Outcomes rated the condition of a fish community as Very Good, Good, Moderate, Poor, or Very Poor. This information provides a baseline by which changes in community condition can be measured. The NSW Fish Community Status Project also documents current threatened species distribution information for NSW listed species, which will help to inform the planning of recovery actions for threatened species. Indicative distribution maps for threatened species in the NSW waters of the MDB are included in Appendix B.

The preliminary results from these analyses align with those of the SRA2, with fish community status throughout significant stretches of rivers and creeks in the NSW regions of the Southern MDB (particularly in mid and upland streams) assessed as ‘Poor’ to ‘Very Poor’ (Figure 3).

The ‘NSW Fish Community Status Project’ was published in 2016. Since then, hypoxic (blackwater) fish kills in the Murray and Murrumbidgee systems in 2016-17, and numerous fish kills across NSW during extended drought (2018-2020). The long-term impacts of these events will be highlighted in future fish long-term community stats assessments.

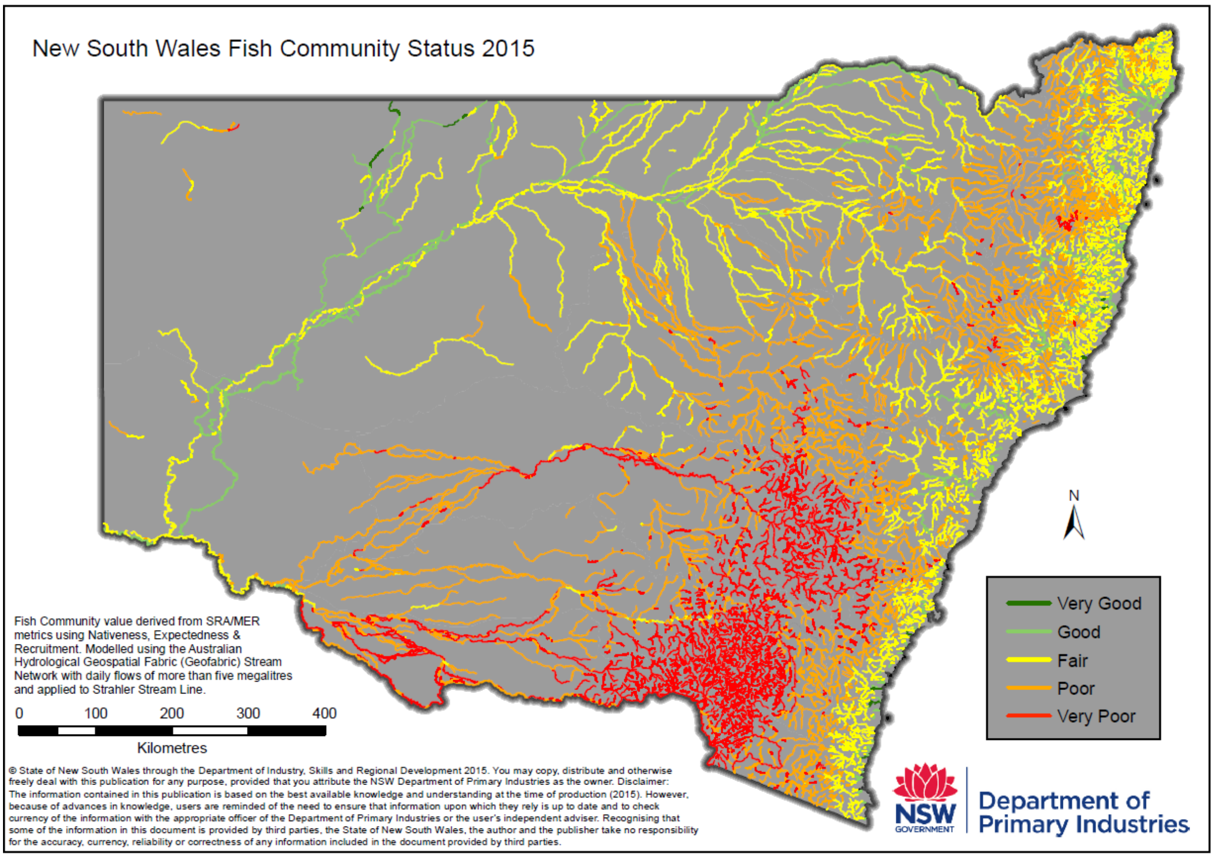

Figure 3. Fish Community Status in the NSW MDB (NSW DPI 2016a).

Flow and habitat

Flow is a major factor structuring freshwater fish communities as it influences the range of physical habitats available each developmental stage for fish, as well as ecological processes and functions to which their life history is linked (e.g., productivity and connectivity) (Baumgartner et al. 2013; Rolls et al. 2013).

Flows play a range of important roles including:

- The creation of hydrodynamic diversity (particularly important for species that require faster flowing habitats, such as Murray Cod, Golden Perch, Silver Perch, Trout Cod and Macquarie Perch).
- Maintaining health of in-stream and emergent vegetation and other habitat features needed by many fish species.
- Influencing quality, size, and persistence of refuge habitats in dry periods.
- Inundation of benches and floodplains to support the cycling of nutrients (particularly carbon) which is important for system productivity and hence food supply, recruitment and condition (i.e., maintenance and survival of fish and populations).
- Enabling access to a range of aquatic habitats and providing cues that stimulate movement, such as for spawning or larval dispersal, with movement opportunities including upstream or downstream, and lateral movement into off-channel habitats such as wetlands.

Altered hydrology and hydrodynamics

Native fish throughout the MDB have evolved in highly variable and hydraulically diverse systems characterised by extreme environmental conditions (Humphries et al. 1999; Baumgartner et al. 2013). Recent research in the MDB indicates that key drivers of population dynamics, in particular growth, spawning and recruitment, for several long-lived native fish species may be operating at a whole-of-river scale and over extended time periods (Sharpe 2011; Mallen-Cooper and Zampatti; 2015b, Zampatti et al. 2015).

Modified hydrology within rivers can therefore result in detrimental impacts on life history elements and processes (Poff et al. 1997). Altered flow regimes in the MDB are implicated in the demise of many native fishes because of impacts on physiology, spawning, recruitment, movement, and habitat availability (Gehrke and Harris 2001; Koehn et al. 2014a; Koehn et al. 2020a). For example, in the mid–upper reaches of the Murray River, fish that require low flow areas for nursery habitats in summer may be disadvantaged by high volume, high velocity irrigation flows (Humphries et al. 2006). In contrast, weir pool environments in the Lower Murray River disadvantage species whose life histories require flowing habitats and hydraulic variability (e.g., Murray Cod and Trout Cod) and favour species which prefer slower flowing habitats (such as non-native Carp) (Walker 2006; Walker and Thoms 1993; Cheshire et al. 2010).

In the Northern MDB's Barwon-Darling river (from which the Lower Darling Baaka River receives its flow) a reduction in the frequency and magnitude of small floods and within channel flows due to development in northern catchments was identified prior to the "Millennium Drought" from around 2000 to 2010 (Thoms and Sheldon 2000). Increasing development in the Northern MDB coupled with climate change impacts have since compounded changes to the natural flow with considerable impacts on aquatic fauna and flora (Sheldon 2017; MDBA 2018a; MDBA 2018b). These impacts are threatening the viability of the traditionally robust Murray Cod and Golden perch populations in the Lower Darling River (including the Menindee Lakes). Furthermore, these impacts are of concern more broadly in the mid and Lower Murray region given golden perch recruits originating in the Barwon-Darling River contribute substantially to populations in the Southern MDB (Stuart and Sharpe 2018 and 2020; Zampatti et al. 2015).

Many floodplain wetland systems have also suffered altered hydrology associated with river regulation, and destruction of habitat associated with land clearing and non-native species (Kingsford and Thomas 2004; Koehn et al. 2020a).

While flow management generally focusses on hydrology (water volume or threshold, duration, seasonality and timing), the hydrodynamics of flow is equally important (Mallen-Cooper and Zampatti 2018). Hydrodynamic complexity (i.e., the distribution and change in velocity, depth, turbulence) has been significantly reduced throughout the MDB, through factors including weirs creating still-water habitats, removal of large woody material (snags), and increased sedimentation (Mallen-Cooper and Zampatti 2015a).

To achieve the best outcomes, flows need to be managed at spatial scales that match the life - history requirements of different species or guilds, whilst considering parallel reinstatement of hydrodynamic complexity where possible.

Life history

Life history refers to the sequence of events in an organism's lifetime related to survival and reproduction, including spawning, growth, and movement (e.g., migration and dispersal). In general, the life cycle of fish includes adults which lay eggs which hatch into larvae; larvae develop into juveniles and ultimately to adults. At a more detailed level fish in the MDB exhibit variability within this general life cycle (e.g., longevity, fecundity, parental care, habitat requirements, or scales of migration), developed in response to the range of environmental conditions experienced across the Basin (Lintermans 2007; Mallen-Cooper and Zampatti 2015c).

Longevity refers to how long a species generally lives for. In this report we adopt the longevity categories presented by Mallen-Cooper and Zampatti (2015c). That is, short-lived species that live for less than 4 years, medium-lived that can survive for 5-10 years, and long-lived that may survive for more than 25 years. For short-lived species the life cycle is completed relatively quickly to ensure populations persist. Hence, short-lived species which are dependent on regular higher flows (e.g., to inundate floodplain wetlands) may be particularly vulnerable to changes in natural flow regimes. Populations of moderate and long-lived species are more likely to be able to persist through periods of environmental stress (e.g., droughts) in which breeding, and recruitment success may be low.

The fecundity of native fish varies considerably between species ranging from 10s to 100,000s of eggs produced by individual females per year. Many native species spawns in particular habitats or on particular substrates, with some even using what are often referred to as 'nests' consisting of physical structure (in some cases constructed from local materials). Eggs and young of some species are protected by the parents during early development, while others receive no parental care after spawning. Flow may be critical in facilitating downstream dispersal of tiny eggs and larvae to productive 'nursery' habitat in which their growth and survival may be supported, or in triggering and facilitating return migrations later in life.

Therefore, the protection or recovery native fish populations must cater for the differences across various spatial and temporal scales. Understanding the sources and dispersal of early life stages, the presence (and movements) of adult spawning stock, and the factors which support survival through each life-history stage is necessary in preserving native fish populations.

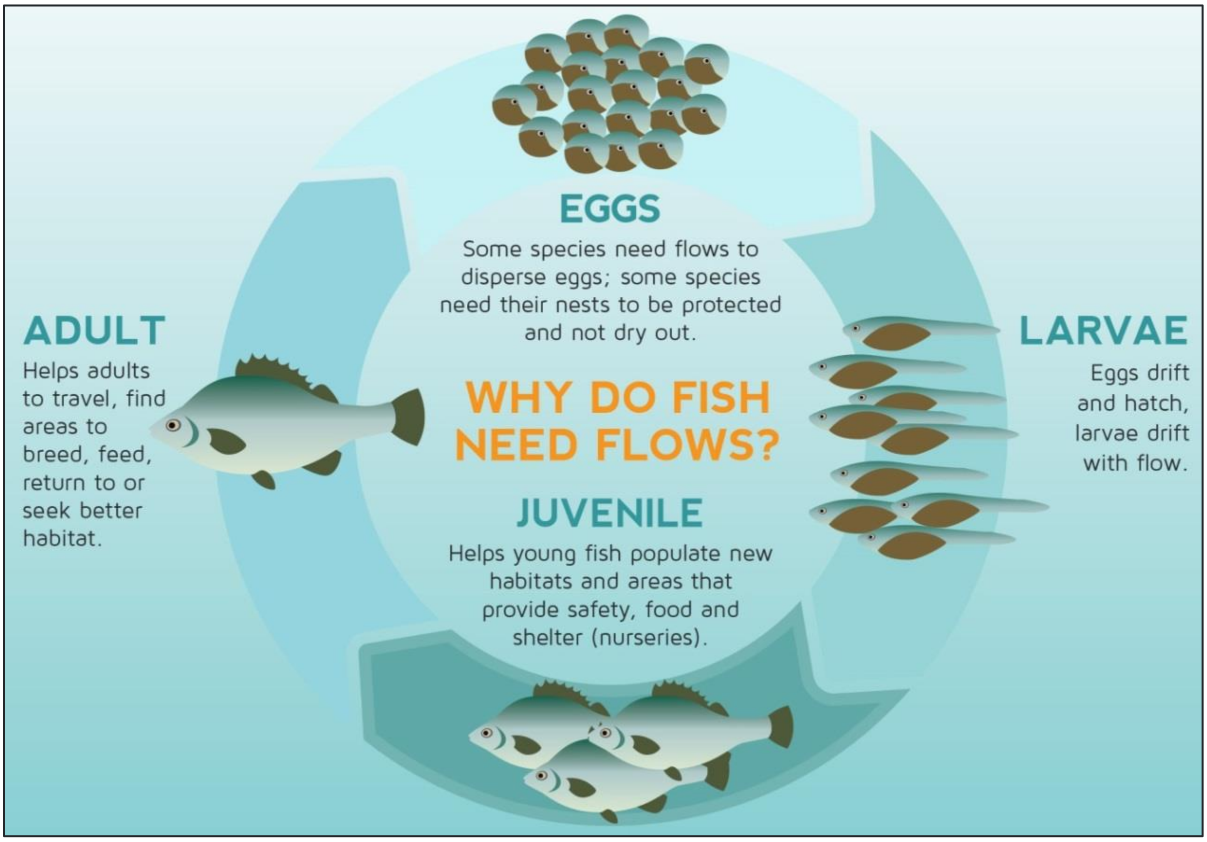

Figure 4. The influence of flows on the difference stages within the lifecycle of fish (NSW DPI 2018).

Critical life history elements

We frame the linkages between flow requirements and the different life history stages of fish using five life history elements and processes, each of which we regard as critical to the maintenance of self-sustaining populations and communities. These life history elements and processes are:

- Habitat access
- Growth and body condition
- Reproduction and recruitment
- Movement and connectivity

- Maintenance (or survival).

Habitat access

Habitat incorporates the type of waterbody a fish lives in (e.g. lakes, wetlands or rivers), water quality and hydrology of this waterbody (e.g. flow, depth and seasonal water availability) and physical characteristics such as woody debris or plants that can be found within them. Different species of fish have different habitat needs and may select ‘patches’ of suitable habitat which constitute a small proportion of all available habitats (‘micro habitats’). These patches of habitat may overlap considerably with other species (Koehn and Nicol 2014).

Aquatic habitats can be broadly categorised as lotic (flowing) or lentic (still or low-flow). Different fish will prefer lotic or lentic habitats. For example, Golden Perch and Murray Cod prefer to live in faster flowing steams, while Southern Pygmy Perch avoid flowing water, preferring still pools or wetlands (Lintermans 2007). The quality of the water and the way it interacts with the environment also influence habitat for fish. For example, Spangled Perch live in the relatively warmer water temperatures typical of the Northern MDB, while Barred Galaxias are adapted for life in cooler mountain streams. Barred Galaxias require low salinity, while the Murray Hardyhead tolerates saline wetland habitats (Lintermans 2007).

Hydraulic complexity promotes habitat heterogeneity and riverine productivity, which in turn promotes biological diversity (Mallen-Cooper and Zampatti 2018). Historically, diversity and variability in flow and hydrodynamic complexity was a regular feature of the Murray River. Flow regulation creates lentic weir pool environments, impacting species that require flowing habitats during parts of their lifecycle (e.g. Murray Cod, Trout Cod). Alternatively, unnaturally high velocity, or highly fluctuating flows at inappropriate times (such as during spawning periods for nesting species) may impact on life history outcomes.

Increasing flow, generally increases the amount of (and access to) off-channel floodplain habitats critical for several ‘wetland-dependent’ species like Murray Hardyhead and Southern Pygmy Perch (Beesley et al. 2012; Whiterod et al. 2020). Early life stages of Flow Pulse Specialist species (e.g. Golden Perch and Silver Perch) may settle in off-channel floodplain habitat during elevated flows, resulting in high growth rates and increased survival rates (Sharpe 2011; Ellis et al. 2015). Other more generalist species access lentic floodplain habitats opportunistically, using submerged structures (vegetation and snags) for spawning of adhesive eggs (e.g. Carp Gudgeon, Murray-Darling Rainbowfish). Reduced flood frequency and duration isolates floodplain habitat and may result in stranding of a population and eventual extirpation.

Habitats differ in terms of physical characteristics such as shape, depth, roughness (e.g. rocks, woody habitat) and connectivity (Mallen-Cooper and Zampatti 2015b). Physical structures within flowing or still waterbodies may be important for the survival and reproduction of species of developmental stages within. For example, snags in flowing rivers create sheltered areas in which Murray Cod often lay their eggs (nest). Removal of snags and reduction in flow variability reduces the ‘patchiness’ of habitats in a waterbody, thus reducing its suitability to a variety of fish. Higher flows can also provide access to additional physical instream habitat (via inundation of woody structure and benches) and to floodplain anabranches (Koehn et al. 2009).

Growth and body condition

Fish need a reliable food supply to support growth and good body condition. Historically, naturally variable flow regimes in the MDB promoted diverse aquatic food webs, which in turn supported healthy fish communities. Large flows that inundate floodplains and intermediate flows inundating within-channel benches promote the exchange nutrients and carbon between rivers and their floodplains (Junk et al. 1989; Baldwin and Mitchell 2000). Without natural flow variability, nutrients and resources become depleted and food webs are compromised.

The increased productivity and habitat availability associated with higher flows and floods can promote food availability and enhances fish growth and body condition (Geddes and Puckridge 1989; Harris and Gehrke 1994; Balcombe et al. 2012; Sharpe 2011). High growth rates may also influence breeding and recruitment outcomes within a population. For example, strong recruitment and high growth rates of Golden Perch, Trout Cod and Murray Cod in the Southern MDB appear to be positively related to discharge and flow variability (Zampatti et al. 2015; Tonkin et al. 2014; Stoffels et al 2020). Good body condition is often associated with recent flow events, while protracted low flow periods are associated with poor condition (Tonkin et al. 2011; Balcombe et al. 2012).

Reproduction and recruitment

Most native MDB fish species synchronise their breeding to occur in warmer months, when there is likely to be more resources available to support survival. For some species, such as Freshwater Catfish, Bony Herring, and Murray Cod, spawning is principally linked to season and temperature rather than high flow conditions (Cheshire et al. 2010; King et al. 2010). For these species, flow within river channels (and the associated hydraulic variability) may be sufficient to provide opportunities for spawning and recruitment (Humphries et al. 1999). For other species, a rising hydrograph coinciding with warmer water temperatures is required to cue adult migration and spawning (e.g. Golden Perch) (Mallen-Cooper and Stuart 2003; Sharpe 2011; Cheshire et al. 2010).

There is increasing evidence that recruitment for most fish species benefits from flooding or elevated flows through improved environmental conditions and productivity (King et al. 2009, Sharpe 2011; Stuart and Sharpe 2018a; Tonkin et al. 2019; Stuart and Sharpe 2020; Tonkin et al. 2020). Floodplain or riverbed inundation promotes increased productivity and provides additional habitat for fish, particularly in early life-history stages (Harris and Gehrke 1994; Sharpe 2011). Recent assessments of Golden Perch life history in the Barwon-Darling River system demonstrated strong recruitment in large floodplain lakes following flood-cued spawning (Stuart and Sharpe 2020a). Higher flows also promote dispersal of early life stages from the breeding site, enhancing genetic diversity among catchments (Humphries and King 2004; Stuart and Sharpe 2020).

Altered flow regimes can impact directly and indirectly on fish reproductive outputs. For nesting and substrate spawning species such as Murray Cod, River Blackfish, Macquarie Perch and Freshwater Catfish, unnaturally rapid variations in depth and discharge (particularly decreases) can cause abandonment of spawning sites or nests (Rowland 1998; Stuart et al. 2019) or disturbance/displacement of eggs and larvae (Tonkin et al. 2015). Maintaining natural rates of change in water levels during the breeding season is therefore important for nesting species where river operations to meet irrigation demand can cause rapid fluctuations which are out of sync with natural patterns and climatic cues (Sharpe and Stuart 2018b; Tonkin et al. 2021; Stuart et al 202).

Cold water releases (cold water pollution) from the depths of reservoirs behind large dams in spring can also disrupt the development of larvae in nests, given eggs are generally laid at a time of year when warm water is expected (Lugg and Copeland 2014; Baumgartner et al 2019; Koehn 2020a.

For some species breeding and recruitment occurs over large geographic scales, and a sequence of flow events may be necessary to generate strong recruitment outcomes (i.e. spawning through to large scale recruitment). For example, the Barwon-Darling system provides a critical spawning, recruitment and dispersal pathway for Golden Perch that extends from the Barwon River and its tributaries in the Northern MDB to the Lower Murray River in the south (Sharpe 2011; Stuart and Sharpe 2020; Stuart et al 2021). Following spawning in the upper Barwon-Darling system, larvae drift downstream and may travel as far as the Menindee Lakes and beyond. Higher growth and survivorship are exhibited by young fish that colonise the lakes “nursery habitat “compared to those that remain in the river channel due to higher densities of zooplankton (their principal food) and warmer temperatures in the shallow, ephemeral lakes (Sharpe 2011). Subsequent Freshes (in-channel and Overbank) that re-connect these nursery habitats promote longitudinal dispersal and re-colonisation movements by juvenile and adult fish both downstream and upstream throughout the rivers of the MDB (Stuart et al. 2021).

Assessment of natal origin of Golden Perch in the Murray River system suggests breeding in the Barwon-Darling River system may be an important driver of Golden perch populations throughout the Southern MDB (Zampatti et al. 2015). For example, in 2014-15, Golden Perch populations throughout the Murray River system were dominated by cohorts originating in the Darling-Baaka River system during years of high discharge (2010 to 2012). Thus, sequences of flow events and river connections over one or more years may influence reproductive success and ultimately the status of fish populations throughout the MDB. In the example above, recruitment which can span thousands of kilometres from northern tributaries through the length of the Barwon-Darling River system, may be critical to sustaining Golden Perch in the southern MDB given similar 'recruitment pathways' in the Murray and Murrumbidgee catchments have been heavily impacted by river regulation and water extraction (Stuart et al. 2020).

Movement and connectivity

Movement between habitats is important for the completion of life cycles for many fish species for the purposes of spawning, dispersal, foraging, and to seek refuge from threatening processes. Different fish may undertake large 'macro-scale' movements up to 100s or 1000s of kilometres (e.g., Golden Perch), or smaller 'meso-scale' movements of 100s of meters to 10s of kilometres within and between habitats in wetlands or river channels (e.g. Southern Pygmy Perch). Some smaller species conduct movements over even smaller 'micro -scales' of less than one kilometre (Mallen-Cooper and Zampatti 2015a).

Flows that support appropriate hydraulic connectivity and movement are therefore critical to the persistence of viable populations. Longitudinal connectivity along the length of a river or between catchments may be critical for species that occupy a range of habitats over vast areas (e.g., Golden Perch). Lateral connectivity between rivers and their floodplain is equally important in providing access to non-flowing wetlands important for species like Southern Pygmy Perch and Murray Hardyhead. Lateral connectivity between the river and floodplain is also important for those species and life history stages that use floodplain wetlands and anabranches for refuge, feeding, reproduction or recruitment opportunities (Jones and Stuart 2008; Lyon et al. 2010; Sharpe 2011).

Flows may be critical in facilitating the connectivity required for re-colonisation of former habitats or movements into suitable adult breeding habitat by maturing fish. For many species flows can be important for the dispersal movements of eggs and early life stages from breeding sites to suitable nursery habitats. These movements also increase distribution and promote genetic mixing (Humphries and King 2004).

Maintenance and survival (preserving populations)

Flows support fish populations by preserving habitat availability and longitudinal connectivity, facilitating movement and potentially higher population carrying capacity. Higher flows that inundate river benches and floodplains can trigger the release of a pulse of nutrients (e.g., carbon, phosphorous and nitrogen) into the water column. This increases primary productivity and stimulates other aquatic productivity processes such as plant propagation and growth (Baldwin and Mitchell 2000). These processes may be important for maintaining key habitats and food sources for different fish life-history stages (Geddes and Puckridge 1989; Koehn et al. 2020a).

Flows can also maintain suitable water quality through mixing in the water column (preventing thermal stratification), and by exporting salt and nutrients. Floodplain inundation following long dry periods can mobilise large carbon loads which can lead to a depletion of dissolved oxygen (hypoxic blackwater) and associated fish kills. Regular floodplain inundation via managed flow delivery (including water for the environment) can prevent unnatural build-up of floodplain carbon and in turn support fish populations by reducing the risk if hypoxic blackwater. Managed flows can also be delivered to try and dilute hypoxic blackwater (Watts et al. 2017).

For nesting species with parental care such as Murray Cod and Freshwater Catfish, flow that prevents unnatural variations in depth or inundation (e.g., due to diversion or extraction for agriculture) is important to protect eggs and nests during spawning periods (Rowland 1998; King et al. 2009; Koster et al. 2014; Stuart et al. 2019).

Flow also provides broader ecological outcomes essential for the viability of fish assemblages, such as the preservation of channel morphology, structural habitat and sediment transport. These assist in the creation and maintenance of habitat that can provide refuge for fish during extreme events such as prolonged drought (Robison 2007; Nilsson and Malm-Renöfält 2008; Brierley and Fryirs 2013; Ellis et al. 2021).

Southern Murray-Darling Basin Functional Fish Groups

The range of life history strategies and movement behaviours exhibited by native fish of the MDB means a single flow regime cannot provide equal benefits for the whole fish community (King et al. 2010; Baumgartner et al. 2013). By allocating species of fish into functional groups based on similarities in reproductive strategies, movement capabilities and habitat requirements, we simplify the development of fish specific EWRs and flow related management actions, (See Ellis et al. 2016).

A hybrid approach to deriving fish functional groups was applied to the fish of the MDB by combining elements of the reproductive spawning-movement (Baumgartner et al. 2013) and eco-hydraulic groupings (Mallen-Cooper and Zampatti 2015b). Elements considered included:

- Cues for migration (dispersal and recolonisation) and spawning (temperature and/or flow).
- Spatial scales of adult/juvenile spawning and dispersal movements (10's – 100's of m; 100's of m – 10's of km; 10s - 100s of km).
- Reproductive mode and fecundity (e.g. broadcast spawning, "nesting" species, adhesive eggs).
- Spawning in still/slow-flowing water or in fast-flowing habitats.
- Egg hatch time (short 1 – 3 days; medium 3 – 10 days; long > 10 days) and egg morphology.
- Scale of larval drift.

Linkage between population health (recruitment) and the increased productivity and lateral connectivity associated with Overbank flows/flooding.

Four functional groups for obligate freshwater species in the Southern MDB were identified in Phase 1 of the Fish and Flows in the Southern MDB project based on key life history traits that can be linked to flow characteristics (Ellis et al. 2016). An additional two functional groups identified as occupying only the Lower Lakes-Coorong region at the terminus of the Murray River have been included in this report (Groups 5 and 6). A brief description of the characteristics for each functional group is below. A more thorough description of the key life history elements and processes for each functional group are presented in Table 1. The flow regime requirements for each Southern MDB Fish functional group are summarised in

Table 2. While we acknowledge the groupings presented here represent a simplistic interpretation of fish requirements, they nevertheless have enabled the subsequent design of conceptual (theoretical) flow regimes that meet the needs of multiple fish species. We recommend further consultation with fish ecologists at a regional level be conducted when referring to these groupings in water planning, to fully ensure particular key species requirements at a regional level are addressed (e.g. populations of threatened species).

Group 1 – Flow Pulse Specialists

Adults may utilise both hydraulically complex river habitat and lentic off-channel wetland habitats, with a preference for submerged structure. Higher within channel or overbank flow events (and the increased flow velocity they generally infer) coinciding with warmer water temperatures are generally considered important to initiate a spawning response and support early life history stages, although circumstances may vary across the Basin (Tonkin et al. 2019; Stuart and Sharpe 2020; Stoffels et al. 2020; Tonkin et al. 2021). Adults are highly fecund and may make long migrations in response to flow but can delay spawning if appropriate conditions are not experienced (Sharpe 2011).

Although annual recruitment is not essential, healthy populations consist of multiple year classes and may be maintained by low levels of recruitment in most years (Tonkin et al. 2019). Recruitment success and individual fish condition are often enhanced by flows that provide lotic habitat and enhance river productivity and connectivity via the inundation of floodplain habitat or in-channel benches (Tonkin et al. 2019; Stuart and Sharpe 2020). For example, Silver Perch populations in the mid-Murray River region are supported by permanent, large-scale lotic habitats, with annual but variable recruitment related to river discharge, specifically in the year after spawning (Tonkin et al. 2021).

Eggs and larvae can drift for weeks and can 'transition' from larvae to juvenile stages in transit, potentially dispersing over long distances. Growth and recruitment success may be enhanced by flows that transport young into inundated off-channel habitat and ephemeral wetlands, which may offer productive and sheltered floodplain 'nursery' habitat (Ebner et al. 2009; Ellis et al. 2015; Stuart and Sharpe 2020, Stuart et al. 2021). Higher flow events or 'freshes' may also cue movement or migration, and provide longitudinal connectivity for upstream re-colonisation movements by juveniles and adults which counters the downstream drift of eggs and larvae. Species are medium to long-lived.

Group 2 – River Specialists (with either lotic or lentic preferences)

Prefer hydraulically complex river habitat with submerged structure (e.g., rocks or woody debris). Adults may make short migrations to spawn in response to increased temperature or flow. Moderately fecund, spawn in nests (except Macquarie Perch) or have specific spawning substrate preferences, often displaying parental care of eggs spawned in 'nests' for 14 days or more. Several species need flowing water for successful spawning and hatching (Macquarie Perch, River Blackfish). Maintaining natural rates of water level increase/decrease during breeding season may be important for nesting species where river operations cause water level fluctuations which are out of sync with natural patterns and climatic cues (e.g., rapid decreases in water levels over short time periods) (Stuart et al. 2019).

Larvae may 'drift' semi-passively over short to moderate distances for dispersal upon hatching and exiting the nest. For some species (particularly Murray Cod and Trout Cod), recruitment may be enhanced by flows that increase river productivity and connectivity via the inundation of floodplain habitat or in-channel benches (King et al. 2009; Sharpe and Stuart 2018b; Tonkin et al. 2021; Stoffels et al. 2020, Stuart et al 2021). Rowland (2004) also identified that strong year-classes are often recorded in rivers that are at or near flood levels during the breeding season.

Periodic within-channel Flow Pulses (Freshes) provide connectivity and cues for upstream recolonisation movements by juveniles. River Specialist species do not necessarily require large scale recruitment every year, but healthy populations consist of multiple year classes and demonstrate some recruitment in most years.

River Specialists can be further categorised as preferring spawning in either lotic habitat (e.g. Murray Cod, Macquarie Perch) or lentic habitat (Freshwater Catfish, Southern Purple-Spotted Gudgeon). In some catchments Southern Purple-Spotted Gudgeon and Freshwater Catfish may be considered 'Wetland Specialists' (likely in relation to local geomorphology). As such they may fall in to either this category or the 'Floodplain Specialists' category depending on local expert opinion and historical habitat preferences. Similarly, Macquarie Perch display spawning and movement characteristics that may overlap with 'Flow Pulse Specialists'.

Group 3 – Floodplain Specialists

Prefer off-channel wetland habitats, usually containing submerged vegetation or complex submerged structure (e.g., woody debris, rocks, or inundated terrestrial material). Adults may make short migrations to spawn in response to increased temperature, into or within lentic (or slow-flowing) off-channel habitats. May have specific spawning substrate preferences (Whiterod et al. 2019), hence increases in inundation extent can enhance breeding opportunities by creating additional spawning habitat as well as increasing floodplain productivity benefits.

Species are relatively short to medium-lived with low fecundity. Most species require spawning and recruitment events every 1-2 years for persistence of populations. Overbank flooding is required (although not necessarily annually) to facilitate dispersal for re-colonisation and establishment of new populations and mixing between populations (e.g. Southern Pygmy Perch, Olive Perchlet, Flat-headed Galaxias, Murray Hardyhead). Southern Purple Spotted Gudgeon may fall in to either this category or the 'River specialists with lotic preferences' category (likely in relation to local geomorphology) depending on local expert opinion and historical habitat preferences.

Complementary actions such as manual water provision (e.g. pumping) or conservation stocking may be necessary to maintain or restore habitat and populations of Floodplain Specialists between Overbank events that provide connectivity.

Group 4 – Generalists

Occupy a range of streams and waterbody types. Display flexible spawning strategies, but generally spawning is linked to increased temperature. Survive within-channel during low flows or on floodplains during Overbank inundation. Adults move short distances and may spawn more than once in a year. Short periods of larval drift may occur, and Small Freshes may enhance dispersal by inundating in-stream habitat and connecting drought refuges. Larger flows that inundate off-stream habitat can also promote growth and recruitment (i.e. increased floodplain productivity and habitat availability). Generally short-lived with low fecundity requiring regular (ideally annual) spawning and recruitment events for persistence (e.g. Australian Smelt, Bony Herring, Carp Gudgeon, Mountain Galaxias, Un-specked Hardyhead).

There are also several non-native species that can be regarded as generalists. Adults may make short migrations to spawn in response to increased temperature and other cues (e.g. movement on to recently inundated floodplains). Non-native generalists are usually highly fecund and may spawn multiple times in a year. Flows that inundate and connect off-channel habitats can promote spawning and recruitment, whereas low within-channel flows produce reduced spawning outcomes. Larval drift over short to moderate scales may be exhibited (e.g. Carp, Goldfish, Redfin Perch, Oriental Weatherloach, Rainbow Trout and Brown Trout).

Group 5 – Diadromous species

Movement between freshwater and marine environments is a fundamental to complete the lifecycle requirements of these species. Species within this group are both short-lived (<5 years, i.e. Common Galaxias) and long-lived (>10 years, Short-finned Eel) and range from 100 to >1000 mm in length.

Catadromous species (i.e. Congolli and Common Galaxias) exhibit freshwater adult residence, downstream spawning migrations, estuarine/marine spawning, marine larval development and corresponding upstream juvenile migrations. Anadromous species (i.e. Lamprey species) exhibit marine adult residence, upstream spawning migrations, freshwater spawning, freshwater larval/juvenile development and corresponding downstream juvenile migrations. Spawning and recruitment is dependent on connectivity and ability to migrate to spawning habitats (Zampatti et al. 2010, 2011). Spawning typically occurs annually, over a defined (Congolli) or protracted (Common Galaxias) season (Bice et al. 2012).

Group 6 – Estuarine dependent species

Species that either complete their lifecycle within estuarine environments (e.g. Black Bream) or spend large periods of their lifecycle in the marine environment but are dependent upon estuaries for a particular life stage (e.g. Mulloway).

Factors affecting spawning and recruitment may differ between species. Several species are likely to spawn and recruit annually (e.g. Goby species), whilst others are likely to exhibit temporal variability in spawning and recruitment (e.g. Black Bream, Mulloway). A freshwater discharge may be important in promoting recruitment in all species. Species within this group are both short- to long-lived, and range in size from small to large adult size (50 to 1,000 mm).

Estuarine-dependant species are present in the Coorong and intermittently in Lower Lakes where they may occupy lake edges, wetlands and streams. Most species complete their lifecycle within the Coorong (e.g. Black Bream), whilst some are reliant on the Coorong for a specific life stage (e.g. juvenile Mulloway). Some species move regularly between the Lower Lakes and Coorong (e.g. Lagoon Goby) (Bice et al. 2012). Some species require movement between the Coorong and Southern Ocean through the Murray Mouth (e.g. Mulloway) (SARDI unpublished data).

Table 1. Fish functional groups and key life history elements and processes for species in the Southern MDB.

Functional group	Species	Key life history elements
Group 1: **Flow Pulse Specialists**	Golden Perch, Silver Perch, Spangled Perch	**HABITAT:** Adults use deeper hydraulically complex habitats with a preference for submerged structure (Koehn and Nicol 2014). Recruitment success may be enhanced by flows that inundate and transport drifting young to off-channel habitat (i.e. increased connectivity and ecosystem productivity) (Sharpe 2011). The timing and operation of floodplain regulators can deny drifting early life history stages access to floodplain 'nursery habitat', thereby impacting recruitment (Sharpe 2011). **GROWTH AND CONDITION:** Adult fish gain condition with increasing water temperature usually between spring and autumn. The first post-winter Flow Pulse may be important for enhancing pre-spawning condition and migration. Growth, and condition (and ultimately recruitment success) may be enhanced by flows that increase connectivity and ecosystem productivity. **REPRODUCTION AND RECRUITMENT:** Floods or within-channel flow freshes coupled with warmer water temperature may generate adult spawning migrations (Mallen-Cooper and Stuart 2003; Zampatti and Leigh 2013a). Eggs are either buoyant and pelagic or non-sticky and demersal with a short hatch time of up to 5 days, relying on flows for dispersal. Ephemeral wetlands may offer productive and sheltered floodplain 'nursery' habitat which supports strong survivorship and growth of juveniles (Sharpe 2011; Ellis et al. 2015). Although floods augment recruitment, infrequent flooding in the Murray River interspersed with within-channel increases in discharge may result in frequent spawning and regular low level recruitment, contributing to a robust population structure (Ebner et al . 2009; Zampatti et al. 2015). **MOVEMENT AND CONNECTIVITY:** May undertake large seasonal migrations associated with an increase in flow where connectivity permits. May undertake spawning movements (10s of km to 100s of km) but can delay spawning if conditions are not suitable. Eggs and larvae drift for weeks potentially dispersing over long distance. Flow Pulses (or Freshes) may be required to cue and aid upstream re-colonisation movements by juveniles. Connectivity over large spatial scales is critical for these species. **MAINTENANCE AND SURVIVAL:** Medium to long-lived and highly fecund, not necessarily requiring annual spawning and recruitment events. Growth, condition and recruitment success potentially enhanced by flows that increase connectivity and ecosystem productivity, and potentially through engaging floodplain nursery habitat (Sharpe 2011; Ellis et al. 2015). Populations may be maintained by low levels of regular (usually annual) recruitment and larger less frequent flood-enhanced recruitment events. **Key difference to other functional groups: long lived and move over large (macro-scale) distances. Require Flow Pulses to generate spawning response and facilitate dispersal.**

Functional group	Species	Key life history elements
Group 2: River Specialists	(a) Lotic preference: Murray Cod, Trout Cod, Macquarie Perch, River Blackfish, Two-spined Blackfish, (b) Lentic preference: Freshwater Catfish, Southern Purple-Spotted Gudgeon.	HABITAT: Displays a preference for (a) lotic channel habitats, or (b) permanent lentic off-channel habitats such as backwaters, anabranches and lakes. Habitat contains submerged structure which provides cover, spawning substrates and contributes to hydraulic complexity. Species with a preference for lotic water generally occupy deep habitats (Koehn and Nicol 2014). Freshwater Catfish and Southern Purple Spotted Gudgeon are generally associated with permanent off-channel lentic habitat (particularly for breeding purposes) but are detected in flowing habitats. Often susceptible to cold water pollution. GROWTH AND CONDITION: Adult fish gain condition with increasing water temperature usually between spring and autumn. Instream Freshes may increase growth and condition when the inundation of benches or off-channel habitat contributes to ecosystem productivity. REPRODUCTION AND RECRUITMENT: Generally have specific spawning substrate preferences. Some spawn in nests and parents provide a degree of care and protection of eggs and young. Have a predictable spawning period from mid-winter to the end of autumn, but most commonly between spring and summer independent of flow. Eggs are demersal or sticky with a relatively long hatch time of up to 14 days, requiring stable flow events during this period to avoid nest abandonment, desiccation or premature dispersal. Higher flows may increase recruitment success by increasing river productivity, inundating additional spawning habitat and dispersing drifting young to productive nursery habitat. MOVEMENT AND CONNECTIVITY: Adults may undertake short to moderate scale migrations (100s of m to 100s of km) to spawn. Larvae drift over short to moderate distances for dispersal. Recruitment success potentially enhanced by flow events that transport drifting young to productive off-channel nursery habitat. Periodic Flow Pulses (Freshes) provide connectivity for upstream re-colonisation movements by juveniles. MAINTENANCE AND SURVIVAL: Species are medium to long-lived and although they don't necessarily require successful recruitment every year, populations may be maintained by low levels of regular (usually annual) recruitment. It may take many years for noticeable population improvements due to low or moderate fecundity. **Key difference to other functional groups: medium to long-lived and, do not require Flow Pulses to generate spawning response, uncommon in ephemeral habitats.**
Group 3: Floodplain Specialists	Southern Pygmy Perch, Murray Hardyhead, Olive Perchlet, Flat-	HABITAT: Have specific spawning substrate preferences (often aquatic macrophytes). Some have water quality requirements unique to off-channel habitats (e.g. elevated salinity for Murray Hardyhead, cooler temperatures for Flat-headed Galaxias).

Functional group	Species	Key life history elements
	headed Galaxias, Gambusia (non-native)	GROWTH AND CONDITION: Adult fish gain condition with increasing water temperature usually between spring and autumn (except Flat-headed Galaxias). Increases in flow may enhance breeding opportunities by inundating additional spawning habitat and contributing to ecosystem productivity. REPRODUCTION AND RECRUITMENT: Spawning between spring and autumn (except Flat-headed Galaxias) and may spawn more than once during the year. Eggs are sticky and demersal (not buoyant or pelagic), with a hatch time of up to 10 days (except Gambusia which produce live young, and do not therefore have spawning substrate requirements). MOVEMENT AND CONNECTIVITY: Adult fish undertake short scale movements (100s of m to 10s of km) for spawning, potentially to off-channel habitats, where spawning takes place in still or slow-moving environments. Dispersal relies on flows that reconnect the river channel to the floodplain, although this does not need to occur annually. Flows promote dispersal across floodplain habitats and create connectivity between drought refuges. MAINTENANCE AND SURVIVAL: Relatively short-lived and have low fecundities, requiring regular spawning and recruitment events. For some species this implies reliance on large Overbank flows (or alternative 'managed' methods of water delivery to particular sites) to maintain aquatic habitat and provide connectivity with the river channel (and hence populations). **Key difference to other functional groups – short-lived, preference for off-channel habitat, do not require Flow Pulses to generate spawning response, dispersal enhanced by high flows that connected floodplain habitats.**
Group 4: Generalists	Australian Smelt, Carp Gudgeon, Flat-headed Gudgeon, Bony Herring, Murray–Darling Rainbowfish, Unspecked Hardyhead, Mountain Galaxias, Spotted Galaxias, and Climbing Galaxias.	HABITAT: Able to occupy a range of streams and waterbody types. Generally persist within-channel during extended low flow conditions but do access floodplains. Generally resilient to extended low flow conditions having developed flexible spawning strategies, and as such may be poor indicators of environmental flow effectiveness. However these species provide an important component of productivity in a system and food source for larger fauna. GROWTH AND CONDITION: Adult fish gain condition with increasing water temperature usually between spring and autumn, and access floodplain benefit from on high prey abundance. Low to moderate flow events that inundate within-channel habitat enhances spawning conditions and connectivity of drought refuge. REPRODUCTION AND RECRUITMENT: Adult fish prepare for spawning in response to increasing water temperature (generally spring-summer). May spawn more than once during the year, eggs are sticky and demersal with a hatch time of up to 10 days.

Functional group	Species	Key life history elements
		MOVEMENT AND CONNECTIVITY: Adults move short distances (100s of m to 10s of km) over a wide range of hydrological conditions to spawn. Larval drift is exhibited by majority of species over short to moderate scales, with recruitment reliant on flows for dispersal and conditioning. MAINTENANCE AND SURVIVAL: Species are short to medium-lived requiring regular spawning and recruitment events but may take many years for noticeable population improvements due to low fecundity. While their habitat use is flexible, populations will only be maintained if water quality and food criteria are suitable. **Key difference to other functional groups: flexible spawning and recruitment strategies. Do not require Flow Pulses to generate spawning response, dispersal and recruitment enhanced by flows.**
Group 5: Diadromous species	(a) Anadromous species: Short-headed Lamprey, Pouched Lamprey. (b) Catadromous species: Congolli, Common Galaxias, Short-finned Eel	HABITAT: Representatives in this group exhibit two contrasting diadromous life histories, namely (a) anadromy: adult marine residence, and freshwater spawning and larval/juvenile development; and (b) catadromy: adult freshwater residence, and estuarine/marine spawning and larval/juvenile development. Catadromous species use a range of freshwater habitats including lake edges, wetlands and streams, typically lower reaches of rivers. In freshwater habitats, anadromous species typically spawn in nests in shallow fast–flowing habitats, whilst juveniles (ammocoetes) live in silty/muddy sediments of slow-flowing habitats. GROWTH AND CONDITION: Adults catadromous species appear to prepare for spawning in response to decreasing temperature and/or day length rather than flow. Nevertheless, enhanced productivity associated with flow may enhance individual condition prior to spawning. Gonad development in anadromous lampreys occurs during upstream riverine migrations but is not reliant on flow as individuals do not feed during migration, but rather rely on resources previously obtained from marine habitats. REPRODUCTION AND RECRUITMENT: Spawning of catadromous species occurs in estuarine (Common Galaxias) or marine environments (Congolli) mostly in winter, but extending into early spring, following downstream migrations from adult freshwater habitats. Spawning in Congolli (and often in Common Galaxias) is followed by adult mortality. Common Galaxias attach adhesive eggs to terrestrial vegetation on spring high tides, with eggs hatching the following spring tide. Anadromous species (Lampreys) likely spawn in spring the year following migrating into freshwater from adult marine habitats. Whilst details on Australian Lamprey species spawning are scarce, spawning likely occurs in constructed nests or depressions and is followed by adult mortality.

Functional group	Species	Key life history elements
		MOVEMENT AND CONNECTIVITY: All species within this group undertake large-scale migrations as both juveniles and adults, and subsequently rely on flow to provide cues for movement and hydrological connectivity. The catadromous Congolli and Common Galaxias undertake downstream adult spawning migrations in winter, typically in the order of 10s km's, whilst in the case of Short-finned Eel, this migration involves movements of 1000s kms to spawning grounds in the Coral Sea. Larvae are planktonic and drift passively in the marine environment, before juveniles undertake upstream migrations into freshwater environments, of a similar scale to the corresponding adult migrations, in spring/summer. Adults of anadromous Lampreys potentially undertake large-scale upstream migrations (100s–1000s km's) from marine environments to freshwater spawning habitats, typically entering rivers from the ocean during winter/early spring. The spawning run may take 12–16 months before spawning occurs. Larvae and juveniles are relatively sedentary, undertaking only small-scale movements (10s–100s m's) before metamorphosed sub-adults (i.e. macrothalmia) undertake large-scale downstream migrations to the marine environment. MAINTENANCE AND SURVIVAL: Migration, spawning and recruitment are reliant on flow to stimulate migrations (Lamprey) and facilitate hydrological connectivity (all species). This is particularly important from June–January, encompassing downstream and upstream migration for all species. Catadromous species are short- to medium-lived, requiring regular recruitment to maintain abundant populations. **Key difference to other functional group: unique meso- to macro-scale life histories dependent on both freshwater and marine environments, and importantly, connectivity/migration between them. Flow Pulses required to stimulate upstream migrations for anadromous species and facilitate connectivity for upstream and downstream migrations of all species.**
Group 6: Estuarine dependent species	(a) Solely estuarine: Black Bream, Lagoon Goby, Tamar River Goby, Bluespot Goby, Bridled Goby, Small-mouthed Hardyhead. (b) Estuarine dependent marine species: Mulloway, Greenback	HABITAT: Diverse group which includes species that (a) complete their lifecycle within estuarine environments; and (b) spawn and reside in the marine environment but are dependent on estuarine habitats for specific stages of their life history. Habitat use varies between species and ranges from brackish (e.g. black Bream, Mulloway) to hypersaline (Small-mouthed Hardyhead) estuaries and adjacent freshwater habitats for some species (e.g. Lagoon Goby). GROWTH AND CONDITION: Freshwater flows to estuarine habitats facilitate the downstream transport of carbon and nutrients that subsidize estuarine food webs, and promote enhanced primary and secondary productivity, including fish condition, growth and abundance. REPRODUCTION AND RECRUITMENT: Reproductive characteristics (e.g. timing) are species-specific and variable, but best delineated by those that spawn within (a) estuarine environments and (b) those that spawn in marine environments. Recruitment of many species occurs annually (e.g. Goby species,

Functional group	Species	Key life history elements
	Flounder, Long-snouted Flounder, Yellow-eyed Mullet, Sandy Sprat	Small-mouthed Hardyhead) irrespective of flow, but the influence of flow on salinity dictates distribution and recruitment strength. Other species exhibit enhanced recruitment and abundance in association with years of high flow (e.g. Mulloway, Sandy Sprat). MOVEMENT AND CONNECTIVITY: Movement patterns are also species-specific and highly variable. Whilst many species have pelagic larvae that may presumably move passively over meso- to macro-scales, juveniles and adults of some species are likely to be largely sedentary (i.e. Goby species). Alternatively, estuarine dependent marine species migrate into estuarine environments as juveniles, with corresponding return migrations to marine environments for spawning. Estuarine ingress is dependent on physical (i.e. open Murray Mouth) and hydrological (i.e. freshwater discharge) connectivity between estuarine and marine environments. Many species are likely to undertake meso-scale (10s km's) intra-estuarine movements in association with variability in discharge, salinity and water levels. MAINTENANCE AND SURVIVAL: Most species persist within estuarine environments during periods of low flow, but exhibit restricted distributions, low abundance and in some instances, limited recruitment. Flow facilitates the establishment of favorable estuarine salinity regimes and promotes estuarine–marine connectivity (hydrological and ecological), typically resulting in broadly distributed and abundant populations, and enhanced recruitment. **Key difference to other functional groups: species specifically reliant on estuarine habitats. Flow facilitates establishment of favorable salinity regimes, enhanced productivity, and estuarine–marine connectivity, which in turn facilitate broad distributions, enhanced recruitment and abundance.**

Table 2. Flow regime influences on life history for fish functional groups.

Functional Group	Flow regime influence on life history
Group 1. Flow Pulse Specialists Silver Perch, Golden Perch, Spangled Perch	• Prefer hydraulically complex habitats, and may undertake large seasonal migrations associated with an increase in flow where connectivity permits. • The first annual post-winter flow event (OB, BF or LF) may be significant for enhancing pre-spawning condition (i.e. increases ecosystem productivity) and in facilitating long distant movements. This flow event will frequently coincide with increased irrigation demand, hence, could present an opportunity for environmental water to enhance flow magnitudes and native fish outcomes. • A rapid rise or fall in flow (corresponding to natural rates of variability at a given reach in the catchment) between spring and autumn may be important in cueing spawning (OB, BF, LF). Such an event should span a minimum of 5 days (including rise and fall) at a given location and should occur annually. • Lateral connectivity with low lying ephemeral wetlands may offer productive and sheltered floodplain 'nursery' habitat which supports strong survivorship and growth of juveniles (Sharpe 2011; Elis et al. 2015). Overbank flow connecting low-lying wetlands (OB) are recommended to occur at least every 3-4 years to promote large scale recruitment. • Large within-channel fresh (LF) to occur every 1-2 years (in addition to Overbank flow events) to support regular annual recruitment (LF). Gradual recession (within natural rates of variability corresponding to the position within a catchment) can assist with egg dispersal and may also support subsequent spawning (Sharpe 2011, Sharpe and Stuart 2018). • A late summer – autumn Small Fresh may promote juvenile dispersal movements. Small Freshes would occur two to three times per year in perennial systems (SF), with Large Freshes experienced every 1 - 2 years in intermittent systems (LF). • Integrity of flow events need to be maintained over long distances (10s to 100s of km) to maximise the capacity for in-stream spawning, downstream dispersal by drifting eggs and larvae and movements by adults and juveniles. • Flow variability (i.e. large or Small Freshes and variable Base Flows) (LF, SF or BA) enhances growth and condition of larvae and juveniles by maintaining aquatic habitat, providing connectivity for dispersal between habitats (particularly river channels and low lying off-channel habitat) and promoting ecosystem productivity • Although these species are capable of withstanding short cease-to-flow periods, Base Flows maintain habitat (e.g. depth and submerged structure), productivity and water quality (e.g. oxygenation in drought refuge). Base Flows will also support winter conditioning through maintenance of ecosystem processes (D). • Expected ecological outcomes include increased within-channel habitat availability and maintenance of hydrodynamic complexity; improved productivity throughout the system from inundation of within-channel benches and low-lying floodplain, and provision of flowing conditions for moderate to large-scale movement by adults and juveniles and dispersal away from spawning and refuge sites by eggs and larvae.

