FISH AND FLOWS | AQUATIC HABITAT REHABILITATION

Fish and Flows in the Murray River Catchment

A review of environmental water requirements for native fish in the Murray River Catchment

Report for the Murray - Darling Basin Authority project MD 3112

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Cover image: A Lower Murray River anabranch, I. Ellis

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Executive Summary

Fish need water to survive, however different species of fish respond differently to different flows, and this means that assuming any water will have positive outcomes for all fish is too simplistic. We know that restoring fish populations through smarter water delivery and protection of natural flows can be an effective way to manage river health. Management of water for fish needs to be targeted to support critical life history elements and key population processes to support ongoing viable populations. For fish survival is related to the quality of the water itself, the availability of food, and the suitability of habitat and connectivity within the fish's broader ecological niche.

The movement of water within and between waterbodies (i.e. flow) has a major influence on each of these elements and processes, and hence on the suitability of an environment for different fish life stages and species. Flows promote the exchange of nutrients and productivity in aquatic ecosystems, and provide connectivity between aquatic habitats (e.g. rivers and floodplain habitats, valleys or reaches within a valley). The biological rhythms of fish are often linked to flow so that opportunities for spawning, growth and dispersal are synchronised. For example, survival of eggs and larvae may also be dependent on flow in order to transport them to suitable nursery habitat, or to maintain habitat while the eggs hatch and larvae develop.

Historically, diversity and variability in flowing conditions was a natural feature of the Murray–Darling Basin (MDB), to which fish and other aquatic biota adapted over millennia. Human influences and the exploitation of freshwater resources, however, have significantly altered MDB flow regimes in a relatively short time period. These impacts include reduced flow variability and hydraulic complexity, seasonal flow reversal, loss of small to medium floods, permanent inundation of some areas and altered connectivity. Furthermore, regulatory structures prevent or impair the movements of fish, and cold water releases from the larger dams can severely impact the breeding cycles of native fishes in downstream reaches. As a result, native fish populations in the MDB remain in a poor state and improvements will not be achieved without continued concerted management efforts and the incorporation of recently generated knowledge (Koehn et. al. 2014a).

Restoring flow regimes through the delivery of environmental water has become a key aspect of ecosystem management. However, effective flow restoration requires an understanding of the relationships between hydrology, life history and population dynamics of biota, so that these can then be linked to management decisions. To effectively manage riverine fish populations we therefore need to understand the drivers that support healthy fish populations and communities and the threats and pressures impacting on them. To achieve such understanding we need to invest in research and knowledge generation.

Fish play a critical role in the whole river system by cycling nutrients, providing food for other parts of the food web like waterbirds, and sustaining a billion dollar a year recreational fishing industry. Looking after fish, therefore, provides a range of environmental, social and economic benefits.

Review of fish and flow relationships

In developing the Basin Plan, the MDBA used an indicator site method to assess the environmental water needs of the MDB using the best science available at the time (2009). DPI Fisheries (NSW) in partnership with the Arthur Rylah Institute (ARI) were contracted by the Murray–Darling Basin Authority (MDBA) to undertake a review of the information available (as of 2015) regarding the flow requirements of fish in the Southern MDB. Key advances in our understanding of fish and flow relationships since 2009 include:

- The importance of hydrodynamic complexity (i.e. the distribution and change in velocity, depth, turbulence) in supporting life cycles and diversity within fish communities.
- The linkages between flow requirements and the different life history stages of fish.
- 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 unobstructed connectivity (between channels and floodplains, and also between locations and catchments), and translucency of flows to fish condition, recruitment, movement and population dynamics.

- How hydrological variability influences riverine productivity, which in-turn promotes food and breeding opportunities for within-channel fishes (i.e. the links between flow, growth, body condition and recruitment success).
- 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 in steam flows may augment recruitment; infrequent overbank flooding interspersed with within-channel increases in discharge may result in more frequent spawning and recruitment (trickle recruitment) and more robust population structure.
- That negative outcomes may arise from managed flow regimes (e.g. increased risk of non-native fish recruitment, hypoxic blackwater events and sedimentation).
- That the extent of water and land use in the MDB may mean there is a need for complementary actions in addition to the delivery of optimal flow regimes to achieve meaningful outcomes for native fish.