Functional Group	Flow regime influence on life history
Group 2. River Specialists (a) Lotic preference: Murray Cod, Trout Cod, Macquarie Perch, River Blackfish, Two-spined Blackfish, (b) Lentic preference: Freshwater Catfish, Southern Purple-Spotted Gudgeon.	• Prefer hydraulically complex flowing streams containing submerged structure which provides cover and spawning substrates. May undertake seasonal migrations associated with an increase in flow where connectivity permits. • Spawning usually occurs annually, independent of flow; however, response or 'investment' in terms of energy afforded to breeding may be enhanced by increase in flow during spring which promotes ecosystem productivity and inundates additional spawning habitat (OB, BF and LF) (Sharpe and Stuart 2018). • Maintaining water levels may be important for nesting species (SN) where river operations to meet irrigation demand cause water level fluctuations which are out of sync with natural patterns and climatic cues (e.g., rapid decreases in water levels over short time periods). Where this is not a critical limiting factor for fish populations (e.g., the Lower Murray) water management should instead focus on returning the natural hydraulic complexity and shape of events as they correspond to position in catchment and avoid rapid drops in water level. • Recruitment of larvae and juveniles enhanced from secondary peak event for dispersal and access to habitat and suitable prey sources (SN, LF). • Integrity of flow events needs to be maintained over moderate distances (10s to 100s of km) to maximise response. • Regular small-scale spawning and recruitment events are required to sustain local populations (every 1-2 years) and may occur in conjunction with large within-channel Freshes (LF). Larger flood-enhanced events (i.e., Overbank flows) support larger scale spawning and recruitment will ideally occur two to three times per decade (OB). • Flow variability (BF, LF, SN and SF) enhances growth and condition of larvae and juveniles by maintaining aquatic habitat, providing connectivity for dispersal between habitats (particularly river channels and low lying off-channel habitat) and promoting ecosystem productivity. Small Freshes would occur two to three times per year in perennial systems, with Large Freshes experienced every 1-2 years in intermittent systems (LF and SN). • Although these species are capable of withstanding short cease-to-flow periods, Base Flows maintain habitat (e.g., depth and submerged structure) and water quality (e.g. oxygenation in drought refuge). Base Flows will also support winter conditioning through maintenance of ecosystem processes (BA). • Expected ecological outcomes include increased within-channel habitat availability and maintenance through hydrodynamic complexity; improved productivity throughout the system from flow peak inundating within-channel benches; and supporting short to moderate scale fish movement and dispersal throughout the system away from spawning and refuge sites.
Group 3. Floodplain Specialists Southern Pygmy Perch, Murray	• Spawning generally occurs in non-flowing floodplain habitats, most commonly in spring and summer. Spawning response is enhanced by Overbank flow during warmer seasons due to creation of additional spawning habitat and floodplain productivity benefits (OB). Modified flow regimes increase the potential for isolation and extirpation of floodplain population.

Functional Group	Flow regime influence on life history
Hardyhead, Olive Perchlet, Flat-headed Galaxias, Gambusia (non-native)	• Water level needs to be maintained for a period greater than 14 days to allow for spawning and egg development, with gradual recession of event required for adult movement. • Overbank flooding events also promote dispersal, re-colonisation, and mixing between populations. This need not occur annually but need to occur frequently enough to prevent extirpation of isolated populations. Flood-enhanced events will ideally occur two to three times per decade. Complementary action in the form of water delivery (e.g. pumping) may be necessary to prevent desiccation and maintain habitat for isolated populations in between connecting Overbank flows (location dependant). • Recruitment of larvae and juveniles enhanced by subsequent flow events that provide lateral connection and facilitate dispersal. This can occur weeks after the initial peak event, with gradual recession of event important for larvae and juvenile movement (OB, BF and LF in some cases, location dependant). • For some species autumn spawning events may occur, supported by flow events which connect floodplain habitats and create additional spawning habitat (OB and BF, and LF in some cases location dependant). • Relatively short-lived with low fecundity. Most species require spawning and recruitment every 1-2 years for survival of populations, particularly fragmented floodplain populations (e.g. Murray Hardyhead). Given provision of Overbank floodplain connectivity every 1-2 years may be unachievable, complimentary actions such as manual water provision (e.g. pumping) or conservation stocking may be necessary to maintain or restore habitat and populations of Floodplain Specialists. • Expected ecological outcomes include flowing conditions for short scale longitudinal and lateral fish movement and dispersal both within-channel and across lateral habitats (e.g. anabranches); increased habitat availability; improved productivity throughout the system.
Group 4. Generalists Native: Australian Smelt, Carp Gudgeon, Flat-headed Gudgeon, Bony Herring, Murray – Darling Rainbowfish, Unspecked Hardyhead, Mountain Galaxias, Spotted Galaxias, and Climbing Galaxias. Non-native: Carp, Goldfish, Redfin Perch,	• Spawning occurs independent of flow events; however response is enhanced by increase in flow during warmer months (most common timing amongst species between Sept and Feb) (OB, BF, LF and SN). • Multiple peak events during spawning season provide flexibility in species response, as well as opportunities for multiple spawning events from serial spawning species (OB, BF, LF and SN). • Flow peaks generally need to be maintained for a period greater than 7 days to allow for egg development and hatching, with gradual recession of event required. • Recruitment of larvae and juveniles enhanced from subsequent flow events for dispersal and access to habitat and suitable prey sources (LF and SN). • Although capable of withstanding short cease-to-flow periods, Base Flows maintain habitat (e.g., depth and submerged structure) and water quality (e.g. oxygenation in drought refuge). Base Flows will also support winter conditioning through maintenance of ecosystem processes (BA).

Functional Group	Flow regime influence on life history
Oriental Weatherloach, Rainbow Trout, Brown Trout.	• Generally short-lived with low fecundity requiring regular (ideally annual) spawning and recruitment events for persistence. • Ecological outcomes include provision of flowing conditions for short scale fish movement and dispersal throughout the system; increased within-channel habitat availability and hydraulic complexity, increase in abundance of small-bodied natives, providing important food source for medium and large bodied fish. • Consideration of generalist pest species breeding, and recruitment outcomes should be made when planning water management activities and flow management.
Group 5. Diadromous species (a) Anadromous species: Short-headed Lamprey, Pouched Lamprey. (b) Catadromous species: Congolli, Common Galaxias, Short-finned Eel	*Anadromous species* • Spawning occurs in freshwater habitats and is not reliant on flow per se; however, freshwater flow is critical to stimulate upstream movement and facilitate connectivity for estuarine–freshwater transition (BA, SF and LF). • Continuous low-level discharge punctuated by multiple Freshes in winter (small or large) is important to stimulate upstream movement and facilitate connectivity between the river and the sea (i.e. attraction flow) (BA, SF and LF). • Longitudinal integrity of flow and olfactory cues (pheromones from larval conspecifics) may be important for stimulating migrations. • Influence of flow regime on juvenile development and sub-adult downstream migration is currently unknown. • Expected ecological outcomes include the provision of flow to enhance hydrological connectivity (longitudinal and between the river and the sea) and movement cues to facilitate obligate upstream spawning migrations required to maintain viable populations. *Catadromous species* • Gonad development and downstream migration occurs annually irrespective of flow; however, transition to estuarine/marine spawning habitats and subsequent spawning is reliant on connectivity between the river and the sea facilitated by flow persistence during winter (SF, BA). • Continuous connectivity between the river and the sea required from June–August (this may represent the opening of several barrage gates) (SF, BA). • Flow peaks in spring likely stimulate marine–estuarine ingress and promote estuarine productivity, in turn supporting juvenile growth and survival (OB, BF, and LF). • Flow peaks in spring/summer to stimulate upstream movement and facilitate connectivity between the river and the sea (attraction flow) for juvenile estuarine–freshwater migrations (BF, LF, SN and SF). • Short- to medium-lived, requiring regular recruitment to maintain resilient populations.

Functional Group	Flow regime influence on life history
	• Expected ecological outcomes include the provision of flow to enhance hydrological connectivity and movement cues to facilitate obligate upstream and downstream migrations required to maintain viable populations.
Group 6. Estuarine dependent species (a) Solely estuarine: Black Bream, Lagoon Goby, Tamar River Goby, Bluespot Goby, Bridled Goby, Small-mouthed Hardyhead. (b) Estuarine dependent marine species: Mulloway, Greenback Flounder, Long-snouted Flounder, Yellow-eyed Mullet, Sandy Sprat	• Timing of spawning is species-specific, may occur within estuarine or marine environments, and is typically (but not always) independent of flow. • Although these species are capable of withstanding short cease-to-flow periods, increases in salinity associated with such conditions result in contracted distributions (and subsequent increased predation and exploitation rates), limited recruitment, low abundance and simplification of food webs. • Continuous Base Flows are important for maintaining a limited area of favourable estuarine habitats (i.e. salinity gradient from freshwater–hypermarine) (BF). • Flow events are critical for promoting enhanced productivity and favourable estuarine salinity regimes over appropriate spatial scales that in turn, promote broad distributions and area suitable for residence, spawning and recruitment (BF, LF, SF, SN). • Flow events during winter, spring and early summer are likely critical to stimulate estuarine ingress by estuarine dependent marine species (LF, SF, SN). • Expected ecological outcomes include the provision of flow to foster maintenance of an appropriate salinity gradient (freshwater–hypermarine) that facilitates broad adult distributions and areas suitable for spawning and recruitment, stimulate the estuarine ingress of marine spawned species, and promote estuarine primary and secondary productivity.

Developing flows for fish

Higher flows and floods were usually experienced in late winter and spring in the Murray, Murrumbidgee, Lachlan and Goulburn River systems. Highest flows in the Darling-Baaka River generally occur in summer-autumn resulting from summer monsoon rain but can also occur as a result of temperate winter storms.

Restoring flow regimes to benefit fish necessitates an understanding of relationships between hydrology and life history, and the subsequent population dynamics. This can be done by considering specific components of a rivers flow regime which may influence population outcomes such as spawning, recruitment and movement. These are referred to here as Ecologically Significant Components (ESCs) (MDBA 2011b).

Ecologically significant components of the flow regime

Ecologically Significant Components (ESCs) of the flow regime serve as a common reference to which flow management targets such as EWRs can be applied and gauged (Figure 5). ESCs referred to in this report are:

- Cease to Flow (CTF) – short periods in which flow ceases occur in ephemeral, or non-perennial rivers (weeks to months), and for longer periods in some intermittent streams (months to years), during which a series of disconnected pools or complete drying may eventuate. Historically, sections of larger rivers in the MDB occasionally ceased flowing during extreme droughts, but usually for short periods of weeks to months (Mallen Cooper and Zampatti 2018; 2020). Cease-to-flow periods can play an important role in promoting growth of biofilms (i.e. through reduced scour) and productivity, although they can also be associated with poor fish condition; particularly for species at lower trophic levels (Balcombe et al. 2012). High food availability for predatory species at higher trophic levels may occur initially during cease-to-flow periods, given the limited refuge habitat for prey. However, during extended cease-to-flow periods, food supply and water quality would be expected to diminish in pools as water levels contract. Non-flowing pools can become thermally stratified in warmer climates and seasons, with a related potential for de-oxygenation of deeper water. Rapid mixing of stratified pools, in response to small resumption flows or sudden weather events, can cause hypoxia throughout the pool with the risk of fish kills (Ellis and Meredith 2004; Vertessy et al. 2019). In some cases, cease to flow may restrict Carp breeding by limiting access to their preferred shallow submerged spawning substrate and habitat.
- Base Flows (BA) – Usually confined to deeper low-lying parts of the river channel, and would typically provide connectivity between pools and riffles, preventing cease to flow events. They would generally occur on a near-ongoing basis in perennial systems maintaining longitudinal connectivity and associated dispersal opportunities. Base Flows may be important in maintaining drought refuges for fish, plants and invertebrates when low flow conditions prevail, and help maintain water quality (e.g. oxygenation through riffle habitats or refuge pools prone to thermal stratification). Base Flows may also benefit small-bodied native species in terminal wetlands. By enhancing the condition of individuals, Base Flows can sustain a larger population carrying capacity for density dependant species during low flow periods. Base Flows also allow for the accumulation of allochthonous carbon and vegetation on higher benches and dry river channel sediments, which then contribute to ecosystem productivity during subsequent flow events. They also contribute to nutrient dilution during wet periods or after a flood event. Small variations in flow within the base flow band can mimic natural variability and promote productivity during base flow periods.
- Small Fresh (SF) – Generally short increases in flow (10 days minimum) that provides longitudinal connectivity and may provide productivity benefits by replenishing soil water for riparian vegetation, inundating low-lying benches and cycling nutrients between different parts of the river channel. Small Freshes are generally relatively slow flowing and are distinct from Large Freshes (e.g. less than 0.3m/s). They can contribute to the maintenance of suitable water quality and key aquatic habitat such as snags and aquatic vegetation, which supports diverse

heterotrophic biofilm generation with greater nutritional value to higher organisms. The magnitude of Small Freshes may be informed by habitat mapping which identifies river heights at which within-channel features (e.g. benches and snags) are inundated. Small within-channel Freshes would have generally occurred annually throughout the majority of the MDB (including most ephemeral streams), and potentially two to three times in a year for perennial (permanent or near permanently flowing) river and stream systems.

- Large Fresh (LF) – Substantial increases in flow for short durations (5 days minimum) that provide inundation of within-channel features (e.g. benches), hydraulic complexity and longitudinal connectivity. In some reaches Large Freshes may connect low lying backwaters and wetlands with low commence to flow thresholds. Generally, provide fast flowing within-channel habitats (e.g. velocity greater than 0.3m/s), although in highly regulated reaches concurrent lowering of weirs or regulatory infrastructure may be required to restore hydraulic complexity and higher flow velocity. Large within-channel freshes enhance productivity and nutrient exchange, promote dispersal and recruitment and may trigger spawning in some species including Flow Pulse Specialists (e.g. Golden Perch, Silver Perch). Large Freshes are also important for maintaining refuges and minimising geomorphological impacts of regulation (e.g. sedimentation). Maintaining natural rates of change in water level may be important when Large Freshes overlap with predictable spring breeding season of key nesting River Specialists (e.g. Murray Cod, Freshwater Catfish) as rapid change in water levels may lead to nest abandonment. Large within-channel Freshes would have generally occurred annually across most of the MDB, and up to two to three times a year in some river systems.
- Spring nesting component (SN) –represents a seasonal period of flow during which unnaturally rapid change in water levels are absent during the predictable spring breeding season for nesting River Specialists (e.g. Murray Cod, Freshwater Catfish), thus avoiding stranding or abandonment of nests. Minimum event duration of 14 days, during which changes in flow magnitude and stream height (particularly decreases) should be maintained within natural rates of variability to allow eggs to hatch and for larvae to leave nest sites. Larger/longer duration for spring nesting components (30-50 days from early October through to late November where and when possible) may enhance breeding outcomes by increasing productivity, inundating additional spawning sites and dispersing drifting young to productive nursery habitat. Depending on location, nesting could be supported at flow magnitude representative of Base flow levels through to Large Fresh levels, although breeding success is likely to be higher in fast flowing in-channel habitats (e.g. velocity greater than 0.3m/s). A short increase in flow at the end of the spring nesting component could be initiated (in managed flow situations) to inundate additional in-stream habitat and further enhance productivity and food generation (Sharpe and Stuart 2018).
- Bank full (BF) –For the purposes of this project, Bank full flows are flow magnitudes at which inundation of ephemeral floodplain habitats with low commence to flow levels adjacent to river and stream channels may occur (such as wetlands, creeks and anabranches). These events generally provide fast flowing within-channel habitats (e.g. velocity greater than 0.3m/s).
- Overbank flows (OB): Overbank flows can inundate large areas of floodplain habitat. Overbank events can enhance breeding opportunities for many species by creating additional spawning habitat and floodplain productivity benefits which contribute to increased condition and recruitment. These events are generally unregulated, although there may be scenarios where environmental water activities could augment within-channel flows to create small overbank events in which case the shape of these events should ideally reflect the natural rates of flow increase or decrease corresponding to position in the catchment. Overbank events generally would have occurred every 1-25 years (depending on the magnitude of the event) for both intermittent and perennial systems.

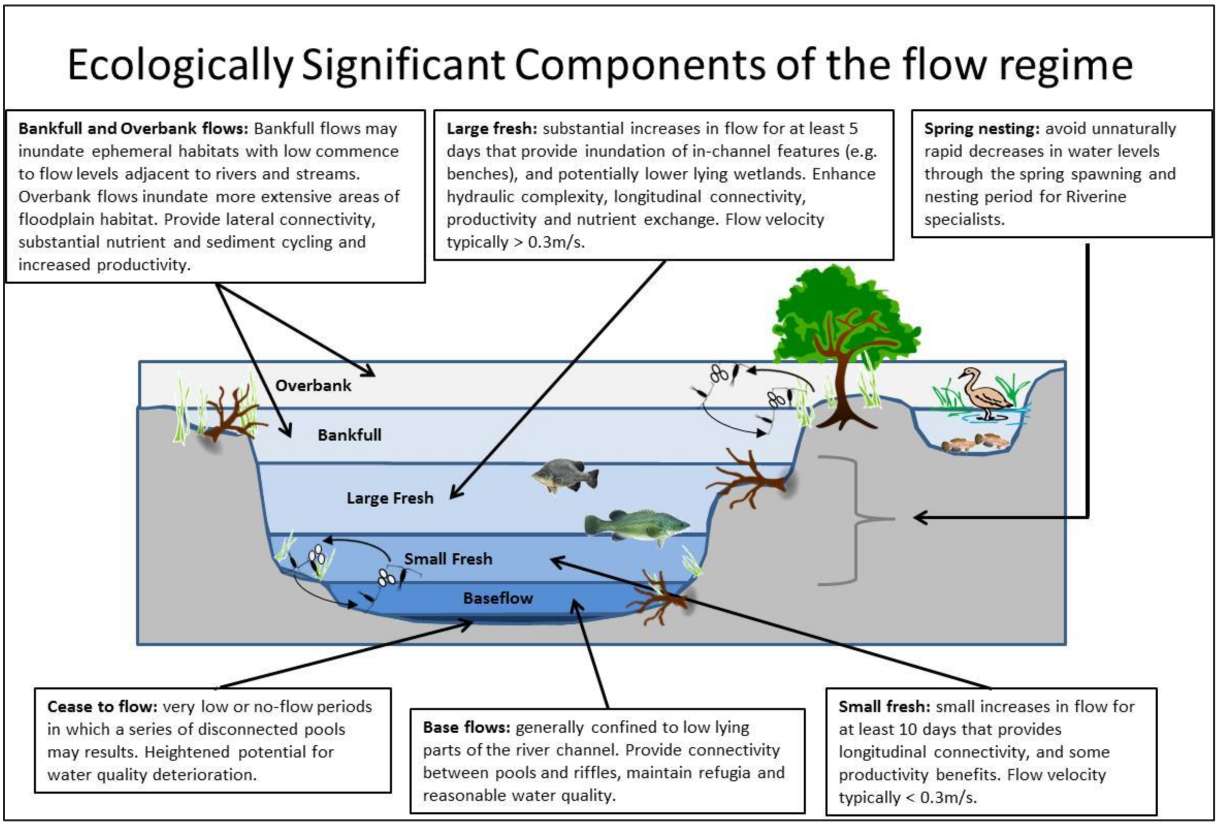

Figure 5. Ecologically significant components of the within-channel flow regime (including Cease to flow, Base Flows, Small Fresh, Large Fresh, Spring nesting component, Bank full and Overbank flows).

Conceptual hydrographs

Conceptual hydrographs incorporating the ESCs presented above were developed for rivers in the Southern MDB (Figure 6). These conceptual hydrographs provide a visual representation of key flow components under three different water resource availability scenarios (High, Moderate, and Low water availability), and suggested timing for each ESC in relation to the seasonal requirements for functional groups of Southern MDB fishes (i.e., habitat, condition, reproduction, movement and maintenance).

Conceptual flow hydrographs are useful tools to assist with environmental water planning processes. Larger flow components will be less achievable in periods of limited water availability. The flow components depicted in Figure 6 are used later in this document to develop fish specific EWRs at the individual HIS.

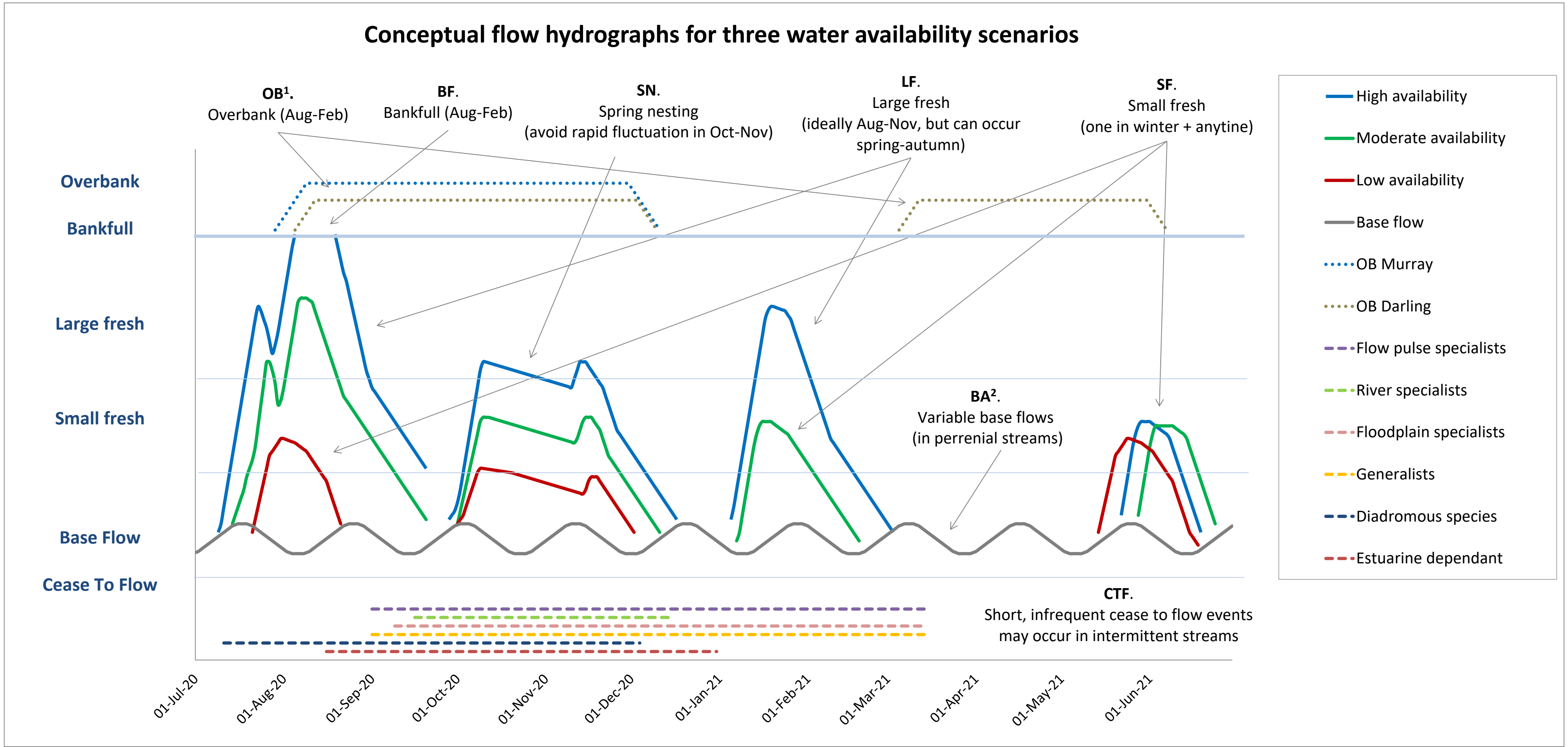

Figure 6. Conceptual flow hydrographs for three water availability scenarios (High, Moderate, and Low). Breeding season windows for each functional group of Southern MDB fishes are identified by dashed lines. Ecologically significant flow components which may promote key life history elements for fish (such as movement, spawning and condition) are labelled BF (Bank Full), Overbank (OB), Large Fresh (LF), Spring nesting component (SN), Small Fresh (SF), and Cease to Flow (CTF).

Responsible water management

The conceptual hydrograph and EWRs we present in this report are by no means prescriptive. Responsible water management will require coordinated efforts between jurisdictions across both the Southern and Northern MDB and sustained consultation with expert fish ecologists. Planning managed flow events must also consider antecedent hydrology, forecast water availability and the prioritisation of hydraulic requirements within and between systems both spatially and temporally.

Furthermore, the flow elements we present here for one functional group of fishes may not necessarily provide benefits for another. A combination of conceptual flow events may be necessary to support the whole native fish community in each reach or valley. As such adaptive management, flexibility, and a long-term commitment to deliver benefits to native fish and river health will be required (Baumgartner et al. 2013; NSW DPI 2015). The conceptual flow hydrographs above were constructed with the capacity to be updated or modified as additional information comes to hand. In practice, this responsiveness means the on-ground delivery of desired flow components can also be adapted in ‘real time’ to accommodate or adapt to changing hydraulic conditions. The following elements should be considered when developing and delivering flows for fish outcomes:

Timing

Larger watering events are likely to be guided by natural flow cues. The conceptual hydrographs presented in Figure 6 are based on generalised natural flow regimes for Southern MDB systems. Given the complexity and variability in ecological systems within the Southern MDB, most ESCs could occur anytime within a year, although the productivity response may differ between seasons (see Robertson et al. 2001). For wholly managed environmental watering events:

- Spring nesting components should occur during the predictable breeding season for nesting River Specialists (e.g. Murray Cod, Trout Cod, and Freshwater Catfish).
- When targeting reproductive outcomes, the planning of Large Freshes (or Bank full flows) during the ‘breeding season’ should consider the potential for nest disturbance or abandonment during flow recession (when nesting sites higher in the water column may be come exposed. Consideration of subsequent flow management, or overlap with seasonal flow requirements, may also be required to enhance survival and recruitment following a breeding response, and to maximise the condition of individuals and populations.
- A Small Fresh through the terminus of the Murray River (the Coorong-Lower Lakes region) in winter will benefit Diadromous species. Additional Small Freshes could occur any time of the year although they may be deliberately applied at a certain time to target particular outcomes (e.g. for maintenance of water quality, or to facilitate/cue movements).
- The provision of variable Base Flows that prevent streams from contracting to lentic pools between flow events will provide refuge habitat and maintain appropriate water quality.

Multiple outcomes

Where possible, the conceptual hydrographs and EWRs presented attempt to benefit multiple functional groups, thus providing efficiency in flow delivery. For example, large within-channel Freshes in spring may primarily target spawning by Flow Pulse Specialists but will also support spawning by Generalist species and promote larval and adult dispersal for all groups (except Floodplain Specialists). Large and Small Freshes also promote hydraulic variability and lotic habitat within riverine habitats (location dependant) and can support ecological processes such as biofilm complexity and productivity or the dispersal and establishment of aquatic vegetation (habitat for many fish species).

In many cases flow components of a higher magnitude will also meet the requirement for lower events. For example, the spring nesting component for River Specialist species may be accommodated within protracted managed Small or Large Fresh events by ensuring unnaturally rapid decreases in water levels through the October and November spawning and nesting period for these species are avoided. Similarly, a managed Small Fresh may be disrupted by a natural increase in flow which extends into the Large Fresh flow band in a stream or reach. In this instance we should not consider the attempted delivery of a Small Fresh to have failed, but rather it deferred to a Large Fresh (so long as the flow rate at that site is exceeded for the recommended duration of a Large Fresh event).

Cumulative flows

The achievement of ecological outcomes through the delivery of a particular flow component will be influenced by antecedent conditions and may depend on cumulative outcomes from multiple events within a year and over successive years. For flexibility in the application of managed flows, we suggest individual flow components should not necessarily be considered as discreet flow events.

For example:

- Spawning cues provided by a Large Fresh are best followed by flows conditions conducive to recruitment and subsequent dispersal of larvae and juveniles (i.e. Small Freshes or sequences of Large Freshes).
- Large Freshes delivered in late-winter or spring could be 'blended' into a spring nesting component in which rapid drops in flow are avoided (throughout October and November) to support breeding by nesting River Specialists.
- Conversely, a spring nesting component for River Specialists could be followed by increases in flow to potentially induce a spawning response from Flow Pulse Specialists.

Regional variability

The natural variation in hydrology across the Southern MDB will necessitate adaptation of conceptual hydrographs to suit different geographic locations. Breeding seasons may vary within and between catchments or streams in the Southern MDB. For example, Murray Cod spawning season can vary latitudinally (Rowland 2004). Regionally specific details such as the timing of breeding seasons, channel capacities and inundation levels for critical habitat features, as well as antecedent conditions (e.g. protracted drought as compared to recent flooding) should be considered when planning flow events for fish outcomes. Consultation with ecological experts in the target valley is recommended during flow planning and delivery.

Natural flow protection and enhancement

Although few unregulated streams remain in the Southern MDB, natural flows and cues (e.g. tributary inflows, rainfall rejection events) should be protected and where appropriate, complemented with environmental flows to achieve in-channel flow variability. Where third party impacts are negated, overbank flows may be achievable to connect floodplains and promote productivity (and potentially limit unnatural build-up of floodplain carbon). This will preserve critical flow elements such as seasonality, and longitudinal connectivity, and is more likely to delivery biological, chemical and climatic cues that support key ecosystem functions and river productivity. Delivery of environmental flows to floodplains in a manner that simulates the properties of natural flood events are more likely to result in positive outcomes for native fish (although consideration for pest fish breeding and potential for hypoxic blackwater generation is required). The MDBA and CEWO both incorporate 'natural cues' principles in their planning processes for environmental water delivery.

Flow augmentation

There may be opportunities to modify or enhance the delivery of existing water or delivery of operational water for other users or river operations to achieve desired fish outcomes. Operational flows such as irrigation delivery can be shaped or augmented with environmental water to modify or prolong flow components and that support native fish outcomes. There may also be opportunities to facilitate Bank full or Small Overbank flows to key floodplain wetlands which support Floodplain Specialist species (where constraints permit) either via connectivity or by simplifying logistical requirements for complementary watering actions (such as pumping).

Conversely, consideration should be given to the risk that positive outcomes achieved during flow augmentation may be somewhat offset by negative outcomes such as entrainment of larval or juvenile native fish in irrigation offtakes and pumps. In recent years, flow augmentation opportunities have been trialled as part of day-to-day river operations in some catchments. This is likely to continue as the Basin Plan progresses and water managers adaptively 'learn by doing'.

Perverse outcomes

Water managers are mindful of potential perverse impacts on native fish communities arising from water for the environment and adopt a cautious approach. Environmental water management may also consider the use of environmental flows to mitigate negative impacts. Some examples of perverse outcomes that may occur in relation to, or be mitigated through, informed environmental watering include:

- Hypoxic Blackwater - In recent decades river regulation has reduced floodplain inundation frequency, increasing the severity of hypoxic blackwater events. Longer dry phases reduce floodplain flushing and allows for extensive accumulation of carbon sources on the floodplain between flooding events. Whilst the dissolved carbon which gives blackwater its name is ordinarily beneficial to aquatic food webs, excessive dissolved carbon concentration creates higher biological demand, which can result prolonged hypoxia and the death of fish. Managers have recently been pro-active in delivering environmental water (when possible) during flood events and throughout flood recession to dilute hypoxic water and provide localised refuge areas throughout effected landscapes (Commonwealth Environmental Water Office, 2017; Watts et al. 2017).
- Thermal stratification – Deeper slow or non-flowing areas in river and stream or refuge pools can thermally stratify during warmer months, with warmer surface and cooler deeper (denser) layers of water forming. With limited mixing between the layers of water dissolved oxygen is depleted in deeper water (hypoxia), thus restricting fish to the surface waters which are oxygenated through daily photosynthesis by algae and plants, and potentially via air-surface aeration. Sudden de-stratification, or 'Turn over' of stratified pools results in the mixing of the hypoxic deeper water throughout the water column which poses a risk to fish kill. Rapid destratification can occur due to the resumption or an increase in flow, or due to sudden weather events (Ellis and Meredith 2004; Baldwin 2019; Baldwin 2021). In these situations, large flow releases that dilute hypoxic water upon destratification or enable movement away from hypoxic water may alleviate or prevent perverse outcomes.
- Algal blooms - In warmer months, lentic water bodies may experience blue-green algal blooms (particularly in association with thermally stratified water columns rich in nutrients). In addition to the potentially harmful toxins produced by some blue green algae, severe blooms can deplete dissolved oxygen in rivers or wetlands which poses added risk to fish communities. The sudden die-off of an algal bloom can result in additional oxygen stress as the dead algae decompose. Environmental flows have been utilised to prevent the development of or mitigate the impacts of widespread blue-green algal blooms.
- Carp - By inundating floodplain habitat environmental watering can provide access to spawning substrate for Carp, which can in turn result in unwanted population increases (Koehn et al. 2017). Unfortunately, the breeding season of Carp overlaps with many native fish species in the MDB, so avoiding environmental watering to minimise Carp recruitment may also preclude positive native fish outcomes. Hence, although minimising Carp recruitment during environmental watering is an important consideration in the planning of environmental flows, it may not be the primary watering objective.

In their framework for determining Commonwealth Environmental Water use, the CEWO plan environmental flow activities in accordance with several key principles (Commonwealth Environmental Water Office 2013). Principle 4a stipulates watering for the environment undertaken by the CEWO will have regard to potential risks, including downstream risks that may result from applying flows and risk minimisation and mitigation measures. Importantly Principle 6 (Apply the precautionary principle) also stipulates that a lack of full scientific certainty as to whether there are threats of serious or irreversible environmental damage should not be used as a reason for postponing measures to prevent environmental degradation.

Water quality

Water temperature drives life history responses for most native species; while turbidity, dissolved oxygen and productivity (related to chemical, nutrient and plankton composition) also play an important role in maximising condition and recruitment (Gorski et al. 2013; Mallen-Cooper and Zampatti 2015c). The influence of water quality on fish life-history will generally result in management actions primarily occurring in the warmer spring and summer months. However, the importance of winter Base Flows to maintain water quality and maximise habitat availability (and thus population carrying capacity for density dependant species) and late-winter high flow events to enhance productivity (Robertson et al 2001) or movement by diadromous species (Bice et al. 2017) still need to be considered, as they may contribute to enhanced spring-summer spawning and recruitment outcomes.

Natural flooding

We assume that during very wet periods, large natural flood events which are unable to be regulated will result in substantial Overbank flooding throughout the MDB. Minor through to major floods are vital for the long-term ecological integrity of the MDB as they promote floodplain productivity and nutrient cycling, mobilise and flush salt and deliver water to ephemeral habitats high on the floodplain. Larger flood events are not considered achievable using environmental water reserves due to the volumes required and current constraints within the system.

Prioritising hydrograph components

The prioritisation of ESCs in a stream hydrograph in any given season will be guided by the required return frequency of flow components. Flow components that have not been met for one or more years will inform prioritisation and planning in subsequent years. Recommended annual return period (ARI; years), duration (days) and maximum period between ESCs relative to each functional group of fish are presented in

Table 3. Comprehensive monitoring of the ecological outcomes or impacts resulting from the delivery of one or more flow components is critical to allow for evaluation, future adaptation and optimisation of prioritisation processes. Degree to which each flow component could be expected to support key life-history elements and processes for each functional group of fishes is presented in Table 4, noting regional and seasonal influences will affect outcomes.

Table 3. Recommended frequency (annual return interval), duration and maximum period between events for ecologically significant flow components (Figure 6) required to support each functional group. Flow event durations are based on exceedance of the minimum flow threshold.

Flow component	Functional Group	Seasonal requirements	Duration (days)	Annual return interval (years)	Max period between events (years)
Overbank flows	Group 1: Flow Pulse Specialists	spring to summer (Aug-Feb)	>5	3 5	5
	Group 2: River Specialists	spring (Oct-Nov) 1	>5	5 5	5
	Group 3: Floodplain Specialists	spring to summer (Aug-Feb)	>10 2	1 2	1 2
	Group 4: Generalists	spring to summer (Aug-Feb)	>5	5 5	5
	Group 5: Diadromous	spring to summer (Aug-Feb)	>5	3 5	5
	Group 6: Estuarine dependent	spring to summer (Aug-Feb)	>5	3 5	5
Large Fresh	Group 1: Flow Pulse Specialists	spring to summer	>5	1 to 2	2
	Group 2: River Specialists	spring (Oct-Nov) 1	>14 3,4	1 to 2	2
	Group 3: Floodplain Specialists	spring to summer	>10 2	1 2	1 2
	Group 4: Generalists	spring to autumn	>5	2	2
	Group 5: Diadromous	spring to summer	>141	1 to 2	2
	Group 6: Estuarine dependent	spring to summer	>141	1 to 2	2
Spring nesting	Group 1: Flow Pulse Specialists	-	-	-	-
	Group 2: River Specialists	spring (Oct-Nov) 1	>14 3,4	1 to 2	2
	Group 3: Floodplain Specialists	-	>10 2	1 2	1 2
	Group 4: Generalists	any time	-	-	-
	Group 5: Diadromous	winter-spring	-	-	-
	Group 6: Estuarine dependent	-	-	-	-
Small Fresh	Group 1: Flow Pulse Specialists	any time	>10	0.5	0.5
	Group 2: River Specialists	at least 1 in spring	>10 3,4	0.5	0.5
	Group 3: Floodplain Specialists	any time	>10	0.5	0.5
	Group 4: Generalists	any time	>10	0.5	0.5

Flow component	Functional Group	Seasonal requirements	Duration (days)	Annual return interval (years)	Max period between events (years)
	Group 5: Diadromous	at least 1 in winter	>10	0.5	0.5
	Group 6: Estuarine dependent	at least 1 in winter	>10	0.5	0.5
Variable base flow	Group 1: Flow Pulse Specialists	all season	-	-	-
	Group 2: River Specialists	all season	-	-	-
	Group 3: Floodplain Specialists	all season	-	-	-
	Group 4: Generalists	all season	-	-	-
	Group 5: Diadromous	all season	-	-	-
	Group 6: Estuarine dependent	all season	-	-	-

[1] regional consideration should be given to critical temperature windows in which flow components must align with reproductive processes for key species.

[2] ideal periods between events for spawning and recruitment objectives is linked to the longevity of species, to avoid risk of significant population decline. For short-lived Floodplain Specialists species (e.g. Murray Hardyhead) additional measures such as pumping to remnant wetlands may be required to maintain habitat and support recruitment in intervening years between floodplain connectivity events.

[3] recommended minimum duration is linked to maximising spawning and recruitment outcomes based on known egg hatch time and morphology; these may be able to be increased based on flow data analysis and/or real time monitoring of fish larval presence, but they should not be reduced. Spring nesting flows would ideally span mid-September to early-December (dependant on water availability).

[4] in highly dynamic systems (where rapid increases in discharge result in substantial increases in water velocity) flows related to the Spring nesting component may need to remain within recommended flow rates (e.g. the Lower Goulburn and Lachlan Rivers).

[5] recommended frequencies are linked to providing conditions that protect and improve native fish populations in heavily impacted systems. To aid recovery, more frequent events that maximise native fish outcomes may be required.

Table 4. Degree to which each flow component is expected to support key life-history elements and processes for each functional group of fishes.

Life history element/process		Degree to which flow regime component supports life history element/process				
		Bank Full-Overbank	Large Fresh	Spring Nesting	Small Fresh	Base Flow
Group 1: Flow Pulse Specialists	Habitat	Good	Good	Good	Moderate	Moderate
	Condition	Good	Good	Good[2]	Moderate	Moderate
	Reproduction	Good	Good	Moderate	Moderate	Poor
	Movement	Good	Good	Good[2]	Moderate	Moderate
	Maintenance	Good	Good	Good	Moderate	Moderate
Group 2: River Specialists	Habitat	Good	Good	Good	Good	Moderate
	Condition	Good	Good	Good[2]	Moderate	Moderate
	Reproduction	Good	Good	Good[2]	Poor	Poor
	Movement	Good	Good	Good[2]	Moderate	Moderate
	Maintenance	Good	Good	Good[2]	Moderate	Moderate
Group 3: Floodplain Specialists	Habitat	Good	Moderate[1]	Poor[1]	Poor[1]	Poor[1]
	Condition	Good	Moderate[1]	Poor[1]	Poor[1]	Poor[1]
	Reproduction	Good	Moderate[1]	Poor[1]	Poor[1]	Poor[1]
	Movement	Good	Moderate[1]	Poor[1]	Poor[1]	Poor[1]
	Maintenance	Good	Moderate[1]	Poor[1]	Poor[1]	Poor[1]
Group 4: Generalists	Habitat	Good	Good	Good	Good	Moderate
	Condition	Good	Good	Good	Good	Moderate
	Reproduction	Good	Good	Good[2]	Moderate	Moderate
	Movement	Good	Good	Good[2]	Moderate	Moderate
	Maintenance	Good	Good	Good	Good	Moderate
Group 5: Diadromous species	Habitat	Good	Good	Good	Good	Moderate
	Condition	Good	Good	Good	Good	Moderate
	Reproduction	Good	Good	Moderate	Moderate	Moderate
	Movement	Good	Good	Moderate	Moderate	Moderate

Life history element/process		Degree to which flow regime component supports life history element/process				
		Bank Full-Overbank	Large Fresh	Spring Nesting	Small Fresh	Base Flow
	Maintenance	Good	Good	Good	Good	Moderate
Group 6: Estuarine dependent species	Habitat	Good	Good	Good	Good	Good
	Condition	Good	Good	Good	Good	Good
	Reproduction	Good	Good	Moderate	Moderate	Good
	Movement	Good	Good	Moderate	Moderate	Good
	Maintenance	Good	Good	Good	Good	Good

[1] measures such as pumping to remnant wetlands may be required to maintain habitat and support recruitment in intervening years between floodplain connectivity events.

[2] Higher flows may increase recruitment success, condition or movement opportunities by increasing river productivity, inundating additional spawning habitat and dispersing drifting young to productive nursery habitat.

Site-Specific Environmental Water Requirements

The Sustainable Diversion Limits (SDLs) in the Basin Plan are required to reflect an Environmentally Sustainable Level of Take (ESLT), which is defined as the level at which water can be taken without compromising key environmental assets, key ecosystem functions, the productive base, and key environmental outcomes (Commonwealth of Australia 2012). To inform the ESLT, the MDBA determined EWRs for 24 Hydrological Indicator Sites (HIS) in the MDB that are considered 'key environmental assets' (MDBA 2011b). Documents pertaining to relevant HIS can be found at: https://www.mdba.gov.au/publications/mdba-reports/assessing-environmental-water-requirements-basins-rivers

The philosophy underpinning the HIS approach is that providing a suitable flow regime across a range of connected indicator sites will support the water requirements of key assets and ecosystem functions across the MDB. That is, water delivered through the river system to address the EWRs at one HIS will also support other upstream and downstream sites it passes through. EWRs also provide for a common language between environmental outcomes and hydrology or river flow management. The EWRs developed for each HIS under the Basin Plan (i.e., in 2009) were intended to represent the broader environmental flow needs of river valleys or reaches and thus the needs of a broad suite of biota, ecological assets and functions. Flow volume thresholds were defined based on known flow–ecology relationships (e.g., the flow required to inundate a certain within-channel area or floodplain feature). At a site level the combination of these flow indicators was considered indicative of the required long-term flow regime and therefore the EWRs of the site.

The EWRs developed in 2009 primarily addressed the requirements of floodplain vegetation and waterbirds. These requirements are often longer in duration or vary seasonally from those required by fish and another within-channel biota. Consequently, consideration of flow-ecology relationships for fish was limited. Where they were presented, site-specific flow indicators for fish were expressed in general terms and focused on providing key fish species with greater access to habitats by wetting benches, banks and in-stream habitat, as well as facilitating opportunities for native fish migration and recruitment (MDBA 2011b).

This report focusses on defining revised fish specific EWRs developed through application of the FFMF (NSW DPI 2015; Ellis et al. 2016). The revised EWRs reflect the objectives of the BWS and best available science (in 2018) regarding fish-flow relationships. Revised EWRs are specified at fixed gauge locations as a set of flow indicators that collectively represent the ESCs of the flow regime (i.e., Base Flows, Freshes, Bank full flows, and Overbank flows). EWRs for each site are described by flow indicators including flow magnitude (volume), duration, timing and frequency (i.e., return interval). Recommended annual return intervals are based on Table 3 above. For sites where EWRs were originally developed under the Basin Plan (i.e., in 2009), we present the original EWRs and associated flow indicators for comparison with the revised fish-specific flow indicators.

Whilst Overbank flood events are vital for the long-term ecological health of the MDB, currently they are not considered achievable using environmental water reserves due to the large volumes required and system constraints. We refer to Overbank floods in this report but do not propose these can be achieved through environmental flows alone.

The fish-specific flow indicators specified in the following section should be read in conjunction with information regarding the holistic environmental water requirements of a site (i.e., to achieve multiple ecological targets for the HIS). The EWRs are based on generalised natural flow regimes for Southern MDB systems to which different biota (i.e., fish, waterbirds, and vegetation) are adapted. We recommend revisiting the section on "Responsible Water Management" above before planning flows for fish outcomes.

Hydrologic Indicator Sites

The HIS listed below and in Figure 7 were selected for application of the FFMF to develop revised fish specific EWRs. Representative gauging locations for each HIS are consistent with those originally used in the Basin Plan except for the Edward-Wakool. DPI Fisheries considered the gauging site downstream of Stevens Weir to be a better representation of flow variability in the system than the original gauge at Deniliquin (which is situated within a weir pool). This also provides consistency with the Murray and Lower Darling LTWP currently in development by the NSW Office of Environment and Heritage (OEH).

Similarly, we considered flow indicators expressed at the NSW-South Australian border (as in the original Basin Plan) to be more representative of conditions through the South Australian Lock 6 to Lock 1 section of the Murray River downstream (influenced by releases from the lake) than for the Lock 10 to Lock 7 reach of the Lower Murray River (upstream of Lake Victoria releases). Accordingly, we have included a gauging location downstream of Lock 9 to reflect the differences between reaches upstream and downstream of Lake Victoria releases.

Fish specific EWRs for the Lock 6 to Lock 1 Murray River within-channel habitat and the adjacent Riverland-Chowilla Floodplain (R-CF) are presented together, as are the Lower Goulburn River channel and floodplain. Given HIS were not specified for the upper and mid- Lachlan River and Darling Anabranch during the development of the Basin Plan, gauges were selected that are representative of the region. The Hydrologic Indicator Sites (HIS) and representative gauging locations in the Southern MDB selected for review in this project comprise:

Murray River (NSW) – 7 gauging sites

- Barmah-Millewa Forest (expressed downstream of Yarrawonga Weir)
- Edward-Wakool system (downstream of Stevens Weir)
- Gunbower, Koondrook and Perricoota forests (downstream of Torrumbarry Weir)
- Hattah Lakes (downstream of Euston Weir)
- Lower Murray in-channel Lock 7-10 (downstream of Lock 9)
- Lower Murray Lock 1-6 and Riverland-Chowilla Floodplain (at the NSW-SA border)
- Coorong, Lower Lakes and Murray Mouth (at the Barrages and the NSW-SA border combined)

Lower Darling-Baaka River – 2 sites

- Menindee Lakes (expressed as lake volume, level or duration of connection with the river)
- LDR in-channel (upstream of Weir 32)
- Darling Anabranch (at Wycott station)

Lachlan River - 3 sites

- Upper Lachlan (downstream of Cottons Weir)
- Mid Lachlan (downstream of Willandra Weir)
- Lower Lachlan (at Booligal)

Murrumbidgee River - 3 sites

- Mid-Bidgee wetlands (downstream of Narrandera)
- Lower Murrumbidgee floodplain (downstream of Maude Weir)
- Lower Murrumbidgee in-channel flows (downstream of Balranald Weir)

Goulburn-Broken system – 1 site

- Lower Goulburn in-channel and floodplain (downstream of Shepparton).

Flow Threshold Estimates

Hydrological analyses were undertaken to develop estimates for flow thresholds (discharge rates) that distinguish ESCs of the within-channel flow regime at HIS in the Southern MDB. For consistency with components of the Basin Plan being developed, we have adapted our flow threshold from those being developed concurrently by LTWP teams at the NSW Office of Environment and Heritage (NSW OEH). Spring nesting component flow bands extend from the base flow thresholds to mid-range Large Fresh thresholds provided by NSW OEH for each HIS. Regional expertise (i.e. MDBA and Water NSW River operators, ecologists) further informed the development of Spring nesting magnitudes.

For HIS where NSW OEH flow estimates were unavailable, corresponding values were derived by DPI Fisheries AHR staff in consultation with regional water managers, using a similar methodology to ensure consistency. Additional lines of evidence used in developing these estimates were:

- MDBA and NSW OEH hydrological analysis
- MDBA geospatial inundation assessments
- Analysis of Murray wetland databases (which include commence to flow levels)
- Databases (which include commence to flow levels)
- Verbal collaboration with expert river operations staff at the MDBA and regional water managers in Southern MDB valleys
- Scrutiny of historic flow records data and stream cross-section profiles at HIS
- River bench inundation at different flow magnitudes (where available)

Additional consideration has been given to determining appropriate flow-height and flow-velocity relationships in waterways of the MDB that account for connectivity and hydraulic requirements of native fish using the overarching principles below to guide the identification of flow rates:

- Requirement for very low flows for maintaining water quality by de-stratifying refuge pools is a flow velocity of 0.03-0.05m/s (Mitrovic et al. 2003)
- Minimum depth for small bodied and moderate bodied fish movement is 0.3m above Cease to Flow (Gippel 2013; O'Connor et al. 2015)
- Minimum depth for large-bodied fish movement is 0.5m above Cease to Flow (Fairfull and Witheridge 2003; Gippel 2013; O'Connor et al. 2015)
- Optimal transition of Small Fresh to Large Fresh events for the Flow Specialist spawning and movement response is 2m above Cease to Flow and/or velocity greater than or equal to 0.3-0.4m/s (Marshall et al. 2016; Mallen-Cooper and Zampatti 2015a; Bice et al. 2017)

Flow threshold estimates for each HIS are presented in Table 5. In addition, we present suggested EWRs for the Menindee Lakes (on the LDR). Given the lakes are wetlands and not river channels, EWRs are described in terms of volume, water level (depth) and duration of lateral connectivity or inundation/retention prior to release downstream to the LDR channel. The EWRs we present were informed by EWRs originally suggested for the Menindee Lakes by the MDBA in 2012 (see MDBA 2012h) with additional consideration of recent research and knowledge regarding the flow requirements for native fish in the Lower Darling and Murray Rivers (Sharpe 2011; Zampatti et al. 2015; Stuart and Sharpe 2017).

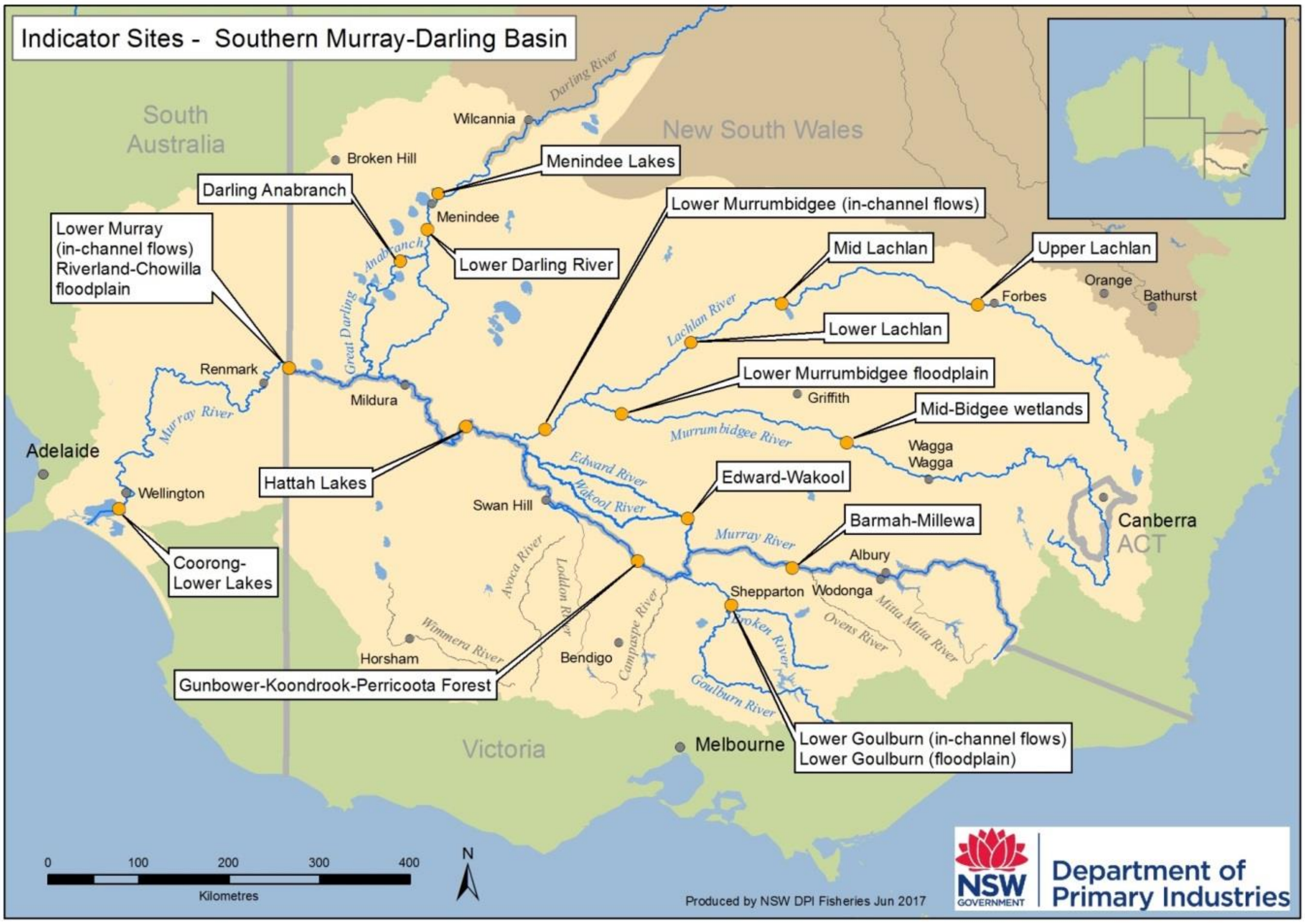

Figure 7. Major streams in the Southern MDB and location of flow gauging points for MDBA Hydrologic Indicator Sites referred to in this report.