Supporting decision making

The information synthesised in the review of fish and flow relationships was then used to develop a framework to apply this knowledge. In this document we formulate an approach that will support decision making in the application of environmental water for fish. This framework:

1. Stipulates **Ecologically Significant Components** of the in-stream flow regime (base flows, small and large within-channel 'fresher' flows, bank full and overbank flows) for native fish.
2. Prescribes modelled **Flow Thresholds Estimates** for the ecologically significant flow components at nine key Hydrologic indicator sites in the Southern MDB (MDBA in prep.).
3. Classifies Southern MDB fish species into **Functional Groups** based on flow-related life history attributes to simplifying flow management requirements for fish.
4. Develops conceptualised **Optimal Annual Hydrographs** which describe the ecologically significant components of the flow regime required by each functional group of fish (and life history stages within).

The conceptual flow hydrographs presented in this report are primarily based on a generalised natural flow regime for streams within the Murray River catchment, and describe significant components of the hydrograph that will support groups of fishes. Water managers can use these conceptual hydrographs in the prioritisation of hydrograph components to be achieved through environmental water delivery in any given season, based on the required return frequency of hydrograph components presented in this report. **Natural variation in flow magnitude, timing and duration across the catchment will however necessitate adaptation of the conceptual hydrographs to suit different geographic locations.**

It is anticipated the outputs of this project will assist agencies with environmental water management responsibilities in the implementation of Murray–Darling Basin Plan, including the Basin-wide Watering Strategy and the development of Long term Environmental Watering Plans (in NSW, Victoria and South Australia). It is proposed that Basin Plan Environmental Water Requirements (EWRs) are reviewed and that fish specific EWRs which reflect the objectives of the BWS and functional guilds and conceptual hydrographs developed for this project. However, this report is not intended to be a comprehensive 'guidebook', and the conceptual models within it are by no means prescriptive. The hydrographs presented in this report are based on our scientific understanding of the requirements for fish, and do not consider management and operational elements such as constraints, rivers operations or third party impacts.

Responsible water management and the prioritisation of hydrograph requirements within and between systems (both spatially and temporally) will require coordinated efforts by water managers across both the Southern and Northern MDB, and sustained consultation with expert fish ecologists. The framework presented here will be trialled through monitoring and evaluation of Basin Plan Implementation over the next 5 years. Knowledge gained will contribute to improved adaptive management of native fish into the future.

Background

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). Within the Basin Plan, an Environmental Watering Plan (EWP) will ensure that the size, timing and nature of river 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 Murray–Darling Basin (MDB) together with their plants and animals including native fish and other aquatic biota. At a local scale, Water Resource Plans (WRP; see Chapter 10 of Basin Plan) will drive and inform environmental watering to ensure consistency in the implementation of the Basin Plan and the EWP 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 (e.g. 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.

Important scientific developments have occurred in the MDB since the EWRs were developed (pre-2009). Research developed through the decade long Millennium Drought and the following flood years has resulted in substantially improved understanding of the responses of fish to flow management regimes.

The EWRs originally developed to inform Basin Plan development did not reflect newer (post-2009) scientific advancements. The Basin-wide Watering Strategy (BWS; MDBA 2014b) does however incorporate more recent information regarding the responses of fish to flows. Given Basin and State-wide Long-Term Watering Plans (LTWPs) and WRP currently being developed are required to "have regard" to the objectives of the BWS, the Basin Plan EWRs should be reviewed to also reflect best available science if they are to be used to support Basin Plan implementation.

This report synthesises and reviews current knowledge of fish and flow relationships in the Southern MDB for key hydrologic indicator sites selected as those that contribute to multi-site watering events in the Murray River catchment from its tributaries (in NSW and Victoria) to the Riverland region in South Australia. To keep the scope of the current project manageable the Lower Darling River and Coorong, Lower Lakes and Murray Mouth regions were not included in this review of EWRs. We acknowledge that both of these regions are integral parts of the inter-connected MDB, which we anticipate will be captured in subsequent projects linked to this one.

The refined EWRs we present herein reflect the objectives of the BWS and current best available science regarding fish-flow relationships. Updated EWRs will support the MDBA to systematically develop annual priorities and in future reviews of Basin Plan implementation. They will also support MDB States in the development of their LTWPs, WRP and annual priorities to reflect the objectives of the BWS and will also support the coordinated development of multi-site watering.

The functional groups, conceptual hydrographs and EWR are presented in this report are by no means prescriptive. Responsible water management and manipulation of the flow regime will require coordinated efforts between jurisdictions across both the Southern and Northern MDB, and sustained consultation with expert fish ecologists. It will also require ongoing consideration of antecedent hydrology, forecast water availability and prioritisation of hydraulic requirements within and between systems both spatially and temporally.

Project objectives

This project contributes toward the systematic planning for State WRP, LTWPs, and future Annual Watering Priorities, as well as longer-term adaptive management under the Basin Plan implementation framework. Specifically, the project:

- focuses on native fish requirements, identifying opportunities for environmental watering to support outcomes for fish and considering potential impacts and opportunities for risk mitigation.
- collates a synthesis information and consolidates our understanding of the responses of key fish species to specific flows in the MDB where there is sufficient existing information to support the project.
- ensures that the science available to guide EWRs in relation to fish species in the Southern MDB is current and based on best available science.
- formulates an approach that will support decision making in the application of environmental water for fish.

Project methodology

This review of fish ecology in the Southern-Connected Murray River System included information targeted at the following Basin Plan Hydrologic Indicator Sites (Figure 1):

- Five in the Murray River main stem:
    - Barmah-Millewa Forest, (MDBA 2012a)
    - Edward Wakool system, (MDBA 2012b)
    - Gunbower, Koondrook and Perricoota forests, (MDBA 2012c)
    - Hattah Lakes, (MDBA 2012d)
    - Lower Murray in-channel flows (MDBA 2012e) and Riverland-Chowilla Floodplain (MDBA 2012f); both gauged at the NSW-South Australia border
- Three in the Murrumbidgee catchment:
    - Mid-Bidgee wetlands, (MDBA 2012)(MDBA 2012)(MDBA 2012g)
    - Lower Murrumbidgee (in-channel flows) (MDBA 2012h)
    - Lower Murrumbidgee floodplain, (MDBA 2012) (MDBA 2012) (MDBA 2012i)
- One in the Goulburn-Broken catchment (both specified at Shepparton):
    - Lower Goulburn in-channel flows(MDBA 2012j) (MDBA 2012) (MDBA 2012) and Lower Goulburn floodplain(MDBA 2012)(MDBA 2012) (MDBA 2012k); both gauged at Shepparton.

Additional HIS in the Southern MDB include the Lower Darling River and the Coorong, Lower Lakes and Murray Mouth regions (MDBA 2011b). The Darling River historically provided regular summer flows to the lower Murray River, creating variability in terms of hydrology and source water. The Coorong, Lower Lakes and Murray Mouth region includes a diverse range of freshwater, estuarine and marine habitats and is listed under the Ramsar Convention. We acknowledge that both of these regions are vitally linked to ecosystem processes throughout the rest of the MDB. Similarly, the Lachlan River is not included given the infrequency of connection between its streams and the Southern MDB (i.e. the Murrumbidgee River). We anticipate the review of fish ecology for the Lachlan River, Lower Darling River and the Coorong, Lower Lakes and Murray Mouth regions will be captured in subsequent projects linked to this one.