Table 5. Flow thresholds estimates (ML/day) for the ESCs of the in-stream flow regime at sites in the Southern MDB addressed in this report.

Hydrological Indicator Site	Gauge Location	Base flow	Small fresh	Nesting Flow	Large Fresh	Bank Full	Small Overbank	Large Overbank
Barmah-Millewa forest	Murray downstream of Yarrawonga	1,800-7,000	7,000-12,000	4,000-12,000	12,000-29,000	29,000	>30,000	>50000
Edward-Wakool system	Edward River downstream Stevens Weir	170-1,600	1,600-2,600	300-1,600	2,600-6,000	6,000	>8,000	>10000
Gunbower–Koondrook–Perricoota forests	Murray downstream of Torrumbarry	2,000-7,000	7,000-12,000	4,500-12,000	12,000-22,000	22,000	>25,000	>40000
Hattah Lakes	Murray downstream of Euston	2,500-14,000	14,000-20,000	5,000-10,000 [2]	20,000-38,000 [2]	38,000	>50,000	>80000
NSW Lower Murray River Locks 10-7	Murray downstream of Lock 9	3,500-14,000	14,000-20,000	5,000-14,000 [2]	20,000-40,000 [2]	40,000	>55,000	>80000
S.A. Murray Lock 1-6 & Riverland-Chowilla Floodplain	Murray River at NSW- SA border	3,500-14,000	14,000-20,000	5,000-14,000 [2]	20,000-40,000 [2]	40,000	>55,000	>80,000
Coorong, Lower Lakes and Murray Mouth [1]	Murray at Barrages and NSW- SA border(combined)	4,000 - 14,000	14,000 - 25,000	4,000 - 35,000 [2]	25,000 - 60,000 [2]	60,000	>64,000	>80,000
Lower Darling River	Darling River upstream of Weir 32	150-2,000	2,000-7,000	250-7,000	7,000-10,000 [3]	10,000	>15,000	>25,000

Hydrological Indicator Site	Gauge Location	Base flow	Small fresh	Nesting Flow	Large Fresh	Bank Full	Small Overbank	Large Overbank
Darling Anabranch	Darling Anabranch at Wycott Station	NA	NA	800-1,500	800-2,000 [4]	2,000	>3000	>8000
Mid-Murrumbidgee Wetlands	Murrumbidgee downstream of Narrandera	230-4,000	4,000-14,000	1,000-14,000	14,000-38,000	38,000	>38000	
Lower Murrumbidgee floodplain	Murrumbidgee downstream of Maude	170-2,500	2,500-6,000	600-6,000	6,000-1,300	13,000	>15,000	>22,000
Lower Murrumbidgee in-channel	Murrumbidgee downstream of Balranald	170-2,500	2,500-6,000	500-6,000	6,000-8,900	8,900	>10,500	>20,000
Lower Goulburn River and Floodplain	Goulburn downstream of Shepparton	500 - 2,000	2,000 - 5,600	1,500 - 6,000	5,600 - 15,000	15,000	>15,000	>40,000
Upper Lachlan	Lachlan downstream of Cottons Weir	50-600	600-8,500	200-8,000	8,500-13,000	13,000	>13,900	>45,000
Mid Lachlan	Lachlan at Hillston	20-280	280-1,600	100-1,600	1,600-4,000	4,000	>5000	>7,000
Lower Lachlan	Lachlan at Booligal	10-200	200-650	100-650	650-2,000	2,000	>2500	>4000

[1] Lower Lakes flow indicators are expressed at the NSW-SA border.

[2] At the recommended flow magnitudes managed weir pool drawdown may be required to generate desired hydrodynamics within the upstream reach (i.e. flow velocity of >0.3 m/s).

[3] Flows begin to spill from the Darling River west in to the Darling Anabranch at flow rate of 9,000-11,000 ML/day which may incur substantial delivery losses.

[4] Flow begins breaking out of the Darling Anabranch channel in to the Anabranch Lakes at 1,500- 2000 ML/d which may incur substantial delivery losses.

Murray River System

The headwaters of the Murray River are in the Australian Alps, and flow 2,530km to the Southern Ocean in South Australia (see Figure 7). Total run-off for the Murray River averages 32,553 GL/year, but only about 5,100 GL/year reaches the sea — a very low annual discharge by world standards (MDBA 2010). Historically the Murray River generally experienced low flows in summer and larger flows in winter and spring, fed by mountain streams and melting snow. Flows were, however, variable from season to season and year to year. Upland regions are cooler and wetter than lowland regions.

Flow regulation and water use throughout the Murray River system has resulted in reductions in the magnitude of high-flow events and annual flow volumes (Davies et al. 2008). Major storages capture the bulk of winter– spring flows to be released for downstream consumptive use primarily in spring –summer, resulting in a seasonal reversal in flow regime and reduced flooding (i.e. Hume Weir on the Murray River upstream of Albury; Dartmouth Dam on the Mitta Mitta River upstream of Hume Weir, and Yarrawonga Weir downstream of Albury). This seasonal flow reversal means that in the central and upper reaches of the Murray River (Hume Dam to Euston) fish that require low flow areas for nursery habitats in summer are disadvantaged by high volume, high velocity irrigation flows (Humphries et al. 2006).

Furthermore, eleven weirs on the Lower Murray River downstream of Euston have produced a shift from highly variable riverine conditions to a series of generally stable pools (Walker 2006). Weir pool environments in the lower Murray disadvantage species whose life histories require lotic habitats (e.g. Murray Cod see Koehn 2009) and favour species which prefer lentic waters (such as non-native Carp and Eastern Gambusia) (Walker 2006). Within rivers or reaches where weir pool environments prevail, recent efforts to re-instate more natural flow regimes involve both delivery of environmental flows and the parallel reinstatement of hydraulic complexity (e.g. managed drawdown or surcharge of weir pool levels).

There are currently a range of ‘constraints’ which limit our capacity to deliver water to certain areas of the floodplain (e.g. low-lying bridges or roads near rivers or river management practices and rules). Addressing key constraints will allow rivers to connect to their floodplains more frequently, which is expected to contribute to environment recovery. Addressing constraints is not about flooding towns and properties, rather it is about modest changes to allow water delivery onto floodplains, while avoiding or mitigating impacts to riparian landholders, communities and industries.

In the Central Murray region, the Barmah choke is a natural constriction in the Murray River channel that that was formed because of a geological feature called the Cadel Tilt. The Cadel Tilt is an uplift that extends from near Deniliquin to Echuca and resulted in a change of course for the River Murray about 25,000 years ago. The Barmah choke has a significant influence on flow pathways during higher River Murray flows. River flows of >10,400 ML/day (measured just upstream at Tocumwal) will back up behind the choke, and spill over the riverbanks into the Barmah-Millewa Forests. Higher flows (> 18,000 ML/day at Tocumwal) push water through the forests into anabranches of the Edward-Wakool system, such as the Tuppal and Bullatale Creeks. Historically such flows occurred regularly, fed by snow melt and rainfall in the upstream catchment in late winter and spring, and lasted from weeks to months. In the last 20 years only a handful of large unregulated floods resulted in substantial overbank spills through the Central Murray region.

The Barmah Choke is currently considered an operational constraint to the downstream delivery of flows in the Murray River system, as flows greater than ~18,000 ML/day (at Tocumwal) will spill over bank affecting low-level creek crossings and interrupting property access through the Edward-Wakool River system. This constraint significantly limits the ability for water managers and river operators to deliver larger volumes of water through the central Murray Region (including the Barmah-Millewa Forests and the Edward-Wakool System) to reaches and floodplains downstream of the Choke.

Fish community condition

The natural drainage system of the Lower Murray River including all native fish species and aquatic biota in the main-channel and anabranches and effluents downstream of Hume Weir is listed as an EEC (NSW NSW DPI 2007a). This EEC includes Billabong Creek, Yanco Creek, Columbo Creek, Creek, Yanco Creek, Colombo Creek, the Edward River and the Wakool River, the Frenchman's Creek, the Rufus River and Lake Victoria associated tributaries, anabranches and effluents. The Murray Cod population in the Murray River main channel is also listed as significant and 'important' (NMCRT 2010).

The Sustainable Rivers Audit assessed ecosystem health in 23 Valleys within the MDB, with the Murray River represented by three Valleys; the Upper, Central and Lower (Davies et al. 2008; 2012). Although the Murray River main stem historically supported a high diversity and abundance of native fish, the SRA2 for the period 2008-2010 indicated that the condition of native fish populations in Upper, Central and Lower Murray Valleys were Extremely Poor, Very Poor and Poor respectively (Davies et al. 2008; 2012). Hypoxic blackwater flooding in 2011/11 and 2016/17 further impacted fish communities throughout the Murray River downstream of Yarrawonga. However, in there years following these hypoxic events evidence has been building which indicates fish communities in some areas are removing, supported by targeted delivery of managed flow events through the Murray and its connected tributaries.

Barmah-Millewa Forest

The Barmah–Millewa Forest (B-MF) is located downstream of Yarrawonga Weir on the Murray River, covering approximately 66,000 ha of floodplain (Figure 8). Barmah Forest (29,500 ha) comprises the forest on the Victorian side of the Murray River and Millewa Forest (36,500 ha) the NSW side (MDBA 2012a). Listed under the Ramsar Convention on Wetlands, the B-MF supports the largest River Red Gum forest in Australia providing important feeding and breeding habitat for approximately 54 species of waterbirds (MDBA 2012a). It also includes a variety of ephemeral and permanent aquatic habitats that historically supported an abundant and diverse range of native fish (King et al. 2010). River regulation has contributed to a decrease in the size, frequency and duration of medium sized spring flood events, an increase in the number of small floods in summer, and a reduced variability in flow (King et al. 2009).

Table 6. Characteristics of the natural and post regulation flow regime in the Murray River downstream of Yarrawonga.

Modelled natural hydrology	Modelled current hydrology (regulated)
• extremely variable • Bank full or Overbank flooding in most years (usually late winter-spring, rarely at other times of the year) • large and small in-channel Freshes occurred anytime throughout the year but most frequently between May and December	• decreased flow variability • large in-channel and Overbank flows less frequent and reduced in magnitude • smaller in-channel flows and Base Flows are now a regular feature of the river year round • increase in the number of small floods in summer • more summer - autumn in-channel flows represent a seasonal reversal in flow patterns

Fish community condition

- The central Murray region from the Mulwala Weir to the Euston Weir and downstream (including the Edward-Wakool system) supports a sizeable and self-sustaining population of Silver Perch (DoE 2013).

- Condition monitoring has been conducted in the B-MF since 2006 as part of The Living Murray (TLM) assessment program. Murray Cod, Trout Cod, Golden Perch and Silver Perch are all present within the B-MF and the adjacent Murray River channel, with self-sustaining (recruiting) populations of each.
- SRA2 for the period 2008-2010 indicated that the native fish populations in the Middle Zone of the Central Murray Valley (within which the Millewa Forest is located) were in a very poor condition (Davies et al. 2012; Raymond et al. 2017).
- NSW DPI Fisheries community mapping for the region identifies that much of the B-MF is in poor-to-very poor condition (Figure 8; NSW DPI 2016a).
- Over an 11-year period from 2007-2018, fish conditions and population indices were generally high from 2007 to 2010, declined in 2011 and increased thereafter.
- Hypoxic blackwater conditions that arose during the 2010-11 floods resulted in a fish kill, and again in 2016, had a negative impact on the native fish communities in the mid and lower Murray River (Commonwealth Environmental Water Office, 2017).
- The B-MF fish community improved from 2017 to 2018 and was considered 'good' by Raymond et al. (2018), likely the result of more frequent connection between riverine and floodplain habitats over the preceding 2 years. These outcomes suggest the impacts of the fish kill within the B-MF itself were less severe than in reaches and anabranches downstream.

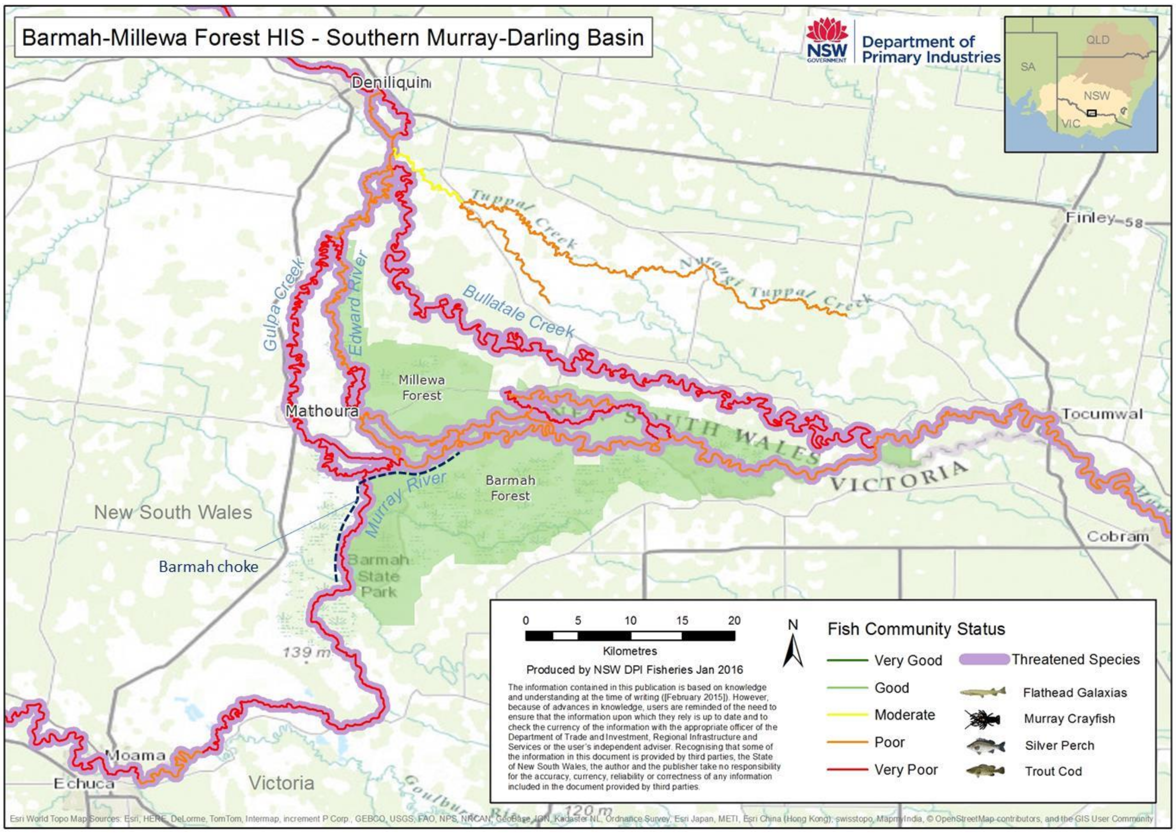

Figure 8. Barmah–Millewa Forest HIS including Fish Community Status within the NSW waters of the region (where available) and potential distribution of threatened species (NSW DPI 2016a). Note that although Freshwater Catfish are not included, anecdotal evidence suggests their presence in the region if possible.

Basin Plan flow indicators for Barmah-Millewa Forest HIS

Site-specific flow indicators are expressed at the Murray River downstream of Yarrawonga Weir which generally represents the flow into the B-MF. Under the Basin Plan the MDBA proposed seven flow indicators for the B-MF region. These represented an amalgamation of information and vegetation inundation hydrodynamic modelling data, checked against analysis of modelled without development and baseline flow data.

Flow indicators described by the MDBA for the Bank full and Overbank elements of the flow regime primarily attempted to strike a balance between desirable flow threshold, duration and timing with desirable frequency and represent a variable flow regime that is consistent with the “without development” hydrology of the site. Site-specific flow indicators primarily targeted for fish needs were not included.

Flow indicators were primarily based on the water requirements determined to achieve the ecological targets relating to the current extent of native vegetation communities and the habitat requirements for waterbirds. It was anticipated these would also have valuable beneficial effects on the life cycle and habitat requirements of native fish, including provision of cues for spawning and migration and access to food sources (MDBA 2012a).

The original site-specific flow indicators for B-MF HIS were:

1. 12,500 ML/d for a total duration of 70 days (with a minimum duration of 7 consecutive days) between June and November for 70% of years
2. 16,000 ML/d for a total duration of 98 days (with a minimum duration of 7 consecutive days) between June and November for 40% of years
3. 25,000 ML/d for a total duration of 42 days (with a minimum duration of 7 consecutive days) between June and November for 40% of years
4. 35,000 ML/d for a total duration of 30 days (with a minimum duration of 7 consecutive days) between June and May for 33% of years
5. 50,000 ML/d for a total duration of 21 days (with a minimum duration of 7 consecutive days) between June and May for 25% of years
6. 60,000 ML/d for a total duration of 14 days (with a minimum duration of 7 consecutive days) between June and May for 20% of years
7. 15,000 ML/d for a total duration of 150 days (with a minimum duration of 7 consecutive days) between June and December for 30% of years.

Revised fish-specific flow indicators for Barmah-Millewa HIS

Revised fish-specific flow indicators developed for the B-MF and rationale for each are presented in Table 7. The flow indicators described for the within-channel elements of the flow regime are recommended to achieve the ecological targets relating to the life cycle and habitat requirements of native fish. In most instances the duration of in-channel flow events necessary for supporting fish outcomes will be lower than those proposed for other elements of the floodplain ecosystem.

Table 7. Revised fish-specific flow indicators developed for the Barmah-Millewa Forest HIS (expressed on the Murray River downstream of Yarrawonga Weir)

Flow indicator	Rationale
Variable Base Flows (BA) of 1,800-7,000 ML/day throughout the year (between within-channel fresh and Overbank events). Cease to flow events should be avoided to promote recovery of the fish community	Provide main channel refuge habitat, longitudinal connectivity and maintain suitable water quality for all species (except Floodplain Specialists)[2]
	Allow for the accumulation of allochthonous carbon and vegetation on benches and dry sections of riverbed, which contributes to ecosystem productivity during subsequent higher flow events.
Small Fresh (SF): 7,000-12,000 ML/day for at least 10 consecutive days. Ideally between October and April but can occur anytime. Provide a minimum of	Contribute to the maintenance of suitable water quality

Flow indicator	Rationale
2 Small Fresh events in high and moderate water availability years and at least one during low water availability years. Maximum inter-flow period of 1 year.	[flow variability enhances system productivity and in-turn condition of adults and juvenile of most species
	provide connectivity laterally between the main channel and floodplain creeks and anabranches
Annual prolonged and continuous Spring nesting component (SN) from 4,000 to 12,000 ML/day avoiding rapid drops in water level for at least 14 days every year (to maximize recovery) during October/early November (to be informed by expert understanding of regional spawning season). Rates of rise or fall during the event should not exceed those of historic or modelled "without development" for the season. Maximum inter-flow period of 2 years. May coincide with (OB) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat. Important where river operations to meet irrigation demand cause extreme water level fluctuations which are out of sync with natural patterns and climatic cues.	Support nesting of River Specialists (e.g. Murray Cod, Trout Cod and Freshwater Catfish)
	Promote/maintain connectivity and movement of native species longitudinally as well as laterally with floodplain creeks and anabranches
	Increase habitat availability for all species except Floodplain Specialists[2] during spring when many species breed
	Support dispersal of eggs and larvae for all species
	Flow variability enhances system productivity and in-turn condition of adults and juvenile of most species
Large Fresh (LF) from 12,000 to 29,000 ML/day for at least 5 consecutive days in two years out of every successive three-year period (not required in years experiencing the Overbank event above). Ideally between August and November but may also occur in summer. Maximum inter-flow period of 2 years. A priming 'spike' may trigger breeding response by Flow Pulse Specialists. Or Overbank event (OB) >30,000 ML/day for at least 10 consecutive days between August and February at least one year in every three-year period. Maximum inter-flow period of 3 years.	Promote connectivity and movement of native species longitudinally and laterally into anabranches and floodplain wetlands[1]
	Promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch), support habitat for Floodplain Specialists[2].
	Inundate in-stream benches and low-lying Floodplain wetlands which may provide nursery habitat for Flow Pulse, River and Floodplain Specialists[3].
	Promote within-channel hydraulic variability to support a diverse range of habitats and enhance system productivity (and in-turn condition of adults and juveniles of most species) promote dispersal of eggs and larvae for all species
Large unregulated Overbank floods (>50,000 ML/day) for long durations will be required to address all of the original flow indicators for the B-MF HIS.	Critical to the long-term viability of fish communities due to the ecosystem processes floods promote, the opportunistic potential for large scale floodplain recruitment by many species, and the unobstructed longitudinal and lateral connectivity they facilitate

[1] The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.
[2] Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

[3] Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

Edward-Wakool River System

The Edward–Wakool River System covers an area of more than 1,000 km2 (100,000ha) between the Murray and Edward Rivers downstream of Deniliquin (on the Edward River), including the Wakool River, and other interconnecting streams and ephemeral creeks and wetlands (MDBA 2012b). The Edward–Wakool system supports important habitat and species listed in the Ramsar Convention and includes vulnerable and endangered species.

The Edward–Wakool supports significant populations of native fish and provides important fish habitat, particularly refuge habitat during drought. The fish community of the Edward–Wakool includes relatively large populations of the vulnerable Murray Cod and Silver Perch (Davies et al. 2008; 2012).

The hydrology of the Edward–Wakool is complex as flow can arrive from several locations independently or at the same time. When flow in the Murray River downstream of Yarrawonga Weir is greater than 10,400 ML/d, the flow exceeds the capacity of the main-channel through the Barmah Choke and substantial volumes of water flow through the Barmah-Millewa Forests into the Edward–Wakool River System. The natural flow regime of the Edward–Wakool was characterised by low flows in summer and autumn and higher average flows in winter and Spring driven by snow melt and rainfall in the upper catchment.

In general, the flow regime of the Central Murray region (which includes the Edward-Wakool system) is modified by reductions in the magnitude of high-flow events and annual flow volumes, with significant shifts in seasonality (Davies et al. 2008). Regulated flows in the Edward River reflect seasonal water demands for the irrigation season, with higher flows in the summer months than would have occurred naturally (Table 8; MDBA 2012b).

Table 8. Characteristics of the natural and post regulation flow regime in the Edward-Wakool River System.

Modelled natural hydrology	Modelled current hydrology (regulated)
• highly variable • Bank full or Overbank flooding in most years (usually late winter-spring, rarely at other times of the year) • in-channel Freshes occurred anytime throughout the year but most frequently between June and December.	• decreased flow variability • large in-channel and Bank full flows are more frequent but reduced in duration • reduced frequency of large Overbank floods • increase in the number of flows inundating low lying floodplain habitat in spring and summer.

Fish community condition

- SRA2 for the period 2008-2010 indicated that the condition of native fish populations in the middle zone of the Central Murray Valley (within which the Edward–Wakool system is located) was in a very poor condition (Davies et al. 2008, 2012; MDBA 2012b).
- Despite extensive stocking of Golden perch and Murray Cod throughout the system, natural spawning and recruitment and possibly immigration were the main drivers of Golden perch and Silver Perch recovery (Thiem et al. 2017).
- Long-Term Intervention Monitoring (LTIM) of fish responses to environmental watering events in the Edward–Wakool indicated that 9 of the 13 species present in the Edward-Wakool were recorded to have successfully spawned; however larvae of Golden perch and Silver Perch were notably absent, as was Unspecked Hardyhead (Watts et al. 2013).

- NSW DPI fish community mapping for the region identifies that much of the Edward–Wakool River System is in poor to very poor condition (**Error! Reference source not found.**; NSW DPI 2016a).
- Hypoxic blackwater conditions that arose during the 2010-11 floods, and again in 2016, had a negative impact on the native fish communities in mid and lower Murray River, resulting in extensive fish kills and a reduction or absence of spawning by native species during the event (Commonwealth Environmental Water Office, 2017).
- The Edward Wakool fish assemblage is showing signs of recovery post the 2016-17 hypoxic blackwater event that resulted in large scale fish kills in the southern Murray-Darling Basin (Watts et al. 2020).

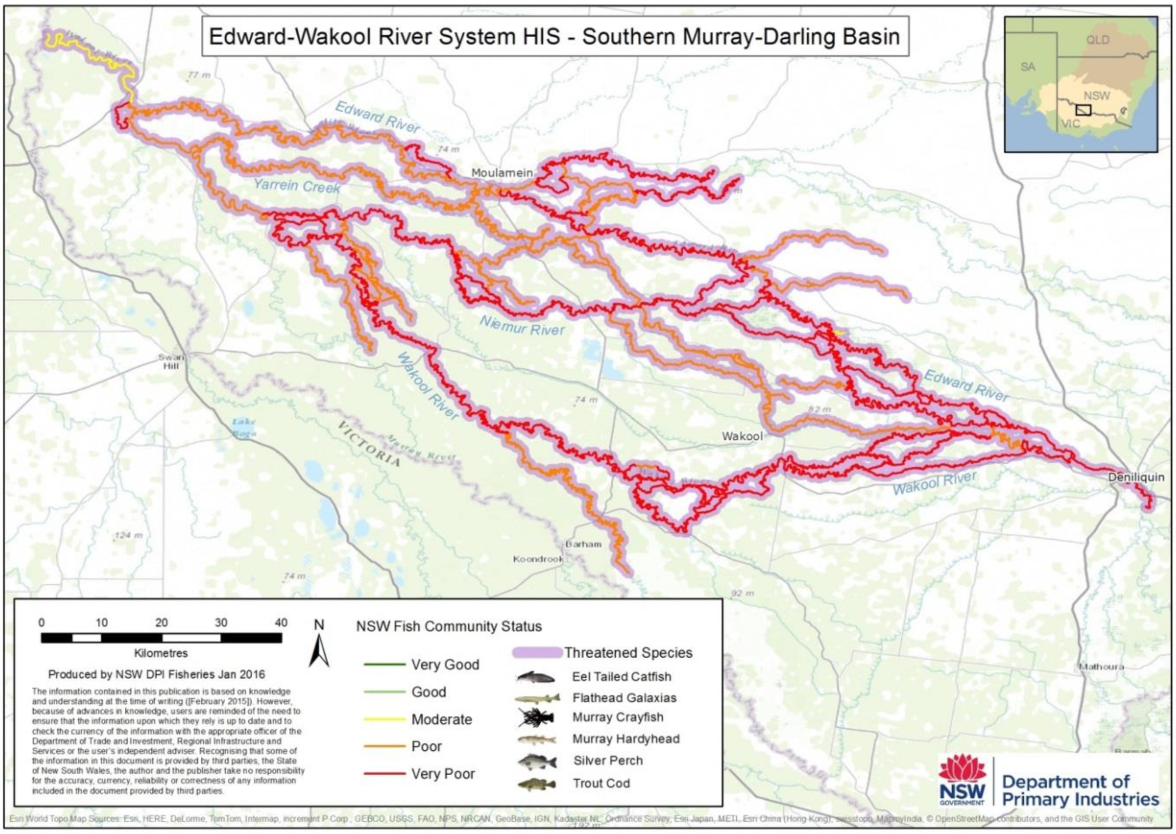

Figure 9. Edward–Wakool River System HIS, including Fish Community Status within the NSW Waters of the region (where available) and potential distribution of threatened species (NSW DPI 2016a).

Basin Plan flow indicators for the Edward-Wakool system

Site-specific flow indicators under the Basin Plan were expressed at Deniliquin on the Edward River. Under the Basin Plan the MDBA proposed five flow indicators for the Edward–Wakool system which represented an amalgam of information within existing literature and vegetation inundation hydrodynamic modelling data, checked against analysis of modelled without development and baseline flow data. Flow indicators described by the MDBA for the Bank full and Overbank elements of the flow regime primarily attempted to strike a balance between desirable flow threshold, duration and timing with desirable frequency and represent a variable flow regime that is consistent with the “without development” hydrology of the site.

One flow indicator primarily focused on assessment of the within-channel base flow element of the flow regime necessary to maintain drought refuges important for significant populations of native fish (Indicator 1 below). Remaining flow indicators were primarily based on the water requirements determined to achieve the ecological targets relating to the current extent of native vegetation communities and the habitat requirements for waterbirds. It was anticipated these would also have valuable beneficial effects on the life cycle and habitat requirements of native fish, including provision of cues for spawning and migration and access to food sources.

The original flow indicators for the Edward–Wakool HIS under the Basin Plan were:

1. 1,500 ML/d for a total duration of 180 days (with a minimum duration of 1 consecutive day) between June and March for 99% of years. Flows of 1,500 ML/d at Deniliquin and strategic use of off take regulators was expected to maintain > 1000 km of vital fish habitats in permanent and semi-permanent regulated rivers and creeks within the Edward–Wakool.
2. 5,000 ML/d for a total duration of 60 days (with a minimum duration of 7 consecutive days) days between June and December for 60% of years
3. 5,000 ML/d for a total of 120 days (with a minimum duration of 7 consecutive days) between June and December for 35% of years
4. 18,000 ML/d for a total of 28 days (with a minimum duration of 5 consecutive days) between June and December for 25% of years
5. 30,000 ML/d for a total of 21 days (with a minimum duration of 6 consecutive days) between June and December for 17% of years.

Revised fish-specific flow indicators (expressed on the Edward River downstream of Stevens River)

Revised fish-specific flow indicators developed for the Edward–Wakool system and rationale for each are presented in Table 9**Error! Reference source not found.**. Note that the flow indicators described for the within-channel elements of the flow regime are for the Edward River gauging location downstream of Stevens Weir, and not at Deniliquin (as in many Basin Plan documents). We considered the gauging site downstream of Stevens Weir to be a better representation of flow variability in the system as it does not lie within a weir pool (which the Deniliquin gauge does). The revised fish-specific flow indicators are recommended to achieve the ecological targets relating to the life cycle and habitat requirements of native fish.

In most instances the duration of in-channel flow events necessary for supporting fish outcomes will be lower than those proposed for other elements of the floodplain ecosystem.

Key components of the hydrograph identified are labelled for identification in Figure 6. Suggested Flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change.

Table 9. Revised fish-specific flow indicators developed for the Edward–Wakool System HIS (expressed on the Edward River downstream of Stevens Weir).

Flow indicator	Rationale
Variable Base Flows (BA) of 170-1,600 ML/day throughout the year (between within-channel fresh and Overbank events). Cease to flow events should be avoided.	provide main channel refuge habitat, longitudinal connectivity and maintain suitable water quality for all species except Floodplain Specialists2
	allow for the accumulation of allochthonous carbon and vegetation on benches and dry sections of riverbed, which contributes to ecosystem productivity during subsequent higher flow events.
Small Fresh (SF): 1,600 - 2,600 ML/day for at least 10 consecutive days. Ideally between October and April but can occur anytime. Provide a minimum of 2 Small Fresh events in high and moderate water availability years and at least one during low water availability years. Maximum inter-flow period of 1 year.	contribute to the maintenance of suitable water quality
	flow variability enhances system productivity and in-turn condition of adults and juvenile of most species

Flow indicator	Rationale
Annual prolonged and continuous Spring nesting component (SN) from 300-1,600 ML/day avoiding rapid drops in water level for at least 14 days every year during October/early November (to be informed by expert understanding of regional spawning season). Rates of rise or fall during the event should not exceed those of historic or modelled “without development” for the season. Maximum inter-flow period of 2 years. May coincide with (OB) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat. Important where river operations to meet irrigation demand cause extreme water level fluctuations which are out of sync with natural patterns and climatic cues.	support nesting of River Specialists (e.g. Murray Cod, Trout Cod and Freshwater Catfish)
	promote/maintain connectivity and movement of native species longitudinally as well as laterally with floodplain creeks and anabranches
	increase habitat availability for all species (except Floodplain Specialists[2]) during spring when many species breed
	support dispersal of eggs and larvae for all species
	flow variability enhances system productivity and in-turn condition of adults and juvenile of most species
Large Fresh (LF) from 2,600-6,000 ML/day for at least 5 consecutive days in two years out of every successive three-year period (not required in years experiencing the Overbank event above). Ideally between August and November but may also occur in summer. Maximum inter-flow period of 2 years. A priming ‘spike’ may trigger breeding response by Flow Pulse Specialists. Or, Overbank event (OB) >8,000 ML/day for at least 10 consecutive days between August and February at least one year in every three-year period. Maximum inter-flow period of 3 years.	promote connectivity and movement of native species longitudinally and laterally into anabranches and floodplain wetlands[1]
	promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch), support habitat for Floodplain Specialists[2].
	inundate in-stream benches and low-lying Floodplain wetlands which may provide nursery habitat for Flow Pulse, River and Floodplain Specialists[3]
	promote within-channel hydraulic variability to support a diverse range of habitats and enhance system productivity (and in-turn condition of adults and juveniles of most species)
	promote dispersal of eggs and larvae for all species
Large unregulated Overbank floods (OB) over 10,000 ML/day for long durations will be required to address all the original flow indicators for the Edward–Wakool HIS.	critical to the long-term viability of fish communities due to the ecosystem processes floods promote, the opportunistic potential for large scale floodplain recruitment by many species, and the unobstructed longitudinal and lateral connectivity they facilitate.

[1] The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

[2] Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

[3] Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

Gunbower-Koondrook-Perricoota

The Gunbower–Koondrook–Perricoota (GKP) Forests are a TLM Icon Site covering approximately 51,000 ha of the Murray River floodplain downstream of Torrumbarry Weir (Figure 10). Gunbower Forest (19,931 ha) is located on the Victorian side of the Murray River and Koondrook–Perricoota Forest (31,150 ha) is on the NSW side. Connectivity of the site with the neighbouring Murray River and Edward-Wakool systems is significant in terms of energy transfer (carbon and nutrients) between the floodplain and the river. As both sides of the river channel experience Overbank flows under similar conditions, MDBA treat the GKP forests as one asset for the purpose of determining EWRs (MDBA 2012c). GKP is a highly significant conservation area, particularly for waterbirds and floodplain and wetland vegetation. The site encompasses a diverse range of habitats and is listed under the Ramsar Convention on Wetlands.

River regulation has contributed to a decrease in the size, frequency and duration of medium sized spring flood events, an increase in the number of small floods in summer, and a reduced variability in flows through the Mid-Murray (Table 10) (King et al. 2009).

Table 10. Characteristics of the natural and post regulation flow regime in the Murray River downstream of Torrumbarry.

Modelled natural hydrology	Modelled current hydrology (regulated)
• extremely variable • Bank full or Overbank flooding in most years (usually late winter-spring, rarely at other times of the year) • large and small in-channel Freshes occurred anytime throughout the year but most frequently between May and December	• decreased flow variability • large in-channel and Overbank flows less frequent and reduced in magnitude • smaller in-channel flows and Base Flows are now a regular feature of the river year round • increase in the number of small floods in summer • more summer - autumn in-channel flows represent a seasonal reversal in flow patterns

As part of The Living Murray Environmental Works and Measures Program (EWMP), a series of regulators and levee banks were constructed in Koondrook-Perricoota Forest to water wetland and forest ecosystem (up to 16, 000Ha) by supplementing natural high flows or floods diverted to the forests from the Torrumbarry weir pool. Similarly, environmental works completed in 2014 allow water to be directed from Gunbower Creek (part of the Torrumbarry irrigation system) into Gunbower Forest to simulate a more natural flooding regime. Under full operation, the works will allow wide-scale watering of up to 4,800 ha of forest (MDBA 2016).

Fish community condition

- The mid-Murray region (including the Edward - Wakool anabranches) supports the only known self-sustaining population of Silver Perch in the MDB (DoE 2013).
- Twelve native fish species have been collected in Gunbower Forest wetlands and Gunbower Creek, the most common are small-bodied species, with large- and medium- bodied fish species generally having low abundance. Notably four threatened species, Murray Cod, Silver Perch, Trout Cod and Freshwater Catfish have been recorded (Rehwinkel and Sharpe 2009; Mallen-Cooper et al. 2014).
- SRA2 for the period 2008-2010 indicated that the condition of native fish populations in the Middle Zone of the Central Murray Valley was in a very poor condition (Davies et al. 2012).
- Fish assemblages in creek and connected lagoon habitats in Gunbower Forest are reasonably diverse and stable although populations of large-bodied species are fractured in terms of age structure with low recruitment. The diversity of wetland communities in the Gunbower Forest is low due to poor connectivity with source populations in creek and lagoon habitats (Sharpe et al. 2014).

- NSW DPI fish community mapping for the region identified that the Murray River channel in the GKP system is in poor to very poor condition (**Error! Reference source not found.**; NSW DPI 2016a).
- Hypoxic blackwater conditions that arose during the 2010-11 and 2016 floods had a negative impact on the native fish communities in mid and lower Murray regions, resulting in extensive fish kills and a reduction or absence of spawning by native species during the event (Commonwealth Environmental Water Office, 2017).
- Annual condition monitoring of fish in the Koondrook–Perricoota Forest undertaken by NSW DPIF since 2011 indicates the fish community is generally in a very poor condition, dominated by non-native species (Carp), with native species dominated by small-bodied generalists (Bindokas and Rourke 2011, Duncan and Martin 2017). Young of year golden perch and silver perch were collected for the first time in Koondrook–Perricoota fir the first time in 2017-18 (Duncan et al. 2018)
- A perennial environmental flow regime implemented in the Gunbower channel since 2013 has contributed to improved recruitment in the local Murray cod population (Stuart et al. 2019).

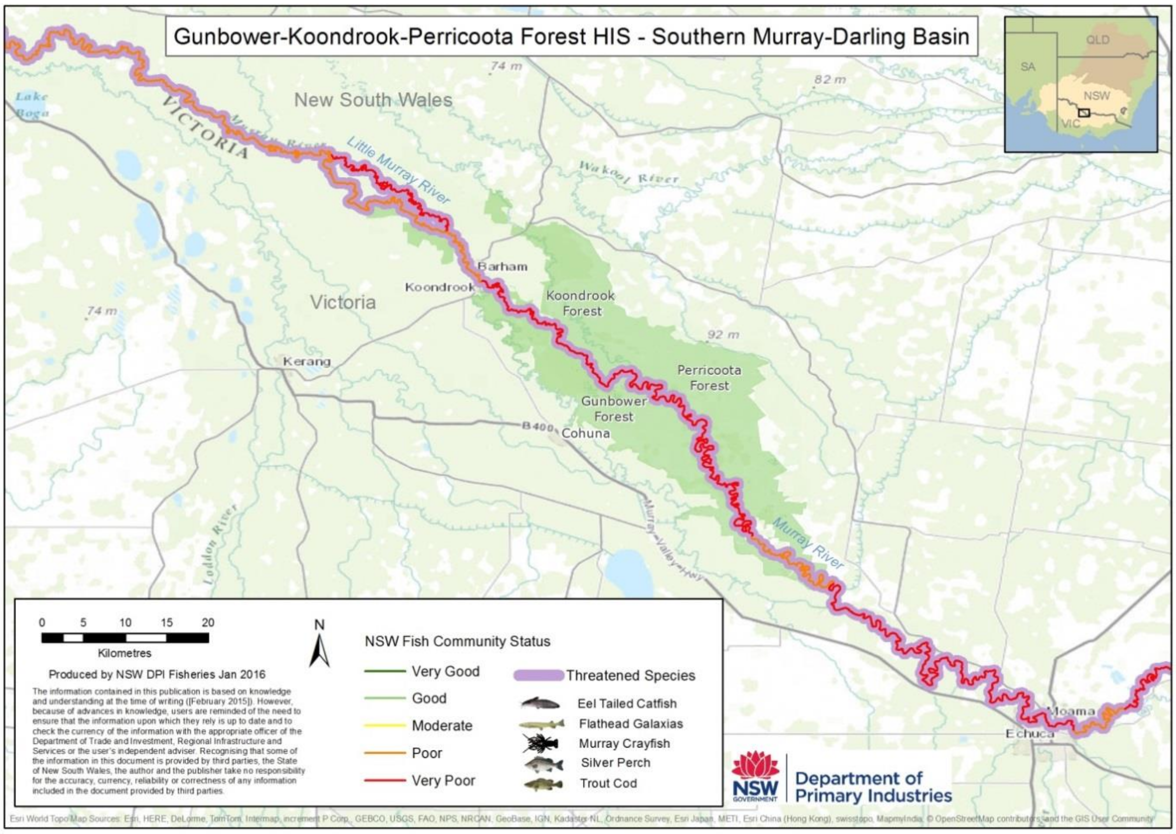

Figure 10. The Gunbower–Koondrook–Perricoota HIS, including Fish Community Status within the NSW Waters of the region (where available) and potential distribution of threatened species (NSW DPI 2016a).

Basin Plan flow indicators for the Gunbower-Koondrook-Perricoota HIS

Site-specific flow indicators are expressed at Murray River downstream of Torrumbarry Weir, which generally represents the flow into the GKP Forests. Under the Basin Plan the MDBA proposed five flow indicators for the GKP Forests which represented an amalgam of information within existing literature and vegetation inundation hydrodynamic modelling data, checked against analysis of modelled without development and baseline flow data.

Flow indicators described by the MDBA for the Bank full and Overbank elements of the flow regime primarily attempted to strike a balance between desirable flow threshold, duration and timing with desirable frequency and represent a variable flow regime that is consistent with the "without development" hydrology of the site. Flow indicators were primarily based on the water requirements determined to achieve the ecological targets relating to the current extent of native vegetation communities and the habitat requirements for waterbirds and have not been modified to consider the presence of environmental works (MDBA 2012c).

Flow indicators targeting specific fish needs were not included in the MDBA's EWR report for the GKP Forests. It was anticipated the flow indicators identified would also have valuable beneficial effects on the life cycle and habitat requirements of native fish, including provision of cues for spawning and migration and access to food sources. The original flow indicators for the GKP HIS under the Basin Plan were:

1. 16,000 ML/d for a total duration of 90 days (with a minimum duration of 7 consecutive days) between June and November for 70% of years
2. 20,000 ML/d for a total duration of 60 days (with a minimum duration of 7 consecutive days) between June and November for 60% of years
3. 30,000 ML/d for a total duration of 60 days (with a minimum duration of 7 consecutive days) between June and May for 33% of years
4. 40,000 ML/d for a total duration of 60 days (with a minimum duration of 7 consecutive days) between June and May for 25% of years
5. 20,000 ML/d for a total duration of 150 days (with a minimum duration of 7 consecutive days) between June and December for 30% of years.

Revised fish-specific flow indicators for Gunbower-Koondrook-Perricoota

Revised fish-specific flow indicators developed for the GKP system and rationale for each are presented in Table 11. The natural drainage system of the Lower Murray River including all native fish species and aquatic biota in the main-channel and anabranches and effluents downstream of Hume Weir are listed as an EEC (NSW DPI 2007a). This EEC includes Billabong Creek, Yanco Creek, Columbo Creek, Creek, Yanco Creek, Colombo Creek, the Edward River and the Wakool River, the Frenchman's Creek, the Rufus River and Lake Victoria associated tributaries, anabranches and effluents. The Murray Cod population in the Murray River main channel is also listed as significant and 'important' (NMCRT 2010). The flow indicators described for the within-channel elements of the flow regime are recommended to achieve the ecological targets relating to the life cycle and habitat requirements of native fish. In most instances the duration of in-channel flow events necessary for supporting fish outcomes will be lower than those proposed for other elements of the floodplain ecosystem.

The use of floodplain works (particularly ponding of water on floodplains above regulatory structures) to meet the objectives of either the original EWRs or the revised flow indicators presented for the GKP system could increase the potential for adverse water quality impacts such as the development hypoxic blackwater (Bond et al. 2014). Such artificial floodplain inundation can also create habitat ideal for the propagation of several non-native pest fish (such as Carp) while simultaneously disrupting natural downstream flow-related cues for native species. Consideration of these impacts will inform future adaptive management of water delivery and return flows.

Key components of the hydrograph identified are labelled for identification in Figure 6. Suggested Flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change.

Table 11. Revised fish-specific flow indicators developed for the Gunbower–Koondrook–Perricoota system HIS (expressed on the Murray River downstream of Torrumbarry Weir)

Flow indicator	Rationale
Variable Base Flows (BA) of 2,000-7,000 ML/day throughout the year (between within-channel fresh and Overbank events). Cease to flow events should be avoided.	Provide main channel refuge habitat, longitudinal connectivity and maintain suitable water quality for all species (except Floodplain Specialists[2]).
	Allow for the accumulation of allochthonous carbon and vegetation on benches and dry sections of riverbed, which contributes to ecosystem productivity during subsequent higher flow events.
Small Fresh (SF): 7,000-1,2000 ML/day for at least 10 consecutive days. Ideally between October and April but can occur anytime. Provide a minimum of 2 Small Fresh events in high and moderate water availability years and at least one during low water availability years. Maximum inter-flow period of 1 year.	Contribute to the maintenance of suitable water quality
	flow variability enhances system productivity and in-turn condition of adults and juvenile of most species
Annual prolonged and continuous Spring nesting component (SN) from 4,500-12,000 ML/day avoiding rapid drops in water level for at least 14 days every year during October/early November (to be informed by expert understanding of regional spawning season). Rates of rise or fall during the event should not exceed those of historic or modelled “without development” for the season. Maximum inter-flow period of 2 years. May coincide with (OB) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat. Important where river operations to meet irrigation demand cause extreme water level fluctuations which are out of sync with natural patterns and climatic cues	support nesting of River Specialists (e.g. Murray Cod, Trout Cod and Freshwater Catfish)
	promote/maintain connectivity and movement of native species longitudinally
	increase habitat availability for all species (except Floodplain Specialists[2]) during Spring when many species breed
	support dispersal of eggs and larvae for all species
	flow variability enhances system productivity and in-turn condition of adults and juvenile of most species
Large Fresh (LF) from 12,000-22,000 ML/day for at least 5 consecutive days in two years out of every successive three-year period (not required in years experiencing the Overbank event above). Ideally between August and November but may also occur in summer. Maximum inter-flow period of 2 years. A	promote connectivity and movement of native species longitudinally and laterally into anabranches and floodplain wetlands[1.]
	promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch), support habitat for Floodplain Specialists[2].
	inundate in-stream benches and low-lying Floodplain wetlands which may provide nursery habitat for Flow Pulse, River and Floodplain Specialists3.

Flow indicator	Rationale
priming 'spike' may trigger breeding response by Flow Pulse Specialists. Or Overbank event (OB) >25,000 ML/day for at least 10 consecutive days between August and February at least one year in every three-year period. Maximum inter-flow period of 3 years.	promote within-channel hydraulic variability to support a diverse range of habitats and enhance system productivity (and in-turn condition of adults and juveniles of most species) promote dispersal of eggs and larvae for all species
Large unregulated Overbank floods (well over 30,000 ML/day) for long durations will be required to address all the original flow indicators for the GKP HIS.	critical to the long-term viability of fish communities due to the ecosystem processes floods promote, the opportunistic potential for large scale floodplain recruitment by many species, and the unobstructed longitudinal and lateral connectivity they facilitate

1 The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

2 Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

3 Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

Hattah Lakes

The Hattah Lakes in north-west Victoria downstream of Euston Weir (Lock 15) are an icon site under the TLM project and an SDL hydrologic indicator site (Figure 11; MDBA 2012d). The Hattah Lakes includes a mosaic (over 13,000 ha) of more than 20 lakes and floodplain habitat fed naturally from the Murray River by Chalka Creek during medium to high flow (when flows in the Murray River exceed about 37,000 ML/d). The system encompasses aquatic habitats ranging from episodically flooded lakes to almost permanent lakes. Twelve of the lakes are listed as internationally important wetland systems under the Ramsar Convention on Wetlands of International significance (the Ramsar Convention), primarily for their value as waterbird habitat and importance in maintaining regional biodiversity.

The Murray River downstream from Euston (to Iraak) is one of few remaining stretches of river in the Lower Murray which is not influenced by a downstream weir. The Hattah Lakes region including the flowing section of the Murray River adjacent to the lakes supports important habitat and species that are listed in international agreements, including vulnerable Murray Cod, Silver Perch and (potentially) Murray Hardyhead.

Murray River regulation has contributed to a decrease in the size, frequency and duration of medium sized spring flood events, an increase in the number of small floods in summer, and a reduced variability in flows (Table 10) (King et al. 2009).

Table 12. Characteristics of the natural and post regulation flow regime in the Murray River downstream of Euston.

Modelled natural hydrology	Modelled current hydrology (regulated)
Extremely variable	Decreased flow variability
Bank full or Overbank flooding in most years (usually late winter-spring, rarely at other times of the year)	Large in-channel and Overbank flows less frequent and reduced in magnitude
large and small in-channel Freshes occurred anytime throughout the year but most frequently between May and December	Smaller in-channel flows and Base Flows are now a regular feature of the river year-round Increase in the number of small floods in summer

Modelled natural hydrology	Modelled current hydrology (regulated)
	More summer - autumn in-channel flows represent a seasonal reversal in flow patterns

Historically flooding of Hattah Lakes would have occurred approximately annually providing regular uninterrupted fish passage between the Murray River and the Hattah Lakes. Consequently, flows that connect the river channel to the Hattah Lakes floodplain are likely to be important to sustaining native fish populations in the region. Post Murray River regulation, natural flooding of Hattah Lakes is now considerably less frequent, and generally of smaller magnitude and shorter duration when it does occur (Maheshwari et al. 1995).

Pumps have been used to deliver environmental water to the Hattah Lake since 2005 (Vilizzi et al. 2012). In 2014 a package of works (a permanent pumping station, levee banks and a three flow regulators) was completed at the Hattah lakes to inundate over 6,000 ha of Murray River floodplain (MDBA 2016). The infrastructure will be used to deliver water to fill the lakes every 2 to 3 years, with more extensive watering to reach the floodplain every 8 to 10 years, subject to natural cues and water availability. About half the water used in the more extensive managed watering events can be returned to the Murray River by opening flow regulators.

Fish community condition

- Between 2005 and 2010, pumping from the Murray River periodically inundated floodplain and lake habitat with the intention of implementing a more natural hydrology to the system. TLM condition monitoring during this period identified that several native fish species were able to colonise the Hattah Lakes via the pumps, whilst Carp and Gambusia were largely excluded (McCarthy et al. 2009; Vilizzi et al. 2012).
- SRA2 for the period 2008-2010 indicated that the condition of native fish populations in the lower zone of the Central Murray Valley (the section of the Murray River from which the Hattah Lakes are filled) was in a poor condition (Davies et al. 2012).
- A natural flood event in 2011 established connectivity between the riverine habitat and the floodplain habitats of the Hattah Lakes. After the flooding in 2011 the fish community within the Hattah Lakes became dominated by non-native fish (particularly Carp) and native Carp Gudgeon, while the community in the Murray River adjacent to Hattah Lakes was dominated by native Carp Gudgeon and Bony Herring with Murray Cod, Golden Perch and Silver Perch also present (Henderson et al. 2014b).
- Condition monitoring in 2013-14 suggested that the new pump structure at Hattah Lakes has replicated conditions like those provided by the natural flood event in 2010–11 (Henderson et al. 2014b).
- NSW DPI fish community mapping for identifies that the fish community status in the Murray River near the Hattah Lakes is generally in moderate condition (Figure 11) (NSW DPI 2016a).
- Hypoxic blackwater conditions that arose during the 2010-11 and 2016 floods had a negative impact on the native fish communities in mid and lower Murray regions, resulting in extensive fish kills (Commonwealth Environmental Water Office, 2017).

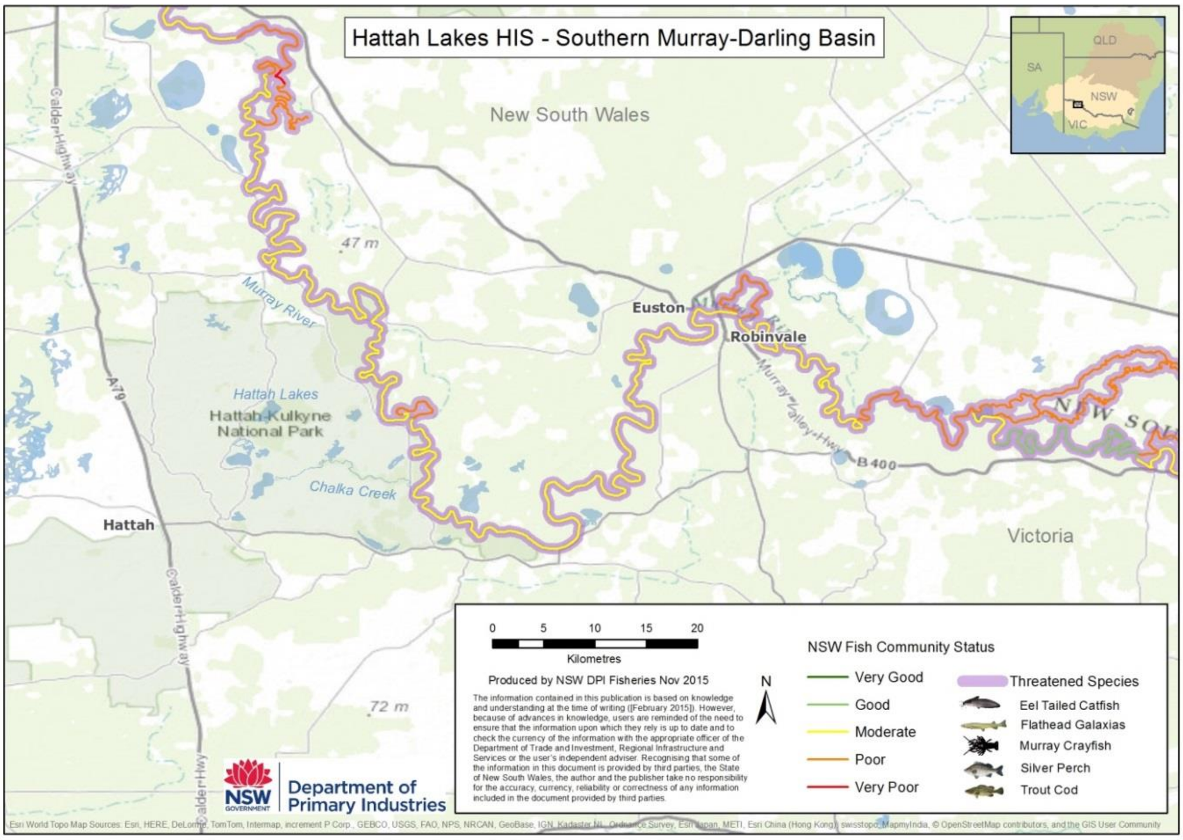

Figure 11. Hattah Lakes HIS, including Fish Community Status within the NSW Waters of the region (where available) and potential distribution of threatened species (NSW DPI 2016a).

Basin Plan flow indicators for the Hattah Lakes HIS

Site-specific flow indicators are expressed at Murray River downstream of Euston Weir, which generally represents the flow into Hattah Lakes when flows exceed commence to flow level of Chalka Creek. Under the Basin Plan the MDBA proposed six flow indicators for the Hattah Lakes HIS which represented an amalgam of information within existing literature and vegetation inundation hydrodynamic modelling data, checked against analysis of modelled without development and baseline flow data.

Flow indicators described by the MDBA for the Bank full and Overbank elements of the flow regime primarily attempted to strike a balance between desirable flow threshold, duration and timing with desirable frequency and represent a variable flow regime that is consistent with the "without development" hydrology of the site. Site-specific flow indicators primarily targeted for fish needs were not included in the MDBA's EWR report for the Hattah Lakes region. Instead, flow indicators were primarily based on the water requirements determined to achieve the ecological targets relating to the current extent of native vegetation communities and the habitat requirements for waterbirds and have not been modified to consider the presence of environmental works (MDBA 2012d). It was anticipated that the flow indicators derived would also have valuable beneficial effects on the life cycle and habitat requirements of native fish, including provision of cues for spawning and migration and access to food sources.

1. The original flow indicators for the Hattah Lakes HIS under the Basin Plan were:
2. 40,000 ML/d for a total duration of 60 days (with a minimum duration of 7 consecutive days) between June and December for 40% of years
3. 50,000 ML/d for a total duration of 60 days (with a minimum duration of 7 consecutive days) between June and December for 30% of years
4. 70,000 ML/d for a total duration of 42 days (with a minimum duration of 7 consecutive days) between June and December for 20% of years

5. 85,000 ML/d for a total duration of 30 days anytime in the water year (with a minimum duration of 7 consecutive days) for 20% of years
6. 120,000 ML/d for a total duration of 14 days anytime in the water year (with a minimum duration of 7 consecutive days) for 14% of years
7. 150,000 ML/d for 7 consecutive days anytime in the water year for 10% of years.

Revised fish-specific flow indicators for the Hattah Lakes HIS

Revised fish-specific flow indicators developed for the Hattah Lakes HIS and rationale for each are presented in Table 13. The flow indicators described for the within-channel elements of the flow regime are recommended to achieve the ecological targets relating to the life cycle and habitat requirements of native fish. In most instances the duration of in-channel flow events necessary for supporting fish outcomes will be lower than those proposed for other elements of the floodplain ecosystem.

The use of floodplain works (particularly ponding of water on floodplains above regulatory structures) to meet the objectives of either the original EWRs or the revised flow indicators presented for the Hattah Lakes system could increase the potential for adverse water quality impacts such as the development hypoxic blackwater (Bond et al. 2014). Such artificial floodplain inundation can also create habitat ideal for the propagation of several non-native pest fish (such as Carp) while simultaneously disrupting natural downstream flow-related cues for native species. Consideration of these impacts will inform future adaptive management of water delivery and return flows.

Table 13. Revised fish-specific flow indicators developed for the Hattah Lakes HIS (expressed on the Murray River downstream of Torrumbarry Weir).

Flow indicator	Rationale
Variable Base Flows (BA) of 2,500-14,000 ML/day throughout the year (between within-channel fresh and Overbank events). Cease to flow events should be avoided.	provide main channel refuge habitat, longitudinal connectivity and maintain suitable water quality for all species except Floodplain Specialists[2]
	allow for the accumulation of allochthonous carbon and vegetation on benches and dry sections of riverbed, which contributes to ecosystem productivity during subsequent higher flow events.
Small Fresh (SF): 14,000-20,000 ML/day for at least 10 consecutive days. Ideally between October and April but can occur anytime. Provide a minimum of 2 Small Fresh events in high and moderate water availability years and at least one during low water availability years. Maximum inter-flow period of 1 year.	contribute to the maintenance of suitable water quality
	flow variability enhances system productivity and in-turn condition of adults and juvenile of most species
Annual prolonged and continuous Spring nesting component (SN) from 5,000-10,000 ML/day avoiding rapid drops in water level for at least 14 days every year during October/early November (to be informed by expert understanding of regional spawning season). Rates of rise or fall during the event should not exceed those of historic or modelled “without development” for the season. Maximum inter-flow period of 2 years.	support nesting of River Specialists (e.g. Murray Cod, Trout Cod and Freshwater Catfish)
	promote/maintain connectivity and movement of native species longitudinally
	increase habitat availability for all species (except Floodplain Specialists[2]) during spring when many species breed
	support dispersal of eggs and larvae for all species
	flow variability enhances system productivity and in-turn condition of adults and juvenile of most species.

Flow indicator	Rationale
May coincide with (OB) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat. Important where river operations to meet irrigation demand cause extreme water level fluctuations which are out of sync with natural patterns and climatic cues.	
Large Fresh (LF) from 20,000-38,000 ML/day for at least 5 consecutive days in two years out of every successive three-year period (not required in years experiencing the Overbank event above). Ideally between August and November but may also occur in summer. Maximum inter-flow period of 2 years. A priming 'spike' may trigger breeding response by Flow Pulse Specialists. Or, Overbank event (OB) >50,000 ML/day for at least 10 consecutive days between August and February at least one year in every three-year period. Maximum inter-flow period of 3 years.	promote connectivity and movement of native species longitudinally and laterally into anabranches and floodplain wetlands[1]
	promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch), support habitat for Floodplain Specialists[2].
	inundate in-stream benches and low-lying Floodplain wetlands which may provide nursery habitat for Flow Pulse, River and Floodplain Specialists[3].
	promote within-channel hydraulic variability to support a diverse range of habitats and enhance system productivity (and in-turn condition of adults and juveniles of most species)
	promote dispersal of eggs and larvae for all species
Large unregulated Overbank floods (well over 80,000 ML/day) for long durations will be required to address all of the original flow indicators for the Hattah Lakes HIS.	critical to the long-term viability of fish communities due to the ecosystem processes floods promote, the opportunistic potential for large scale floodplain recruitment by many species, and the unobstructed longitudinal and lateral connectivity they facilitate

[1] The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

[2] Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

[3] Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

Lower Murray River

The Lower Murray River extends from the junction of the Murray and Darling rivers downstream to the confluence of the Murray River and Lake Alexandrina near Wellington and supports a range of habitats along its course including floodplain forests, Ramsar-listed wetlands and the estuary at the river's mouth (MDBA 2012e). Given its position below the junction of the Murray and Darling rivers, hydrology in the Lower Murray River represents a combination of these two rivers. Most flow originates from the Murray, with smaller, but variable, contributions from the Darling (typically <10%). Nonetheless, the Darling River historically contributed regular summer flows to the Lower Murray River resulting in substantial differences in flow regimes between the Lower Murray River and upstream reaches (Maheshwari et al. 1995). The Murray River main channel (including the lower

Murray River) has been identified as having an 'important population' of Murray Cod (NMCRT 2010), with a range of habitats exploited by different size classes (Zampatti et al. 2011). The region also supports threatened Freshwater Catfish, Silver Perch and Murray Hardyhead (MDBA 2012f).

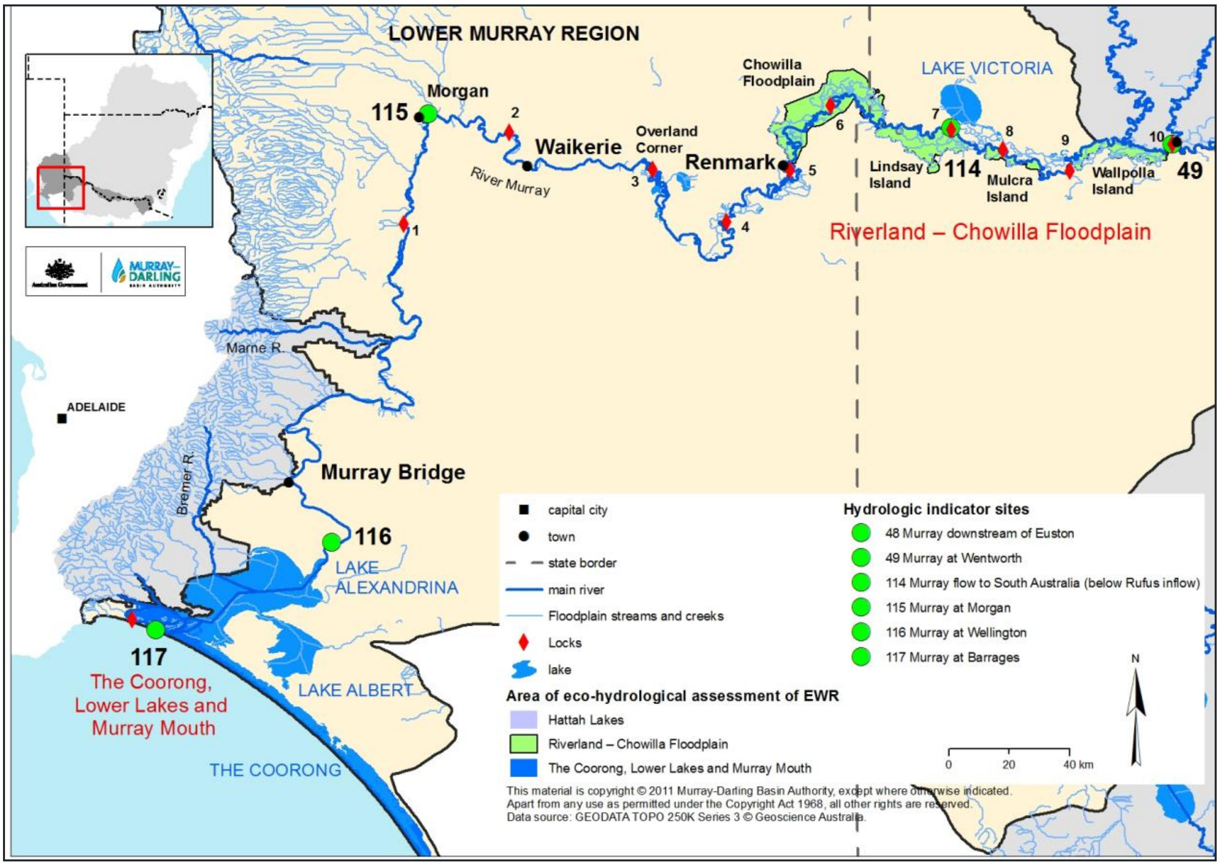

Figure 12. The Lower Murray River (in-channel) and Riverland-Chowilla Floodplain HIS (source MDBA 2012e).The Lower Murray River (in-channel) and Riverland-Chowilla Floodplain HIS (source MDBA 2012e).

Whilst the seasonality of flows in the Lower Murray River has been retained (flows peaking in spring/summer), their magnitude is substantially reduced because of regulation and abstraction (Walker and Thoms 1993; Maheshwari et al. 1995) (**Error! Reference source not found.**). Flow reduction is more pronounced during the high flow period from August to December resulting in a less defined seasonal peak (MDBA 2012e). Within-channel Freshes in spring are now generally regulated out of the flow regime or dampened downstream of Lock 10 (Wentworth) by the operation of Lock 9 and diversion of flows to Lake Victoria to provide additional storage security for South Australia (Zampatti and Leigh 2013a). Baseline median annual flow at the South Australian border is now 4,762 GL, relative to 11,624 GL under natural or 'without development' conditions (Gibbs et al. 2012).

Table 14. Characteristics of the natural and post regulation flow regime in the lower Murray River.

Modelled natural hydrology	Modelled current hydrology (regulated)
inter-annual variability in flow volumes	Decreased flow variability
Bank full or Overbank flooding in most years (usually late winter-spring, rarely at other times of the year)	large in-channel and Overbank flows less frequent and reduced in magnitude and duration
large and small in-channel Freshes occurred anytime throughout the year but most frequently between May and December	Smaller in-channel flows and Base Flows are now a regular feature of the river year-round
lotic conditions prevailed in the main channel, even under low flows	Increase in the number of small floods in summer
	More summer - autumn in-channel flows represent a seasonal reversal in flow patterns
	lentic conditions prevail under flows of <20,000 ML/day, which predominate

Lower Murray Indicator sites:

In the original Basin Plan, flow requirements of two HIS were presented separately as Lower Murray in-channel and the Riverland-Chowilla Floodplain (R-CF), with flow indicators for both expressed at the NSW-SA border.

The use of floodplain works (particularly ponding of water on floodplains above regulatory structures) to meet the objectives of either the original EWRs or the revised flow indicators presented for the Lower Murray system could increase the potential for adverse water quality impacts such as the development hypoxic blackwater (Bond et al. 2014). Such artificial floodplain inundation can also create habitat ideal for the propagation of several non-native pest fish (such as Carp) while simultaneously disrupting natural downstream flow-related cues for native species. Consideration of these impacts will inform future adaptive management of water delivery and return flows.

The Lower Murray in-channel habitat

The Lower Murray in-channel habitat is characterised by the presence of ten sequential low-level weirs (<3.5 m) between Mildura and Blanchetown (Lock 10 to Lock 3). The weirs have had a profound effect on the geomorphology, hydrodynamics and ecology of the Lower Murray, and most notably, have transformed a lotic river into a series of cascading weir pools that are predominantly lentic in character (Walker 2006, Mallen-Cooper and Zampatti 2018). Weir pools exhibit substantial reductions in velocity and hydraulic diversity in the impounded areas (Bice et al. 2017). Under current regulated operations and discharges of <20,000 ML/day, the weir pools of the Lower Murray River are predominantly lentic in character (Bice et al. 2017).

Under pre-regulation conditions, flows of 20,000 ML/day were equalled or exceeded 62% of the time, compared with 26% under current conditions (Zampatti and Leigh 2013b). Thus, weir pool environments disadvantage species whose life histories require lotic habitats (e.g. Murray Cod, Silver Perch, Murray Crayfish) (Koehn 2009) and favour species with lentic preferences such as non-native Carp and Eastern Gambusia (Walker 2006).

Within several reaches in which weir pool environments prevail, efforts are being trialled to re-instate more variable flow regimes via managed drawdown (to promote partial drying and hydraulic complexity) or surcharge (to increases the area of inundation in riparian and floodplain habitats of) weir pool levels. As an emerging water management measure, the potential influence of weir pool manipulation on both hydraulic complexity (particularly flow velocity) and floodplain inundation will require ongoing scrutiny in coming years to ensure environmental benefits are optimised and outweigh any negative consequences.

Riverland-Chowchilla Floodplain

The R-CF comprises floodplain adjacent to the Lower Murray River from the Darling River confluence to Renmark. This includes incorporates a Riverland Ramsar site (extending from the NSW-S.A. border to Renmark) and a Living Murray icon site (which includes Chowilla Floodplain in South Australia and Lindsay-Mulcra-Wallpolla Islands in Victoria). The R-CF contains a mosaic of lotic and lentic (creeks, wetlands, lakes and floodplain) which support populations of rare endangered and nationally threatened species and significant populations of native fish (MDBA 2011a). Modelled 'natural' daily flow data indicates that flows in the Lower Murray River exceeded Bank full levels of 40,000 ML/day in approximately 80% of years (Gibbs et al. 2012). A system of regulators built on the Chowilla Floodplain to enable artificial inundation of large areas of the floodplain and wetlands was first tested in 2014. Existing and proposed regulators and levee banks on the Lindsay-Mulcra-Wallpolla Islands also allow for environmental water to be used to artificially inundate floodplain (MDBA 2016).

Fish community condition

- The Murray River main channel has been identified as having an 'important population' of Murray Cod (NMCRT 2010), with a range of habitats exploited by different size classes (Zampatti et al. 2011).
- SRA2 for the period 2008-2010 indicated that the condition of native fish populations across the Lower Murray River Valley was Poor (Davies et al. 2012).
- Monitoring in the R-CF between 2005 and 2018 indicated small bodied native species Bony Herring, Australian Smelt were prevalent, with three species of conservation significance also collected across the HIS (Murray Cod, Silver Perch and Freshwater Catfish). Recruitment by Murray Cod, Golden Perch and Silver Perch has generally been limited (Wilson et al. 2014; Henderson et al. 2014b; Fredberg et al. 2018).
- NSW DPI fish community mapping for the NSW section of the Lower Murray River identifies that the fish community status is generally in a moderate to good condition 'good' condition (NSW DPI 2016a) (Figure 13).
- Hypoxic blackwater conditions that arose during the 2010-11 and 2016 floods had a negative impact on the native fish communities in d lower Murray region, resulting in extensive fish kills and a reduction or absence of spawning by native species during the event (Commonwealth Environmental Water Office, 2017).
- From 2015 up until 2020, regular Murray cod recruitment to young-of-year was observed in the Lower Murray during varying flow scenarios (12,000 to 90,000 ML/day). While recent monitoring has detected spawning by Silver Perch, recruitment has not yet been determined (https://flow-mer.org.au/lower-murray-river-project-updates-october-april-2021/)

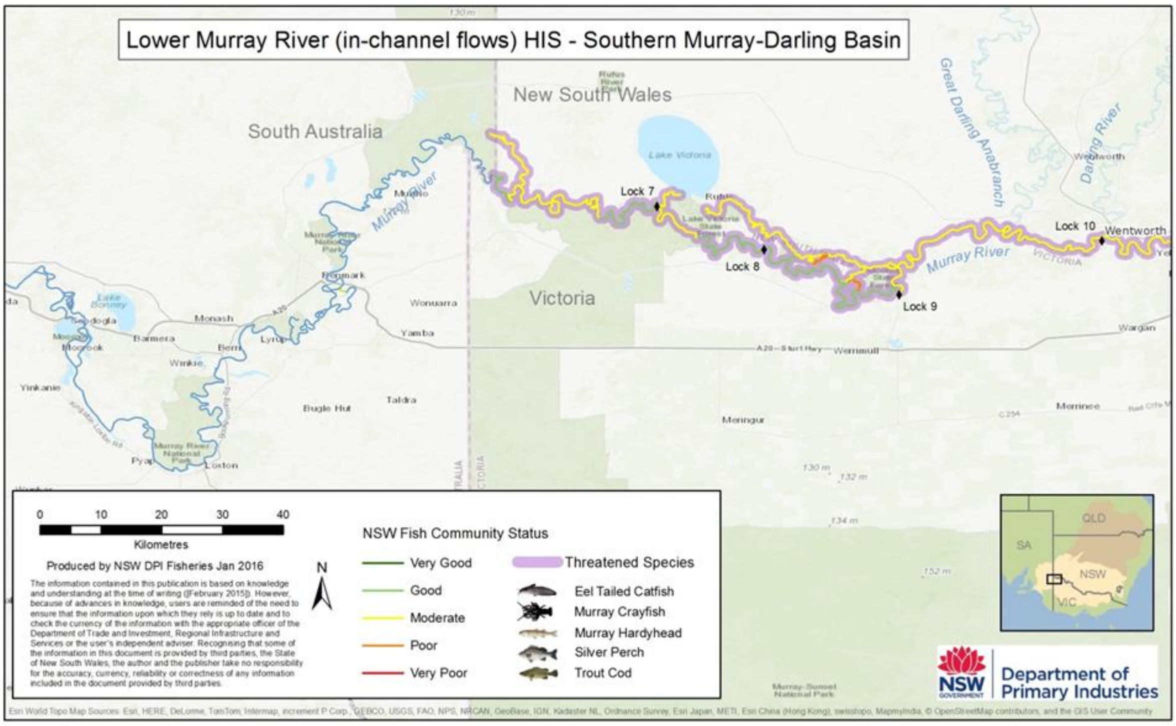

Figure 13. The Lower Murray River (in-channel) and Riverland-Chowilla Floodplain HIS, including Fish Community Status within the NSW Waters of the region (where available) and potential distribution of threatened species (NSW DPI 2016a).

Basin Plan flow indicators for the Lower Murray River (in-channel) HIS

A single site-specific in-channel flow indicator for the Lower Murray River (in-channel) HIS was expressed at the Murray River on the NSW-SA border:

20,000 ML/d for 60 consecutive days between August and December for 71% of years

This flow indicator focussed on the 'within-channel fresh' (or pulse) element of the flow regime, to inundate key within-channel habitat, promotes lotic habitats in weir pools and maintain native fish populations. Freshes can also increase connectivity of high value diverse habitats in the anabranch systems of the Lower Murray River. Freshes can also assist in improving water quality by reducing thermal stratification and increasing dissolved oxygen concentrations via mixing (Cottingham et al. 2010).

However, recent hydrodynamic modelling suggests that flow events of less than 20,000 ML/day have little impact on the distribution of hydraulic habitat within weir pools of the lower Murray (Wallace et al. 2014b). Therefore in the absence of complementary measures which would further facilitate the reinstatement of complex flowing habitat (e.g. weir pool level manipulation) within-channel flows well in excess of 20,000 ML/day will be required to re-instate hydraulic diversity considered necessary for many native fish present (or formerly present) in the Lower Murray River channel (e.g. Trout Cod, Freshwater Catfish, Silver Perch and Murray Crayfish).

Basin Plan flow indicators for Riverland-Chowchilla Floodplain HIS

The MDBA proposed six flow indicators for the R-CF HIS. These flow indicators were primarily based on the water requirements determined to achieve the ecological targets relating to the current extent of native floodplain vegetation communities and the habitat requirements for waterbirds and were not modified to consider the presence of environmental works (MDBA 2012f). Flow indicators specifically targeting fish needs were not included in the MDBA's EWR report for the R-CF. However, it was anticipated that the flow indicators that were described would also have valuable beneficial effects on the life cycle and habitat requirements of native fish, including provision of cues for spawning and migration and access to food sources.

The original flow indicators for the R-CF HIS under the Basin Plan were:

1. 40,000 ML/d for a total duration of 30 days (with a minimum duration of 7 consecutive days) between June and December for 50% of years.
2. 40,000 ML/d for a total duration of 90 days (with a minimum duration of 7 consecutive days) between June and December for 33% of years.
3. 60,000 ML/d for a total duration of 60 days (with a minimum duration of 7 consecutive days) between June and December for 25% of years.
4. 80,000 ML/d for a total duration of 30 days (with a minimum duration of 7 consecutive days) anytime in the water year for 17% of years.
5. 100,000 ML/d for a total duration of 21 days anytime in the water year for 13% of years.
6. 125,000 ML/d for a total duration of 7 days anytime in the water year for 10% of years.

Revised fish-specific flow indicators for the Lower Murray

In development of this document, we present fish-specific EWRs for both the Lower Murray in-channel and the R-CF combined. Furthermore, we considered flow indicators expressed at NSW-SA border (as in the original Basin plan) to be more representative of conditions in the Murray River downstream of Lake Victoria (influenced by releases from Lake Victoria) than they are for the Lock 10 to Lock 7 reach of the Lower Murray River (upstream of Lake Victoria releases).

Accordingly, we present here fish specific EWRs at an additional HIS downstream of Lock 9 to reflect the differences between reaches upstream and downstream of Lake Victoria releases. Fish specific flow requirements of both the lower Murray River within-channel habitat and the R-CF habitat adjacent to the Murray River are presented together and reflect EWRs.

Due to the operation of Lake Victoria the flow indicators expressed at the NSW-SA border are more representative of flow through the South Australian section of the Murray River than they are for flow in the NSW Lock 10 to Lock 7 reach. To address this, we developed Fish-specific EWRs for the following:

1. The NSW Lower Murray Lock 10 to Lock 7 reach (expressed downstream of Lock 9), and
2. The SA Lower Murray Lock 6 to Wellington reach incorporating the R-CF HIS (expressed at the NSW-SA border).

Lock 10 to Lock 7 reach of the Lower Murray River

Fish-specific flow indicators developed for the Lock 10 to Lock 7 Lower Murray River reach expressed downstream of Lock 9 are presented in Table 15 along with rationale for each flow indicator. The flow indicators described for the within-channel elements of the flow regime are recommended to achieve the ecological targets relating to the life cycle and habitat requirements of native fish.

Key components of the hydrograph identified are labelled for identification in Figure 6. Suggested Flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change.

Table 15. Revised fish-specific flow indicators developed for the Lock 7-10 Lower Murray River reach (expressed downstream of Lock 9).

Flow indicator	Rationale
Variable Base Flows (BA) of 3,500-14,000 ML/day throughout the year (between within-channel fresh and Overbank events). Cease to flow events should be avoided.	contribute to the maintenance of suitable water quality
	flow variability enhances system productivity and in-turn condition of adults and juvenile of most species
Small Fresh (SF): 14,000-20,000 ML/day for at least 10 consecutive	contribute to the maintenance of suitable water quality

Flow indicator	Rationale
days. Ideally between October and April but can occur anytime. Provide a minimum of 2 Small Fresh events in high and moderate water availability years and at least one during low water availability years. Maximum inter-flow period of 1 year.	flow variability enhances system productivity and in-turn condition of adults and juvenile of most species
Annual prolonged and continuous spring nesting component (SN) from 5,000-14,000 ML/day avoiding rapid drops in water level for at least 14 days every year during October/early November (to be informed by expert understanding of regional spawning season). Rates of rise or fall during the event should not exceed those of historic or modelled “without development” for the season. Maximum inter-flow period of 2 years. May coincide with (OB) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat. Important where river operations to meet irrigation demand cause extreme water level fluctuations which are out of sync with natural patterns and climatic cues.	support nesting of River Specialists (e.g. Murray Cod, Trout Cod and Freshwater Catfish)
	promote/maintain connectivity and movement of native species longitudinally
	increase habitat availability for all species (except Floodplain Specialists[2]) during spring when many species breed
	support dispersal of eggs and larvae for all species
	flow variability enhances system productivity and in-turn condition of adults and juvenile of most species.
Large Fresh (LF) from 20,000-40,000 ML/day for at least 5 consecutive days in two years out of every successive three-year period (not required in years experiencing the Overbank event above). Ideally between August and November but may also occur in summer. Maximum inter-flow period of 2 years. A priming ‘spike’ may trigger breeding response by Flow Pulse Specialists. Or Overbank event (OB) >55,000 ML/day for at least 10 consecutive days between August and February at least one year in every three-year period. Maximum inter-flow period of 3 years.	promote connectivity and movement of native species longitudinally and laterally into anabranches and floodplain wetlands[1]
	promote spawning and dispersal of Flow Pulse Specialists (Golden Perch and Silver Perch), support habitat for Floodplain Specialists[2].
	inundate in-stream benches and low-lying Floodplain wetlands which may provide nursery habitat for Flow Pulse, River and Floodplain Specialists[3].
	promote within-channel hydraulic variability to support a diverse range of habitats and enhance system productivity (and in-turn condition of adults and juveniles of most species)
	promote dispersal of eggs and larvae for all species
Large unregulated Overbank floods (well over 80,000 ML/day) for long	critical to the long-term viability of fish communities due to the ecosystem processes floods promote, the opportunistic

Flow indicator	Rationale
durations will be required to address all of the original flow indicators for the Hattah Lakes HIS.	potential for large scale floodplain recruitment by many species, and the unobstructed longitudinal and lateral connectivity they facilitate

[1] The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

[2] Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

[3] Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

Lock 6 to Wellington Reach of the Lower Murray River (including the Riverland-Chowchilla Floodplain)

Fish-specific flow indicators developed for the Lower Murray River downstream of Lock 7 (including the R-CF HIS) are presented in **Error! Reference source not found.** along with rationale for each. Where possible we have incorporated consistency with the EWRs presented in the LTWP for the South Australian Murray River (Wallace et al. 2014a). It is important to note that extended Overbank floods (well over 80,000 ML/day) are beyond the current capacity for environmental water delivery. Large natural flooding in conjunction with complementary flow management activities may be necessary to stimulate floodplain productivity outcomes (which occurred historically in the R-CF HIS) and achieve the ecological targets relating to the life cycle and habitat requirements of floodplain dependant native fish.

Key components of the hydrograph identified are labelled for identification in Figure 6. Suggested Flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change.

Table 16. Revised fish-specific flow indicators developed for the Lock 6 to Wellington Lower Murray River reach including the Riverland-Chowilla Floodplain HIS downstream of the NSW-SA border.

Flow indicator	Rationale
Variable Base Flows (BA) of 3,500-14,000 ML/day throughout the year (between within-channel fresh and Overbank events). Cease to flow events should be avoided.	provide main channel refuge habitat, longitudinal connectivity and maintain suitable water quality for all species (except Floodplain Specialists2).
	allow for the accumulation of allochthonous carbon and vegetation on benches and dry sections of riverbed, which contributes to ecosystem productivity during subsequent higher flow events.
Small Fresh (SF): 14,000-20,000 ML/day for at least 10 consecutive days. Ideally between October and April but can occur anytime. Provide a minimum of 2 Small Fresh events in high and moderate water availability years and at least one during low water availability years. Maximum inter-flow period of 1 year.	contribute to the maintenance of suitable water quality
	flow variability enhances system productivity and in-turn condition of adults and juvenile of most species
Annual prolonged and continuous spring nesting component (SN) from 5,000-14,000 ML/day avoiding rapid drops in water level for at least 14 days every year during October/early November (to be informed by expert understanding of regional spawning	support nesting of River Specialists (e.g. Murray Cod and Freshwater Catfish)
	promote/maintain connectivity and movement of native species longitudinally
	increase habitat availability for all species (except Floodplain Specialists2) during spring when many species breed
	support dispersal of eggs and larvae for all species

Flow indicator	Rationale
season). Rates of rise or fall during the event should not exceed those of historic or modelled “without development” for the season. Maximum inter-flow period of 2 years. May coincide with (OB) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat. Important where river operations to meet irrigation demand cause extreme water level fluctuations which are out of sync with natural patterns and climatic cues.	flow variability enhances system productivity and in-turn condition of adults and juvenile of most species
Large Fresh (LF) from 20,000-40,000 ML/day for at least 5 consecutive days in two years out of every successive three-year period (not required in years experiencing the Overbank event above). Ideally between August and November but may also occur in summer. Maximum inter-flow period of 2 years. A priming ‘spike’ may trigger breeding response by Flow Pulse Specialists. Or Overbank event (OB) >55,000 ML/day for at least 10 consecutive days between August and February at least one year in every three-year period. Maximum inter-flow period of 3 years.	promote connectivity and movement of native species longitudinally and laterally into anabranches and floodplain wetlands[1]
	promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch), support habitat for Floodplain Specialists[2].
	inundate in-stream benches and low-lying Floodplain wetlands which may provide nursery habitat for Flow Pulse, River and Floodplain Specialists[3].
	promote within-channel hydraulic variability to support a diverse range of habitats and enhance system productivity (and in-turn condition of adults and juveniles of most species)
	promote dispersal of eggs and larvae for all species
Periodic large unregulated Overbank floods (well over 80,000 ML/day) for extended duration will be required to address all the original flow indicators.	critical to the long-term viability of fish communities due to the ecosystem processes floods promote, the opportunistic potential for large scale floodplain recruitment by many species, and the unobstructed longitudinal and lateral connectivity they facilitate

1 The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

2 Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

3 Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

Coorong-Lower Lakes

Located near the terminus of the Murray River, the Lower Lakes and the Coorong are collectively considered as wetlands of international importance under the Ramsar Convention, and an Icon Site under TLM (Figure 14). The River Murray terminates in South Australia at the Southern Ocean, having passed through Lake Alexandrina, the Murray Estuary and finally, the Murray Mouth. Lake Albert is a terminal lake connected to Lake Alexandrina by a narrow channel. These two lakes are often called the Lower Lakes (MDBA 2012g). The site supports important species that are listed under international State and/or Commonwealth legislation including Murray Cod, Southern Pygmy Perch, Yarra Pygmy Perch, Murray Hardyhead, Southern Purple-spotted Gudgeon, Short-headed Lamprey, Pouched Lamprey, Estuary Perch and Congolli (Lintermans 2007; MDBA 2012g).

The Coorong–Lower Lakes HIS comprises two distinct spatial units, separated by the Murray Barrages and typically representing freshwater and estuarine environments. These regions are:

- the freshwater region including Lake Albert, Lake Alexandrina and the lowland stream reaches/terminal wetlands of the Eastern Mount Lofty Ranges (EMLR) tributaries; and
- the Coorong, comprising the Murray Estuary, North Lagoon and South Lagoon.

Lake Alexandrina and Lake Albert are large (c. 760 km^2 and 168 km^2), shallow (deepest points –4.0 m and –1.7 m Australian Height Datum [AHD], respectively) and turbid freshwater lakes (Aldridge et al. 2011). The bulk of freshwater flow to the Lower Lakes is derived from the Lower Murray River (typically >98% of total annual flow), with a smaller contribution (typically <2%) from tributary streams of the EMLR (i.e. Currency Creek and Finniss, Angas and Bremer rivers).

The South-West region of Lake Alexandrina (comprising Hindmarsh Island, Mundoo Island and several smaller islands, the Goolwa Channel and the confluences with the Finniss River and Currency Creek) harbours a diversity of aquatic habitats, characterised by heterogeneous emergent and submerged vegetation (Phillips and Muller 2006). Several small bodied threatened species, which are rare or extinct elsewhere in the MDB, persist in these habitats.

The Coorong is a narrow estuarine lagoon that runs south-east from the river mouth parallel to the coast for *c*. 140 km. It is commonly divided into three subunits based upon geographical features and a persistent salinity gradient, namely: a) the Murray Estuary; b) the North Lagoon; and c) the South Lagoon. The physico-chemical character of the Coorong is driven by discharge of freshwater through the Murray Barrages (and to a lesser degree discharge from the upper south-east through Salt Creek) and marine water exchange through the Murray Mouth. As such, salinity in the Murray Estuary is highly variable. During times of high freshwater discharge, salinity is brackish, but variable (0.1–35 $g.L^{-1}$), whilst during times of low or no discharge it typically reflects marine conditions (i.e. 35–40 $g.L^{-1}$; Geddes 1987). Salinity increases through the Lagoons, relative to the Murray Estuary, with salinity in the South Lagoon reaching >100 $g.L^{-1}$ during extended periods of low flow (Geddes and Butler 1984; Wedderburn et al. 2016). Nonetheless, during times of high river flows, salinities in the North Lagoon are typically brackish (i.e. 5–35$g.L^{-1}$) with reductions in salinity in the South Lagoon also observed (Geddes 1987). In contrast to the upstream Murray River channel habitat, within-channel hydraulics and floodplain inundation are of less importance in the 'Lower Lakes and Coorong'. Instead, salinity, water level variability and physical connectivity are the primary drivers of ecological response.

As the interface between the Lower Murray River and Southern Ocean, the Coorong and Lower Lakes comprise habitats unique within the MDB, and subsequently harbour fish assemblages disparate from the rest of the basin. Over 100 species of fish have been recorded from the region, comprising a diversity of freshwater, diadromous, estuarine and marine species; nonetheless, >50% of recorded species could be considered marine vagrants that only occasionally use the system.

Due to separation of the Coorong and Lower Lakes by the Murray Barrages and associated differences in physico-chemical conditions, fish assemblages of the Coorong and Lower Lakes differ substantially, as does the role these habitats play in the life-history of different species and the influence of flow on population dynamics.

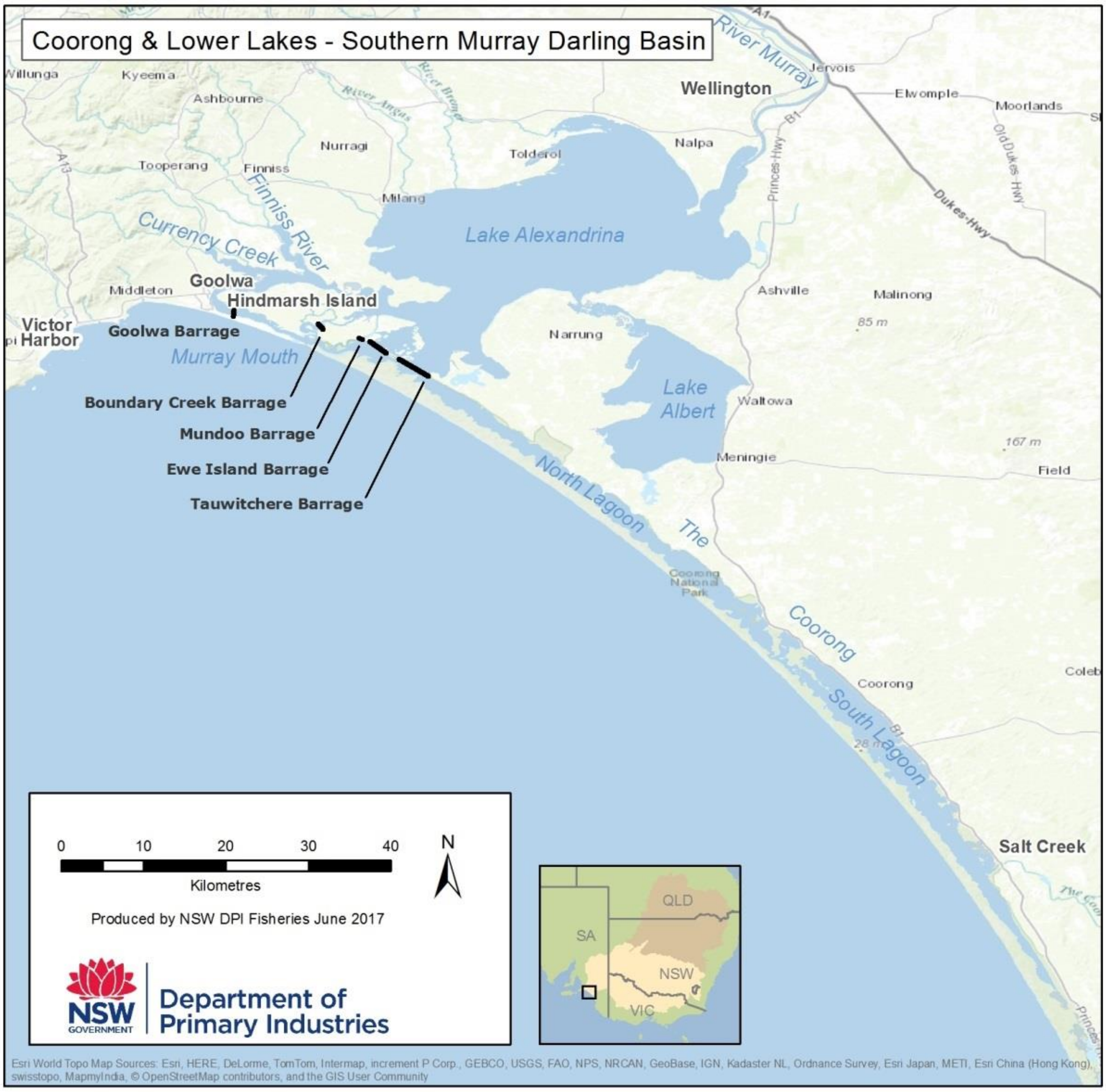

Figure 14. The Lower Lakes and Coorong region of the Southern MDB. DPI NSW Fish Community Status for threatened species distribution information does not extend into the SA regions of the MDB; however note that several small populations of the threatened Murray Hardyhead, Southern Pygmy Perch, Yarra Pygmy Perch and Southern Purple-Spotted Gudgeon persist within this region.

The fish assemblage of the Lower Lakes is dominated by obligate freshwater species (comprising all functional groups presented in Appendix A: Fish of the Southern MDB), including numerous threatened species (e.g. Yarra Pygmy Perch, Murray Hardyhead), together with diadromous (both anadromous (e.g. Pouched Lamprey) and catadromous species (e.g. Congolli) and a small number of euryhaline estuarine species (e.g. Lagoon Goby).

Whilst flow volumes to the Lower Lakes are of obvious importance to fishes, the interplay of inflow from the lower Murray and outflow as a function of barrage operation manifests in water level variability in the Lower Lakes. Consequently, water level variability is a primary driver of the distribution of vegetated habitat (as opposed to flow discharge), and thus the distribution and abundance of fish associated with such habitats. Nevertheless, flow in the lower Murray River, subsequent population processes (i.e. spawning and downstream drift), and connectivity (hydrological and biological) between the Lower Lakes and both the Lower Murray River upstream and the Coorong downstream, also has a large bearing on patterns of distribution and abundance of fishes (Ye et al. 2016).

Fish assemblages in the Coorong are spatio-temporally variable, as driven by barrage discharge and resulting variability in salinity (Zampatti et al. 2010) and productivity but are typically dominated by estuarine and marine species. Nonetheless, freshwater species are abundant during times of high freshwater discharge (Bice et al. 2016). The salinity regime, productivity and connectivity with both the Lower Lakes and Southern Ocean, as mediated by barrage discharge, are the primary drivers of patterns of distribution and abundance of fishes in the Coorong (Ye et al. 2013).

Importantly, the Coorong represents a critical migratory pathway for diadromous fishes, permanent habitat for estuarine residents (e.g. Black Bream) and nursery habitat for a suite of estuarine-dependent marine species (e.g. Mulloway). Several freshwater species (e.g. Golden Perch), estuarine resident species (e.g. Black Bream) and estuarine-dependent marine species (e.g. Mulloway, Yelloweye Mullet) support a commercial fishery in the region.

In addition to the four functional groups of fish present in the upstream catchments of the Southern Connected MDB, two groups of fishes are identified as occupying the Lower Lakes-Coorong. These are Diadromous species and Estuarine Dependent species, which do not occur elsewhere in the Southern MDB.

Fish community condition

A substantial amount of monitoring and research has occurred in the Coorong and Lower Lakes from 2006 to 2017, a period characterised by highly variable hydrology.

- From 2007 to 2010, reduced flow from the lower Murray River resulted in the closure of the barrages and complete disconnection of the Lower Lakes from Coorong. Water levels in the Lower Lakes decreased to below sea level for the first time in recorded history, with concomitant loss of vegetated habitats and increases in salinity. No freshwater was discharged to the Coorong for a period of approximately 3 years, with associated increases in salinity throughout the Coorong.
- During the 2007 to 2010 period, substantial declines in the abundance of small-bodied threatened species were documented in the Lower Lakes (including the likely extirpation of Yarra Pygmy Perch), due to the loss of obligate habitats (i.e. vegetated off-channel and littoral habitats) (Wedderburn et al. 2012).
- A substantial decline in diadromous species (Zampatti et al. 2010) was also observed because of limited connectivity between the Lower Lakes and Coorong. Notably, the proportional catch of native species (e.g. Golden Perch) was reduced relative to common Carp in the Lower Lakes portion of the local commercial fishery. In the Coorong, fish assemblages became characterised by low diversity and abundance, and the presence of several truly marine species. As a result of elevated salinity, the ranges of several estuarine (e.g. Smallmouth Hardyhead, Black Bream) and estuarine-dependent marine species (e.g. Mulloway, Greenback Flounder) were drastically reduced relative to years with freshwater discharge, whilst recruitment was diminished for several species.
- From 2010 to 2016 discharge was variable including periods of both high and low flow but was characterised by continuous connectivity between the Lower Lakes and Coorong. The return of typical water levels within the Lower Lakes was accompanied by reductions in salinity and recovery of aquatic habitat (i.e. vegetation cover).
- From 2010 to 2016 fish assemblages were characterised by greater diversity and overall abundance than during 2007–2010. Reduced salinities facilitated range expansions for many species including those important to the commercial fishery. Abundances of catadromous species (i.e. Congolli and Common Galaxias) also increased substantially in association with uninterrupted connectivity and enhanced recruitment over multiple years.
- With drought again affecting the MDB from 2017-2020, the Coorong and Lower Lakes Fish assemblage was similar to that in earlier years of low freshwater discharge, characterised by low overall abundance but high diversity and moderate abundance of catadromous species (Bice et al. 2019).

Fish-specific flow indicators for the Coorong-Lower Lakes

Site-specific flow indicators in the Basin Plan were expressed as total discharge through the Murray Barrages. Under the Basin plan the MDBA proposed four flow indicators for the Coorong, Lower Lakes and Murray Mouth HIS, all of which represent annual flow volumes related to the maintenance of salinity regimes (i.e. threshold average and maximum salinities) in the Coorong that are favourable for growth and recruitment of keystone plant species (i.e. *Ruppia tuberosa* and *Ruppia megacarpa*). Ecological targets were also developed regarding salt export and maintenance of water levels in the Lowers Lakes >0 m AHD, but these targets had no associated flow indicators. Flow indicators described by the MDBA were based on the environmental water requirements of *Ruppia* species (i.e. favourable salinity regimes), which in turn are a critical food source for migratory wading birds, but there were no specific indicators targeting fishes.

The original flow indicators for the Coorong and Lower Lakes HIS under the Basin Plan (expressed as barrage discharge) were:

1. Long-term average barrage flow of 5,100 GL. yr^{-1}.
2. Rolling 3-year average >2,000 GL. yr^{-1} in 95% of years.
3. Rolling 3-year average >1,000 GL. yr^{-1} in 100% of years; and
4. Maintain at least the proportion of years with high flows (5,100–10,000 GL. yr^{-1}) that is experienced under baseline conditions.

It was anticipated that salinity-based barrage discharge indicators for the Coorong would also benefit fishes by providing salinity regimes that would facilitate broad distributions, and conditions suitable for spawning and recruitment. Whilst this is true to some degree, flow indicators were specifically related to annual flow volumes and thus lacked any intra-annual (seasonal) detail.

The absence of specific flow indicators for the Lower Lakes was based on an ecological target of maintaining water levels in the Lower Lakes >0 m AHD to limit acid sulfate soil exposure. It was assumed this target would be achieved if the barrage discharge indicators were achieved, as lake water levels need to be >0 m AHD to discharge water from the barrages. Nonetheless, this is a simplistic view of ecological pattern and process in the Lower Lakes. Hydrologically (e.g. habitat availability) and hydraulically (downstream larval drift) mediated processes that may influence fish population dynamics in the Lower Lakes and are dependent on connectivity (hydrological and biological) with the lower Murray River.

Revised fish-specific flow indicators for the Coorong and Lower Lakes

Revised fish-specific flow indicators developed for the Coorong and Lower Lakes HIS and rationale for each are presented in Table 17. Comparison of historic flow data indicated that within bank flows at the NSW-SA border generally remain unaltered in magnitude and character as they progress to the gauge downstream of Lock1 (i.e. to Wellington and the Lower Lakes). Thus, for consistency with the preceding section (Lower Murray HIS), the EWRs we present for the Lower Lakes are expressed at the NSW-SA border.

Flow indicators described herein are based on conceptual hydrographs developed to represent flow both at Wellington (generally reflective of within-channel flows at the NSW-SA border) and through the barrages. Whilst flow through the Lower Murray River and the barrages are often different (as a result of barrage operations), the integration of flow from these two locations in the conceptual hydrograph and associated set of EWRs seeks to maintain the connectivity and integrity of flow through the region which existed pre-development and river regulation. Whilst there are losses in flow volumes between Wellington and the barrages due to evaporation, the underlying shape of hydrographs and timing of flow peaks should be consistent.

Where flow indicators relate specifically to the Lower Lakes (i.e. flow at the NSW-SA border/Wellington) or the Coorong (i.e. flow through the barrages) it is indicated in Table 17. Some of the original barrage discharge indicators are retained as they adequately address issues related to the salinity regime of the Coorong, which is equally important to fish as to Ruppia plant species.

In particular, the distribution and abundance of the estuarine Smallmouth Hardyhead (a keystone species in the food web of the Coorong North and South lagoons) is dictated by the salinity regime, with threshold values in the South Lagoon (approximately 100,000 mg. L-1) similar to those used to develop flow indicators for Ruppia. Nevertheless, additional indicators are included to provide greater nuance to these original flow indicators.

Key components of the hydrograph identified are labelled for identification in Figure 6. Suggested Flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change. Some of the original barrage discharge indicators are retained as they adequately address issues related to the salinity regime of the Coorong. For consistency with the previous HIS, the Lower Lakes flow indicators are expressed at the NSW-SA border as within-channel flow components generally progress unaltered in magnitude and character downstream to Wellington.

Table 17. Revised fish-specific flow indicators developed for the Coorong-Lower Lakes HIS.

Flow indicator	Rationale
Long-term average barrage flow of 5,100 GL. yr^{-1}	Facilitate broad distributions of estuarine-dependent fishes by maintaining long-term average salinities in the South Lagoon <60 g.L-1.
Rolling 3-year average barrage flow >2000 GL. yr^{-1} in 95% of years	Facilitate broad distributions of Smallmouth Hardyhead by maintaining peak salinities in the South Lagoon <100 g.L-1.
Variable base flow (BA) of 4,000 to 14,000 ML/day throughout the year at the SA border (between within-channel fresh and Overbank events) to maintain flows to the Lower Lakes and Coorong (through the barrages) outside within-channel pulse and Overbank events. Cease to flow events during summer should be avoided.	Maintain water levels in the Lower Lakes >0.3 m AHD to provide obligate habitats for threatened Floodplain Specialists (i.e. Yarra Pygmy Perch, Southern Pygmy Perch and Murray Hardyhead).
	Maintain a salinity gradient in the Coorong, from freshwater (0.5 g. L-1) to marine (35 ppt) between discharge locations (i.e. the barrages) and 1) the Murray Mouth and 2) the North Lagoon, throughout the year.
	Maintain connectivity (i.e. for upstream fish migration) by providing flow for fishways and attractant flow adjacent fishways year-round.
	Cease to flow events: winter represents the key downstream migration period for Congolli and key upstream migration period for Pouched Lamprey. The provision of open gates is required to allow downstream passage of Congolli. spring/summer is the key upstream migration for Congolli and Common Galaxias.
Small Fresh 1 (SF): 14,000 to 25,000 ML/day for at least 10 consecutive days. Ideally between December and May but can occur anytime. Provide a minimum of 1 Small Fresh event in high and moderate water availability years in addition to Small Fresh 2 (below). Maximum inter-flow period of 1 year.	promote system productivity and in-turn condition of adults and juveniles of most species
	promote longitudinal connectivity through the Lower Murray River, the Lower Lakes and the barrages to support life-history requirements of diadromous and estuarine dependent species.
Small Fresh 2 (SF): in addition to Small Fresh 1, provide a flow of 14,000 to 25,000 ML/day at the SA border for at least 14 consecutive days during winter-early spring (June – September) each year. Maximum inter-flow period of 1 year.	Facilitate the attraction and upstream migration of Pouched Lamprey and Short-headed Lamprey
	Facilitate the downstream spawning migrations of adult female Congolli and Common Galaxias

Flow indicator	Rationale
Annual prolonged and continuous Spring nesting component (SN) from 4,000 to 35,000 ML/day avoiding rapid drops in water level for at least 14 days every year during October/early November (to be informed by expert understanding of regional spawning season). Rates of rise or fall during the event should not exceed those of historic or modelled “without development” for the season. Maximum inter-flow period of 2 years. May coincide with (OB) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat.	support nesting of River Specialists (e.g. Murray Cod and Freshwater Catfish)
	promote/maintain connectivity and movement of native species longitudinally
	increase habitat availability for all species except Floodplain Specialists2 during spring when many species breed
	support dispersal of eggs and larvae for all species
	flow variability enhances system productivity and in-turn condition of adults and juvenile of most species
Large Fresh (LF) from 25,000 to 60,000 ML/day for at least 5 consecutive days in two years out of every successive three-year period (not required in years experiencing the Overbank event above). Ideally between August and November but may also occur in summer. Maximum inter-flow period of 2 years. A priming ‘spike’ may trigger breeding response by Flow Pulse Specialists. Or, Overbank event (OB) >64000 ML/day for at least 10 consecutive days between August and February at least one year in every three-year period. Maximum inter-flow period of 3 years.	promote connectivity and movement of native species (longitudinally between the Lower Murray River and Lower Lakes, and between the Coorong and Lower Lakes)
	promote spawning, dispersal and recruitment of Flow Pulse Specialists in the lower Murray River (Golden Perch[3])
	inundate in-stream benches and low-lying floodplain wetlands which may provide nursery habitat for Flow Pulse, River and Floodplain Specialists[2]
	promote dispersal of eggs and larvae for all native species
	promote low salinity and diverse fish assemblages in the Coorong
	flow variability enhances system productivity in the Lower Lakes and Coorong, and in-turn condition of adults and juveniles of most species
	Specifically in the Coorong, high flow events enhance system productivity (and more diverse food webs), promoting high abundances of small-bodied estuarine-dependent species important in trophic dynamics (e.g. Sandy Sprat) and the recruitment of large-bodied estuarine-dependent species (e.g. Mulloway)

[1] The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

[2] Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

[3] Golden perch populations in the Lower Lakes (which are harvested by a commercial fishery) are potentially influenced by downstream drift of eggs and larvae spawned in the lower Murray River.

Lower Darling-Baaka Region

The Lower Darling River (LDR) or 'Baaka' as it is known by Traditional owners, extends from the upper reaches of the Menindee Lakes in the north, to the junction of the Darling and Murray rivers in the south, including river channels and adjacent wetlands covering approximately 1,400,000 ha (Figure 15) (MDBA 2012h). The region includes the Great Darling Anabranch, and ancestral stream tom the west of the LDR itself (Figure 15). The LDR is a system of Basin significance for threatened and recreational species in the Murray – Darling Basin including Murray Cod, Silver Perch and Golden Perch. The LDR supports an important population of Murray Cod (NMCRT 2010). Threatened Freshwater Catfish also occur in the LDR (Ellis et al. 2009).

Most of the flow experienced through the LDR is derived from Northern tributaries of the Barwon-Darling system that originate on the western slopes of the Great Dividing Range in southern QLD and northern NSW (Thoms and Sheldon 2000). These tributaries merge with the Barwon-Darling (mostly upstream of Bourke) before flowing southwest across NSW to the Menindee Lakes system, then south to the confluence between the Darling and Murray Rivers at Wentworth. Historically the flow regime in the Barwon-Darling system was characterised by near-perennial flows (85% of the time), with lotic (flowing water) habitats; and near-annual, in-channel, flow pulses. (Mallen-Cooper and Zampatti 2020). Downstream of Bourke high flow events spill into the Talywalka Creek anabranch system to the east, which may later re-enter the LDR below the Menindee Lakes.

The Barwon-Darling River system flows through predominantly arid and semiarid regions with a catchment area of approximately 650,000 km2, or 60% of the MDB (Thoms and Sheldon 2000). Highest flows in the Barwon-Darling system generally occur in summer-autumn resulting from summer monsoon rain but can also occur as a result of temperate winter storms.

It was recognised as early as 1996 that water resource development in the Northern MDB, including the Barwon-Darling River system, had significantly altered the flow regime of the river by reducing the median annual discharge and dampening flood, resulting in reduced frequency of overbank and within bank flow events (Thoms and Sheldon 2000). There had been a 32% increase in the diversion of flows from the upper Darling River system and a 187% increase in diversion of surface flows (floodplain harvesting) from the Queensland portion of the Darling River catchment for the period 1960 -1994.

More recently, Sheldon (2017) identified an increase in the length of dry spells (i.e. the length of cease to flow events) compared with the previous 10-year period (1990-1999), particularly downstream of Bourke. The increased duration of cease to flow events was expected to impact on water quality and native fish spawning and recruitment due to stratification of standing water bodies, which can induce hypoxic or anoxic conditions in lower parts of the water column and provide conditions conducive to algal blooms in surface waters (Sheldon 2017). Furthermore, hydrologic analysis of observed low flow and Small Fresh events in the Barwon–Darling River system (i.e. < 2,000ML/day) from 1990–2017 suggest a change to the hydrologic behaviour of the Barwon–Darling has occurred since the turn of the Millennium drought (2000 to 2010), (particularly in the mid-sections of the system) reflected in the characteristics of both individual low and fresh flow events, and in the dry spells between events (MDBA 2018a). The analysis determined some individual flow events in the post-2000 period were very heavily attenuated (some events disappearing completely upstream of Brewarrina), with extraction being a heavy contributor to the attenuation of flow.

Currently, flows to the LDR downstream of Menindee Lakes are often constrained by operating rules that restrict flow at Weir 32 (downstream of the Menindee Lake) to a channel capacity of 9,300 ML/d to prevent water loss down the Darling Anabranch. Flows above 20,000 ML/d at Weir 32 may result in inundation of property including houses in the township of Menindee.

Table 18. Characteristics of the flow regime in the Lower Darling River at Weir 32, both natural and post water resource development.

Modelled natural hydrology	Modelled current hydrology (regulated)
dominated by within-channel flows punctuated by small and large floods, with return periods of 1.1 and 5.1 years, respectively	decreased flow variability
flows typically driven by summer monsoonal rainfall in the upper catchments, reaching the LDR in winter-spring	in-channel and Overbank flows less frequent and reduced in magnitude and duration
Bank full or Overbank flooding occurring in approximately 60% of years pre-regulation	flow seasonality has been altered, with higher flows now occurring in summer rather than in spring
cease to flow periods rare (< 5% of the time)	Bank full or Overbank flooding now occurring in < 30% of years

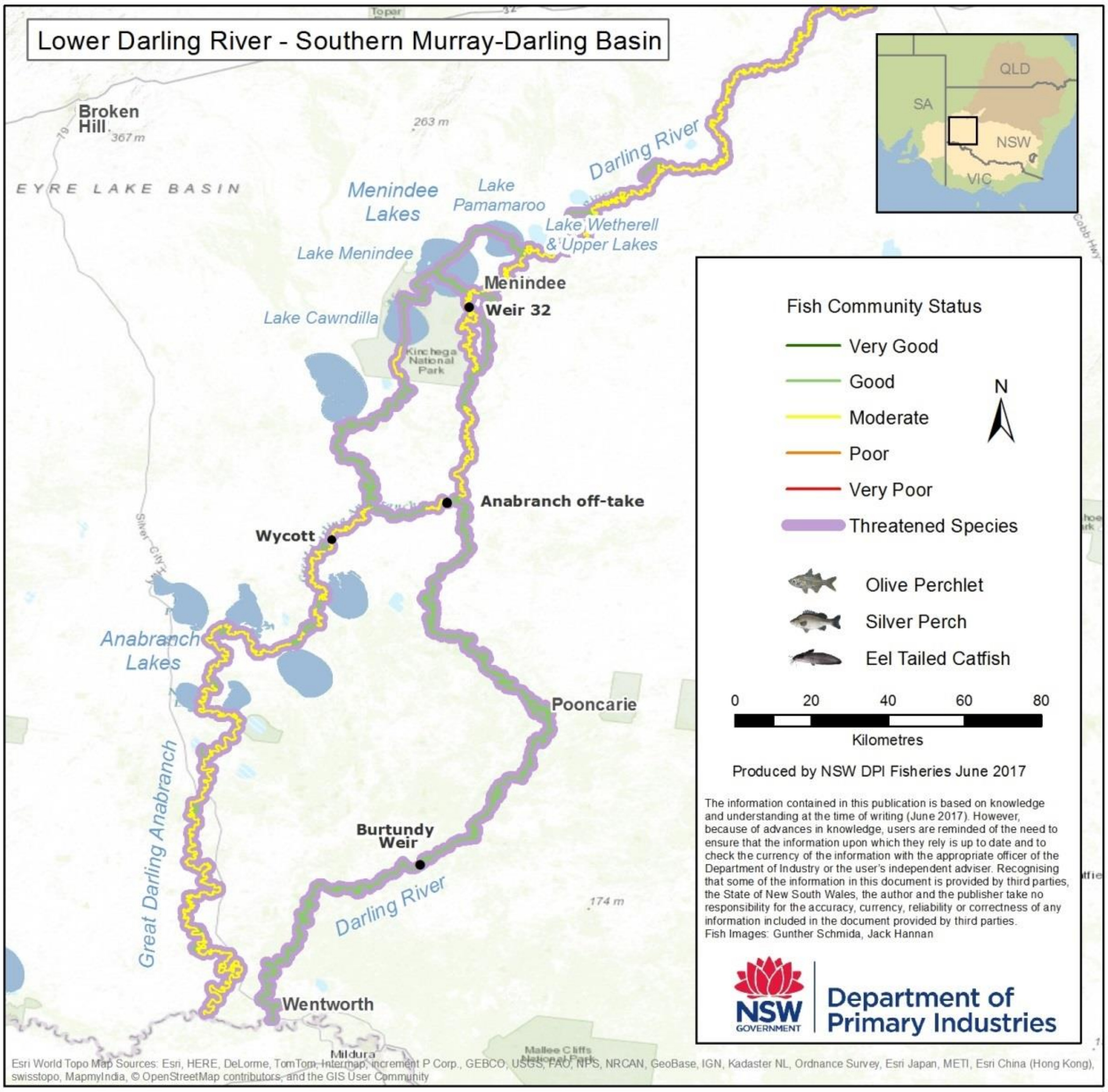

Figure 15. The Lower Darling River system, including Fish Community Status within the NSW Waters of the region and potential distribution of threatened species (NSW DPI 2016a).

Fish community condition

- Prior to the “Millennium Drought” the fish community of the LDR was generally in a good condition, with robust populations of Murray Cod, Golden Perch and native generalist species (Davies et al. 2012).
- Increased water extraction and diversion coupled with pronged drought conditions resulted in series of cease to flow events in the LDR between 2002 and 2010. Fish kills may be experienced during cease to flow periods and upon resumption of flows during summer or autumn (e.g. Ellis and Meredith 2004).
- SRA2 for the period 2008-2010 indicated the condition of the fish community in the lowland zone Darling was in a poor condition, with around half of the predicted native species absent. Biomass was dominated by alien species, and recruitment levels among the remaining native species was poor (Davies et al. 2012).
- Following extensive flooding in 2010-2012, NSW DPI fish community mapping for the Murray identified that the fish community status in the LDR in 2013 was generally in fair-good condition (NSW DPI 2016a) (Figure 15).
- A cohort of Golden perch that were spawned in the Barwon-Darling in 2009-10 entered the Murray River during environmental water delivery (to the Darling Anabranch) and then Darling River floods in 2010-11 (Gilligan 2010; Bogenhuber et al. 2013). Subsequent analysis of natal origin (via otolith micro-chemical analysis) indicated this Darling bred cohort was prominent within Golden perch populations throughout the lower and mid Murray River system (Zampatti et al. 2015).
- Low inflows to the Menindee Lakes from 2013 to 2016 resulted in the LDR contracting to a series of small refuge pools for an extended period (up to 500 days in some lower reaches) from April 2015. Most of the Menindee Lakes dried out, with several fish kills reported in residual lake water and within refuge pools in the LDR in 2015 and 2016.
- Flooding in the Northern MDB resulted in inflows to the Menindee Lakes in late 2016 which transported a cohort of juvenile golden perch from spawning in the northern MDB. Environmental flow delivery from the Menindee Lakes to the LDR in late 2016 supported a strong spawning event by Murray Cod (Sharpe and Stuart 2018b) and facilitated dispersal of juvenile Golden perch from the Menindee Lakes to the Murray River via the LDR and the Darling Anabranch (Sharpe and Stuart 2018b; Stuart and Sharpe 2019).
- From 2018-2020 there were two cease-to-flow events in the LDR, of 524 and 555 consecutive days, respectively. The latter event led to catastrophic declines in water quality and major fish kills at Menindee and along the contracting river channel (Ellis et al. 2021).
- In early 2020 inflows from the northern basin again transported juvenile cohorts of golden perch to the lakes. Environmental flows were later delivered to the LDR to support the recovery of native fish populations in the in 2020-21, building upon concepts and the associated lessons developed from the 2016 environmental flow (Stuart et al 2021).

Indicator sites

For the Basin Plan, the LDR HIS is considered to compromise three distinct areas, or management units:

1. the Menindee Lakes.
2. the Lower Darling River between the Menindee Lakes and the Murray – Darling Rivers confluence at Wentworth (approximately 500 km of river).
3. the Great Darling Anabranch.

The Menindee Lakes

The Menindee Lakes are a series of 11 ephemeral deflation basin lakes connected to the Darling River and covering an area of 4,500 km2 near the town of Menindee (Figure 15). The lakes provide significant tourism and recreation benefits to far-west NSW and are of high environmental and cultural value. Under natural conditions, Menindee Lakes were inundated during high flow events when water levels in the Darling River were higher than the natural sill levels of the creek systems that lead into the lake inlets, with each lake naturally connecting to the Darling River except for Lake Cawndilla (Sinclair Knight Merz 2002; Sharpe 2011). Historically the smaller upper lakes (Malta, Balaka and Bijiji) filled on average every 2 – 3 years, whilst the larger lakes to the south (Tandure, Pamamaroo, Menindee and Cawndilla) filled on average once every 1 – 2 years (Jenkins and Briggs 1997; Sharpe 2011). These larger southern lake systems took a long period to dry, with Lake Menindee taking between 24 – 36 months and Lake Cawndilla usually more than 36 months (Sharpe 2011).

In the 1950s and 1960s the NSW government constructed a series of weir and regulators (the Menindee Lakes Scheme; MLS) to increase storage capacity and manage downstream water requirements (NOW 2010). The MLS today consists of Lakes Wetherell (the impoundment upstream of the Menindee Main Weir and the smaller lakes it encompasses), and the larger lakes Pamamaroo, Menindee and Cawndilla that cover a combined 453 km2 and hold 1,730 GL when full (https://www.waternsw.com.au/supply/visit/menindee-lakes).

The MLS is managed under the Murray – Darling Basin Agreement. Under the Agreement, when the volume stored in the lakes is greater than 640GL the water is managed by the MDBA to supply NSW, Victoria and South Australia (NOW 2010). When volumes fall below 480 GL, all water remaining is managed by NSW to meet the needs of far-west NSW including Broken Hill's water supply and the irrigation needs in the LDR Valley. The Scheme also contributes water to meet the needs of water users and the environment in the NSW and SA Murray Valley (https://www.mdba.gov.au/water-management/infrastructure/menindee-lakes).

Basin Plan flow indicators for the Menindee Lakes (expressed as volume or lake level)

In an assessment of the EWRs for the LDR System (MDBA 2012h) the MDBA suggested five flow indicator targets for each of Lake Menindee and Lake Cawndilla, to promote discussion on the management of the lakes in relation to ecological targets pertaining to vegetation, waterbirds and recruitment opportunities for fish, frogs turtles and invertebrates. Existing operations for Lakes Pamamaroo and Wetherell (including Lakes Tandure, Bijiji, Balaka and Malta) were proposed to be retained to keep water levels as high as possible, allowing these lakes to act as more secure water sources for the biota that inhabit the area and provide drought refuges (MDBA 2012h).

EWRs for lakes Menindee and Cawndilla were described in terms of lake capacity or water level (mAHD) or period of inflow, duration of inundation, and follow up connection requirements. Lake levels were proposed to be reached by filling the lake(s) and then drawing down at a rate consistent with the without-development rate of drawdown. The original MDBA indicators proposed by the MDBA for the Menindee Lakes were (essentially):

1. Retain existing operation of Lakes Pamamaroo and Wetherell (including Lakes Tandure, Bijiji, Balaka and Malta) to allow these lakes to act as more secure water sources for the biota that inhabit the area and provide drought refuges
2. A low-level fill to 56mAHD in Lake Menindee and 53.8 mAHD in Lake Cawndilla in 80% of years. Filling to these levels would result in a depth of approximately 1.5m in each lake and equates to lake volumes of approximately 60GL and 50GL respectively.
3. Fill to 56.5mAHD in Lake Menindee and 54.5mAHD in Lake Cawndilla in 50% of years. Filling to these levels would result in a depth of approximately 1.8m in Lake Menindee and 2.2m in Lake Cawndilla and equates to lake volumes of approximately 116GL and 84GL respectively.
4. Fill to 57.5mAHD in Lake Menindee and 57.5mAHD in Lake Cawndilla in 15% of years. Filling to these levels would result in a depth of approximately 2.8m in Lake Menindee and 4.8m in Lake Cawndilla and equates to lake volumes of approximately 370GL and 370GL respectively.

5. Fill to 58.5mAHD in Lake Menindee and 58.5mAHD in Lake Cawndilla in 9% of years. Filling to these levels would result in a depth of approximately 3.8m in Lake Menindee and 5.8m in Lake Cawndilla and equates to lake volumes of approximately 410GL and 470GL respectively.

Revised fish-specific flow indicators for Menindee Lakes

Revised fish specific EWRs for Lake Menindee and Lake Cawndilla were informed by an improved understanding of the flow and breeding requirements for Flow Pulse and River Specialist species in the Darling and Murray Rivers (Sharpe 2011; Zampatti et al. 2015; Stuart and Sharpe 2017) (**Error! Reference source not found.**). In particular, the recommended EWRs intend to provide regular opportunities for strong recruitment by Flow Pulse Specialists (particularly Golden Perch) in the Menindee Lakes, following flow cued spawning upstream; and for spawning and dispersal by Flow Pulse Specialists and the important Murray Cod population in the LDR channel downstream of the Menindee Lakes.

Key components of the hydrograph identified are labelled for identification in Figure 6. Suggested Flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change.

Table 19. Revised fish-specific flow indicators for the Menindee Lakes (expressed as lake level or connectivity duration).

Flow indicator	Rationale
Connection between Lake Wetherell and the upper lakes (Tandure, Bijiji, Balaka and when possible, Malta) for at least 4 weeks. Triggered by flow >4000 ML/day at Wilcannia, one year out of every successive three-year period. Maximum inter-flow period of 4 years. Followed by drawdown of Lake Wetherell allowing temporary partial or complete disconnection between upper lakes and the Darling River channel. Followed by reconnection between Lake Wetherell and the upper lakes spanning at least 3 weeks. Facilitated via subsequent inflow event (upstream river flows) or managed raising of Menindee Main Weir at least 3 Months after disconnection.	• allow upper lakes to act as productive habitat for the biota that inhabit the area and provide drought refuges • promote nutrient transformation and productivity in the upper lake • promote dispersal and settlement in upper lakes by juvenile Flow Pulse Specialists (Golden perch and Silver Perch) following flow cued spawning events in the Darling River upstream • allow return migration from lakes to riverine habitat by juvenile and adolescent Flow Pulse Specialists, following development period of > 3 months in lakes nursery habitat • promote spawning and dispersal of eggs and larvae for all native species • inundation variability enhances system productivity and in-turn condition of adults and juveniles of most species.

Flow indicator	Rationale
Low levels fill to 56mAHD in Lake Menindee (and associated level of ~ 53.8mAHD in Lake Cawndilla) in 80% of years. Filling to be triggered by upstream flows in the Darling River of a magnitude and duration expected to deliver required inflow volumes for both upper and lower lakes in the system. Begin filling when modelling suggests Darling River flows would have reached sill level (approximately 55-56mAHD) for Lake Menindee. Translucent transfer of a proportion of early flows from the river upstream of the Menindee Lakes to the LDR. Retain water in Lakes Menindee and Cawndilla for at least three months before drawing down at a rate consistent with the without-development rate of drawdown.	• promote nutrient transformation and productivity in the lower lakes and the LDR downstream • promote dispersal and floodplain recruitment of Flow Pulse Specialists in Lakes Menindee and Cawndilla • transfer important flow induced productivity cues and benefits to the LDR. • transfer a proportion of drifting juveniles of Flow Pulse Specialist species to the LDR. • allow dispersal from Lakes Menindee and Cawndilla to downstream riverine habitat by juvenile and adolescent Flow Pulse Specialists following development period of > 3 months in lakes nursery habitat • promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch) and River Specialists in the LDR. • promote spawning and dispersal of eggs and larvae for all native species.
Mid-level fill (or top up) to 56.5mAHD in Lake Menindee and 54.5mAHD in Lake Cawndilla in 50% of years. Filling to be triggered by upstream flows in the Darling River of a magnitude and duration expected to deliver required inflow volumes for both upper and lower lakes in the system. Begin filling when modelling suggests Darling River flows would have reached sill level (approximately 55-56mAHD) for Lake Menindee. Translucent transfer of a proportion of early flows from the river upstream of the Menindee Lakes to the LDR. Retain water in Lakes Menindee and Cawndilla for at least three months before drawing down at a rate consistent with the without-development rate of drawdown.	• promote nutrient transformation and productivity in the Lower lakes and the LDR downstream • promote dispersal and floodplain recruitment of Flow Pulse Specialists in Lakes Menindee and Cawndilla • transfer important flow induced productivity cues and benefits to the LDR • transfer a proportion of drifting juveniles of Flow Pulse Specialist species to the LDR • allow dispersal from lakes Menindee and Cawndilla to downstream riverine habitat by juvenile and adolescent Flow Pulse Specialists following development period of > 3 months in lakes nursery habitat • promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch) and River Specialists in the LDR. • promote spawning and dispersal of eggs and larvae for all native species.

Flow indicator	Rationale
High level fill (or top up) to 58.5mAHD in Lake Menindee and 54.5mAHD in Lake Cawndilla in 10% of years. Filling to be triggered by upstream flows in the Darling River of a magnitude and duration expected to deliver required inflow volumes for both upper and lower lakes in the system. Begin filling when modelling suggests Darling River flows would have reached sill level (approximately 55-56mAHD) for Lake Menindee. Translucent transfer of a proportion of early flows from the river upstream of the Menindee Lakes to the LDR. Retain water in Lakes Menindee and Cawndilla for at least three months before drawing down at a rate consistent with the without-development rate of drawdown.	• promote nutrient transformation and productivity in the lower lakes • promote dispersal and floodplain recruitment of Flow Pulse Specialists Lakes Menindee and Cawndilla (Golden perch and Silver Perch) • transfer important flow induced productivity cues and benefits to the LDR • transfer a proportion of drifting juveniles of Flow Pulse Specialist species to the LDR • promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch) and River Specialists in the LDR • promote spawning and dispersal of eggs and larvae for all native species • inundation enhances system productivity and in-turn condition of adults and juveniles of most species.

Lower Darling-Baaka River

The Lower Darling River channel (LDR) extends for approximately 500km downstream of the Menindee Lakes to the junction of the Darling and Murray rivers at Wentworth.

The LDR has experienced a reduction in the frequency of within-channel Freshes and small floods since the MLS was constructed in the 1960s (Green et al. 1998). Bank full flows are also less frequent and mid-range peaks have halved: flows above 15,000 ML/day now occur in only 30% of years, compared to 60% pre-regulation (Gippel and Blackham 2002). Winter flow variability has also been reduced. The impacts of drought and historic patterns of extractions in the Northern Basin over the last two decades have more recently contributed to higher risk of conditions that can lead to fish deaths during droughts (Vertessy et al. 2019). While historically the Darling River historically experienced occasional cease to flow events, they occurred within a broader flow regime that included regular in-channel flow pulses and overbank floods. This differs from the prevailing flow regime in the last two decades, which has been characterised by protracted periods of low flow punctuated by in-channel flow pulses and fewer overbank flow events (aligned with natural system scale floods in 2011, 2012 and 2016).

Between 2017 and 2020, the Murray-Darling Basin experienced a record drought, culminating in record low river flows and extended cease-to-flow conditions throughout large sections of the Northern Basin and Lower Darling-Baaka River (LDBR). A series of three mass fish kills occurred at Menindee in the summer of 2018/19, where the death of millions of native fish due to declining water quality and reduced connectivity between refugia, captured world-wide attention. Subsequent fish kills occurred along the LDR through 2019 and early 2020 as conditions deteriorated. Fortunately, good flows through the Northern MDB in 2020 saw a return of flow to the LDR and the Menindee Lakes, beginning a long process of recovery for the native fish community.

Basin Plan flow indicators for the Lower Darling-Baaka River (expressed at Weir 32)

Under the Basin Plan, the MDBA proposed five flow indicators for the LDR (expressed at Weir 32 downstream of Menindee) which attempted to strike a balance between desirable flow thresholds, duration and timing with desirable frequency and represented a variable flow regime that was consistent with the “without development” hydrology of the site. These indicators were expected to be sufficient to support life cycle and habitat requirements of native fish including provision of cues for spawning and migration and access to food sources.

The original site-specific flow indicators for the LDR are:

1. 20,000 ML/d for 30 consecutive days between January and December for 20% of years
2. 25,000 ML/d for 45 consecutive days between January and December for 10% of years*
3. 45,000 ML/d for 2 consecutive days between January and December for 10% of years*
4. 7,000 ML/d for 10 consecutive days between January and December for 90% of years
5. 17,000 ML/d for 18 consecutive days between January and December for 40% of years.

* These two flow events are linked. That is, the flow event described is a flow of 25,000 ML/d or more for at least 45 days, including a peak of 45,000 ML or more for at least 2 days. The event is described in this way to reflect the pattern of actual flow events in the Darling and to ensure sufficient volume of flow into the anabranch to water wetlands and floodplain communities.

Revised fish-specific flow indicators for the Lower Darling River HIS

Revised (and additional) fish-specific flow indicators developed for the LDR are presented in Table 20 with rationale for each. The flow indicators described herein for the within-channel elements of the flow regime are recommended to achieve the ecological targets relating to the life cycle and habitat requirements of native fish. In most instances the duration of in-channel flow events necessary for supporting fish outcomes will be lower than those proposed for other elements of the floodplain ecosystem.

Key components of the hydrograph identified are labelled for identification in Figure 6. Suggested Flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change.

Table 20. Revised fish-specific flow indicators for the Lower Darling River HIS (expressed at Weir 32).

Flow indicator	Rationale
Variable Base Flows (BA) of 250 to 2,000 ML/day throughout the year (between within-channel fresh and Overbank events). Cease to flow events during summer should be avoided.	• provide main channel refuge habitat and maintain suitable water quality for all species (except Floodplain Specialists[2]) • allow for the accumulation of allochthonous carbon and vegetation on benches and dry sections of riverbed, which contributes to ecosystem productivity during subsequent higher flow events.
Small Fresh (SF): 2,000 to 7,000 ML/day for at least 10 consecutive days at any time of the year. Provide a minimum of 2 Small Fresh events in high and moderate water availability years and at least one during low water availability years. Maximum inter-flow period of 1 year.	• promote system productivity (inundation of low-lying benches) and in-turn condition of adults and juveniles of most species • contribute to the maintenance of suitable water quality • promote longitudinal connectivity (including with the Murray River) • promote within-channel hydraulic variability to support a diverse range of habitats • promote dispersal of Flow Pulse Specialists.
Annual prolonged and continuous Spring nesting component (SN) from 200 to 9,000 ML/day avoiding rapid drops in water level for at least 14 days every year during October/early November (to be informed by expert understanding of regional spawning season). Rates of rise or fall during the event should not exceed those of historic or modelled "without development" for the season. Maximum inter-flow period of 2 years. May coincide with (OB) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat. Important where river operations to meet irrigation demand cause extreme water level fluctuations which are out of sync with natural patterns and climatic cues.	• support nesting of River Specialists (Murray Cod and Freshwater Catfish) • promote/maintain connectivity and movement of native species (longitudinally and laterally for lower lying off-channel habitats) • maximise habitat availability for all species (except Floodplain Specialists[2]) during Spring when many species breed • support dispersal of eggs and larvae for all native species • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species • potentially inundate in-stream benches and low-lying floodplain wetlands which may provide nursery habitat for Flow Pulse, River Specialists and Generalist species[3] (magnitude and depth dependent).

Flow indicator	Rationale
Large Fresh (LF) from 7,000 to 14,000 ML/day for at least 5 consecutive days in two years out of every successive three-year period, ideally between February and October (not required in years experiencing the Overbank event above). Or Bank full (BF) or Overbank event (OB) >15,200 ML/day for at least 10 consecutive days between August and February at least one year in every four-year period. Maximum inter-flow period of 4 years. Maximum inter-flow period of 3 years. A priming 'spike' may trigger breeding response by Flow Pulse Specialists.	• promote connectivity and movement of native species (longitudinally and laterally into anabranches and low-lying floodplain wetlands)[1] • promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch) • promote downstream dispersal of Flow Pulse Specialist recruits (particularly Golden Perch) exiting the lower Menindee Lakes • inundate in-stream benches and low-lying floodplain wetlands which may provide nursery habitat for Flow Pulse, River Specialists and Generalist species[3] • promote dispersal of eggs and larvae for all native species • flow variability enhances system productivity and in-turn condition of adults and juveniles of most species.
Unregulated Overbank floods (well over 17,000 ML/day for long durations) will be required to address the original flow indicators for the LDR HIS.	• critical to the long-term viability of fish communities due to the ecosystem processes floods promote, the opportunistic potential for large scale floodplain recruitment by many species, and the unobstructed longitudinal and lateral connectivity they facilitate.

[1] The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

[2] Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

[3] Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

The Darling Anabranch

Site description

The Darling Anabranch is ephemeral, flowing through to the Murray River under larger flood events. The Anabranch incorporates the main-channel, substantial floodplain and around 14 floodplain lakes (large floods could potentially connect additional systems). Many of the lakes can hold water for extended periods of time after significant flood events (e.g. Popiltah Lake can retain water for up to five years), whilst others will begin to drain as soon as floodwaters recede (King and Green 1993). Prior to development of the MLS the uppermost reaches of the Darling Anabranch flowed as often as two years out of three, although flows large enough to reach Nearie Lake, (the most downstream 'managed' Anabranch Lake) probably occurred in only 45% of years (Thoms et al. 2000) (**Error! Reference source not found.**). Under current conditions the Darling Anabranch begins to flow when flows in the Darling River exceed 10,000 ML/d at Weir 32.

Fish specific flow indicators for the Darling Anabranch (expressed at Wycott)

Under the Basin Plan, site-specific EWRs were not developed for indicator sites in the Darling Anabranch. We present here a series of Fish-specific EWRs for the Darling Anabranch (expressed at Wycott in the upper reaches of the system) based on the species present, their ecological requirements and assessment of historic flow patterns. Fish-specific flow indicators developed for the Darling Anabranch expressed at Wycott are presented in Table 21 with rationale for each.

Key components of the hydrograph identified are labelled for identification in Figure 6. Suggested Flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change.

Table 21. Revised fish-specific flow indicators developed for the Darling Anabranch (expressed at Wycott).

Flow indicator	Rationale
Cease to flow periods in the Anabranch will prevail outside of the recommended flow events above	• wetting-drying regimes in ephemeral systems promote sediment and nutrient transformation, providing a 'boom' in productivity upon inundation • terrestrial plants provide temporary breeding and foraging for a range of species and life history stages. They also provide cover from predators and residual carbon source during breakdown (wet phase)
Large Fresh (LF) event of 800-2,000 ML/day for at least 70 consecutive days between September and May, 3-5 events in each 10-year period. Connectivity with Murray River for >30 days should be provided with a protracted recession spanning at least 15 days to promote exit to the Murray River. Maximum inter-flow period of 7 (ideally 4) years. Can be delivered from directly Lake Cawndilla or indirectly from the LDR (requiring maintained flows greater than ~14,000 ML/day at Weir 32 to meet the criteria above). To be triggered by flows in the Barwon-Darling system and inflows to the Menindee Lakes. Will have a high priority following flow events in	• promote system productivity and in-turn condition of adults and juveniles of most species • promote longitudinal connectivity (including with the Murray River) • promote dispersal of Flow Pulse Specialist recruits (particularly Golden Perch) exiting Lake Cawndilla • inundate in-stream benches and low-lying floodplain wetlands which may provide nursery habitat for Flow Pulse Specialists, River Specialists as well as Generalist species[3].

Flow indicator	Rationale
the Barwon-Darling system that induce spawning by Flow Pulse Specialists and transport of young to the Menindee Lakes, and in particular Lake Cawndilla (i.e. floodplain recruitment). This flow component may require large volumes of environmental water and will best be achieved in conjunction with natural flow events in the Barwon-Darling River that result in substantial inflows to the Menindee Lakes.	
Overbank event (OB) of >3,000 ML/day (Bank full or Overbank) for at least 60 consecutive days between September and April at least 1 year (ideally 2) in every 10-year period. Maximum inter-flow period of 10 (ideally 7) years. Likely to only occur during natural flood events.	• promote connectivity and movement of native species (longitudinally and laterally into anabranches and low-lying floodplain wetlands)1 • promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch) from the Darling to Murray River systems • inundate low lying floodplain wetlands which may provide floodplain recruitment nursery habitat for Flow Pulse Specialists • promote dispersal of eggs and larvae for all native species • flow variability enhances system productivity and in-turn condition of adults and juveniles of most species.
If (OB) or (LF) events occur through Spring, provide a continuous Spring nesting component (SN) from 800 to 1,500 ML/day. Avoid rapid drops in water level for at least 14 days during October/early November (informed by local fish ecologists understanding of peak nesting timing). Rates of rise or fall during the event should not exceed those of historic or modelled “without development” for the season. Could be delivered from Lake Cawndilla directly or indirectly from the LDR (requiring maintained flows greater than ~14,000 ML/day at Weir 32).	• intermittent opportunity for nesting of River Specialists (Murray Cod and Freshwater Catfish) that may inhabit the Darling Anabranch • promote/maintain connectivity and movement of native species (longitudinally and laterally for lower lying off-channel habitats) • maximise habitat availability for all species (except Floodplain Specialists2) • support dispersal of eggs and larvae for all native species • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species.

[1] The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

[2] Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

[3] Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

Murrumbidgee River Catchment

Site description

The Murrumbidgee River source waters are in the northern regions of Kosciuszko National Park and the Monaro High Plains in New South Wales. The river flows north through the Australian Capital Territory before heading west through lowland floodplains. Downstream of Hay it fans out into the Lower Murrumbidgee Floodplain before reaching its confluence with the Murray River near Boundary Bend. The natural flow regime of the Murrumbidgee River was historically variable, characterised by low average flows in summer and autumn and higher average flows in winter and spring driven by snow melt and rainfall in the upper catchment (Page et al. 2005). Today, the Murrumbidgee River is highly regulated with an average diversion rate of 53% (2,257 GL/year) of all available water (CSIRO 2008b). his has considerably altered the flow regime in terms of volume, seasonal patterns of discharge, magnitude and frequency of floods, and frequency and duration of floodplain inundation (CSIRO 2008b).

The Murrumbidgee provides a diverse range of habitats that support several federally listed endangered fish species including Trout Cod, Murray Cod, Silver Perch, and Macquarie Perch. The Murrumbidgee River downstream of Burrinjuck Dam lies within the EEC of the lower Murray River, which provides endangered status to all native fish and other aquatic biota within its boundaries (NSW DPI 2007a). The section from Wagga to Hay supports an 'important' population of Murray Cod (NMCRT 2010). Many factors have contributed to the degradation of fish communities in the Murrumbidgee catchment; including habitat degradation, pollution, reduced environmental flows, and barriers to migration, overfishing and the proliferation of non-native species (Gilligan 2005).

The Mid Murrumbidgee Wetlands, Lower Murrumbidgee River channel and the Lower Murrumbidgee Floodplain are used as HIS under the Basin Plan (Figure 7) for which the MDBA proposed 3, 5 and 6 flow indicators respectively. Flow indicators for the Lower Murrumbidgee River channel are expressed at Balranald, and the Mid Murrumbidgee Wetlands HIS at Narrandera. Flow indicators for the lower Murrumbidgee Floodplain are achieved through a combination of regulated releases and unregulated events from Maude and Redbank Weirs. These flow indicators represent an amalgam of information within existing literature and vegetation inundation hydrodynamic modelling data, checked against analysis of modelled without development and baseline flow data.

Refined fish-specific flow indicators developed for the Murrumbidgee catchment HIS are presented below along with rationale for each.

Mid Murrumbidgee River Wetlands ('Mid-Bidgee Wetlands')

Site description

The Mid-Bidgee Wetlands are an assemblage of approximately 1,600 lagoons and billabongs located on the lowland floodplain of the Murrumbidgee River between Wagga Wagga and Carrathool, covering an area of around 45,000 ha (MDBA 2012i) (Figure 16). Prior to the Millennium Drought, most wetlands through the Mid-Bidgee Wetlands were semi-permanent, with others exhibiting fluctuating seasonal water levels that rarely resulted in complete drying (Chessman 2003). The wetlands support a range of organisms listed as threatened under both Commonwealth and state legislation.

Riparian and wetland vegetation communities that provide drought refuge also play an important role in the functioning of the river ecosystems and are critical to several fish species (Gilligan 2005).

River regulation has significantly reduced the magnitude of the smaller, relatively frequent floods in the Murrumbidgee (Read 2001). These changes to flows have had a significant impact on the hydrology of the Mid-Bidgee Wetlands. Wetlands influenced by weir pools are now almost permanently inundated, while the inundation frequency has halved for wetlands between Gundagai and Hay, with river connections higher than the level of irrigation flows (Frazier and Page 2006). At the time of writing, a range of capacity constraints limited the extent to which water levels in the

Murrumbidgee River could be increased, with concerns regarding third party impacts at levels above approximately 20,000 ML (Wassens et al. 2014) (Table 22).

Table 22. Characteristics of the natural and post regulation flow regime in the Murrumbidgee River downstream of Narrandera.

Modelled natural hydrology	Modelled current hydrology (regulated)
Highly variable	decreased flow variability
Bank full or Overbank flooding every 1-2 years (usually late winter-Spring, rarely at other times of the year), with larger flood events experienced every ~ 5 years	Large in-channel and Overbank flows less frequent and reduced in magnitude
Large and small in-channel Freshes occurred anytime throughout the year but most frequently between May and December	Smaller in-channel flows and Base Flows are now a regular feature of the river year round
Generally lower flows in summer-autumn	Substantial reduction in the number of small floods in summer and reduction in the number of large floods.
	Higher summer - autumn in-channel flows, representing a seasonal reversal in flow patterns

Fish community condition

- SRA2, for the period 2008-2010, indicated the condition of the fish community in the lowland zone Murrumbidgee was in a Very Poor condition, with no evidence for recruitment by Golden perch (Davies et al. 2012).
- Golden perch spawning in the Carrathool and Narrandera reaches of the Murrumbidgee River associated with a river level rise were associated with the delivery of Commonwealth environmental water in 2013-14 (Wassens et al. 2014).
- Delivery of Commonwealth environmental water to off-channel wetland habitats in the Mid Murrumbidgee during 2013-14 provided key spawning areas for several small-bodied native species (e.g. Australian Smelt, Carp Gudgeon) (Wassens et al. 2014).
- NSW DPI fish community mapping for the Murrumbidgee River identifies that the fish community status is generally in Poor condition except for sections of (Figure 16) (NSWDPI 2016a).
- NSW fish community status mapping identifies that the fish condition of the Murrumbidgee from its junction with the Tumut River downstream to Hay ranges from moderate to very poor. The reach between Wagga and Narrandera were assessed as Moderate, whilst the fish community condition downstream of Hay was generally in ‘poor’ condition (Figure 16) (NSW DPI 2016a).
- Hypoxic blackwater conditions that arose during the 2010-11 and 2016 floods had a negative impact on the native fish communities in the Murrumbidgee River, (Commonwealth Environmental Water Office, 2017).
- Wetland fish communities across the Murrumbidgee remain in poor condition and are dominated by abundant generalist species while more sensitive floodplain specialist species are typically absent (Wassens et al. 2018).

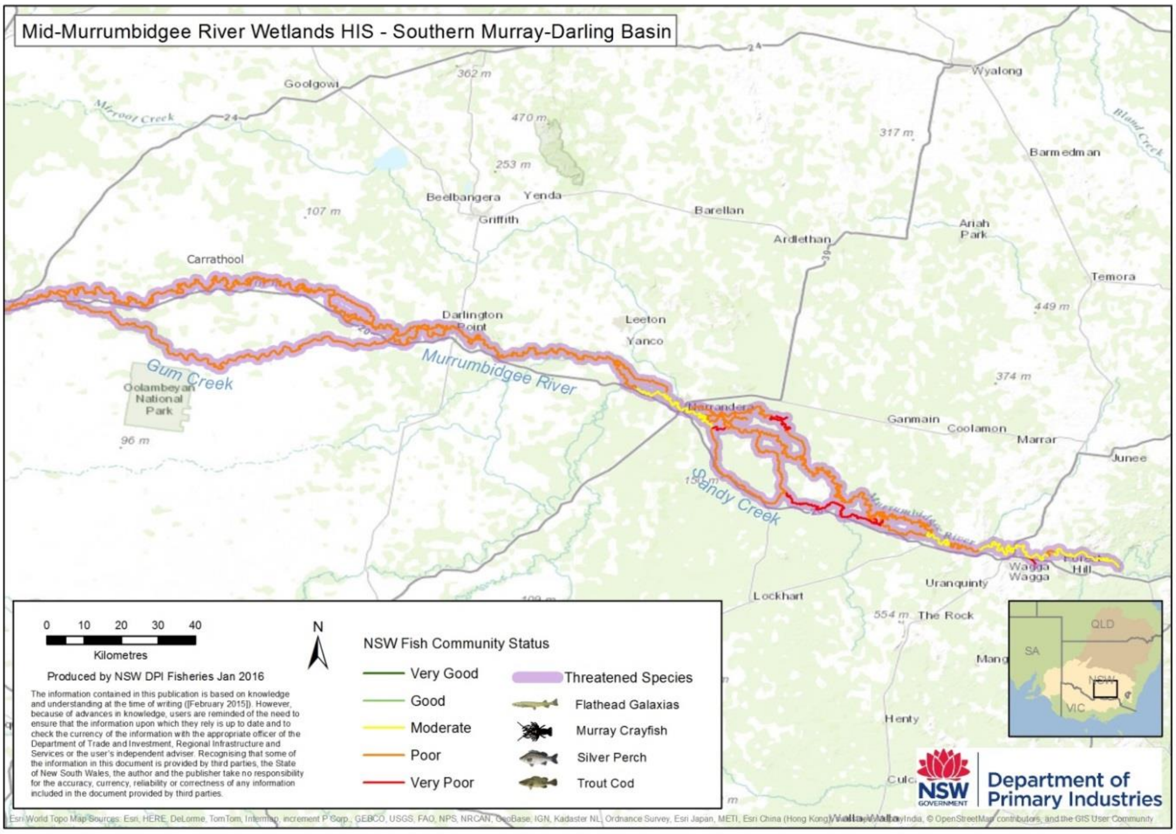

Figure 16. The Mid Murrumbidgee Wetlands HIS, including Fish Community Status in streams within the region (where available) and potential distribution of threatened species (NSW DPI 2016a).

Basin Plan flow indicators for the Mid Murrumbidgee Wetlands HIS

Site-specific flow indicators for the Mid-Bidgee Wetlands HIS are expressed at Narrandera on the Murrumbidgee River, which generally represents flow through the mid-section of the Murrumbidgee system. Under the Basin Plan the MDBA proposed five flow indicators for Mid-Bidgee Wetlands which represents an amalgam of information within existing literature and vegetation inundation hydrodynamic modelling data, checked against analysis of modelled without development and baseline flow data. Flow indicators described for the Bank full and Overbank elements of the flow regime primarily attempted to strike a balance between desirable flow threshold, duration and timing with desirable frequency and represent a variable flow regime that is consistent with the "without development" hydrology of the site. It is intended that these flows are indicative of water requirements for native fish populations within a broader reach of the Mid-Bidgee Wetlands and will improve outcomes for native fish at a broader scale.

The original site-specific flow indicators for the Mid-Bidgee Wetlands were:

1. 26,850 ML/d for a duration of 45 days between July and November between 20 to 25% of years
2. 26,850 ML/d for 5 consecutive days between June and November between 50 to 60% of years
3. 34,650 ML/d for 5 consecutive days between June and November between 35 to 40% of years
4. 44,000 ML/d for 3 consecutive days between June and November between 30 to 35% of years
5. 63,250 ML/d for 3 consecutive days between June and November between 12 to 15% of years.

Revised fish-specific flow indicators for the Mid-Bidgee Wetlands

Revised (and additional) fish-specific flow indicators developed for the Mid-Bidgee Wetlands HIS are presented in Table 23 along with rationale for each. The flow indicators described herein for the within-channel elements of the flow regime are recommended to achieve the ecological targets relating to the life cycle and habitat requirements of native fish. In most instances the duration of in-channel flow events necessary for supporting fish outcomes will be lower than those proposed for other elements of the floodplain ecosystem.

Key components of the hydrograph identified are labelled for identification in Figure 6. Suggested Flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change.

Table 23. Revised fish-specific flow indicators for the Mid Murrumbidgee Wetlands HIS (expressed on the Murrumbidgee River at Narrandera).

Flow indicator	Rationale
Variable Base Flows (BA) of 230-4,000 ML/day throughout the year (between within-channel fresh and Overbank events). Cease to flow events should be avoided.	• provide main channel refuge habitat, longitudinal connectivity and maintain suitable water quality for all species (except Floodplain Specialists[2]) • allow for the accumulation of allochthonous carbon and vegetation on benches and dry sections of riverbed, which contributes to ecosystem productivity during subsequent higher flow events.
Small Fresh (SF): 4,000-14,000 ML/day for at least 10 consecutive days. Ideally between October and April but can occur anytime. Provide a minimum of 2 Small Fresh events in high and moderate water availability years and at least one during low water availability years. Maximum inter-flow period of 1 year.	• contribute to the maintenance of suitable water quality • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species.
Annual prolonged and continuous Spring nesting component (SN) from 1,000-14,000 ML/day avoiding rapid drops in water level for at least 14 days every year during October/early November (to be informed by expert understanding of regional spawning season). Rates of rise or fall during the event should not exceed those of historic or modelled "without development" for the season. Maximum inter-flow period of 2 years. May coincide with (OB), (BF) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat. Important where river operations to meet irrigation demand cause extreme water level fluctuations	• support nesting of River Specialists (e.g. Murray Cod, Trout Cod and Freshwater Catfish) • promote/maintain connectivity and movement of native species longitudinally • increase habitat availability for all species (except Floodplain Specialists[2]) during Spring when many species breed • support dispersal of eggs and larvae for all species • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species.

Flow indicator	Rationale
which are out of sync with natural patterns and climatic cues.	
Large Fresh (LF) from 14,000-38,000 ML/day for at least 5 consecutive days in two years out of every successive three-year period (not required in years experiencing the Overbank event above). Ideally between August and November but may also occur in summer. Maximum inter-flow period of 2 years. A priming 'spike' may trigger breeding response by Flow Pulse Specialists. Or Bank full (BF) or Overbank event (OB) >38,000 ML/day for at least 10 consecutive days between August and February at least one year in every three-year period. Maximum inter-flow period of 3 years.	• promote connectivity and movement of native species longitudinally and laterally into anabranches and floodplain wetlands[1] • promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch), support habitat for Floodplain Specialists[2] • inundate in-stream benches and low-lying Floodplain wetlands which may provide nursery habitat for Flow Pulse, River and Floodplain Specialists[3] • promote within-channel hydraulic variability to support a diverse range of habitats and enhance system productivity (and in-turn condition of adults and juveniles of most species) • promote dispersal of eggs and larvae for all species
Large unregulated Overbank floods (well over 40,000 ML/day) for long durations will be required to address all the original flow indicators for the Mid-Bidgee Wetlands HIS.	• critical to the long-term viability of fish communities due to the ecosystem processes floods promote, the opportunistic potential for large scale floodplain recruitment by many species, and the unobstructed longitudinal and lateral connectivity they facilitate.

[1] The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

[2] Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

[3] Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

The Lower Murrumbidgee River Floodplain ('Lowbidgee')

Site description

The Lowbidgee extends from Maude Weir to Balranald and contains the largest complex of wetlands in the Murrumbidgee system (MDBA 2012j). The floodplain is considered an area of national and international significance through the presence of protected waterbird species. The Lowbidgee floodplain historically received considerable inundation each year with

The Lowbidgee can be considered to comprise four management units based on ecologic and hydrologic characteristics. These are the Nimmie–Caira, Redbank, Murrumbidgee and Fiddlers–Uara creek systems (Figure 17**Error! Reference source not found.**) (MDBA 2012j). Prior to river regulation the Lowbidgee floodplain received considerable inundation each year with Overbank flows in winter and Spring maintaining over 200,000 ha of lignum, black box and river red gum wetland complexes (Kingsford and Thomas 2001).

Two fish species listed as 'vulnerable' under NSW or federal legislation have been recorded in the Lowbidgee in recent years: Silver Perch and Murray Cod. Historically the Lowbidgee supported several threatened small-bodied Floodplain Specialists (such as Southern Purple-spotted Gudgeon and Flat-headed Galaxias) but these have not been detected since the 1970s. The NSW Murrumbidgee (Wagga to Hay) Murray Cod population is identified as important, based on 'scale, population size/integrity, regional importance (and) quality fish community' (NMCRT 2010).

The Murrumbidgee River naturally experienced lower flows in summer and autumn and higher flows in winter and spring. River regulation has significantly reduced the magnitude of the smaller, relatively frequent floods in the Murrumbidgee (Read 2001). **Error! Reference source not found.** describes some of the key characteristics of the pre and post regulation flow regime in the Murrumbidgee River downstream of Maude Weir.

Table 24. Characteristics of the natural and post regulation flow regime in the Murrumbidgee River downstream of Maude.

Modelled natural hydrology	Modelled current hydrology (regulated)
Variable	decreased flow variability
Bank full or Overbank flooding every 1-2 years (usually late winter-Spring, rarely at other times of the year), with larger flood events experienced approximately every 5 years	Large in-channel and Overbank flows less frequent and reduced in magnitude
Large and small in-channel Freshes occurred anytime throughout the year but most frequently between May and December	Smaller in-channel flows and Base Flows are now a regular feature of the river year round
Generally lower flows in summer-autumn	Substantial reduction in the number of small floods in summer and reduction in the number of large floods.

Fish community condition

- SRA2, for the period 2008-2010, indicated the condition of the fish community in the lowland zone Murrumbidgee (within which the Lowbidgee is located) was in a Very Poor condition, with no evidence for recruitment by Golden perch (Davies et al. 2012).
- Environmental watering in the Lowbidgee in 2013-14 resulted in strong recruitment by several small-bodied native fish species on the Lowbidgee floodplain. Although Carp spawning was also detected on the floodplain in response to the environmental watering, recruitment was limited (Wassens et al. 2014).
- NSW fish community status mapping identifies that the fish condition in much of the Lowbidgee is in 'poor' condition (Figure 17) (NSW DPI 2016a).
- Hypoxic blackwater conditions that arose during the 2010-11 and 2016 floods had a negative impact on the native fish communities in the Murrumbidgee River, (Commonwealth Environmental Water Office, 2017).

- Wetland fish communities across the Murrumbidgee remain in poor condition and are dominated by abundant generalist species while more sensitive floodplain specialist species are typically absent (Wassens et al. 2018).
- Spawning and recruitment of golden perch within the Lowbidgee has been detected in conjunction with high flow events and environmental flow deliveries since 2018 (Sharpe 2018; Kopf et al. 2019; Whiterod and Gannon 2020).

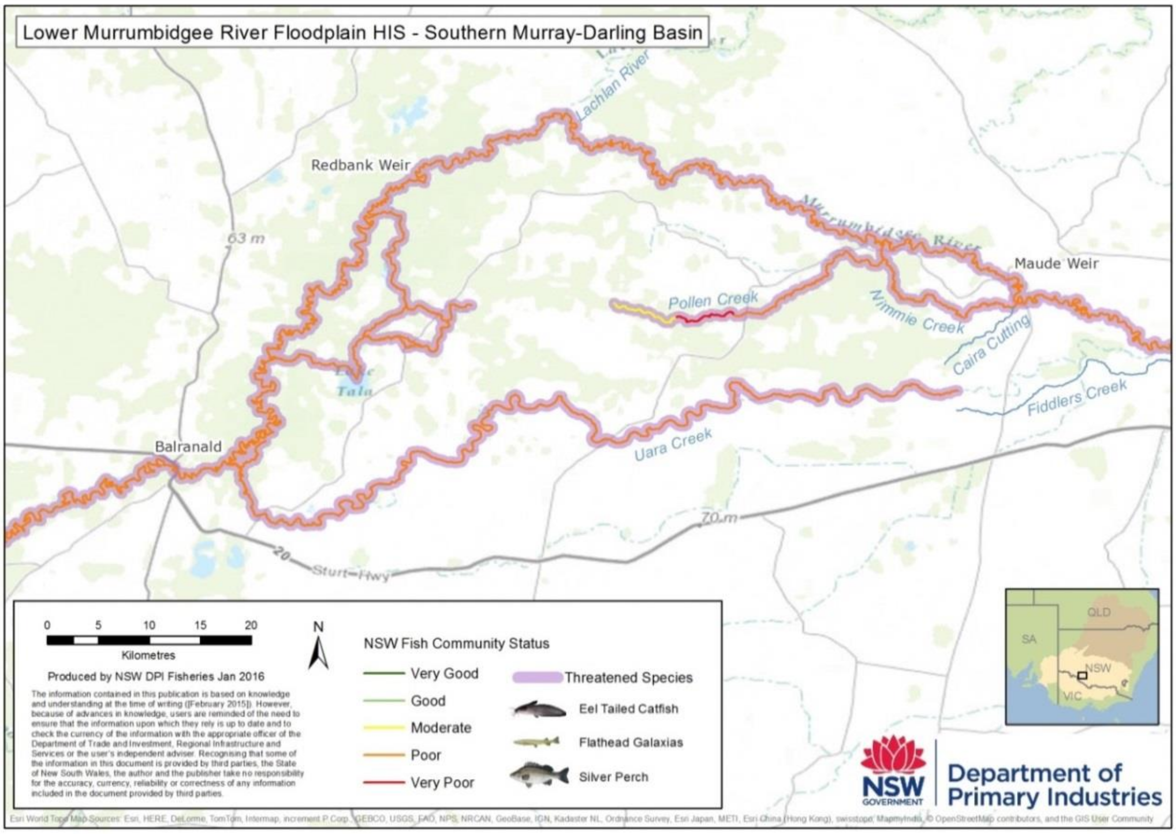

Figure 17. The Lower Murrumbidgee River Floodplain HIS, including Fish Community Status in streams within the region (where available) and potential distribution of threatened species (NSW DPI 2016a).

Basin Plan flow indicators for the Lowbidgee HIS

Site-specific flow indicators are achieved through a combination of regulated releases and unregulated events from Maude and Redbank Weirs (Figure 17). Under the Basin Plan the MDBA proposed six flow indicators for the Lowbidgee, which represent an amalgam of information within existing literature and vegetation inundation hydrodynamic modelling data, checked against analysis of modelled without development and baseline flow data. Flow indicators for the Bank full and Overbank elements of the flow regime were primarily based on the water requirements of flood dependent vegetation communities and waterbirds are expected to be sufficient to support life cycle and habitat requirements of native fish, including provision of cues for spawning and migration and access to food sources.

The original site-specific flow indicators for the Lowbidgee expressed at Maude Weir were:

1. Total inflow 175 GL between July and September between 70 to 75% of years
2. Total inflow 270 GL between July and September between 60 to 70% of years
3. Total inflow 400 GL between July and October between 55 to 60% of years
4. Total inflow 800 GL between July and October between 40 to 50% of years
5. Total inflow 1,700 GL between July and November between 20 to 25% of years

6. Total inflow 2,700 GL between May and February between 10 to 15% of years.

Revised fish-specific flow indicators for the Lower Murrumbidgee HIS

Revised fish-specific flow indicators developed for the Lowbidgee HIS are presented in Table 25 with rationale for each. The flow indicators described for the within-channel elements of the flow regime are recommended to achieve the ecological targets relating to the life cycle and habitat requirements of native fish. In most instances the duration of in-channel flow events necessary for supporting fish outcomes will be lower than those proposed for other elements of the floodplain ecosystem.

Key components of the hydrograph identified are labelled for identification in Figure 6. Suggested Flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change.

Table 25. Revised fish-specific flow indicators for the Lower Murrumbidgee River Floodplain HIS expressed at downstream Maude Weir.

Flow indicator	Rationale
Variable Base Flows (BA) of 170-2,500 ML/day throughout the year (between within-channel fresh and Overbank events). Cease to flow events should be avoided.	• provide main channel refuge habitat, longitudinal connectivity and maintain suitable water quality for all species (except Floodplain Specialists[2]) • allow for the accumulation of allochthonous carbon and vegetation on benches and dry sections of riverbed, which contributes to ecosystem productivity during subsequent higher flow events.
Small Fresh (SF): 2,500 to 6,000 ML/day for at least 10 consecutive days. Ideally between October and April but can occur anytime. Provide a minimum of 2 Small Fresh events in high and moderate water availability years and at least one during low water availability years. Maximum inter-flow period of 1 year.	• contribute to the maintenance of suitable water quality • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species
Annual prolonged and continuous Spring nesting component (SN) from 600-6,000 ML/day avoiding rapid drops in water level for at least 14 days every year during October/early November (to be informed by expert understanding of regional spawning season). Rates of rise or fall during the event should not exceed those of historic or modelled "without development" for the season. Maximum inter-flow period of 2 years. May coincide with (OB), (BF) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat.	• support nesting of River Specialists (e.g. Murray Cod, Trout Cod and Freshwater Catfish) • promote/maintain connectivity and movement of native species longitudinally • increase habitat availability for all species (except Floodplain Specialists[2]) during Spring when many species breed • support dispersal of eggs and larvae for all species • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species

Important where river operations to meet irrigation demand cause extreme water level fluctuations which are out of sync with natural patterns and climatic cues.	
Large Fresh (LF) from 6,000-13,000 ML/day for at least 5 consecutive days in two years out of every successive three-year period (not required in years experiencing the Overbank event above). Ideally between August and November but may also occur in summer. Maximum inter-flow period of 2 years. A priming 'spike' may trigger breeding response by Flow Pulse Specialists. Or Bank full (BF) or Overbank event (OB) >13,000 ML/day for at least 10 consecutive days between August and February at least one year in every three-year period. Maximum inter-flow period of 3 years.	• promote connectivity and movement of native species longitudinally and laterally into anabranches and floodplain wetlands[1] • promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch), support habitat for Floodplain Specialists[2]. • inundate in-stream benches and low-lying Floodplain wetlands which may provide nursery habitat for Flow Pulse, River and Floodplain Specialists[3]. • promote within-channel hydraulic variability to support a diverse range of habitats and enhance system productivity (and in-turn condition of adults and juveniles of most species) • promote dispersal of eggs and larvae for all species.
Large unregulated Overbank floods (well over 15,000 ML/day) for long durations will be required to address the original flow indicators for the Lower Murrumbidgee Floodplain HIS.	• critical to the long-term viability of fish communities due to the ecosystem processes floods promote, the opportunistic potential for large scale floodplain recruitment by many species, and the unobstructed longitudinal and lateral connectivity they facilitate.

[1] The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

[2] Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

[3] Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

Lower Murrumbidgee River

Site description

The lowland section of the Murrumbidgee River from Wagga Wagga downstream to Balranald has a well-defined meandering channel and provides a range of aquatic habitats (Figure 18) (MDBA 2012k). The Lower Murrumbidgee River experiences limited impacts from thermal pollution and maintains a flow seasonality close to natural resulting in connectivity between the Murray River and upstream communities in the Murrumbidgee, albeit with greatly reduced flow magnitudes (Hillman 2004). The Murrumbidgee Murray Cod population is identified as important, based on the population size/integrity and regional importance (NMCRT 2010).

The Murrumbidgee River naturally experienced lower flows in summer and autumn and higher flows in winter and Spring. River regulation has significantly reduced the magnitude of the smaller floods in the Murrumbidgee (Read 2001) (**Error! Reference source not found.**).

Table 26. Characteristics of the natural and post regulation flow regime in the Murrumbidgee River downstream of Wagga Wagga.

Modelled natural hydrology	Modelled current hydrology (regulated)
Variable flow regime	decreased flow variability
Bank full or Overbank flooding every 1-2 years (usually late winter-Spring, rarely at other times of the year), with larger flood events experienced approximately every 5 years	Large in-channel and Overbank flows less frequent and reduced in magnitude
large and small in-channel Freshes occurred anytime throughout the year but most frequently between May and December	Smaller in-channel flows and Base Flows are now a regular feature of the river year round
Generally lower flows in summer-autumn	Substantial reduction in the number of small floods in summer, reduction in the number of large floods.
	Higher summer - autumn in-channel flows, representing a seasonal reversal in flow patterns

Fish community condition

- SRA2, for the period 2008-2010, indicated the condition of the fish community in the lowland zone Murrumbidgee was in a Very Poor condition, with no evidence for recruitment by Golden perch (Davies et al. 2012).
- Delivery of Commonwealth environmental water to floodplain habitats in the Lower Murrumbidgee during 2013-14 also contributed to spawning and larval fish survival by Murray Cod (and possibly Trout Cod) and small-bodied native species (e.g. Australian Smelt, Carp Gudgeon) (Wassens et al. 2014).
- NSW fish community status mapping identifies that the fish condition in much of the Murrumbidgee downstream of Hay is in 'poor' condition (Figure 18) (NSW DPI 2016a).
- Hypoxic blackwater conditions that arose during the 2010-11 and 2016 floods had a negative impact on the native fish communities in the Murrumbidgee River, (Commonwealth Environmental Water Office, 2017).
- Wetland fish communities across the Murrumbidgee remain in poor condition and are dominated by abundant generalist species while more sensitive floodplain specialist species are typically absent (Wassens et al. 2018).
- Spawning by Murray cod, golden perch and silver perch has been detected in the Murrumbidgee channel in most years from 2014-2019, but recruitment has generally been poor, contribution to aging populations (Wassens et al. 2020).

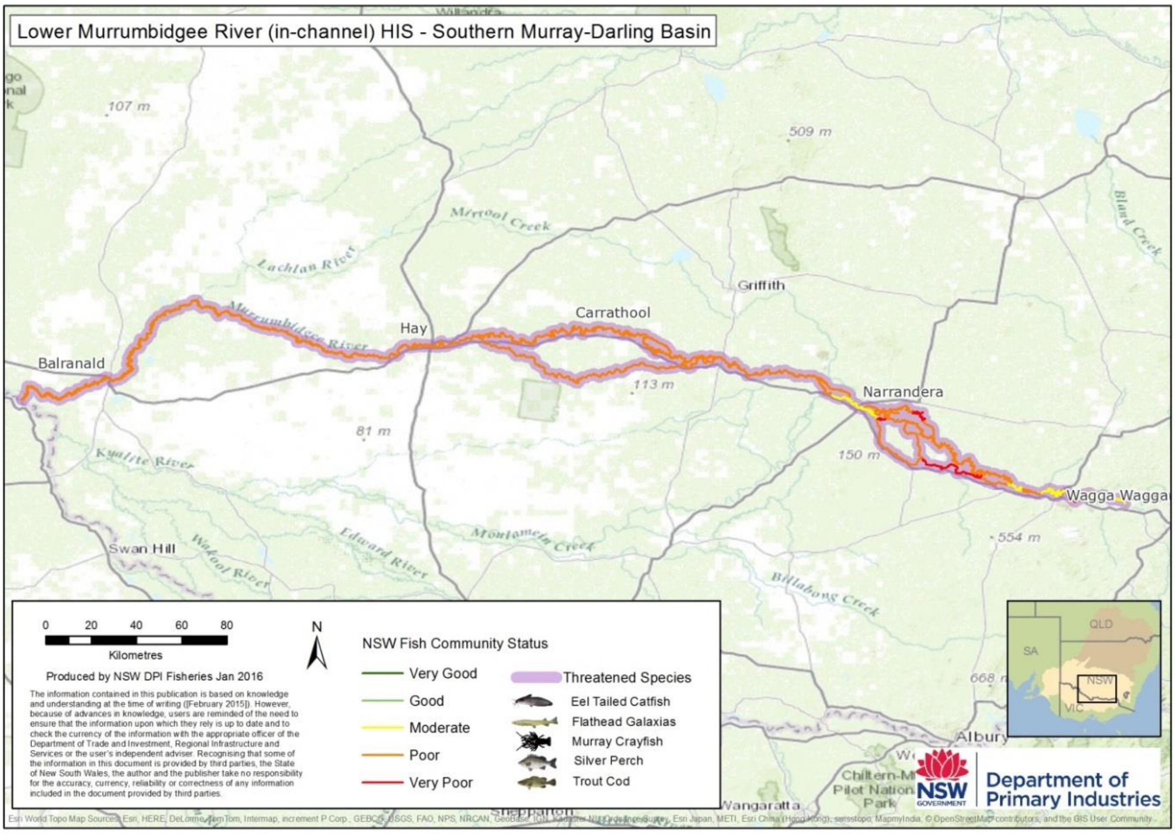

Figure 18. The Lower Murrumbidgee River HIS, including Fish Community Status in streams within the region (where available) and potential distribution of threatened species (NSW DPI 2016a).

Basin Plan flow indicators for the Lower Murrumbidgee River in-channel HIS

Site-specific flow indicators for the Lower Murrumbidgee River (in-channel) HIS are expressed at Balranald on the Murrumbidgee River, which generally represents flow through the lower section of the Murrumbidgee system (i.e. to the end of the system) and reflect flow magnitudes for upstream sites included in this document. Under the Basin Plan, the MDBA proposed three flow indicators for Lower Murrumbidgee River Channel which focused primarily on the base flow elements of the flow regime necessary to maintain connectivity in the lower sections of the Murrumbidgee, whilst recognising the additional importance of Freshes for sustaining healthy populations of several key native large-bodied fish species.

The original site-specific flow indicators for the Lower Murrumbidgee River were:

1. 1,100 ML/d for 25 consecutive days between December and May for 58% of years
2. 4,500 ML/d for 20 consecutive days between October and December for 54% of years
3. 3,100 ML/d for 30 consecutive days between October and March for 55% of years.

Revised fish-specific flow indicators Lower Murrumbidgee River in-channel HIS

Revised fish-specific flow indicators developed for the Lower Murrumbidgee River (in-channel) HIS are presented in **Error! Reference source not found.** along with rationale for each. The flow indicators described for the within-channel elements of the flow regime are recommended to achieve the ecological targets relating to the life cycle and habitat requirements of native fish. In most instances the duration of in-channel flow events necessary for supporting fish outcomes will be lower than those proposed for other elements of the floodplain ecosystem.

Key components of the hydrograph identified are labelled for identification in Figure 6. Suggested Flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change.

Table 27. Revised fish-specific flow indicators for the Lower-Murrumbidgee in-channel HIS (expressed at Balranald).

Flow indicator	Rationale
Variable Base Flows (BA) of 170-2,500 ML/day throughout the year (between within-channel fresh and Overbank events). Cease to flow events should be avoided.	• provide main channel refuge habitat, longitudinal connectivity and maintain suitable water quality for all species (except Floodplain Specialists2) • allow for the accumulation of allochthonous carbon and vegetation on benches and dry sections of riverbed, which contributes to ecosystem productivity during subsequent higher flow events.
Small Fresh (SF): 2,500-6,000 ML/day for at least 10 consecutive days. Ideally between October and April but can occur anytime. Provide a minimum of 2 Small Fresh events in high and moderate water availability years and at least one during low water availability years. Maximum inter-flow period of 1 year.	• contribute to the maintenance of suitable water quality • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species.
Annual prolonged and continuous Spring nesting component (SN) from 500-6,000 ML/day avoiding rapid drops in water level for at least 14 days every year during October/early November (to be informed by expert understanding of regional spawning season). Rates of rise or fall during the event should not exceed those of historic or modelled “without development” for the season. Maximum inter-flow period of 2 years. May coincide with (OB), (BF) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat. Important where river operations to meet irrigation demand cause extreme water level fluctuations which are out of sync with natural patterns and climatic cues.	• support nesting of River Specialists (e.g. Murray Cod, Trout Cod and Freshwater Catfish) • promote/maintain connectivity and movement of native species longitudinally • increase habitat availability for all species (except Floodplain Specialists2) during Spring when many species breed • support dispersal of eggs and larvae for all species • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species.
Large Fresh (LF) from 6,000-8,900 ML/day for at least 5 consecutive days in two years out of every successive three-year period (not required in years experiencing the Overbank event above). Ideally between August and November but may also occur in summer. Maximum inter-flow period of 2 years. A	• promote connectivity and movement of native species longitudinally and laterally into anabranches and floodplain wetlands1 • promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch), support habitat for Floodplain Specialists2. • inundate in-stream benches and low-lying Floodplain wetlands which may provide nursery habitat for Flow Pulse, River and Floodplain Specialists2.

priming 'spike' may trigger breeding response by Flow Pulse Specialists. Or Bank full (BF) or Overbank event (OB) >8,900 ML/day for at least 10 consecutive days between August and February at least one year in every three-year period. Maximum inter-flow period of 3 years.	• promote within-channel hydraulic variability to support a diverse range of habitats and enhance system productivity (and in-turn condition of adults and juveniles of most species)3 • promote dispersal of eggs and larvae for all species.
Large unregulated Overbank floods (well over 10,500 ML/day) for long durations will be required to address all of the original flow indicators for the Lower Murrumbidgee (in-channel) HIS.	• Critical to the long-term viability of fish communities due to the ecosystem processes floods promote, the opportunistic potential for large scale floodplain recruitment by many species, and the unobstructed longitudinal and lateral connectivity they facilitate.

[1] The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

[2] Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

[3] Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

Goulburn River

Site description

The Goulburn River is the largest Victorian tributary of the Murray River, extending from the slopes of the Great Dividing Range in Victoria north to the Murray River near Echuca (Figure 19; MDBA 2012l). In the Basin Plan, the Lower Goulburn River within-channel HIS includes 195 km of river downstream of Goulburn Weir to the junction of the Murray River which supports a range of environmental assets including nationally listed fauna and flora, wetlands of national significance and diverse native fish communities (MDBA 2012l). The Broken River is the major tributary of the Goulburn River and enters the Goulburn River near Shepparton, whilst Broken Creek is a distributary of the Broken River which exits the Broken River downstream of Benalla to join the Murray River upstream of the town of Barmah. The Goulburn River is ecologically and hydrologically linked to the Murray River, and flooding of Gunbower Forest could be highly dependent on flows from the Goulburn River, given the limited ability to move water from the upper Murray River through the Barmah Choke (Water Technology 2010).

Compared to the adjacent Murray River, flows are much 'flashier', with large flows often persisting for only a few days or weeks, compared to weeks or months in adjacent reaches of the Murray River (MDBA 2012l). Historically the Goulburn River experienced higher flows in winter-Spring and lower flows in summer-autumn (Cottingham and SKM 2011). Two major regulation structures at Lake Eildon and Goulburn Weir (near Nagambie) have significantly altered the hydrology of the Goulburn River (Davies et al. 2008). To meet irrigation and consumptive demand, high flows in the mid Goulburn River channel now occur in summer to autumn, while low flows occur in winter to Spring due to storage of water in Lake Eildon.

The Lower Goulburn River Floodplain HIS extends from downstream of Shepparton to the junction with the Murray River and covers an area of about 13,000 ha (**Error! Reference source not found.**; MDBA 2012m). The hydrology of the Lower Goulburn River Floodplain is driven by flows in the Goulburn River, via Goulburn Weir diversions as well as several effluent channels (CSIRO 2008c). Large flows often persist for only a few days or weeks, compared to weeks or months in adjacent reaches of the Murray River.

Table 28. Characteristics of the natural and post regulation flow regime in the Goulburn River at Shepparton.

Modelled natural hydrology	Modelled current hydrology (regulated)
Variable flow regime	decreased flow variability
Bank full or Overbank flooding every 1-2 years (usually late winter-Spring, rarely at other times of the year)	Large in-channel and Overbank flows less frequent and reduced in magnitude and duration
Large and small in-channel Freshes occurred anytime throughout the year but most frequently between May and December	Smaller in-channel flows and Base Flows are now a regular feature of the river year round
Generally lower flows in summer-autumn	Substantial reduction in the number of small floods in summer, reduction in the number of large floods.

Fish community condition

Significant populations of native fish occur in the lower Goulburn River, including the species of conservation significance Trout Cod, Murray Cod, Silver Perch and Freshwater Catfish (Koster et al. 2012). Breeding populations of Freshwater Catfish, Trout Cod and Silver Perch still exist within the lower Goulburn River, although these species are very rare compared to their former abundances. Although formerly abundant, Macquarie Perch are now uncommon in the main channel of the Lower Goulburn River. Golden perch spawning in the Lower Goulburn River is associated with increases in discharge (although this may not necessarily lead to immediate local recruitment. Murray Cod spawn annually in the lower Goulburn River regardless of river discharge (Koster et al. 2012; 2014).

Native fish in the lower Goulburn River have been affected by flow regulation, barriers to movement, loss of habitat via removal of woody habitat, reductions in water quality and the spread of non-native pest fish species (Pollino et al. 2004). Cold water releases from Lake Eildon also affect fauna and flora in the upper reaches of the Goulburn River. Murray Cod, Trout Cod and Macquarie Perch have only been detected in low abundance in recent decades (Cottingham et al. 2003, ARI unpublished data). A more natural seasonal flow pattern is retained downstream of the Goulburn Weir with minimal cold-water impacts (Cottingham et al. 2011).

Regulatory structures at Lake Eildon and Goulburn Weir have reduced average daily flows in the Lower Goulburn River throughout the year particularly during the high flow period from June to November, although the seasonal pattern of flow is relatively unchanged (MDBA 2012l; **Error! Reference source not found.**).

- The SRA for the period 2008-2010 indicated the condition of the fish community in the lowland zone of the Goulburn River Valley was in an Extremely Poor condition having lost much of its native species richness, with non-native species contributing to over 60% of the biomass (Davies et al. 2012).
- A blackwater event in December 2010 resulted in fish deaths and impacted the abundance of Murray Cod in the lower reaches of the Goulburn River (Koster et al. 2012).
- Surveys in 2015/16, detected Trout Cod further downstream than previous surveys, suggesting a potential expansion in their range, perhaps due to improved habitat including re-snagging efforts.

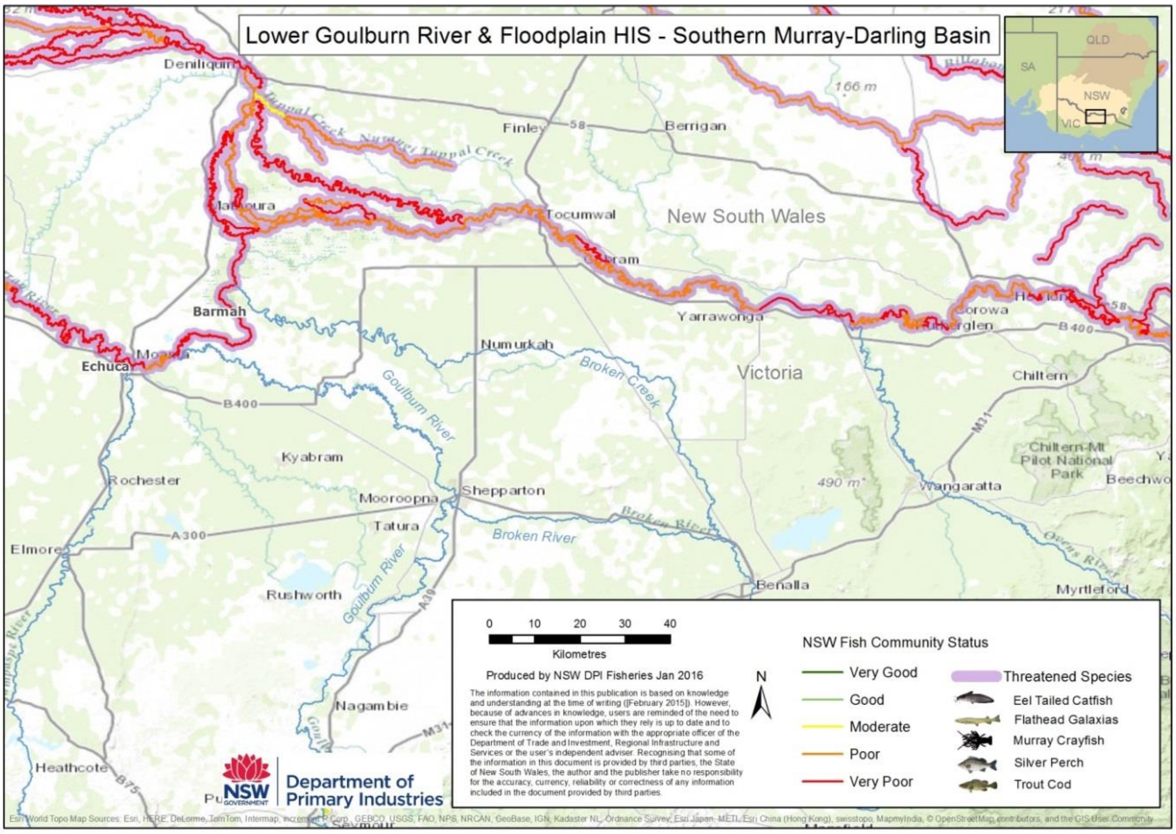

Figure 19. Lower Goulburn River in-channel and Floodplain HIS. DPI NSW Fish Community Status for threatened species distribution information does not extend into the Victorian catchments (i.e. the Goulburn and Broken Rivers) but are included for the adjacent streams in NSW (NSW DPI 2016a). Each of the threatened species pictured are however, currently present within the Goulburn River System.

Basin Plan flow indicators for the Lower Goulburn River (in-channel) HIS

Under the Basin Plan the MDBA proposed separate flow indicators for two HIS, one for the Lower Goulburn River (in -channel) and two for the Lower Goulburn River Floodplain. Site-specific flow indicators for both HIS were expressed on the Goulburn River at Shepparton (both represented in Table 29)).

These represent an amalgam of information within existing literature and vegetation inundation hydrodynamic modelling data, checked against analysis of modelled without development and baseline flow data.

The two flow indicators for the Lower Goulburn River in- channel HIS focussed on the within-channel fresh element of the flow regime to inundate key within-channel habitat (e.g. benches) and maintain native fish populations. They were expected to be sufficient to support the life cycle and habitat requirements of native fish including provision of cues for spawning and migration and access to food sources.

The original site-specific flow indicators for the Lower Goulburn River (in-channel) are:

1. 5,000 ML/d for 14 consecutive days between October and November for 49% of years.
2. Two events annually of 2,500 ML/d for 4 consecutive days between December and April for 36% of years.

Basin Plan flow indicators for the Lower Goulburn River Floodplain HIS

Under the Basin Plan the two flow indicators for the Lower Goulburn River Floodplain were primarily based on inundation of high value wetlands and flood dependent vegetation communities. They were expected to be sufficient to support the life cycle and habitat requirements of native fish including provision of cues for spawning and migration and access to food sources.

The original site-specific flow indicators for the Lower Goulburn River Floodplain are:

1. 25,000 ML/d for a median duration of 5 days between June and November for 70% of years.
2. 40,000 ML/d for a median duration of 4 days between June and November for 40% of years.

Lower Goulburn River and Floodplain (combined)

Fish-specific flow indicators developed for the Lower Goulburn River in-channel and floodplains HIS (combined) are presented in Table 29 along with rationale for each. The flow indicators described herein for the within-channel elements of the flow regime are recommended to achieve the ecological targets relating to the life cycle and habitat requirements of native fish.

In most instances the duration of in-channel flow events necessary for supporting fish outcomes will be lower than those proposed for other elements of the floodplain ecosystem. Given the Goulburn River is dynamic, whereby rapid increases in discharge may result in substantial increases in water velocity, flows related to the Spring nesting component for River Specialist species may need to remain reasonably stable for the duration of the nesting period to avoid nest disruption. We highly recommend regular consultation with local fish ecologists regarding flow management in the Lower Goulburn River during Spring.

Extended Overbank floods (well over 15,000 ML/day) will be required to stimulate productivity outcomes in the Goulburn River Floodplain HIS and achieve the ecological targets relating to the life cycle and habitat requirements of Floodplain dependent native fish. In most instances the duration of Overbank flow events necessary for supporting Floodplain dependent fish outcomes will be lower than those proposed for other elements of the floodplain ecosystem.

To address the ecological outcomes for the Overbank habitats and anabranch systems in the Goulburn River Floodplain complementary flow management activities may be necessary.

Key components of the hydrograph identified are labelled for identification in Figure 6**Error! Reference source not found.**. Suggested Flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change.

Table 29. Revised fish-specific flow indicators for the Lower Goulburn River in-channel and Floodplain HIS.

Flow indicator	Rationale
Variable Base Flows (BA) of 500 to 2,000 ML/day throughout the year (between within-channel fresh and Overbank events). Cease to flow events should be avoided.	• provide main channel refuge habitat, longitudinal connectivity and maintain suitable water quality for all species (except Floodplain Specialists2) • allow for the accumulation of allochthonous carbon and vegetation on benches and dry sections of riverbed, which contributes to ecosystem productivity during subsequent higher flow events.
Small Fresh (SF): 2,000 to 5,600 ML/day for at least 10 consecutive days. Ideally between October and April but can occur anytime. Provide a minimum of 2 Small Fresh events in high and moderate water availability years and at least one during low water availability years. Maximum inter-flow period of 1 year.	• contribute to the maintenance of suitable water quality • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species.
Annual prolonged and continuous Spring nesting component (SN)3 from 1,500 to 6,000 ML/day avoiding rapid rise1 or fall in water level for at least 14 days every year during October/early November (to be	• support nesting of River Specialists (e.g. Murray Cod, Trout Cod and Freshwater Catfish)4 • promote / maintain connectivity and movement of native species (longitudinally and laterally for lower lying off-channel habitats)

informed by expert understanding of regional spawning season). Rates of rise or fall during the event should not exceed those of historic or modelled “without development” for the season. Maximum inter-flow period of 2 years. May coincide with (OB) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat. Important where river operations to meet irrigation demand cause extreme water level fluctuations which are out of sync with natural patterns and climatic cues.	• increase habitat availability for all species (except Floodplain Specialists2) during Spring when many species breed • support dispersal of eggs and larvae for all native species • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species.
Large Fresh (LF) from 5,600 to 15,000 ML/day for at least 5 consecutive days in two years out of every successive three-year period (not required in years experiencing the Overbank event above). Ideally between August and November but may also occur in summer. Maximum inter-flow period of 2 years. A priming ‘spike’ may trigger breeding response by Flow Pulse Specialists, Or, Bank full (BF) or Overbank event (OB) >15,000 ML/day for at least 10 consecutive days between August and February at least one year in every three-year period. Maximum inter-flow period of 3 years.	• promote connectivity and movement of native species longitudinally and laterally into anabranches and floodplain wetlands1 • promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch), support habitat for Floodplain Specialists2. • inundate in-stream benches and low-lying Floodplain wetlands which may provide nursery habitat for Flow Pulse, River and Floodplain Specialists3. • promote within-channel hydraulic variability to support a diverse range of habitats and enhance system productivity (and in-turn condition of adults and juveniles of most species) • promote dispersal of eggs and larvae for all species.
Periodic large unregulated Overbank floods (well over 40,000 ML/day) for an extended duration will be required to address all the original flow indicators for the LGB HIS site.	• Critical to the long-term viability of fish communities due to the ecosystem processes floods promote, the opportunistic potential for large scale floodplain recruitment by many species, and the unobstructed longitudinal and lateral connectivity they facilitate.

[1] The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

[2] Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

[3] Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

[4] In the Goulburn River rapid increases in discharge may result in substantial increases in water velocity. Hence, flows related to the Spring nesting component may need to remain reasonably stable for the duration of the nesting period to avoid nest disruption.

Lachlan River System

Site description

The Lachlan River source waters originate on the western slopes of the Great Dividing Range in the Southern Tablelands area of New South Wales. The catchment consists of 37 tributaries including the Abercrombie, Boorowa, Belubula, Crookwell, Goobang, Bland and Mirool (Green et al. 2011). Flows in the developed Lachlan generally terminate near Oxley in the Great Cumbung Swamp; however these can flow into the Murrumbidgee when both systems are in flood (which has occurred at least three times during the period from 2010-2016). The Lachlan River from Wyangala Dam to the convergence with the Murrumbidgee River has been identified as an EEC under the *Fisheries Management Act (1994)* (NSW DPI 2006).

Indicator Sites in the Lachlan Catchment

The Basin Plan incorporates flow indicators for the Booligal Wetlands, the Lachlan Swamp and the Great Cumbung Swamp HIS on the lower Lachlan Floodplain, all gauged at Booligal. However, no flow indicators were produced for the upper and mid-sections of the Lachlan floodplain (i.e. from Forbes to Booligal). To develop EWRs for native fish in the mid and upper sections of the Lachlan, flow thresholds were developed through assessment of historical flow records and cross-sectional river profiles at representative gauging sites, and through consultation with local water managers. Gauging locations we selected as representative of three reaches in the Lachlan River include:

- Downstream of Cottons Weir (at Forbes) to represent of the instream flow regime downstream to Willandra Weir (i.e. downstream of Carcoar and Wyangala Dams). We refer to this section of River as the upper Lachlan in this report (see Figure 20).
- Hillston Weir which we consider representative of the instream flow regime downstream of Willandra Weir to Booligal. We refer to this section of River as the Mmd Lachlan in this report (see Figure 21)
- Booligal Weir, the gauge used in the MDB Plan considered representative of flow regimes for key floodplain habitats in the downstream reaches of the Lachlan River (Booligal Wetlands, Lachlan Swamp and the Great Cumbung Swamp) where higher flows are dispersed throughout low lying wetlands and anabranches. We refer to this section of River as the lower Lachlan in this report (see Figure 21**Error! Reference source not found.**).

Fish species

Up to 17 native species are expected to occur in the Lachlan valley of which nine are listed as threatened or endangered in NSW. These include Macquarie Perch, Southern Purple Spotted Gudgeon, Southern Pygmy Perch, Flathead Galaxias, Freshwater Catfish, the western population of Olive Perchlet, Silver Perch, Trout Cod and Murray Cod (which were historically recorded throughout the catchment). The population of Murray Cod in the Lachlan River catchment is considered to be under serious threat from a range of factors including river regulation and poor water quality (NMCRT 2010). Two threatened River Snail species *Notopala sublineata* (Darling River Snail) and *Notopala hanleyi* (Hanley's River Snail) also have expected distributions in the Lachlan River (NSW DPI 2016d). Alien species recorded or expected in the Lachlan catchment include Common Carp, Eastern Gambusia, Goldfish, and Redfin Perch. Brown Trout and Rainbow Trout have also been recorded in some upland areas of the catchment but have not been considered as part of functional groupings due to the restriction to upland systems.

River regulation and consumptive use of water has altered the flow regime and reduced the frequency of ecologically significant flows throughout the Lachlan River system (**Error! Reference source not found.**). Flows in the catchment are highly regulated by four large storages (Carcoar Dam on the Belubula River; Lake Brewster and Lake Cargelligo re-regulating storages, and Wyangala Dam on the main stem) and multiple weirs on the main stem (Armstrong et al. 2009). Carcoar and Wyangala Dams regulate approximately 70% of inflows while Lake Brewster and Cargelligo regulate approximately 30% of flows (Armstrong et al. 2009). Larger flows in the Lachlan River may also be subject to re-regulation at Lake Brewster, and to a lesser extent Lake Cargelligo (a large, off-river storage upstream of the lower Lachlan) which may affect the magnitude, timing and duration of flooding in the Lower Lachlan River.

Table 30. Characteristics of the natural and post regulation flow regime in the Lachlan River (MDBA modelled data).

Modelled natural hydrology	Modelled current hydrology (regulated)
Variable with rapidly rising and falling limbs	decreased flow variability
Bank full or Overbank flooding every 1-2 years (usually late winter-Spring, rarely at other times of the year)	Large in-channel and Overbank flows less frequent and reduced in magnitude and duration
Large and small in-channel Freshes occurred anytime throughout the year but most frequently between May and December	Substantial reduction in the number of small floods in summer, reduction in the number of large floods.
Generally lower flows in summer-autumn	

Fish community condition

Overall, the fish community of the Lachlan Valley is in very poor condition, with some reaches and smaller steams in a fair to poor condition (**Error! Reference source not found.**; **Error! Reference source not found.**; NSW DPI 2016a).

- SRA2 reported that the Lachlan had the fifth lowest biomass of fish per site of the 23 SRA valleys and that,71% was contributed by alien species, with most native fish recorded small-bodied species (Davies et al. 2012).
- Eastern Gambusia was the most abundant alien species recorded in SRA 2 with high numbers Common Carp also recorded throughout the Lachlan system (Davies et al. 2012).
- SRA2 also reported that Golden perch was found in the upland, slopes and lowland zones (Davies et al 2012). Murray Cod was caught in the lower two zones (Slopes and Lowland) (Davies et al 2012).
- The impacts of thermal pollution from Wyangala Dam extend approximately 210 km downstream (estimated to Forbes) (NSW DPI 2016a).
- NSW fish community status mapping identifies that the fish condition in much of the Lachlan River downstream of Forbes is in ‘poor’ to ‘very poor’ condition (NSW DPI 2016a).
- Hypoxic blackwater conditions that arose during the 2016 floods had a negative impact on the native fish communities in the Lachlan River (Commonwealth Environmental Water Office, 2017).
- Murray cod and golden perch declined in abundance following poor water quality associated with the 2016–2017 floods but in 2020 monitoring indicated signs of recovery for both (Dyer et al 2020).
- In early 2021 young-of year golden perch were detected in the Lachlan River in 2020-21 for the first time since monitoring by the Commonwealth Environmental Water Office began in 2015 (https://flow-mer.org.au/striking-gold-golden-perch-flows-and-spawning-in-the-lachlan-river/)

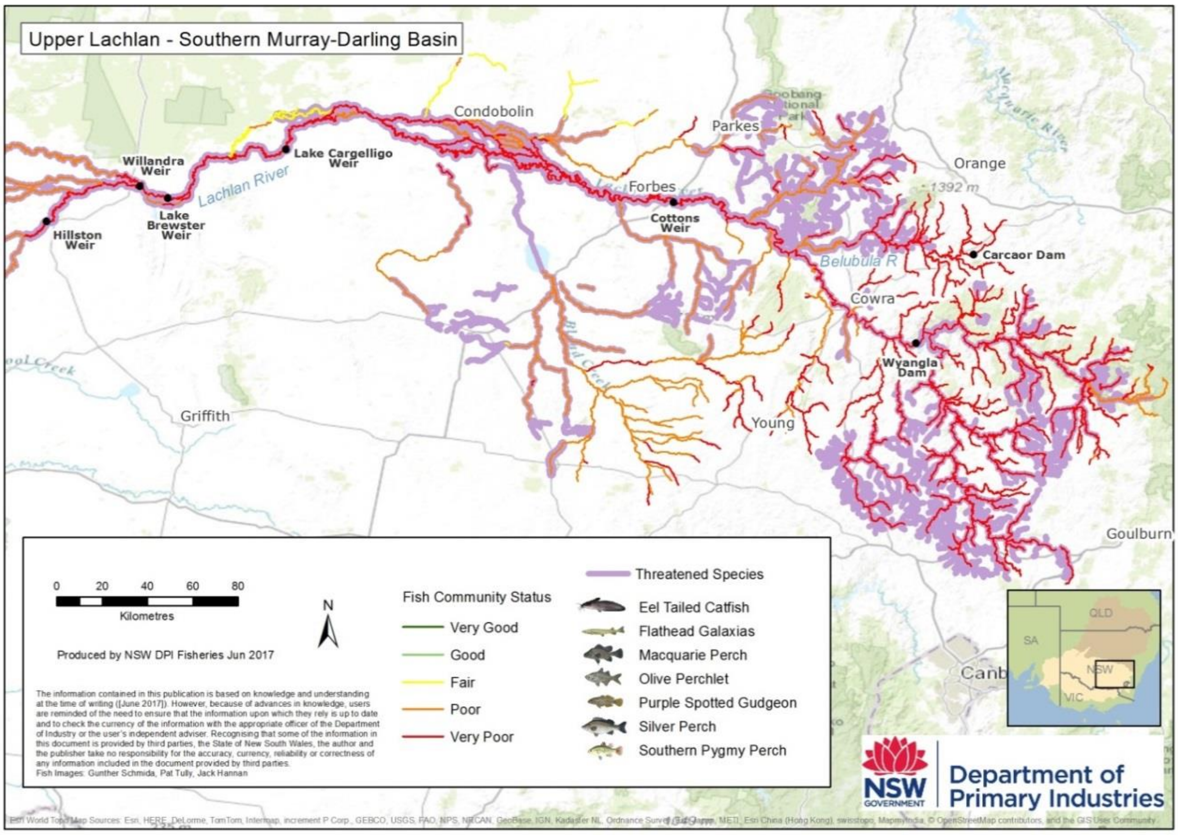

Figure 20. The upper Lachlan River, including Fish Community Status in streams within the region (where available) and potential distribution of threatened species (NSW DPI 2016a).

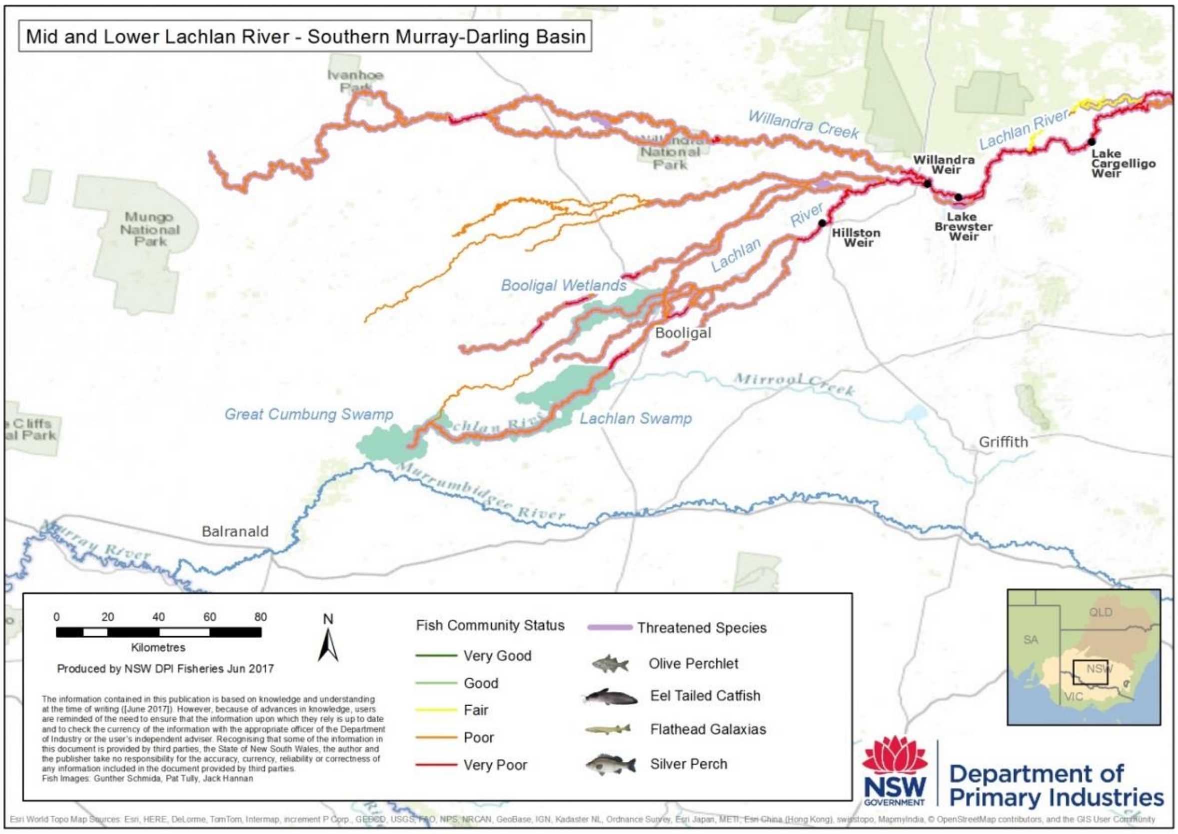

Figure 21. The Mid- and Lower Lachlan River, including Fish Community Status in streams within the region (where available) and potential distribution of threatened species (NSW DPI 2016a).

The Lachlan River downstream of Forbes is highly variable and characterised by predominant low flows, attributed to several instream structures which range in size and impact on hydrology (NSW DPI 2016b). Low flows are periodically punctuated by higher flows which can be regarded as 'flashy' with rapidly rising and falling limbs. In the upper Lachlan, flows greater than 15,000 ML/day (at Forbes) start to break out of the river channel (Green et al. 2011). Large in-channel Freshes or Overbank flows were generally experienced every 1-2 years although longer periods of low flow occurred during protracted droughts. Flows greater than 5,000 and 2,500 ML/day start to break out of the main river channel into various floodplain-channels and wetlands in the mid- and lower Lachlan respectively. The floodplain adjacent to the lower Lachlan River is dissected by a network of anabranches and wetlands and during higher flows and floods. Whilst high flow events in the upper Lachlan were generally transferred through to the mid- and lower Lachlan, Overbank flows were less frequent and extensive (suggesting the mid- and lower Lachlan floodplains and lakes absorbed a substantial proportion of higher flows in low lying anabranches and wetland systems). Higher flow events in the mid- and lower Lachlan are generally more protracted than those in the upper Lachlan, often spanning months.

Upper Lachlan River

Site information

Flows greater than 15,000 ML/day at Forbes start to break out of the river channel. River regulation and consumptive use of water has altered the flow regime and reduced the frequency of ecologically significant flows through the Lachlan River System. Flows in the upper Lachlan are highly regulated by large storages (Carcoar Dam on the Belubula River and Wyangala Dam on the main stem) (NSW DPI 2016b). The main stem river of the upper Lachlan (including some tributaries) is identified as an EEC (NSW DPI 2006). Species listed as present, previously recorded or expected to occur in the upper Lachlan region that are considered threatened include two species of River Snail, Murray Cod, Trout Cod, Macquarie Perch, Silver Perch, Southern Purple-spotted Gudgeon, Olive Perchlet, Freshwater Catfish and Flathead Galaxias.

Fish-specific flow indicators for the upper Lachlan River

Under the Basin Plan, site-specific EWRs were not developed for indicator sites in the upper Lachlan River. We developed a series of Fish-specific EWRs for the upper Lachlan based on the species present, their ecological requirements and assessment of historic flow patterns. Fish-specific flow indicators developed for the upper Lachlan expressed at Cottons Weir (Forbes) are presented in **Error! Reference source not found.** with rationale for each. In most instances the duration of in-channel flow events necessary for supporting fish outcomes will be lower than for other elements of the floodplain ecosystem.

Key components of the hydrograph identified are labelled for identification in Figure 6. Suggested Flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change.

Table 31. Fish-specific flow indicators developed for the upper Lachlan River at Forbes (Cottons Weir).

Flow indicator	Rationale
Variable Base Flows (BA) of 50-600 ML/day throughout the year (between within-channel fresh and Overbank events). Cease to flow events should be avoided.	• provide main channel refuge habitat, longitudinal connectivity and maintain suitable water quality for all species (except Floodplain Specialists2) • allow for the accumulation of allochthonous carbon and vegetation on benches and dry sections of riverbed, which contributes to ecosystem productivity during subsequent higher flow events.

Small Fresh (SF): 600-8,500 ML/day for at least 10 consecutive days. Ideally between October and April but can occur anytime. Provide a minimum of 2 Small Fresh events in high and moderate water availability years and at least one during low water availability years. Maximum inter-flow period of 1 year.	• contribute to the maintenance of suitable water quality • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species
Annual prolonged and continuous Spring nesting component (SN) from 200-8,000 ML/day avoiding rapid drops in water level for at least 14 days every year during October/early November (to be informed by expert understanding of regional spawning season). Rates of rise or fall during the event should not exceed those of historic or modelled "without development" for the season. Maximum inter-flow period of 2 years. May coincide with (OB), (BF) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat. Important where river operations to meet irrigation demand cause extreme water level fluctuations which are out of sync with natural patterns and climatic cues.	• support nesting of River Specialists (e.g. Murray Cod and Freshwater Catfish) • promote/maintain connectivity and movement of native species longitudinally • increase habitat availability for all species (except Floodplain Specialists[2]) during Spring when many species breed • support dispersal of eggs and larvae for all species • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species.
Large Fresh (LF) from 8,500-13,000 ML/day for at least 5 consecutive days in two years out of every successive three-year period (not required in years experiencing the Overbank event above). Ideally between August and November but may also occur in summer. Maximum inter-flow period of 2 years. A priming 'spike' may trigger breeding response by Flow Pulse Specialists. Or, Bank full (BF) or Overbank event (OB) >13,000 ML/day for at least 10 consecutive days between August and February at least one year in every three-year period. Maximum inter-flow period of 3 years.	• promote connectivity and movement of native species longitudinally and laterally into anabranches and floodplain wetlands[1] • promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch), support habitat for Floodplain Specialists[2]. • inundate in-stream benches and low-lying Floodplain wetlands which may provide nursery habitat for Flow Pulse, River and Floodplain Specialists[3]. • promote within-channel hydraulic variability to support a diverse range of habitats and enhance system productivity (and in-turn condition of adults and juveniles of most species) • promote dispersal of eggs and larvae for all species.

Large unregulated Overbank floods (well over 13,900 ML/day) for long durations will be required to address all the original flow indicators for the Upper Lachlan HIS.	• Critical to the long-term viability of fish communities due to the ecosystem processes floods promote, the opportunistic potential for large scale floodplain recruitment by many species, and the unobstructed longitudinal and lateral connectivity they facilitate

[1] The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

[2] Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

[3] Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

Mid Lachlan River

Flows greater than 5,000 ML/day start to break out of the main river channel into various floodplain-channels and wetlands in the mid Lachlan. River regulation and consumptive use of water has altered the flow regime and reduced the frequency of ecologically significant flows through the Lachlan River System. Flows are highly regulated by large storages Carcoar Dam on the Belubula River and Wyangala Dam on the main stem and may also be subject to re-regulation at Lake Brewster and to a lesser extent Lake Cargelligo (NSW DPI 2016c). The mid Lachlan River lies within the EEC of the Lachlan River (NSW DPI 2006). Multiple fish species listed as present, previously recorded or expected to occur in the mid Lachlan region that are considered threatened or 'vulnerable', include two species of River Snail, Murray Cod, Silver Perch, Southern Purple-Spotted Gudgeon, Olive Perchlet, Freshwater Catfish and Flathead Galaxias.

Fish-specific flow indicators for the mid-Lachlan River

Under the Basin Plan, site-specific EWRs were not developed for indicator sites in the mid Lachlan River. We developed a series of Fish-specific EWRs for the mid Lachlan based on the species present, their ecological requirements and assessment of historic flow patterns at Willandra Weir (used as a surrogate for Hillston given its proximity to the Hillston gauge and longer historic flow data set). Fish-specific flow indicators developed for the Lachlan expressed at Hillston are presented in **Error! Reference source not found.** with rationale for each. In most instances the duration of in-channel flow events necessary for supporting fish outcomes will be lower than for other elements of the floodplain ecosystem.

Key components of the hydrograph identified are labelled for identification in Figure 6**Error! Reference source not found.**. Suggested flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change.

Table 32. Fish-specific flow indicators developed for the mid Lachlan River at Hillston.

Flow indicator	Rationale
Variable Base Flows (BA) of 20-280 ML/day throughout the year (between within-channel fresh and Overbank events). Cease to flow events should be avoided.	• provide main channel refuge habitat, longitudinal connectivity and maintain suitable water quality for all species (except Floodplain Specialists[2]) • allow for the accumulation of allochthonous carbon and vegetation on benches and dry sections of riverbed, which contributes to ecosystem productivity during subsequent higher flow events.
Small Fresh (SF): 280-1,600 ML/day for at least 10 consecutive days. Ideally between October and April but can occur anytime. Provide a minimum of 2 Small Fresh events in high and moderate water availability years and at least one during low water availability years. Maximum inter-flow period of 1 year.	• contribute to the maintenance of suitable water quality • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species
Annual prolonged and continuous Spring nesting component (SN) from 100-1,600 ML/day avoiding rapid drops in water level for at least 14 days every year during October/early November (to be informed by expert understanding of regional spawning season). Rates of rise or fall during the event should not exceed those of historic or modelled "without development" for the season.	• support nesting of River Specialists (e.g. Murray Cod and Freshwater Catfish) • promote/maintain connectivity and movement of native species longitudinally • increase habitat availability for all species (except Floodplain Specialists2) during Spring when many species breed • support dispersal of eggs and larvae for all species • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species.

Flow indicator	Rationale
Maximum inter-flow period of 2 years. May coincide with (OB), (BF) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat. Important where river operations to meet irrigation demand cause extreme water level fluctuations which are out of sync with natural patterns and climatic cues. Important where river operations to meet irrigation demand cause extreme water level fluctuations which are out of sync with natural patterns and climatic cues.	
Large Fresh (LF) from 1,600 to 4,000 ML/day for at least 5 consecutive days in two years out of every successive three-year period (not required in years experiencing the Overbank event above). Ideally between August and November but may also occur in summer. Maximum inter-flow period of 2 years. A priming 'spike' may trigger breeding response by Flow Pulse Specialists. Or, Bank full (BF) or Overbank event (OB) >4,000 ML/day for at least 10 consecutive days between August and February at least one year in every three-year period. Maximum inter-flow period of 3 years.	• promote connectivity and movement of native species longitudinally and laterally into anabranches and floodplain wetlands1 • promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch), support habitat for Floodplain Specialists[2] • inundate in-stream benches and low-lying Floodplain wetlands which may provide nursery habitat for Flow Pulse, River and Floodplain Specialists[3] • promote within-channel hydraulic variability to support a diverse range of habitats and enhance system productivity (and in-turn condition of adults and juveniles of most species) • promote dispersal of eggs and larvae for all species.
Large unregulated Overbank floods (well over 5,000 ML/day) for long durations will be required to address all of the original flow indicators for the Mid-Lachlan River HIS.	• Critical to the long-term viability of fish communities due to the ecosystem processes floods promote, the opportunistic potential for large scale floodplain recruitment by many species, and the unobstructed longitudinal and lateral connectivity they facilitate.

[1] The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

[2] Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

[3] Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

Lower Lachlan River

Site description

Flows greater than 2,500 ML/day start to break out of the main river channel into extensive floodplain-channels and wetland systems in the lower Lachlan (including the Booligal Wetlands, Great Cumbung and Lachlan Swamps, see Figure 21). River regulation and consumptive use of water has altered the flow regime and reduced the frequency of ecologically significant flows through the Lachlan River System. Flows are initially regulated by large storages Carcoar Dam on the Belubula River and Wyangala Dam on the main stem and may also be subject to re-regulation at Lake Brewster, and to a lesser extent Lake Cargelligo (NSW DPI 2016b).

The lower Lachlan including the Booligal Wetlands lie within an EEC (NSW DPI 2006). Multiple fish species present, previously recorded or expected to occur in the lower Lachlan region that are considered threatened, include two species of River Snail, Murray Cod, Silver Perch, Olive Perchlet, Flathead Galaxias, and Freshwater Catfish.

Fish-specific flow indicators for the lower Lachlan River (Booligal)

The gauge at Booligal Weir is commonly used to assess environmental flows in the lower Lachlan (including use as a HIS by the MDBA) because it has an acceptable quality and quantity of flow data and is also located below major irrigation extraction and water diversion off-takes. Under the Basin Plan the flow indicators for Booligal HIS were primarily based on the water requirements of flood dependent vegetation communities and waterbirds are expected to be sufficient to support life-cycle and habitat requirements of native fish including provision of cues for spawning and migration and access to food sources.

The original site-specific flow indicators for the Booligal Wetlands are:

1. 300 ML/Day for 25 consecutive days between June and November for 70% of years
2. 850 ML/Day for a total duration of 70 days between June and November for 33% of years
3. 2,500 ML/Day for 50 consecutive days between June and November for 20% of years.

Revised fish-specific flow indicators for the Lower Lachlan River

Fish-specific flow indicators developed for the lower Lachlan River (Booligal Wetland) HIS are presented in **Error! Reference source not found.** along with rationale for each. The flow indicators described herein for the within-channel elements of the flow regime are recommended to achieve the ecological targets relating to the life cycle and habitat requirements of native fish. In most instances the duration of in-channel flow events necessary for supporting fish outcomes will be lower than those proposed for other elements of the floodplain ecosystem.

Key components of the hydrograph identified are labelled for identification in Figure 6. Suggested Flow durations represent the minimum number of days flow exceed the proposed threshold. Rates of rise and fall should reflect 'natural' rates of change.

Table 33. Fish-specific flow indicators developed for the lower Lachlan River (at Booligal).

Flow indicator	Rationale
Variable Base Flows (BA) of 10-200 ML/day throughout the year (between within-channel fresh and Overbank events). Cease to flow events should be avoided.	• provide main channel refuge habitat, longitudinal connectivity and maintain suitable water quality for all species (except Floodplain Specialists2) • allow for the accumulation of allochthonous carbon and vegetation on benches and dry sections of riverbed, which contributes to ecosystem productivity during subsequent higher flow events.

Flow indicator	Rationale
Small Fresh (SF): 200 to 650 ML/day for at least 10 consecutive days. Ideally between October and April but can occur anytime. Provide a minimum of 2 Small Fresh events in high and moderate water availability years and at least one during low water availability years. Maximum inter-flow period of 1 year.	• contribute to the maintenance of suitable water quality • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species.
Annual prolonged and continuous Spring nesting component (SN) from 100-650 ML/day avoiding rapid drops in water level for at least 14 days every year during October/early November (to be informed by expert understanding of regional spawning season). Rates of rise or fall during the event should not exceed those of historic or modelled “without development” for the season. Maximum inter-flow period of 2 years. May coincide with (OB), (BF) or (LF), in which case arrest flow recession rates in October – November to avoid rapid drops in water level. Consider delivery of a short increase in flow at the end of the event to generate productivity (food for young) and nursery habitat. Important where river operations to meet irrigation demand cause extreme water level fluctuations which are out of sync with natural patterns and climatic cues	• support nesting of River Specialists (e.g. Murray Cod and Freshwater Catfish) • promote/maintain connectivity and movement of native species longitudinally • increase habitat availability for all species (except Floodplain Specialists2) during Spring when many species breed • support dispersal of eggs and larvae for all species • flow variability enhances system productivity and in-turn condition of adults and juvenile of most species.
Large Fresh (LF) from 650 to 2,000 ML/day for at least 5 consecutive days in two years out of every successive three-year period (not required in years experiencing the Overbank event above). Ideally between August and November but may also occur in summer. Maximum inter-flow period of 2 years. A priming ‘spike’ may trigger breeding response by Flow Pulse Specialists. Or, Bank full (BF) or Overbank event (OB) >2,000 ML/day for at least 10 consecutive days between August and February at least one year in every three-year period. Maximum inter-flow period of 3 years.	• promote connectivity and movement of native species longitudinally and laterally into anabranches and floodplain wetlands1 • promote spawning and dispersal of Flow Pulse Specialists (Golden perch and Silver Perch), support habitat for Floodplain Specialists2 • inundate in-stream benches and low-lying Floodplain wetlands which may provide nursery habitat for Flow Pulse, River and Floodplain Specialists3 • promote within-channel hydraulic variability to support a diverse range of habitats and enhance system productivity (and in-turn condition of adults and juveniles of most species) • promote dispersal of eggs and larvae for all species.

Flow indicator	Rationale
Large unregulated Overbank floods (well over 4,000 ML/day) for long durations will be required to address all the original flow indicators for the lower Lachlan River HIS.	• Critical to the long-term viability of fish communities due to the ecosystem processes floods promote, the opportunistic potential for large scale floodplain recruitment by many species, and the unobstructed longitudinal and lateral connectivity they facilitate.

[1] The potential for Carp recruitment in floodplain habitats should be considered and management strategies implemented where appropriate.

[2] Complementary actions may be necessary to maintain or restore habitat and populations of Floodplain Specialists.

[3] Complementary actions may be necessary to maintain or restore habitat and populations of threatened species.

Discussion

Significant advancement of our understanding of fish and flow relationships has occurred since the original development of EWRs for the Basin Plan in 2009 (see MDBA 2012a-m). Most of the 2009 EWRs were primarily based on the water requirements of flood dependent vegetation communities and waterbirds and were assumed to be sufficient to support native fish populations. To incorporate new knowledge and address the deficiency of within-channel flow requirements for native fish, NSW DPI Fisheries in partnership with the Arthur Rylah Institute (ARI), South Australian Research and Development Institute (SARDI) and MDBA with input from other Commonwealth and Basin state fisheries, environment and water agencies undertook a review of the water requirements of fish in the Southern MDB, particularly in relation to flows (see Phase 1 of this project, Ellis et al. 2016). This review included consultation with a range of expert ecologists from across the MDB.

Again, we note that the delivery of water is only one step in the process of achieving environmental outcomes for native fish. Due the extent of water and land use in the MDB, in some cases the achievement of meaningful outcomes for fish will require strategies in addition to the delivery of proposed flow regimes (i.e. complementary actions). These actions may include re-snagging programs, mitigating cold water pollution (Lugg and Copeland 2014), weir pool manipulations, improvements to fish passage (Baumgartner et al. 2014), conservation stocking or translocations (Whiterod et al. 2019), screening of irrigation pump offtakes to minimise fish entrainment (Baumgartner et al. 2009; Baumgartner and Boys 2012), pest fish control (e.g. wetland screening or removal programs), riparian restoration and coordinated watering strategies (between States, jurisdictions and sites).

Conduct, benefit and outcomes of the project

The information synthesised in Phase 1 (Ellis et al 2016) was used to develop fish specific EWRs targeting fish outcomes across the southern connected MDB (Phase 2, this report). The development conceptual hydrographs and fish specific EWRs were intended to support the MDBA and MDB States in the development of LTWPs, WRPs. Initially intended for completion in 2017, this report was delayed ensuring consistency with the information and EWR's ultimately published in the NSW LTWP's for the Murray-Lower Darling, Murrumbidgee and Lachlan Rivers.

With the completion of the NSW LTWP's in 2020, we have been able to complete this report ensuring broad consistency with the ERS's published in LTWP's.

https://www.environment.nsw.gov.au/topics/water/water-for-the-environment/planning-and-reporting/long-term-water-plans

In the interim (and despite the delay in finalising this report), DPI Fisheries have used the FFMF and draft fish specific EWR's in assisting state and commonwealth environmental water managers in planning annual priorities and flow deliveries. These efforts are reflected in positive native fish outcomes linked to targeted environmental flow deliveries in the Murray, Lower Darling, Murrumbidgee and Lachlan Rivers since 2016. Some examples of these efforts and outcomes are discussed below.

Informing coordinated, real time water management

The DPI Fisheries FFMF provide EWRs that support water managers in providing regional as well as basin scale native fish outcomes. Most of the HIS in the Southern MDB are hydrologically connected and therefore interdependent. The FFMF is intended to be applied with consideration of adjoining sites, reaches and streams by using information about the fish communities present within each catchment. Hence, we have endeavoured to ensure alignment with the "Towards Southern Connected Basin Plan project" (TSCBP) which was conducted in parallel to the Fish and Flows in the Southern MDB project (see Stuart and Sharpe 2017). The TSCBP outlines the logic, science and practical components of a connected approach which proposes to optimise ecological outcomes at a system scale (e.g. 500-2000km).

The FFMF encourages collaboration and consultation with expert ecologists and neighbouring regional managers to contribute to temporal and longitudinal water delivery programs which promote connectivity between adjoining catchments (and thus provide cumulative benefits for native fish). It also encourages monitoring to accompany the delivery of environmental water to ensure the achievements and lessons learnt through these events contribute to ongoing adaptive management of environmental flow delivery to achieve system-scale ecological benefits for native fish populations.

Components of both the NSW DPI Fisheries FFMF and the SCBP have been implemented in recent years to promote native fish outcomes through informed delivery of environmental water, as well as refined delivery of water for other uses (e.g. conveyance or agricultural supply) to support environmental outcomes. In each of the cases below, the FFMF and the SCBP model were utilised in 'real time' planning of flows.

Lower Darling-Baaka River

In spring of 2016 environmental flows were delivered to the Lower Darling River (LDR) downstream of the Menindee Lakes that incorporated an elevated within-channel Spring nesting component throughout the breeding season of Murray Cod, and a short small fresh at the end of the event to generate productivity (food for young fish) and inundate benches that provide nursery habitat. Subsequent environmental flows were delivered through summer 2016-17 to generate a Large Fresh in the Lower Darling River, providing a spawning cue for Golden perch accumulating downstream of the Menindee Lakes. The environmental flows also supported migrations of juvenile golden perch from in the Menindee Lakes into the Lower Darling River. These juveniles were spawned in northern NSW and southern Queensland in early 2020 in response to high flow events, and then transported along the Barwon-Darling River, with many reaching the Menindee Lakes and the productive nursery habitat they offer. The large fresh was followed by a protracted recession and a variable base flow to maximise dispersal of juvenile Golden perch. Monitoring throughout the event detected strong larval abundance in the LDR in Spring 2016. (Sharpe and Stuart 2018a and b; Stuart et al 2021). Environmental flows were also delivered to the Darling Anabranch in 2017 from Lake Cawndilla to facilitate dispersal of juvenile Golden perch through to the Murray River.

When flows from the north again filled the Menindee Lakes in 2020, a similar suite of flow components was delivered to the Lower Darling River using environmental water in spring and summer of 2020-21 to initiate recovery of local fish populations. Monitoring throughout the event again demonstrated spawning and recruitment by Murray god, and dispersal of Golden perch from the Menindee Lakes into the Lower Darling River (Stuart et al 2021). For more information:

https://www.environment.gov.au/water/cewo/publications/environmental-flows-darling-river-fish-2016-17

http://www.riverspace.com.au/wp-content/uploads/2017/10/MDBA_corridors_3.pdf

https://www.environment.gov.au/water/cewo/catchment/lower-darling-baaka-flow-2020-21

Murray River (2016-20)

Water for the environment was used to provide a protracted flood recession to the 2016 natural flood event, which extended the period of floodplain inundation to maximise productivity processes, as well as dilute hypoxic blackwater that killed many fish during the peak of the flood event. The extended connectivity also enhanced opportunities for longitudinal and lateral movements by native fish throughout the Barmah-Millewa and Edward-Wakool systems.

Environmental flows were later delivered to the Murray River downstream of Yarrawonga in 2017-18 to increase available habitat for nesting by River Specialists in 2017, and to maintain connectivity throughout the low-lying anabranch systems of the Barmah-Millewa Forests. The flow enhanced opportunities for breeding and movements by River and Flood Pulse Specialists as well as Generalists (and potentially Floodplain Specialists that may inhabit the region).

In spring of 2019, and again in 2020, environmental water managers delivered a spring pulse to the Murray River from Hume Dam and the Goulburn River to benefit the river channel and select wetland systems from the mid-Murray to the Coorong and Lower Lakes. multiple environmental assets as it progresses. The flows aim to support the health of the river and provide food and breeding opportunities for native vegetation fish and wildlife.

https://www.environment.gov.au/water/cewo/publications/southern-spring-flow-2019-wrap-up

https://www.environment.gov.au/water/cewo/catchment/southern-spring-flow-2020

Lower Murrumbidgee River

Spawning by Murray cod, golden perch and silver perch has been detected in the Murrumbidgee channel in most years from 2014-2019, but recruitment has generally been poor, contribution to aging populations (Wassens et al. 2020). Delivery of environmental water to inundate floodplain habitats during spring and summer in the Low-Bidgee have been important in supporting native fish populations, through the provision of food and habitat. Larval Murray cod have been detected drifting from the Murrumbidgee River into the Yanga floodplain system in environmental flows. Furthermore, instances of spawning and recruitment by golden perch within the Lowbidgee floodplain and anabranch system have also been demonstrated in conjunction with high flow events and environmental flow deliveries on multiple occasions since 2018 (Sharpe 2018; Kopf et al. 2019; Whiterod and Gannon 2020). These golden perch recruitment events were not widespread, but their potential importance to local populations may important, particularly in the context of recent fish deaths associated with drought and hypoxic blackwater events.

Next steps

Addressing knowledge gaps

This project represents a synthesis of knowledge and conceptual understanding (at the time of writing) of how flow may be managed to benefit fish. However, key knowledge gaps or deficiencies in our understanding of the finer details regarding fish-flow relationships remain. These include (not exclusively):

- influences of flow seasonality on fish conditions and survival
- the value of floodplain recruitment by native fish (in each river system in the MDB)
- influences of flow on reproduction and movement by poorly studied species
- the importance of flow translucency, supplementary flows, and multi-year flow sequences.

Targeted research and robust monitoring of the ecological outcomes or impacts resulting from application of the FFMF presented here will be critical to allow future adaptation and optimisation of this process.

Adaptive management

The framework and conceptual models presented in this report are not prescriptive. Due to the natural variation in flow characteristics both spatially and temporally within the Southern MDB, responsible application of the framework presented here in water management must consider regionally specific details (such as the timing of breeding seasons, channel capacity and discharge values for which various levels of inundation of critical habitat features occurs). The framework and concepts outlined in this report need to be adapted to suit different geographic locations based on these considerations and should include consultation with local experts. Importantly, the outputs presented in this report can be updated as additional information comes to hand. We anticipate that in coming years the outputs included in this report will be refined in support of the objectives, targets and outcomes contained in WRPs, LTWPs and the BWS. As knowledge gaps are addressed our understanding will increase and management options will be refined.

Additional indicator sites

There are likely to be limitations in the capacity for the HIS method to represent the flow-related requirements of all native fish species within a region, particularly those inhabiting floodplain-channels and wetland habitats between indicator site locations (Wallace et al. 2014a). For example, the Lower Murray River HIS located at the NSW–South Australia border does not necessarily represent flows through the Chowilla Floodplain or Lindsay–Wallpolla Islands anabranch systems (due to the influence of Locks 5 -9 and the regulation of flows through Lake Victoria).

Adaptive refinement (informed by monitoring) of the principles described in this document may highlight a need for finer resolution regarding indicator site locations. Additional flow gauging sites located within minor tributaries or floodplain anabranches may also improve the potential for addressing native fish requirements at a finer scale.

Overlap with cultural and recreational fishing values

Consultation with First Nations Representatives (e.g. MLDRIN, Barkandji PBC) and Recreational Fishing groups was conducted during the development of the conceptual hydrographs and EWRs presented in this report. This consultation highlighted that the achievement of fish outcomes through informed water delivery would in many cases also generate significant cultural outcomes for Aboriginal peoples. Achieving positive outcomes for native fish populations would also contribute to the large recreational fishing industry in the MDB. We recommend that the ongoing exploration of these overlapping outcomes continues as the management and delivery of water for environmental benefits progresses. This consultation should ensure collaboration between water management agencies and a range of first nations and recreational fishing organisations, with an aim to develop linkages and guide ongoing adaptive water management which provides efficiencies through the identification of shared outcomes.

References

ARI (in prep.). Native fish population models - Tools to assist water management. Report by the Arthur Rylah Institute for Environmental Research (DELWP, Victoria) to the Murray – Darling Basin Authority, Canberra.

ARI unpublished data. Data collection for ongoing monitoring of fish populations in the lower Goulburn River. Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Heidelberg, Victoria.

Armstrong, J., Kingsford, R. and Jenkins, M. (2009). The effect of regulating the Lachlan River on the Booligal Wetlands- The floodplain Red Gum swamps. wetlands and rivers, School of Earth and Environmental Sciences, University of New South Wales, NSW 2052.

Arthington, A. H., Bunn, S. E., Poff, N. L. R. and Naiman, R. J. (2006). The challenge of providing environmental flow rules to sustain river ecosystems. Ecological Applications 16, 1311-18.

Arthington, A. (2012). Environmental Flows: Saving Rivers for the Third Millennium. University of California Press.

Balcombe S. R., Lobegeiger J. S., Marshall S. M., Marshall J. C., Ly D. and Jones, D.N. (2012). Fish body condition and recruitment success reflect antecedent flows in an Australian dryland river. Fisheries Science 78, 841–847.

Baldwin, D. and Mitchell, A. (2000). The effects of drying and re-flooding on the sediment and soil nutrient dynamics of lowland river–floodplain systems: a synthesis. Regulated Rivers: Research and Management 16, 457-467.

Baumgartner, L. J., Reynoldson, N., Cameron, L. M., & Stanger, J. G. (2009). Effects of irrigation pumps on riverine fish. Fisheries Management and Ecology, 16, 429–437. https://doi.org/10.1111/j.1365-2400.2009.00693.x

Baumgartner, L. J., & Boys, C. (2012). Reducing the perversion of diversion: Applying world standard fish screening practices to the Murray-Darling Basin. Ecological Management & Restoration, 13(2), 135–143. https:// doi.org/10.1111/j.1442-8903.2012.00655.x

Baumgartner, L., Conallin, J., Wooden, I., Campbell, B., Gee, R., Robinson, W. and Mallen-Cooper, M. (2013). Using flow guilds of freshwater fish in an adaptive management framework to simplify environmental flow delivery for semi-arid riverine systems. Fish and Fisheries 15, 410–427.

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

Baumgartner, L., Gell, P., Thiem, J., Finlayson, M. and Ning, N. (2019). Ten complementary measures to assist with environmental watering programs in the Murray–Darling river system, Australia. River Research and Applications. DOI: 10.1002/rra.3438

Beesley, L., King, A., Amstaetter, F., Koehn, J., Gawne, B., Price, A., Nielson, D., Vilizzi, D. and Meredith, S. (2012). Does flooding affect spatiotemporal variation of fish assemblages in temperate floodplain wetlands? Freshwater Biology 57, 2230-2246.

Bice, C., Zampatti, B., Jennings, P. and Wilson, P. (2012). Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2011/12. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Bice, C., Zampatti, B. and Fredberg, J. (2016). Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2015/16. SARDI publication No. F2011/000186-6. SARDI Aquatic Sciences, Henley Beach SA.

Bice, C., Gibbs, M., Kilsby, N., Mallen-Cooper, M. and Zampatti, B. (2017). Putting the 'river' back into the lower River Murray: quantifying the hydraulic impact of river regulation to guide ecological restoration. Transactions of the Royal Society of South Australia 141, 101-131.

Bice, C., Zampatti, B., Jennings, P. and Wilson, P. (2019). Fish assemblage structure, movement and recruitment in the Coorong and Lower Lakes in 2018/19. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Bindokas, J. and Rourke, M. (2011). Koondrook-Perricoota icon site fish condition monitoring annual report August 2011. Narrandera, New South Wales NSW Department of Trade and Investment.

Bogenhuber, D., Linklater, D., Pay, T., Stoffels, R. and Healy, S. (2013). The Darling Anabranch adaptive management monitoring program final report 2010–2013 Baseline to a decade. Report prepared for the NSW Office of Environment and Heritage by The Murray-Darling Freshwater Research Centre, MDFRC Publication 11/2013, June, 171pp

Bond, N., Costelloe, J., King, A., Warfe, D., Reich, P. and Balcombe, S. (2014) Ecological risks and opportunities from engineered artifical flooding as a means of achieving environmental flow objectives. Frontiers in Ecology and the Environment 12, 386-394.

Brierley, G . and Fryirs, K. (2013). Geomorphology and river management: applications of the river styles framework. John Wiley and Sons.

Cheshire, K. J. M. (2010). Larval fish assemblages in the Lower River Murray, Australia: examining the influence of hydrology, habitat and food. Earth and Environmental Science. Adelaide, South Australia, University of Adelaide. Doctor of Philosophy.

Cheshire, K.J.M., Ye, Q., Gillanders, B.M. and King, A.J. (2015). Annual variation in larval fish assemblages in a heavily regulated river during differing hydrological conditions. River Research and Applications.

Chessman, B. (2003). Integrated monitoring of environmental flows: State summary report 1998-2000. NSW, NSW Department of Infrastructure, Planning and Natural Resources.

Commonwealth of Australia (2012). Basin Plan 2012, Water Act 2007. Federal Register of Legislative Instruments F2012L02240.

Commonwealth Environmental Water Office (2013). A framework for determining environmental water use. Commonwealth Environmental Water Office, Canberra.

Commonwealth Environmental Water Office (2017). Blackwater Review: Environmental water used to moderate low dissolved oxygen levels in the southern Murray Darling Basin during 2016/17.

Cottingham, P., Stewardson, M., Crook, D., Hillman, T., Roberts, J. and Rutherfurd, I. (2003), Flow-related environmental issues associated with the Goulburn River below Lake Eildon. Report to Victorian Department of Sustainability and Environment and Murray – Darling Basin Commission by the Cooperative Research Centre for Freshwater Ecology, Canberra.

Cottingham, P., Crook, D., Hillman, T., Oliver, R., Roberts, J. and Stewardson, M. (2010). Objectives for flow freshes in the lower Goulburn River 2010/11. Report to the Goulburn-Broken CMA and Goulburn Murray Water.

Cottingham, P. and SKM (2011). Environmental Water Delivery: Lower Goulburn River. Prepared for Commonwealth Environmental Water, Department of Sustainability, Environment, Water, Population and Communities, Canberra.

CSIRO (2008a). Water availability in the Murray: a report to the Australian Government from the CSIRO Murray – Darling Basin sustainable yields project. Canberra CSIRO.

CSIRO (2008b). Water availability in the Murrumbidgee: a report to the Australian Government from the CSIRO Murray – Darling Basin sustainable yields project. Canberra CSIRO.

CSIRO (2008c). Water availability in the Goulburn–Broken: a report to the Australian Government from the CSIRO Murray–Darling Basin Sustainable Yields Project. Canberra CSIRO.

Davies, P., Harris, J., Hillman, T. and Walker, K. (2008). Sustainable Rivers Audit 1: A Report on the Ecological Health of Rivers in the Murray – Darling Basin, 2004–2007. Prepared by the Independent Sustainable Rivers Audit Group for the Murray– Darling Basin Ministerial Council.

Davies, P., Stewardson, M., Hillman, T., Roberts, J. and Thoms, M. (2012). Sustainable Rivers Audit 2: The ecological health of rivers in the Murray – Darling Basin at the end of the Millennium Drought (2008-2010) Volume 2. Canberra, ACT. Prepared by the Independent Sustainable Rivers Audit Group for the Murray– Darling Basin Ministerial Council.

DELWP (2015). Flora and fauna guarantee act threatened list May 2015. Victorian Department of Environment, Land, Water and Planning Industries, Melbourne, Victoria.

DoE (2013). Environment Protection and Biodiversity Conservation Act 1999 (Cth) Conservation advice: Bidyanus bidyanus (Silver Perch). Australian Government Department of Environment and Energy, Canberra.

Duncan, M. and Martin, K., (2017). Koondrook-Perricoota Forest Icon Site Fish Condition Monitoring 2017 Annual Report. NSW DPI Report.

Duncan, M.,Martin, K., and O'Brien, N. (2018). Koondrook-Perricoota Forest Icon Site Fish Condition Monitoring 2018 Annual Report. NSW DPI Report, 41p.

Dyer, F., Broadhurst, B., Tschierschke, A., Higgisson, W., Thiem, J., Wright, D., Kerezsy, A. Thompson, R. (2020). Commonwealth Environmental Water Office Monitoring, Evaluation and Research Project: Lachlan river system Selected Area 2019-20 Monitoring and Evaluation Technical Report. Commonwealth of Australia, 2020.

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

Ellis, I and Meredith, S. (2004). An independent review of the February 2004 Lower Darling River fish deaths: guidelines for future release effects on Lower Darling River fish populations. A report prepared for NSW Department of Infrastructure, Planning and Natural Resources by the Murray – Darling Freshwater Research Centre.

Ellis, I., Sharpe, C. and Wallace., T. (2009). Assessment of snag-habitat and fish community relationships in the Pomona Priority Habitat Reach, Lower-Darling River. A technical report prepared for the Lower Murray Darling Catchment Management Authority by The Murray-Darling Freshwater Research Centre.

Ellis, I., Huntley, S., Lampard, B. and Wood, D. (2015). Fish movement in response to a managed drawdown of Butlers Creek and Psyche Lagoon, Kings Billabong Nature Reserve, Victoria (winter 2014). Final Report prepared for the Mallee Catchment Management Authority by The Murray – Darling Freshwater Research Centre, MDFRC Publication 63/2015, May, 31 pp.

Ellis, I., Cheshire, K., Townsend, A., Copeland, C., Danaher, K. and Webb, L. (2016). Fish and flows in the Murray catchment – a review of environmental water requirements for native fish in the Murray River catchment. NSW Department of Primary Industries, Queanbeyan.

Ellis, I., Townsend, A., Cheshire, K., Stocks, J., Thiem, J., Boys, C., Heath, P., Lay, C. and Danaher, K. (2021). NSW DPI Fisheries Lower Darling-Baaka River Drought Response and short-term recovery outcomes 2018-2021. NSW DPI Technical report.

EPBC (2004). Environment Protection and Biodiversity Conservation Act 1999. Department of the Environment and Heritage. Available http://www.environment.gov.au/epbc . Accessed 8 March 2016.

Fairfull, S. and Witheridge, G. (2003). Why do fish need to cross the road? Fish passage requirements for waterway crossings. NSW Fisheries, Cronulla, NSW.

FM Act NSW (1994). NSW Fisheries Management Act 1994 No 38. New South Wales Department of Primary Industries, Sydney, Australia,. Current version for 8 January 2016 to date (accessed 8 March 2016).

FM Act SA (2007). South Australia Fisheries Management Act 2007. Primary Industries and Resources South Australia, Adelaide.

Frazier, P. and Page, K. (2006). The effect of river regulation on floodplain wetland inundation, Murrumbidgee River, Australia. Marine and Freshwater Research 57, 133-141.

Fredberg, J., Zampatti, B.P. and Bice, C.M. (2018). Chowilla Icon Site Fish Assemblage Condition Monitoring 2018. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2008/000907-10. SARDI Research Report Series No. 1005. 62pp.

Geddes, M. C., and Puckridge, J. T. (1989). Survival and growth of larval and juvenile native fish: the importance of the floodplain. In 'Proceedings of the Workshop on Native Fish Management'. pp. 101-14. (Murray – Darling Basin Commission, Canberra).

Gehrke, P. C. and Harris, J.H (2001). Regional-scale effects of flow regulation on lowland riverine fish communities in New South Wales, Australia. Regulated Rivers: Research and Management 17, 369-391.

Gibbs, M., Higham J., Bloss C., Bald, M., Maxwell, S., Steggles, T., Montazeri, M., Quin, R. and Souter, N. (2012). Science review of MDBA modelling of relaxing constraints for Basin Plan scenarios. Department of Environment, Water and Natural Resources, Adelaide, South Australia.

Gilligan, D. (2005). Fish communities of the Murrumbidgee catchment: status and trends. NSW Department of Primary Industries –Fisheries Final Report Series No. 75.

Gilligan, D. (2010). Lower Murray-Darling Catchment Action Plan: Fish Community Monitoring Report Card for 2009/10. NSW Department of Primary Industries.

Gippel, C.J. (2013). Assessment of the hydraulics of the Little Murray Weir Pool under alternative operating scenarios. Fluvial Systems Pty Ltd, Stockton. Goulburn-Murray Water, Shepparton, Victoria.

Gippel, C.J. and Blackham, D. (2002). Review of environmental impacts of flow regulation and other water resource developments in the River Murray and Lower Darling River system. Final Report by Fluvial Systems Pty Ltd, Stockton, to Murray – Darling Basin Commission, Canberra, ACT.

Gorski, K., Collier, K., Duggan, I., Taylor, C. and Hamilton, D. (2013). Connectivity and complexity of floodplain habitats govern zooplankton dynamics in a large temperate river system. Freshwater Biology 58, 1458-1470.

Green, D., Petrovic, J., Moss, P. and Burrell, M. (2011). Water resources and management overview: Lachlan catchment, NSW Office of Water, Sydney.

Hammer, M., Wedderburn, S. and van Weenen, J. (2009). Action plan for South Australia: freshwater fishes. Native Fish Australia (SA) Incorporated and Department for Environment and Heritage, Adelaide.

Harris, J.H. and Gehrke, P.C. (1994). Modelling the relationship between streamflow and population recruitment to manage freshwater fisheries. Agricultural Systems and Information Technology 6, 28-30.

Henderson, M., Freestone, F., Vlamis, T., Cranston, G., Huntley, S., Campbell, C. and Brown, P. (2014b). The Living Murray Condition Monitoring at Lindsay, Mulcra and Wallpolla Islands 2013–14 Part A – Main report. Final report prepared for the Mallee Catchment Management Authority by The Murray – Darling Freshwater Research Centre, MDFRC Publication 02/2014, July, 99 pp.

Hillman, T. (2004). Murrumbidgee Valley Ecological Assessment. A study conducted for the Pratt water Murrumbidgee Valley Water Efficiency Feasibility Project.

Humphries, P., King A. J. and Koehn, J. D (1999). Fish flows and flood plains: links between freshwater fishes and their environment in the Murray – Darling River system, Australia. Environmental Biology of Fishes 56, 129-151.

Humphries, P. and King, A. J. (2004). Drifting fish larvae in Murray – Darling Basin rivers: composition, spatial and temporal patterns and distance drifted. In Downstream Movement of Fish in the Murray – Darling Basin. Statement, Recommendations and Supporting Papers from a Workshop held in Canberra 3–4 June 2003 (eds M. Lintermans and B. Phillips). pp. 51–58. Murray – Darling Basin Commission, Canberra, Australia.

Humphries P., Cook R. A., Richardson A. J. and Serafini L. G. (2006). Creating a disturbance: manipulating slackwaters in a lowland river. River Research and Applications 22, 525– 542.

IUCN (2015). IUCN red list of threatened species 2015.2. from http://www.iucnredlist.org.

Jones, M. and Stuart, I. (2008). Regulated floodplains: a trap for unwary fish. Fisheries Management and Ecology 15, 71-79.

Junk, W., Bayley, P. and Sparks, R. (1989). The flood pulse concept in river-floodplain systems. Canadian Special Publication of Fisheries and Aquatic Sciences 106, 110-127.

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

King, A.J., Ward, K.A., 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, 17-31.

King A. J., Tonkin Z. and Lieschke 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, 576– 586.

Kingsford, R.T. and Thomas, R. (2001). Changing water regimes and wetland habitat on the lower Murrumbidgee floodplain of the Murrumbidgee River. NSW NP&WS report to Environment Australia.

Kingsford R. T. and Thomas R. F. (2004). Destruction of wetlands and waterbird populations by dams and irrigation on the Murrumbidgee River in arid Australia. Environmental Management 34, 383–396.

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

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

Koehn, J. and Lintermans, M. (2012). A strategy to rehabilitate fishes of the Murray – Darling Basin, south-eastern Australia. Endangered Species Research 16, 165-181.

Koehn, J. and Nicol, S. (2014). Comparative habitat use by large riverine fishes. Marine and Freshwater Research, 65, 164–174.

Koehn, J., Lintermans, M. and Copeland, C. (2014a). Laying the foundations for fish recovery: the first 10 years of the Native Fish Strategy for the Murray – Darling Basin, Australia. Ecological Management and Restoration 15, 3-12.

Koehn, J.D., King, A.J., Beesley, L., Copeland, C., Zampatti, B.P. and Mallen-Cooper, M. (2014b). Flows for native fish in the Murray – Darling Basin: lessons and considerations for future management. Ecological Management and Restoration 15, 40-50.

Koehn, J., Todd, C., Zampatti, B., Stuart, I., Conallin, A. Thwaites,L. and Ye, Q. (2017). Using a population model to inform the management of river flows and invasive carp (Cyprinus carpio). Environmental Management 61, 432-442.

Koehn, J. D., Raymond, S. M., Stuart, I., Todd, C. R., Balcombe, S. R., Zampatti, B. P., Bamford, H., Ingram, B. A., Bice, C. M., Burndred, K., Butler, G., Baumgartner, L., Clunie, P., Ellis, I., Forbes, J. P., Hutchison, M., Koster, W. M., Lintermans, M., Lyon, J. P., Mallen-Cooper, M., McLellan, M., Pearce, L., Ryall, J., Sharpe, C., Stoessel, D. J., Thiem, J. D., Tonkin, Z., Townsend, A. and Ye, Q. (2020a). A compendium of ecological knowledge for restoration of freshwater fishes in Australia's Murray–Darling Basin. Marine and Freshwater Research, 71 (11). pp. 1391-1463.

Koehn, J., Balcombe, S., Baumgartner, L. J., Bice, C. M., Burndred, K., Ellis, I., Koster, W., Lintermans, M., Pearce, L., Sharpe, C., Stuart, I. G., & Todd, C. (2020b). What is needed to restore native fishes in Australia's Murray-Darling Basin? Marine and Freshwater Research, 71(11), 1464-1468.

Kopf R.K., Wassens S., McPhan L., Dyer J., Maguire J., Spencer J., Amos C., Kopf S., Whiterod N. (2019). Native and invasive fish dispersal, spawning and trophic dynamics during a managed river floodplain connection. Commonwealth Environmental Water Office. Murrumbidgee Selected Area Final report, pp 1-49.

Koster, W., Crook, D., Dawson, D. and Moloney, P. (2012). Status of fish populations in the lower Goulburn River (2003-2012). Arthur Rylah Institute for Environmental Research Client Report, Department of Sustainability and Environment, Heidelberg, Victoria.

Koster, W.M., Dawson, D.R., O'Mahony, D.J., Moloney, P.D. and Crook, D.A. (2014). Timing, Frequency and Environmental Conditions Associated with Mainstem–Tributary Movement by a Lowland River Fish, Golden perch (Macquaria ambigua). PloS one 9, e96044.

Lintermans, M. and Phillips B. (eds) 2005. Management of Murray Cod in the Murray-Darling Basin: Statement, recommendations and supporting papers. Proceedings of a workshop held in Canberra ACT, 3–4 June 2004. Murray-Darling Basin Commission, Canberra.

Lintermans, M. (2007). Fishes of the Murray – Darling Basin: an introductory guide. Canberra, Australia, Murray – Darling Basin Commission.

Lyon, J. and O'Connor, J. (2008). Smoke on the water: can riverine fish populations recover following a catastrophic fire-related sediment slug? Austral Ecology 33, 794-806.

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

Lugg, A.,& Copeland, C. (2014). Review of coldwater pollution in theMurray–Darling Basin and the impacts on fish communities. Ecological Managementand Restoration, 15(1), 71–79. https://doi.org/10.1111/emr.12074

Maheshwari, B. L., Walker, K. F. and McMahon, T. A. (1995). Effects of regulation on the flow regime of the River Murray, Australia. Regulated Rivers: Research and Management 10, 15–38.

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

Mallen-Cooper, M., Stuart, I. and Sharpe, C. (2014). Native fish recovery plan – Gunbower and Lower Loddon. Report prepared by Fishway Consulting Services, Kingfisher Research and CPS Environmental Research for North Central Catchment Management Authority. North Central Catchment Management Authority, Huntly, Victoria.

Mallen-Cooper, M. and. Zampatti, B. (2015a). Background Paper: rethinking the natural flow paradigm in the Murray – Darling Basin. Report prepared for the Murray – Darling Basin Authority.

Mallen-Cooper, M. and. Zampatti, B. (2015b). Background paper: use of life history conceptual models for flow management in the Murray – Darling Basin. Report prepared for the Murray – Darling Basin Authority.

Mallen-Cooper, M. and. Zampatti, B. (2015c). Background paper: Flow-related fish ecology in the Murray – Darling Basin: a summary guide for water management. Report prepared for the Murray – Darling Basin Authority.

Mallen-Cooper, M. and. Zampatti, B. (2018). History, hydrology and hydraulics: Rethinking the ecological management of large rivers. Ecohydrology. 2018; e1965.

Mallen-Cooper, M. and. Zampatti, B. (2020). Restoring the ecological integrity of a dryland river: why low flows in the Barwon-Darling River must flow. Ecological Management & Restoration 21(3) DOI:10.1111/emr.12428

Marshall, J., Menke, N., Crook, D., Lobegeiger, J., Balcombe, S., Huey, J., Fawcett, J., Bond, N., Starkey, A., Sternberg, D., Linke, S. and Arthington, A. (2016). Go with the flow: the movement behaviour of fish from isolated waterhole refugia during connecting flow events in an intermittent dryland river. Freshwater Biology 61, 1242-1258.

McCarthy, B., Tucker, M., Vilizzi, L., Campbell, C. and Walters, S. (2009). Implications of pumping water on the ecology of Hattah Lakes - report to the Murray – Darling Basin Commission by the Murray – Darling Freshwater Research Centre.

MDBA (2010). Guide to the proposed Basin Plan: overview. Australia, Murray – Darling Basin Authority, Canberra

MDBA (2011a). The Living Murray story — one of Australia's largest river restoration projects. Murray – Darling Basin Authority, Canberra.

MDBA (2011b). The proposed 'environmentally sustainable level of take' for surface water of the Murray – Darling Basin: methods and outcomes. Murray – Darling Basin Authority, Canberra.

MDBA (2012a). Assessment of environmental water requirements for the proposed Basin Plan: Barmah–Millewa Forest. Murray – Darling Basin Authority, Canberra.

MDBA (2012b). Assessment of environmental water requirements for the proposed Basin Plan: Edward–Wakool River System. Murray – Darling Basin Authority, Canberra.

MDBA (2012c). Assessment of environmental water requirements for the proposed Basin Plan: Gunbower-Koondrook-Perricoota Forest. Murray – Darling Basin Authority, Canberra.

MDBA (2012d). Assessment of environmental water requirements for the proposed Basin Plan: Hattah Lakes. Murray – Darling Basin Authority, Canberra.

MDBA (2012e). Assessment of environmental water requirements for the proposed Basin Plan: Lower River Murray (in-channel flows). Murray – Darling Basin Authority, Canberra.

MDBA (2012f). Assessment of environmental water requirements for the proposed Basin Plan: Riverland–Chowilla Floodplain. Murray – Darling Basin Authority, Canberra.

MDBA (2012g). Assessment of environmental water requirements for the proposed Basin Plan: The Coorong, Lower Lakes and Murray Mouth. Murray – Darling Basin Authority, Canberra.

MDBA (2012h). Assessment of environmental water requirements for the proposed Basin Plan: Lower Darling River System. Murray – Darling Basin Authority, Canberra.

MDBA (2012i). Assessment of environmental water requirements for the proposed Basin Plan: Mid Murrumbidgee River Wetlands. Murray – Darling Basin Authority, Canberra.

MDBA (2012j). Assessment of environmental water requirements for the proposed Basin Plan: Lower Murrumbidgee River Floodplain. Murray – Darling Basin Authority, Canberra.

MDBA (2012k). Assessment of environmental water requirements for the proposed Basin Plan: Lower Murrumbidgee River (in-channel flows). Murray – Darling Basin Authority, Canberra.

MDBA (2012l). Assessment of environmental water requirements for the proposed Basin Plan: Lower Goulburn River (in-channel flows). Murray – Darling Basin Authority, Canberra.

MDBA (2012m). Assessment of environmental water requirements for the proposed Basin Plan: Lower Goulburn River floodplain. Murray – Darling Basin Authority, Canberra.

MDBA (2013). Constraints Management Strategy 2013 to 2024. Murray – Darling Basin Authority, Canberra.

MDBA (2014a). Basin-wide environmental watering strategy. Murray – Darling Basin Authority, Canberra.

MDBA (2014b). Constraints management strategy. Murray-Darling Basin Authority, Canberra.

MDBA (2015). 2015-16 Basin annual environmental watering priorities: overview and technical summaries. Murray – Darling Basin Authority, Canberra.

MDBA (2016). "Delivering Environmental Water ". Retrieved 2 February 2016, from http://www.mdba.gov.au/managing-water/environmental-water/delivering-environmental-water.

MDBA (2018a). Observed Flows in the Barwon–Darling 1990-2017, A Hydrologic Investigation – list of references and source material .

MDBA (2018b). Ecological needs of low flows in the Barwon-Darling.

MDBA River Murray Data (Accessed 2016). https://riverdata.mdba.gov.au/system-view

MDBC (2004). Native fish strategy for the Murray – Darling Basin 2003-2013. Murray -Darling Basin Commission, Canberra.

MDBC (2006). The River Murray channel icon site management plan 2006-2007. Murray -Darling Basin Commission, Canberra.

Mitrovic, S., Oliver, R., Rees, C., Bowling, L. and Buckney, R. (2003). Critical flow velocities for the growth and dominance of Anabaena circinalis in some turbid freshwater rivers. Freshwater Biology 48, 164-174.

Nilsson, C. and Malm-Renöfält, B. (2008). Linking flow regime and water quality in rivers: a challenge to adaptive catchment management. Ecology and Society 13, 1-20.

NMCRT (2010). National recovery plan for the Murray Cod Maccullochella peelii peelii. National Murray Cod Recovery Team, Victorian Department of Sustainability and Environment, Melbourne.

NSW DPI (2006). Prime fact: Aquatic ecological community in the natural drainage system of the lowland catchment of the Lachlan River. NSW Department of Primary Industries, Port Stephens, New South Wales. https://www.dpi.nsw.gov.au/fishing/habitat/publications/pubs/aquatic-ecological-community-lowland-catchment-lachlan-river

NSW DPI (2007a). Prime fact: Lower Murray River aquatic ecological community. NSW Department of Primary Industries, Nelson Bay, New South Wales. https://www.dpi.nsw.gov.au/fishing/species-protection/conservation/what-current/endangered/murray-river-eec

NSW DPI (2007b). Primefact: Lowland Darling River aquatic ecological community. NSW Department of Primary Industries, Nelson Bay, New South Wales. https://www.dpi.nsw.gov.au/fishing/species-protection/conservation/what-current/endangered/darling-river-eec

NSW DPI (2015). Fish and Flows in the Northern Basin: responses of fish to changes in flow in the Northern Murray – Darling Basin – Reach Scale Report. Final report prepared for the Murray – Darling Basin Authority. NSW Department of Primary Industries, Tamworth.

NSW DPI (2016a). Fish communities and threatened species distributions of NSW. Report prepared for the Commonwealth Government. NSW Department of Primary Industries, Wollongbar.

NSW DPI (2016b). Lachlan River habitat mapping, investment recommendations for Cottons Weir, Forbes to Booberoi Weir reach of the Lachlan River.

NSW DPI (2016c). Lachlan River habitat mapping, investment recommendations for Willandra to Whealbah reach of the Lachlan River.

NSW DPI (2016d). Primefact: Hanley's River Snail. https://www.dpi.nsw.gov.au/fishing/species-protection/conservation/what-current/critically/hanleys-river-snail/primefact-hanleys-river-snail

NSW DPI (2017). Primefact: Silver Perch – Bidyanus bidyanus. NSW Department of Primary Industries, Port Stephens New South Wales.
https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0009/635778/Silver-Perch-Bidyanus-bidyanus.pdf

NSW DPI (2018). Good flows mean more fish: infographic 2. NSW Department of Primary Industries, Dubbo and Queanbeyan NSW.

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

Page, K., Read, A., Frazier, P. and Mount, N. (2005). The effect of altered flow regime on the frequency and duration of Bank full discharge: Murrumbidgee River, Australia. River Research and Applications 21, 567-578.

Phillips, W & Muller, K 2006, Ecological character of the Coorong, Lakes Alexandrina and Albert: wetland of international importance, SA Department of Environment and Heritage, Adelaide.

Poff, N., Allan, J., Bain, M., Karr, J., Prestegaard, K., Richter, B., Sparks, R. and Stromberg, J. (1997). The natural flow regime: a paradigm for river conservation and restoration. Bioscience 47, 769-784.

Pollino, C., Feehan, P., Grace, M. and Hart, B. (2004). Fish communities and habitat changes in the highly modified Goulburn Catchmnet, Victoria, Australia. Marine and Freshwater Research 55, 769-780.

Raymond S., R., M. and Tonkin, Z. (2011). Barmah-Millewa fish condition monitoring: 2010/2011 annual report. Arthur Rylah Institute for Environmental Research, Victorian Department of Sustainability and Environment, Heidelberg, Victoria.

Raymond, S. Duncan, M. Tonkin, Z. and Robinson, W. (2016). Barmah-Millewa Fish Condition Monitoring: 2006 to 2016. Arthur Rylah Institute for Environmental Research Unpublished Client Report for the Murray Darling Basin Authority. Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Raymond, S., Duncan, M., Tonkin, Z. and Robinson, W. (2017). Barmah-Millewa Fish Condition Monitoring 2006-2017. Report to the Murray Darling Basin Authority, 55p.

Raymond, S. Duncan, M. Tonkin, Z. and Robinson, W. (2018). Barmah-Millewa Fish Condition Monitoring: 2018. Arthur Rylah Institute for Environmental Research Unpublished Client Report for the Murray Darling Basin Authority. Department of Environment, Land, Water and Planning, Heidelberg, Victoria

Rehwinkel, R. and Sharpe, C. (2009). Gunbower forest fish monitoring surveys 2008-09: a report prepared for the North Central Catchment Management Authority by the Murray – Darling Freshwater Research Centre. Canberra Murray – Darling Freshwater Research Centre.

Robertson, A. I., Bacon, P. and Heagney, G. (2001). The response of floodplain primary production to flood frequency and timing. Journal of Applied Ecology 38, 126-136.

Robison, E. (2007). Calculating channel maintenance/elevated instream flows when evaluating water right applications for out of stream and storage water rights. Salem, Oregon United States, Oregon Department of Fish and Wildlife.

Rolls, R., Growns, I., Khan, T., Wilson, G., Ellison, T., Prior, A. and Waring, C. (2013). Fish recruitment in rivers with modified discharge depends on the interacting effects of flow and thermal regimes. Freshwater Biology 58, 1804-1819.

Rowland, S. (1998). Aspects of the reproductive biology of Murray Cod (Maccullochella peelii peelii). Proc. Linn. Soc. NSW 120, 147–167.

Rowland, S. (2004). Overview of the history, fishery, biology and aquaculture of Murray cod (Maccullochella peelii peelii) in Lintermans, M. and Phillips B. (eds) 2005. Management of Murray Cod in the Murray-Darling Basin: Statement, recommendations and supporting papers. Proceedings of a workshop held in Canberra ACT, 3–4 June 2004. Murray-Darling Basin Commission, Canberra

Sharpe, C. (2011). Spawning and recruitment ecology of golden perch (Macquaria ambigua Richardson 1845) in the Murray and Darling Rivers. Thesis submitted in fulfilment of the requirements of the degree of Doctor of Philosophy. Griffith School of Environment Faculty of Science, Environment, Engineering and Technology, Griffith University.

Sharpe, C. and Vilizzi, L. (2011). Fish. In: The Living Murray condition monitoring at Lindsay, Mulcra and Walpolla Islands 2009/10. Final report prepared for the Department of Sustainability and Environment (e.d. M.W. Henderson). Pp.174-199.Murray-Darling Freshwater Research Centre, Mildura.

Sharpe, C. and Stuart, I. (2013). Billabong, Yanco and Colombo Creek Fish Baseline Project 2012-2013. Draft report for the Murray Catchment Management Authority by CPS Environmental Research, Irymple Victoria.

Sharpe, C., Vilizzi, L., and Campbell-Brown, S. (2014). Gunbower Island annual fish surveys: 2014. Report for the North Central Catchment Management Authority by CPS Environmental Research, Irymple Victoria.

Stuart, I. and Sharpe, C. (2017). Towards a southern connected basin flow plan: connecting rivers to recover native fish communities. Kingfisher Research and CPS Enviro report to the Murray-Darling Basin Authority.

Sharpe, C. (2018) Lower Murrumbidgee Floodplain fish surveys 2018. Summary of Findings Report for the NSW Office of Environment and Heritage by CPS Enviro P/L.

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

Sharpe, C. and Stuart, I. (2018b). Assessment of Murray cod recruitment in the lower Darling River in response to environmental flows 2016–18. CPS Enviro technical report to The Commonwealth Environmental Water Office.

Sheldon, F. (2017). Characterising the ecological effects of changes in the 'low-flow hydrology' of the Barwon-Darling River. Advice to the Commonwealth Environmental Water Holder Office.

Stoffels, R., Clarke, K., Rehwinkel, R. and McCarthy, B. (2013). Response of a floodplain fish community to river-floodplain connectivity: natural versus managed reconnection. Canadian Journal of Fisheries and Aquatic Sciences 7, 236-245.

Stuart, I. 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, 337-347.

Stuart, I. and Sharpe, C. (2017). Towards a southern connected basin flow plan: connecting rivers to recover native fish communities. Kingfisher Research and CPS Enviro report to the Murray-Darling Basin Authority. Includes Appendix 12 in "*Northern golden perch population recovery: protection and enhancement of Border River flows, from Goondiwindi to Menindee for Murray-Darling Basin benefits*"

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, 1295–1306.

Stuart, I.G. and Sharpe, C.P. (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.

Stuart, I., D'Santos, P., Rourke, M., Ellis, I., Harrisson, K., Michie, L., Sharpe, C. and Thiem, J. (2021). Monitoring native fish response to environmental water delivery in the lower Darling River 2020-2021. State of New South Wales and Department of Planning, Industry and Environment, New South Wales, Australia.

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

Thiem JD, Wooden IJ, Baumgartner LJ, Butler GL, Forbes J, Taylor MD, et al. (2018) Abiotic drivers of activity in a large, free-ranging, freshwater teleost, Murray cod (Maccullochella peelii). PLoS ONE 13(6): e0198972. https://doi.org/10.1371/journal.pone.0198972

Thiem, J.D., Wooden, I.J., Baumgartner, L.J., Butler, G.L., Taylor, M.D. & Watts, R.J. (2020). Hypoxic conditions interrupt flood-response movements of three lowland river fish species: Implications for flow restoration in modified landscapes. *Ecohydrology*; e2197. https://doi.org/10.1002/eco.2197

Thiem, J.D., Baumgartner, L.J., Fanson, B., Sadekov, A., Tonkin, Z. and Zampatti, B.P. (2021). Contrasting natal origin and movement history informs recovery pathways for three lowland river species following a mass fish kill. Marine and Freshwater Research.

Thoms, M. C. and K. F. Walker (1993). Channel changes associated with two adjacent weirs on a regulated lowland alluvial river. Regulated Rivers: Research and Management 8, 271-284.

Thoms, M.C. and Sheldon, F. (2000). Water resource development and hydrological change in a large dryland river: the Barwon-Darling River, Australia. Journal of Hydrology 228, 10-21

Tonkin, Z.D., King, A.J., Robertson, A.I. and Ramsey, D.S.L. (2011). Early fish growth varies in response to components of the flow regime in a temperate floodplain river. Freshwater Biology 56, 1769-1782.

Tonkin, Z., Lyon, J., Kitchingman, A., Kearns, J., O'Mahony, J., Bird, T., Nicol, S., Maloney, P. and Hackett, G. (2014). System scale higher trophic order responses to environmental watering: Growth, recruitment and population responses of large-bodied native fish to flows in the mid-Murray River. Unpublished Client Report for Murray – Darling Basin Authority. Arthur Rylah Institute for Environmental Research. Department of Environment and Primary Industries, Heidelberg, Victoria.

Tonkin, Z., Kearns, J., O'Mahony., J., Mahoney, J. Kitchingman, A. and Ayres, R. (2015). Sustaining Macquarie Perch in the Yarra River – a multi population investigation of recruitment dynamics. Unpublished Client Report for Melbourne Water. Arthur Rylah Institute for Environmental Research, Victorian Department of Sustainability and Environment, Heidelberg, Victoria.

Tonkin, Z., Stuart, I., Kitchingman, A., Thiem, J.D., Zampatti, B., Hackett, G., et al., 2019. Hydrology and water temperature influence recruitment dynamics of the threatened silver perch (Bidyanus bidyanus) in a regulated lowland river.Mar. Freshw. Res. 70, 1333–1344.

Tonkin, Z., Yen, J., Lyon, J., Kitchingman, A., Koehn, J.D., Koster, W.M., Lieschke, J., Raymond, S., Sharley, J. and Stuart, I. 2021. Linking flow attributes to recruitment to inform water management for an Australian freshwater fish with an equilibrium life-history strategy. Science of the Total Environment 752, 141863.

Vilizzi, L., McCarthy, B., Scholz, O., Sharpe, C. and Wood, D. (2012). Managed and natural inundation: benefits for conservation of native fish in a semi-arid wetland system. Aquatic Conservation: Marine and Freshwater Ecosystems 23, 37-50.

Walker, K. F., and Thoms, M. (1993). Environmental effects of flow regulation on the lower River Murray, Australia. Regulated Rivers: Research and Management 8, 103–119.

Walker, K. F. (2006). Serial weirs, cumulative effects: the lower River Murray, Australia. In 'Ecology of Desert Rivers' (Ed. R Kingsford) pp 248-297(Cambridge University Press: Cambridge).

Wallace, T., Daly, R., Aldridge, K., Cox, J., Gibbs, M., Nicol, J., Oliver, R., Walker, K., Ye, Q. and Zampatti, B. (2014a). River Murray Channel: environmental water requirements: ecological objectives and targets. Adelaide, South Australia, Goyder Institute for Water Research.

Wallace, T., Daly, R., Aldridge, K., Cox, J., Gibbs, M., Nicol, J., Oliver, R., Walker, K., Ye, Q. and Zampatti, B. (2014b). River Murray channel environmental water requirements: hydrodynamic modelling results and conceptual models. Adelaide, South Australia, Goyder Institute for Water Research.

Wassens, S., Jenkins, K., Spencer, J., Thiem, J., Wolfenden, B,. Bino, G., Thomas, R., Ocock, J., Lenon, E., Kobayashi, T., Baumgartner, L., Bindokas, J. and Hall, A. (2014). Monitoring the ecological response of Commonwealth environmental water delivered in 2013-14 to the Murrumbidgee River system (Draft final report, September 2014), Commonwealth of Australia 2014.

Wassens, S., Spencer, J., Wolfenden, B., Thiem, J., Thomas, R., Jenkins, K., Hall, A., Ocock, J., Kobayashi, T, Bino, G., Davis, T., Heath, J ., Kuo, W., Amos, C. and Michael, D (2018). Commonwealth Environmental Water Office Long-Term Intervention Monitoring project Murrumbidgee River System Selected Area evaluation. Technical Report, 2014-18. Report prepared for the Commonwealth Environmental Water Office

Water Technology (2010). Goulburn River environmental flows hydraulics study, report for the Goulburn– Broken Catchment Management Authority, Melbourne.

Watts, R., McCasker, N., Baumgartner, L., Bowen, P., Burns, A., Conallin, A., Dyer, J., Grace, M., Healy, S., Howitt, J., Kopf, R. Wassens, S., Watkins, S. and Wooden, I. (2013). Monitoring the ecosystem responses to Commonwealth environmental water delivered to the Edward-Wakool river system, 2012-13 report 2. Canberra Charles Sturt University.

Watts, R., Kopf, K., McCasker, N., Howitt, J., Conallin, J., Wooden, I. and Baumgartner, L. (2017). Adaptive management of environmental flows: using irrigation infrastructure to deliver environmental benefits during a large hypoxic blackwater event in the Southern Murray–Darling Basin, Australia. Environmental Management. Published online, DOI 10.1007/s00267-017-0941-1.

Watts R.J., Bond N.R, Healy S., Liu X., McCasker N.G., Siebers A., Sutton N., Thiem J.D., Trethewie J.A., Vietz G., Wright D.W. (2020). 'Commonwealth Environmental Water Office Monitoring, Evaluation and Research Project: Edward/Kolety-Wakool River System Selected Area Technical Report, 2019-20'. Report prepared for Commonwealth Environmental Water Office. Commonwealth of Australia.

Wedderburn, S. D., M. P. Hammer and Bice, C.M. (2012). Shifts in small-bodied fish assemblages resulting from drought-induced water level recession in terminating lakes of the Murray-Darling Basin, Australia. Hydrobiologia 691, 35-46

Wedderburn, S., Bailey, C., Delean, S. and Paton, D. (2016). Population and osmoregulatory responses of a euryhaline fish to extreme salinity fluctuations in coastal lagoons of the Coorong, Australia. Estuarine, Coastal and Shelf Science, 2016; 168:50-57.

Whiterod, N., Zukowski, S., Ellis, I., Pearce, L., Raadik, T., Rose, P., Stoessel, D. and Wedderburn, S. (2019). The present status of key small-bodied threatened freshwater fishes in the southern Murray-Darling Basin, 2019. A report to the Tri-State Murray NRM Regional Alliance. Aquasave–Nature Glenelg Trust, Goolwa Beach.

Whiterod, N. and Gannon, R. (2020). Fish communities across lower and mid-reaches of the Murrumbidgee River Catchment over 2018–2020. New South Wales Department of Planning, Industry and Environment (NSW DPIE). Aquasave–Nature Glenelg Trust, Hindmarsh Valley.

Wilson, P., Zampatti, B., Leigh, S. and Bice, C. (2014). Chowilla icon site fish assemblage condition monitoring 2013. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Ye, Q., Aldridge, K., Bucater, L., Bice, C., Busch, B., Cheshire, K., Fleer, D., Hipsey, M.,Leigh, S., Livore, J. and Nicol, J. (2013). Monitoring of ecological responses to the delivery of Commonwealth Environmental Water in the lower River Murray, South Australia, during 2011-12. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Zampatti, B., Leigh, S. and Nichol, J. (2011). Fish and aquatic macrophyte communities in the Chowilla anabranch system, South Australia. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Zampatti, B. P. and Leigh, S. J. (2013a). Effects of flooding on recruitment and abundance of Golden perch (Macquaria ambigua ambigua) in the lower River Murray. Ecological Management and Restoration 14(2), 135-143.

Zampatti, B.P. and Leigh, S.J. (2013b). 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, 618-630.

Zampatti, B.P., Wilson, P.J., Baumgartner, L., Koster, W., Livore, J., Thiem, J., Tonkin, Z. and Ye, Q. (2015). Reproduction and recruitment of golden perch (Macquaria ambigua) in the southern Murray – Darling Basin in 2013/14: an exploration of river-scale response, connectivity and population dynamics. Report to Murray – Darling Basin Authority. South Australian Research and Development Institute (Adelaide), Narranderra Fisheries Centre, and Arthur Rylah Institute for Environmental Research (Melbourne).

Appendix A: Fish of the Southern MDB

Table A 1: Fish species recorded or expected in the Southern MDB including the conservation status of each species internationally (IUCN 2015), in the Commonwealth, in each MDB state and inclusion in NSW EEC is presented. Non-native species do not have conservation listing.

Status	International	Commonwealth	New south Wales		Victoria		South Australia	ACT
Species/population	International Union for Conservation of Nature (IUCN 2015)	Commonwealth (EPBC 2004)	NSW Fisheries Management Act (FM Act 1994)	NSW Endangered Ecological Community (NSW DPI 2007a)	Flora and Fauna Guarantee Act 1988 (DELWP 2015)	DSE Advisory List of Threatened Fauna	SA Fisheries Management Act 2007	Nature Conservation Act
Large-bodied native species								
Murray Cod	Critically endangered	Vulnerable	Not listed	Lower Murray	Threatened	Vulnerable	Not Protected	Not listed
Trout Cod	Endangered	Endangered	Endangered	Lower Murray	Threatened	Critically endangered	Protected	Endangered
Mulloway (4)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	N/A
Medium-bodied native species								
Bony Herring	Not listed	Not listed	Not listed	Lower Murray	Not listed	Not listed	Not Protected	Not listed
Freshwater Catfish (Eel-tailed)	Not listed	Not listed	Endangered population	Lower Murray	Threatened	Endangered	Protected	Not listed
Golden Perch	Not listed	Not listed	Not listed	Lower Murray	Not listed	Near threatened	Not Protected	Not listed
Macquarie Perch	Data deficient	Endangered	Endangered	Lower Murray	Threatened	Endangered	Not listed	Endangered
River Blackfish	Not listed	Not listed	Threatened	Lower Murray	Not listed	Critically endangered	Protected	Not listed
Two-spined Blackfish	Least concern	Not listed	Not listed	Lower Murray	Not listed	Not listed	Not listed	Vulnerable
Silver Perch	Vulnerable	Critically endangered	Vulnerable	Lower Murray	Threatened	Vulnerable	Protected	Endangered
Spangled Perch	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Short-finned Eel (1)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not Protected	Not listed

Status	International	Commonwealth	New south Wales		Victoria		South Australia	ACT
Short-headed Lamprey (1)	Not listed	Not listed	Not listed	Lower Murray	Not listed	Not listed	Not Protected	Not listed
Pouched Lamprey (1)	Not listed	Not listed	Not listed	Lower Murray	Not listed	Not listed	Protected	Not listed
Pouched Lamprey (1)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Endangered
Black Bream (4)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Endangered
Greenback Flounder (4)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	N/A
Long-snouted Flounder (4)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	N/A
Yellow-eyed Mullet (4)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	N/A
Congolli (Tupong) (1)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not Protected	Not listed
Small-bodied native species								
Australian Smelt	Not listed	Not listed	Not listed	Lower Murray	Not listed	Not listed	Not Protected	Not listed
Carp Gudgeon (incl. Midgely's, Western and Lakes Gudgeon)	Not listed	Not listed	Not listed	Lower Murray	Not listed	Not listed	Not Protected	Not listed
Dwarf Flat-headed Gudgeon	Not listed	Not listed	Not listed	Lower Murray	Not listed	Not listed	Not Protected	Not listed
Flat-headed Gudgeon	Not listed	Not listed	Not listed	Lower Murray	Not listed	Not listed	Not Protected	Not listed
Mountain Galaxias (3)	Not listed	Not listed	Not listed	Lower Murray	Not listed	Endangered (3)	Not Protected	Not listed
Murray – Darling Rainbowfish	Not listed	Not listed	Not listed	Lower Murray	Threatened	Vulnerable	Not Protected	Not listed
Flat-headed Galaxias (Murray Jollytail)	Vulnerable	Not listed	Critically endangered	Lower Murray	Not listed	Vulnerable	Not Protected	Not listed
Olive Perchlet (Glassfish)	Data deficient	Not listed	Endangered	Lower Murray	Threatened	Regionally extinct	Protected	Not listed

Status	International	Commonwealth	New south Wales		Victoria		South Australia	ACT
(western NSW population)								
Southern Purple-Spotted Gudgeon	Not listed	Not listed	Endangered	Lower Murray	Threatened	Regionally extinct	Protected	Not listed
Southern Pygmy Perch	Not listed	Not listed	Endangered	Lower Murray	Not listed	Vulnerable	Protected	Not listed
Unspecked Hardyhead	Not listed	Not listed	Not listed	Lower Murray	Threatened	Not listed	Not Protected	Not listed
Common Galaxias (1)	Not listed	Not listed	NA	Lower Murray	Not listed	Not listed	Not Protected	Not listed
Climbing Galaxias (2)	Least concern	Not listed	Not listed	Not listed	Not listed	Not listed	Not Protected	Not listed
Spotted Galaxias (2)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not Protected	Not listed
Murray Hardyhead	Endangered	Endangered	Critically endangered	Lower Murray	Threatened	Critically endangered	Not Protected	Not listed
Lagoon Goby (4)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Tamar River Goby (4)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Bluespot Goby (4)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Bridled Goby (4)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Small-mouthed Hardyhead (4)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Sandy Sprat (4)	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed
Non-native species								
Carp	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Gambusia	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Goldfish	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Rainbow Trout	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Brown Trout	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Redfin Perch	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Tench	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Status	International	Commonwealth	New south Wales		Victoria		South Australia	ACT
Oriental Weatherloach	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

(1) diadromous species – spawn in estuarine/marine reaches, although specific spawning information is unclear
(2) introduced to Murray – Darling Basin
(3) recently separated into multiple taxa.

Table A 2. Biological information for fish species recorded or expected in the Southern MDB (sourced from Lintermans 2007;(DPI 2007); Hammer et al. 2009; Baumgartner et al. 2013). Scales of movement comprise micro (< 100 m), meso (100s m to 10s km) and macro (100s km).

Species	River Type	Preferred habitat features	Longevity (years)	Scale of adult/juvenile movements	Spawning season and temperature (estimated)	Spawning method	Fecundity (eggs, per female, per annum)	Larval drift
Large-bodied native species								
Murray Cod	Slopes, lowland	Hydraulically complex streams containing submerged structure (e.g. rocks and snags).	Long-lived (< 60 yr.)	Meso	Sept-Dec (>18 °C)	Nesting, parental care	10,000 - 90,000	Yes
Trout Cod	Montane, slopes	Deep flowing pools containing submerged structure (e.g. rocks and snags)	Long-lived (< 60 yr.)	Meso	Sept-Nov (>20 °C)	Nesting, parental care	1,000 - 10,000	Yes
Mulloway (4)	Lower Lakes, Estuary	Marine as adult (near shore environment), but juveniles use estuarine habitats, particularly deeper channels and gutters	Long-lived (<40 yr.)	Macro	Oct-Jan	Pelagic spawner	>1,000,000	Pelagic marine larvae
Medium-bodied native species								
Bony Herring	Slopes, lowland	Warm lotic and lentic waterbodies (streams and wetlands).	Medium-lived (< 5 yr.)	Meso	Oct-Feb (>18 °C)	Serial (multiple events per year)	33,000-800,000	Yes
Freshwater Catfish (Eel-tailed)	Montane, slopes, lowland	Slow-flowing streams and wetlands; well vegetated habitats containing snags, with fringing and riparian vegetation.	Medium-lived (< 8 yr.)	Meso	Sept-March (>20 °C)	Nesting, parental care	10,000-50,000	Yes

Species	River Type	Preferred habitat features	Longevity (years)	Scale of adult/juvenile movements	Spawning season and temperature (estimated)	Spawning method	Fecundity (eggs, per female, per annum)	Larval drift
Golden Perch	Slopes, lowland	Lowland rivers; submerged structure (e.g. rocks and snags).	Long-lived (< 26 yr.)	Macro	Oct-April (>17 °C)	Serial (multiple events per year)	100,000-500,000	Yes
Macquarie Perch	Montane, slopes	Connected pools riffles and lakes, mainly in upper reaches with fringing and riparian vegetation.	Long-lived (< 25 yr.)	Meso	Oct-Dec (>17 °C)	Batch/Serial	10,000-100,000	No
River Blackfish	Montane, slopes	Clear flowing water, gravel substrate with dense submerged and riparian structure. Occurs in some lakes.	Medium-lived (3-9 yr.)	Meso	Oct-Jan (>16 °C)	Nesting, parental care	200-500	No
Two-spined Blackfish	Montane, slopes	Clear flowing water in upland or montane streams. Dense submerged and riparian structure.	Medium-lived (3-9 yr.)	Meso	Oct-Dec (>17 °C)	Nesting, parental care	80-420	No
Silver Perch	Slopes, lowland	Lowland rivers; submerged structure (e.g. rocks and snags).	Long-lived (< 26 yr.)	Meso	Oct-Apr(>20 °C)	Serial (multiple events per year)	200,000-300,000	Yes
Spangled Perch	Slopes, lowland	Warm lotic and lentic waterbodies including rivers, wetlands, drains and isolated water holes.	Medium-lived (< 5 yr.)	Meso	Nov-Feb (>20 °C)	Serial (multiple events per year)	20,000 - 115,000	Yes
Short-finned Eel (1)	Slopes, lowland	Low flowing rivers and waterbodies in coastal catchments, occasionally in the Murray River. Spawning and early life stages at sea.	Long-lived (< 26 yr.)	Macro	Dec-Feb	Spawn at sea	500,000 - 3,000,000	Yes
Short-headed Lamprey (1)	Slopes, lowland	Marine/estuarine except for upstream spawning runs to flowing lowland rivers.	Medium-lived (8-10 years)	Macro	Aug-Nov	Serial (multiple events per year)	3,800 - 13,400	No
Pouched Lamprey (1)	Slopes, lowland	Marine except for upstream spawning runs to generally faster flowing shallow lowland river habitats.	Medium-lived (8-10 years)	Macro	Aug-Nov	Nesting, no parental care, semelparous	40,000-70,000	No
Black Bream (4)	Lower Lakes, Estuary	Estuarine species, but occasionally in lowland freshwater habitats. Prefers physical structure (snags, rock,	Long-lived (< 25 yr.)	Meso	Aug-Nov	Serial (multiple events per year)	60,000-3,000,000	Pelagic planktonic larvae

Species	River Type	Preferred habitat features	Longevity (years)	Scale of adult/juvenile movements	Spawning season and temperature (estimated)	Spawning method	Fecundity (eggs, per female, per annum)	Larval drift
		tubeworm reefs). Estuarine spawning						
Greenback Flounder (4)	Lower Lakes, Estuary	Benthic estuarine/marine species. Typically found on sandy, silty substrates within estuaries. Marine spawning	Medium-lived (<10 yr.)	Meso	June-August	Serial (multiple events per year)	800,000-2,000,000	Pelagic planktonic larvae
Long-snouted Flounder (4)	Lower Lakes, Estuary	Benthic estuarine/marine species. Typically found on sandy, silty substrates within estuaries. Likely marine spawning	Medium-lived (<10 yr.)	Meso	June-August	Serial (multiple events per year)	unknown	Pelagic planktonic larvae
Yellow-eyed Mullet (4)	Lower Lakes, Estuary	Common in various habitats within estuaries. Marine spawning	Medium-lived (< 5 yr.)	Meso	December-August	Serial (multiple events per year)	120,000-650,000	Pelagic planktonic larvae
Congolli (1)	Slopes, lowland.	Estuarine areas and wetlands of coastal rivers. Prefers submerged structure.	Medium-lived (< 5 yr.)	Macro	May-Sept	Spawn at sea		Unknown
Small-bodied native species								
Australian Smelt	Montane, slopes	Low flowing pelagic habitat.	Short-lived (< 3 yr.)	Micro-meso	Sept-Feb (> 11°C)	Batch	100-1,000 eggs/batch	Yes
Carp Gudgeon (species)	Montane, slopes, lowland	Slow flowing well vegetated streams and wetlands.	Medium-lived (< 5 yr.)	Micro	Sept-April (>20 °C)	Batch, parental care	100-2,000	Sometimes
Dwarf Flat-headed Gudgeon	Slopes, lowland	Slow flowing well vegetated streams and wetlands.	Medium-lived (< 5 yr.)	Micro	Sept-April (>20 °C)	Batch, parental care	500-900	Sometimes
Flat-headed Gudgeon	Montane, slopes	Slow flowing well vegetated streams and wetlands.	Medium-lived (< 5 yr.)	Micro-meso	Sept-Feb (>20 °C)	Batch, parental care	500-900	Sometimes
Mountain Galaxias (3)	Montane, slopes	Pools and riffles in small and large streams (lowland and montane).	Medium-lived (3-9 yr.)	Meso	Sept-Dec (7-11 °C)	Batch	50-400	No

Species	River Type	Preferred habitat features	Longevity (years)	Scale of adult/juvenile movements	Spawning season and temperature (estimated)	Spawning method	Fecundity (eggs, per female, per annum)	Larval drift
Murray – Darling Rainbowfish	Slopes, lowland	Slow flowing well vegetated streams and wetlands.	Medium-lived (< 5 yr.)	Micro-meso	Sept-Feb (>20 °C)	Batch	35-350	Sometimes
Flat-headed Galaxias	Montane, lowland	Slow flowing well vegetated streams and wetlands.	Short-lived (< 2 yr.)	Meso	Aug-Sept (>10.5 °C)	Serial (multiple events per year)	2,000-7,000	No
Olive Perchlet	Slopes, lowland	Slow-flowing streams and wetlands; well vegetated habitats containing snags.	Medium-lived (< 4 yr.)	Micro	Oct-Dec (>22 °C)	Serial (multiple events per year)	200-700	No
Southern Purple spotted Gudgeon	Montane, slopes, lowland	Slow-flowing streams and wetlands; well vegetated habitats containing snags.	Medium-lived (< 10 yr.)	Micro	Sept-Feb (>20 °C)	Batch, parental care	200-1300	No
Southern Pygmy Perch	Montane, slopes, lowland	Still or slow-flowing well vegetated streams and wetlands.	Medium-lived (3-7 yr.)	Micro	Sept-Jan (>16 °C)	Batch	100-4,000	No
Unspecked Hardyhead	Slopes, lowland	Slow flowing well vegetated streams and wetlands.	Short-lived (< 2 yr.)	Micro	Sept-April (>18 °C)	Batch	50-500	Sometimes
Murray Hardyhead	Slopes, lowlands	Saline habitats; often vegetated wetlands.	Short-lived (< 2 yr.)	Micro	Sept-April (>18 °C)	Batch	80-500	No
Climbing Galaxias (2)	Montane, slopes	Normally coastal streams; translocated and persists in upland Murray River tributaries.	Medium-lived (3-7 yr.)	Meso	April-May	Batch	7,000-23,000	Yes
Spotted Galaxias (2)	Slopes, lowlands	Snags, rocks and overhanging banks of lowland coastal habitats. Translocated population in upper Campaspe and Loddon rivers.	Medium-lived (3-7 yr.)	Meso	Sept-Dec	Batch	1,000-16,000	Yes
Common Galaxias (1)	Lower Lakes, Estuary	Pelagic marine larvae. Found in a variety of freshwater habitats as adults, typically slow flowing waters of lakes, wetlands, streams.	Short-lived (< 3 yr.)	Macro	May-Nov	Serial (multiple events per year). Eggs laid on vegetation at high tide mark, with terrestrial development	400-8,000	Pelagic planktonic larvae

Species	River Type	Preferred habitat features	Longevity (years)	Scale of adult/juvenile movements	Spawning season and temperature (estimated)	Spawning method	Fecundity (eggs, per female, per annum)	Larval drift
Lagoon Goby (4)	Lower Lakes, Estuary	Still or slow-flowing on silt or mud substrates with structure i.e. rocks, vegetation, typically in estuary but also adjacent freshwater habitats	Short-lived (< 3 yr.)	Micro	Sept-Feb	Serial (multiple events per year)	unknown	Pelagic planktonic larvae
Tamar river Goby (4)	Lower Lakes, Estuary	Still or slow-flowing on silt or mud substrates with structure i.e. rocks, vegetation, typically in estuary but also adjacent freshwater habitats	Short-lived (< 3 yr.)	Micro	Sept-Feb	Serial (multiple events per year)	unknown	Pelagic planktonic larvae
Bluespot Goby (4)	Lower Lakes, Estuary	Still or slow-flowing on silt or mud substrates with structure i.e. rocks, vegetation, typically in estuary but also adjacent freshwater habitats	Short-lived (< 3 yr.)	Micro	Sept-Feb	Serial (multiple events per year)	unknown	Pelagic planktonic larvae
Bridled Goby (4)	Lower Lakes, Estuary	Still or slow-flowing on silt or mud substrates with structure i.e. rocks, vegetation, typically in estuary but also adjacent freshwater habitats	Short-lived (< 3 yr.)	Micro	Sept-Feb	Serial (multiple events per year)	unknown	Pelagic planktonic larvae
Small-mouthed Hardyhead (4)	Lower Lakes, Estuary	Found in a variety of estuarine habitats, particularly in shallower waters. Found in a wide range of salinities from freshwater to hyper-marine	Short-lived (< 2 yr.)	Meso	Sept-Feb	Serial (multiple events per year)	<500	Pelagic planktonic larvae
Sandy Sprat (4)	Lower Lakes, Estuary	Pelagic habitats of estuaries. Marine spawning	Short-lived (< 4 yr.)	Macro	Oct-Feb	Serial (multiple events per year)	700-5,600	Pelagic planktonic larvae
Non-native species								
Carp	Montane, slopes, lowland	Slow-flowing streams and wetlands, but also common in faster flowing streams.	Long-lived (< 65 yr.)	Meso	Sept-Mar (>17 °C)	Serial (multiple events per year)	75,000-260,000	Sometimes

Species	River Type	Preferred habitat features	Longevity (years)	Scale of adult/juvenile movements	Spawning season and temperature (estimated)	Spawning method	Fecundity (eggs, per female, per annum)	Larval drift
Gambusia	Montane, slopes, lowland	Fringes of still or slow-flowing streams and waterbodies. Often amongst macrophytes.	Medium-lived (< 3 yr.)	Micro	Sept-May (>16 °C)	Batch	<500	N/A
Goldfish	Montane, slopes, lowland	Slow flowing well vegetated streams and wetlands.	Medium-lived (< 10 yr.)	Micro	Oct-Jan (>15 °C)	Serial (multiple events per year)	280-20,000	Sometimes
Rainbow Trout	Montane	Cool, upland streams and lakes.	Medium-lived (3-9 yr.)	Micro	Aug-Oct (<22 °C)	Batch	500-3000	No
Brown Trout	Montane	Cool, upland streams and lakes.	Medium-lived (3-9 yr.)	Micro	Aug-Oct (<22 °C)	Batch	200-1000	No
Redfin Perch	Montane	Slow flowing well vegetated streams and wetlands.	Long-lived (< 22 yr.)	Micro	Sept-Dec (>12 °C)	Batch	5,000-80,000	No
Tench	Slopes, lowland	Slow-flowing streams and waterbodies.	Long-lived (20-30 yr.)	Micro	Sept-Feb	Batch	300,000-900,000	No
Oriental Weatherloach	Montane, slopes, lowland	Slow-flowing streams and waterbodies.	Medium (< 13 yr.)	Micro	Dec-Feb	Serial (multiple events per year)	4,000-8,000	No

(1) diadromous species – spawn in estuarine/marine reaches, although specific spawning information is unclear

(2) introduced to Murray – Darling Basin

(3) recently separated into multiple taxa.

Appendix B: Map series of NSW listed threatened species distributions for the NSW section of the Murray-Darling Basin

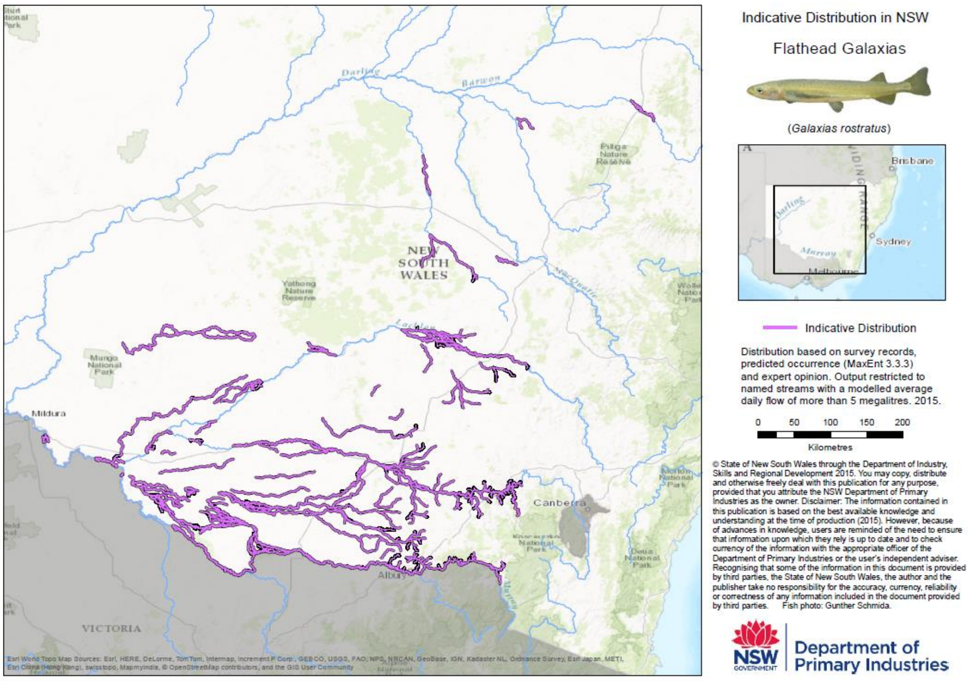

Figure 22. Indicative distribution in NSW – Flathead Galaxias (NSW DPI 2016a).

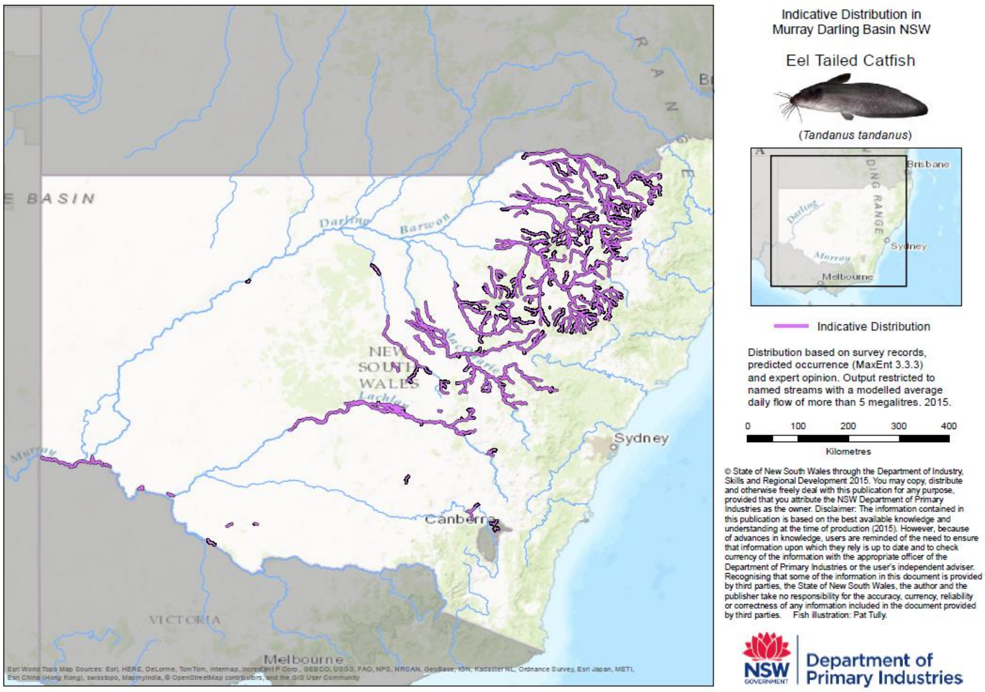

Figure 23. Indicative distribution in NSW MDB – Eel Tailed Catfish (NSW DPI 2016a).

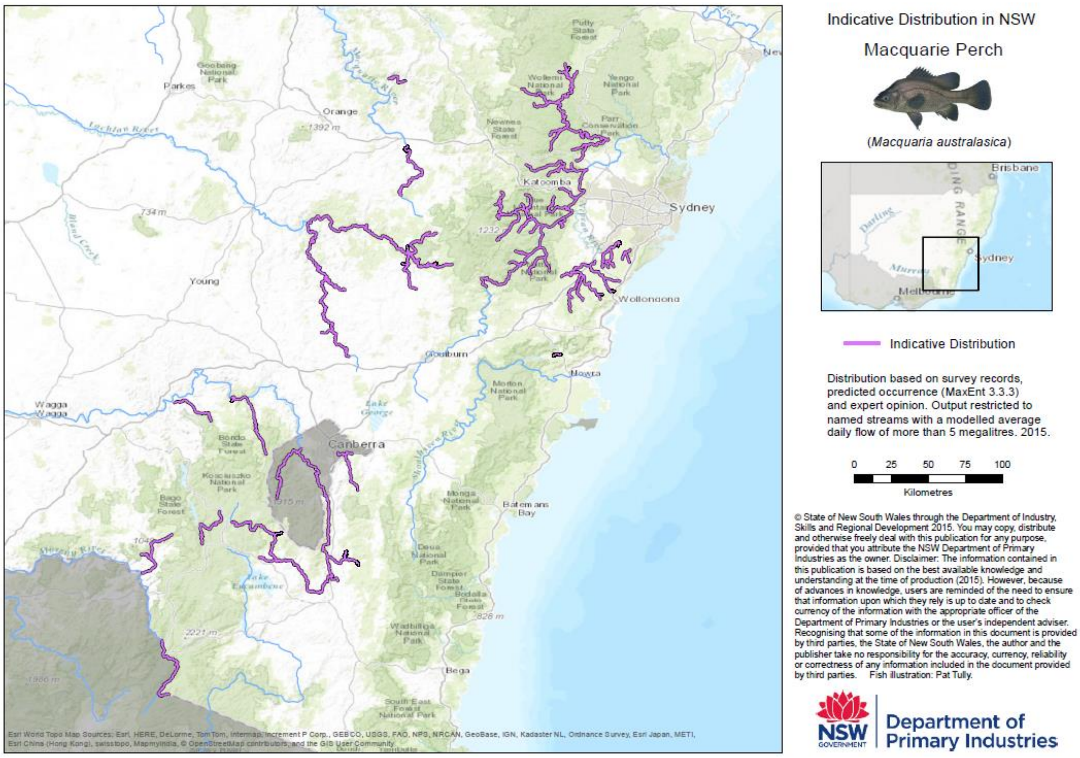

Figure 24. Indicative distribution in NSW – Macquarie Perch (NSW DPI 2016a).

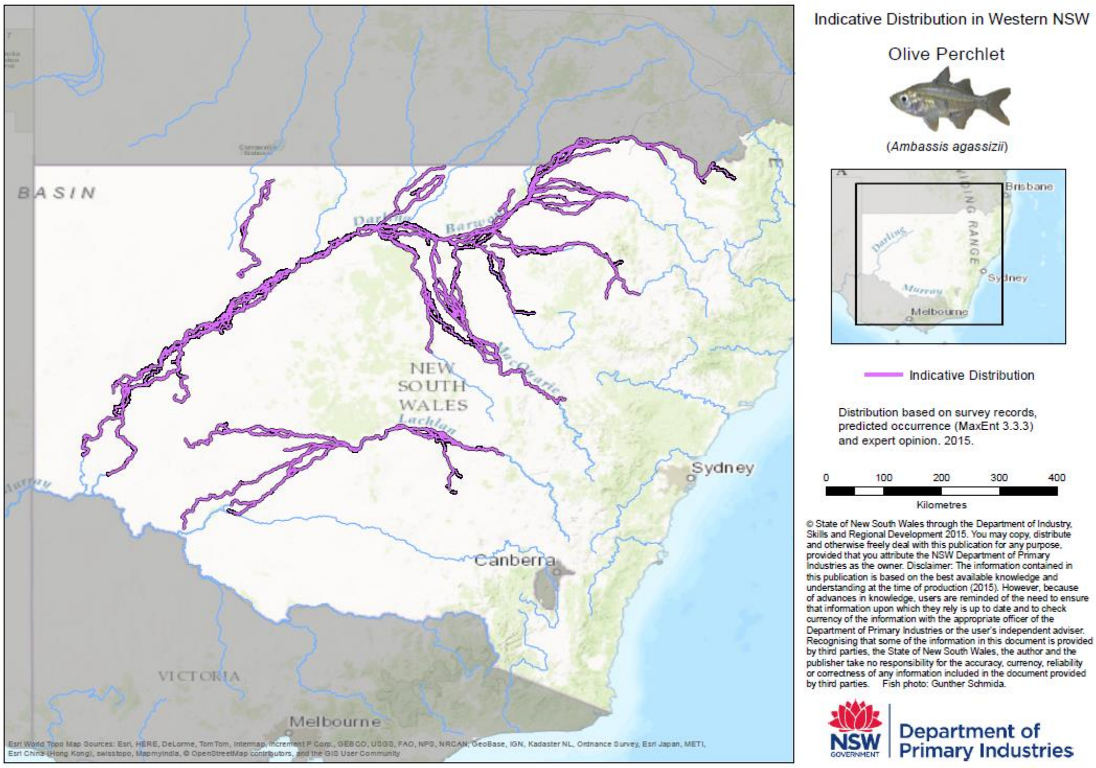

Figure 25. Indicative distribution in Western NSW: Olive Perchlet (NSW DPI 2016a).

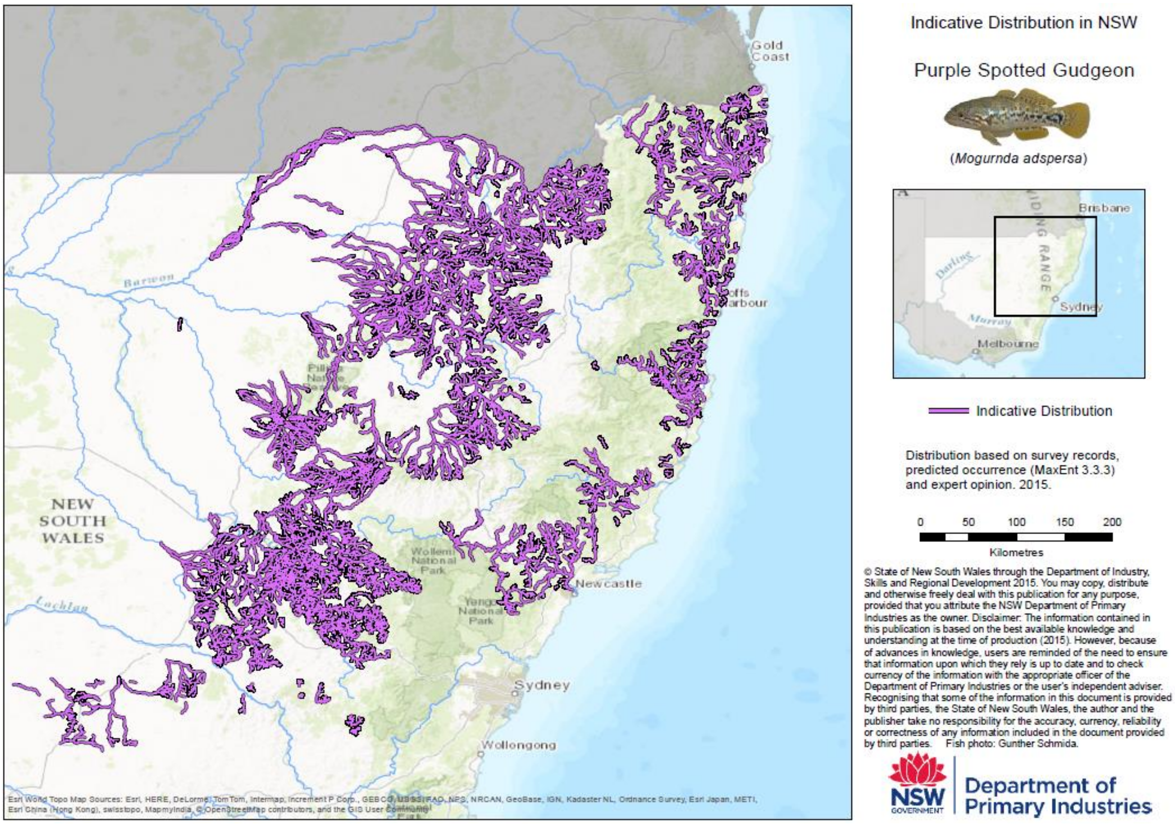

Figure 26. Indicative distribution in NSW – Purple Spotted Gudgeon (NSW DPI 2016a).

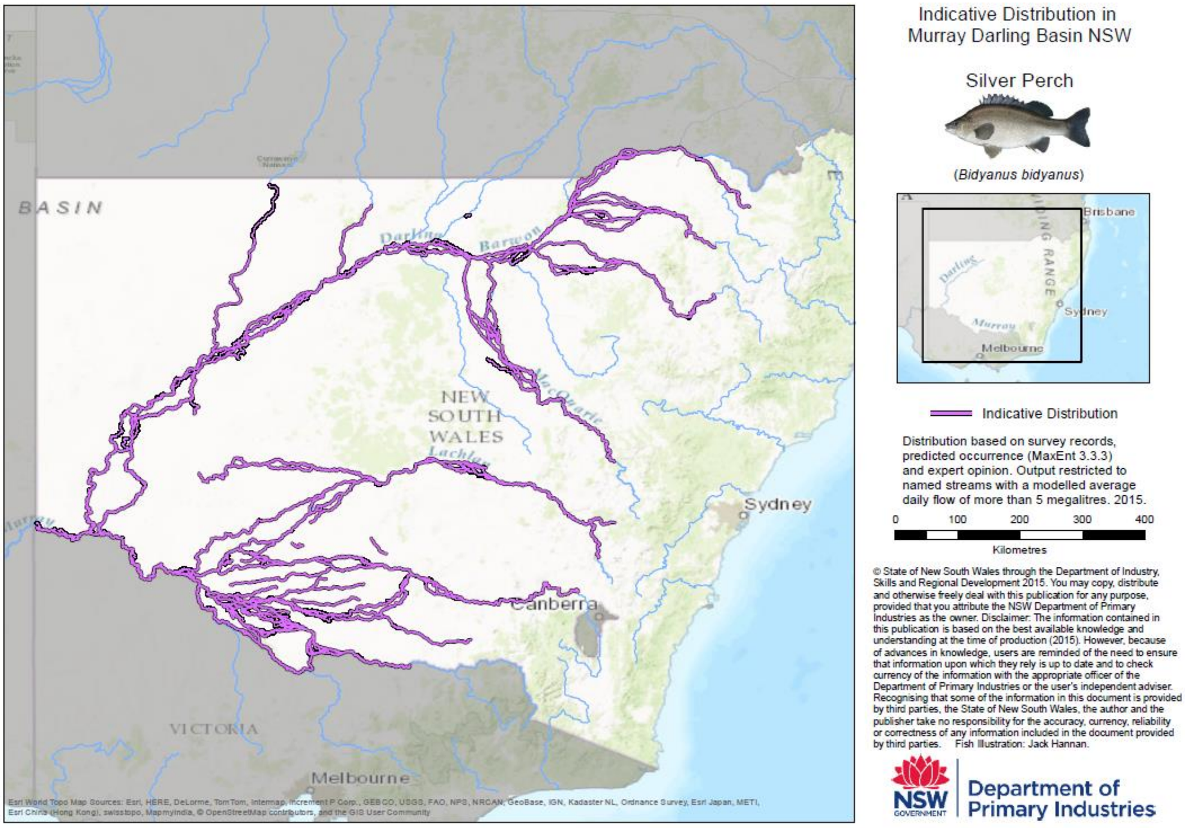

Figure 27. Indicative distribution in Murray-Darling Basin NSW – Silver Perch (NSW DPI 2016a).

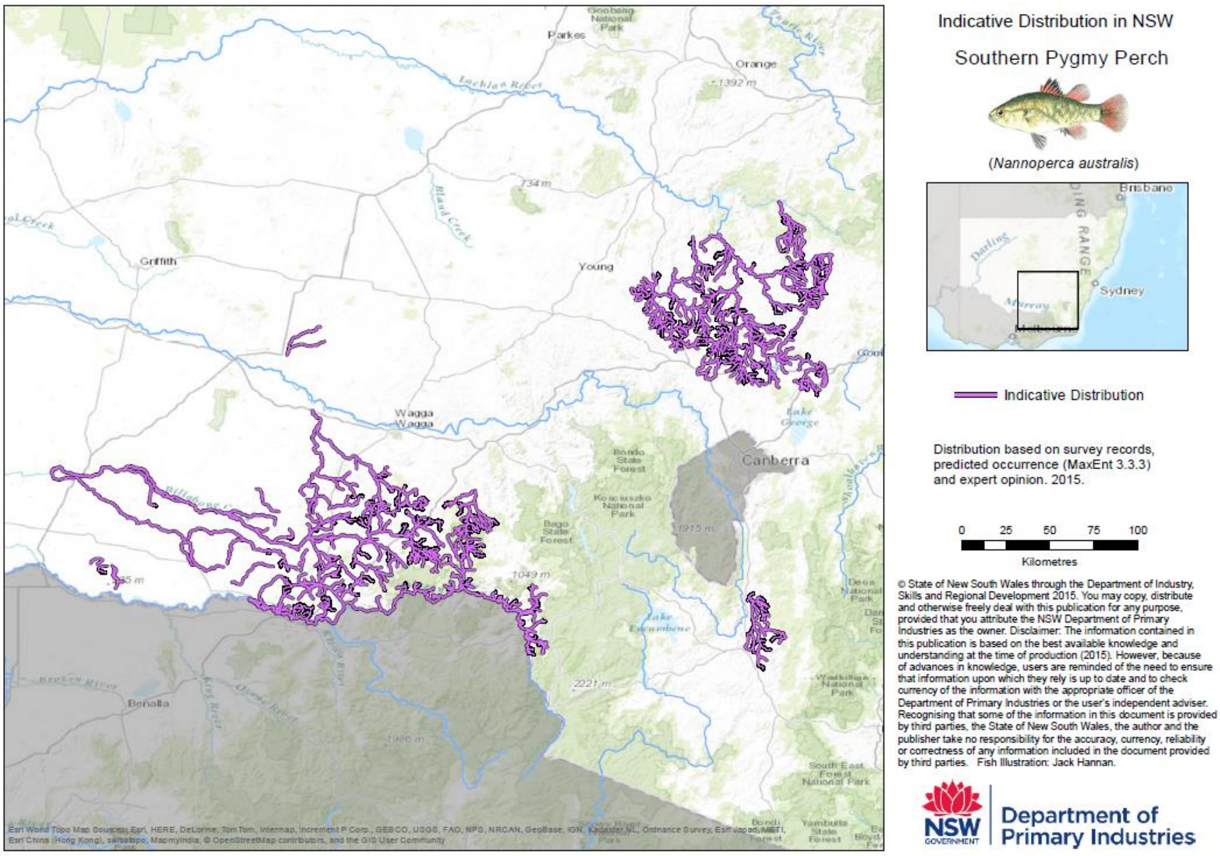

Figure 28. Indicative distribution in NSW – Southern Pygmy Perch (NSW DPI 2016a).

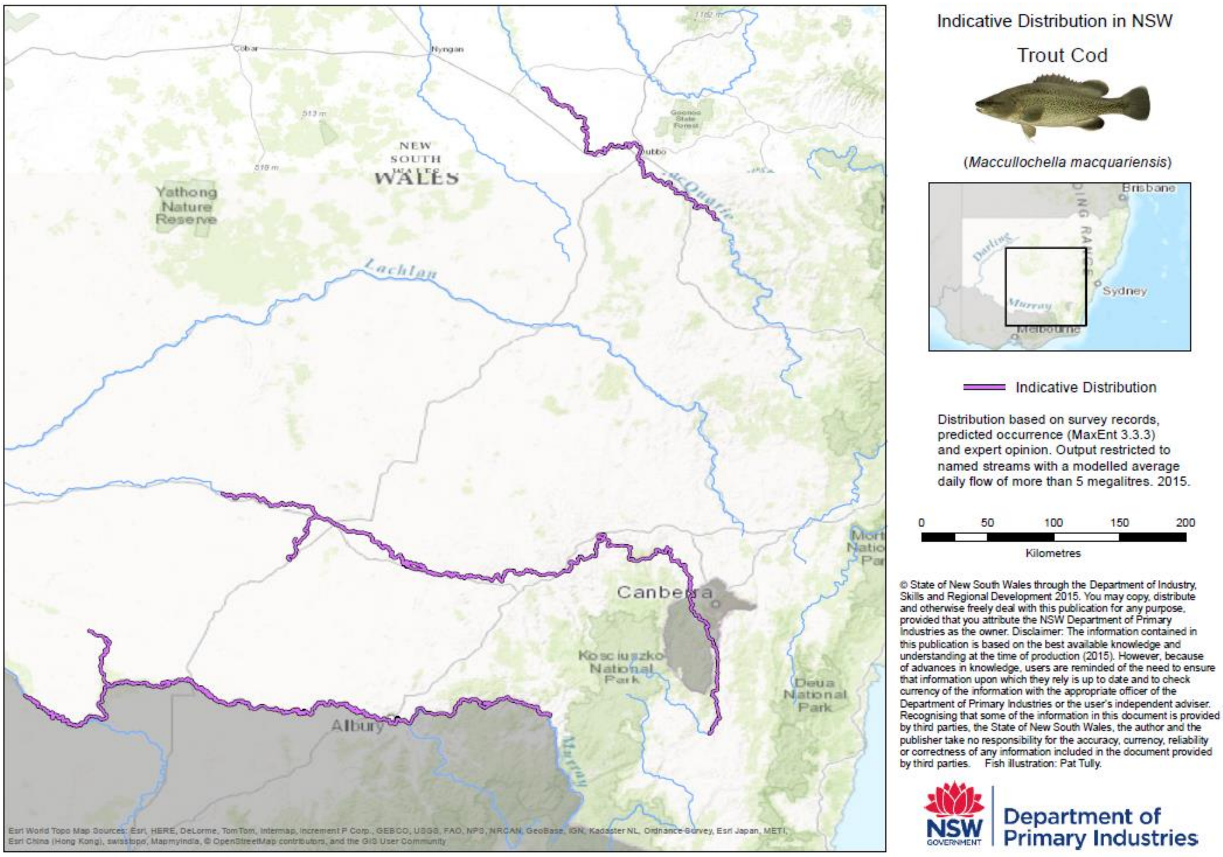

Figure 29. Indicative distribution in NSW – Trout Cod (NSW DPI 2016a).

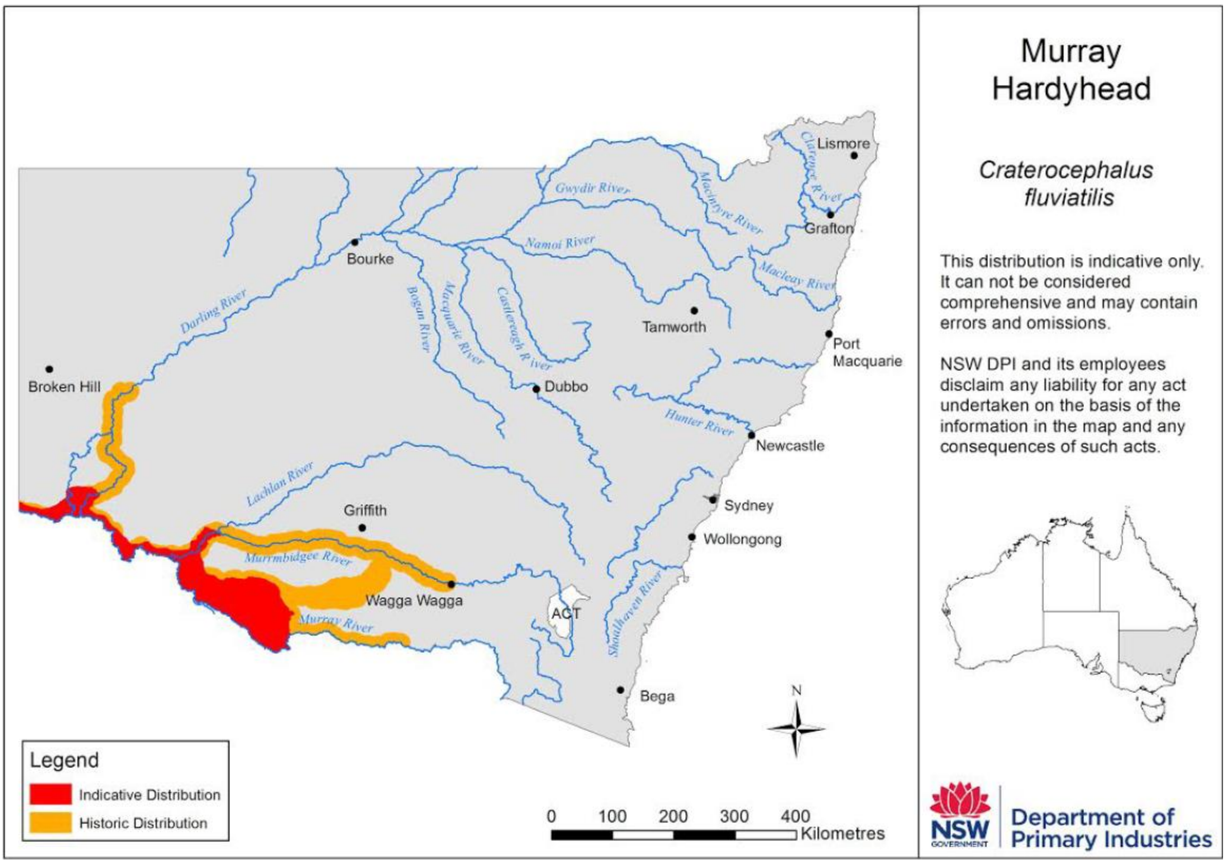

Figure 30. Indicative distribution in NSW – Murray Hardyhead (www.dpi.nsw.gov.au Primefact).