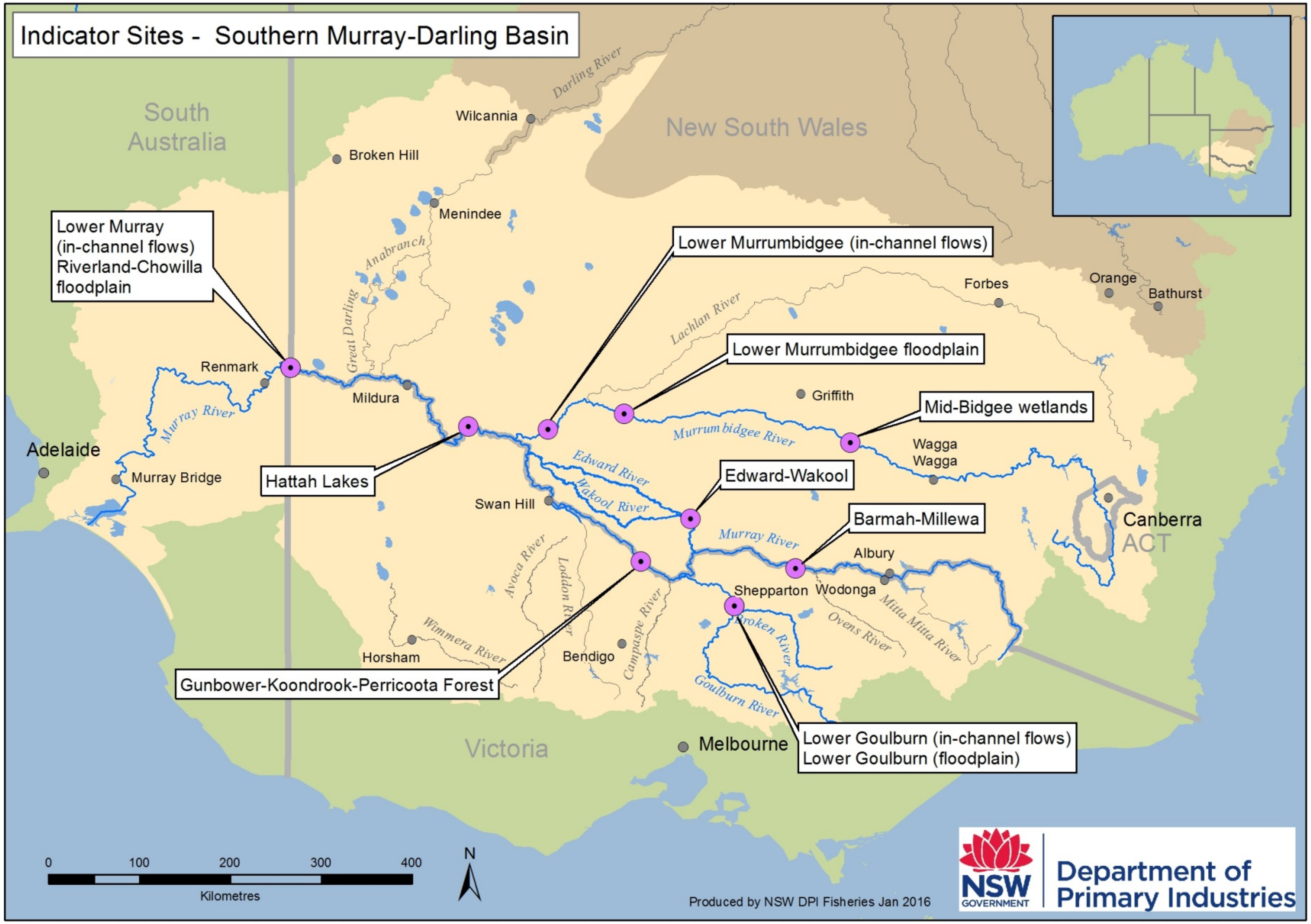

Figure 1. Major streams in the Southern MDB and location of flow gauging points for MDBA Hydrologic Indicator Sites considered in this report.

The framework used in this project will assist water managers in the development of watering plans and strategies to maximise environmental benefits and minimise risks of unwanted outcomes for native fish in their region of interest.

The outputs from this project include:

- A review of available information relating to the flow and habitat requirements of fish species in the Southern MDB.
- Proposed functional groups for managing watering regimes for fish
- conceptual (theoretical) hydrographs to support the requirements for the functional guilds.

The steps in the framework are:

1. Describe Ecologically Significant Components of the in-stream flow regime (base flows, small and large within-channel 'fresher' flows, bank full and overbank flows) relevant for native fish
2. Prescribe modelled Flow Thresholds Estimates for these ecologically significant components of the in-stream flow regime at nine selected Hydrologic indicator sites in the Southern MDB (see MDBA in prep.).
3. Classify Southern MDB fish species into Functional Groups based on flow-related life history attributes (Habitat, Growth and Condition, Reproduction, Movement, Maintenance) to simplify the flow requirements for fish.
4. Develop conceptualised Optimal Annual Hydrographs which describe the ecologically significant components of the flow regime required by each functional group of fish. For each hydrograph some components are identified necessary annually (critical), while other are described 'aspirational' on an annual cycle, with a required annual return frequency stipulated.

Project Outputs and Linkages

The outputs from this project will assist the MDBA (and other agencies with environmental water management responsibilities) in the implementation of Murray–Darling Basin Plan ('Basin Plan') activities, including:

- Implementation of the Basin-wide Environmental Watering Strategy (BWS) (Chapter 8 of the Basin Plan; MDBA 2014b).
- Development and implementation of Basin-wide and regional Annual Watering Priorities and watering outlook reports (Chapter 8 of the Basin Plan; MDBA 2015).
- The development of Basin State Long-Term Environmental Watering Plans (LTWPs) (Chapter 8 of the Basin Plan).
- Development and implementation of Water Quality and Salinity Management Plans and targets (Chapter 9 of the Basin Plan).
- Assessment and accreditation of state Water Resource Plans (WRP) (Chapter 10 of the Basin Plan).
- Review and refinement of the science underpinning Sustainable Diversion Limits (SDLs) in the Southern Murray–Darling Basin as part of future reviews of the Basin Plan (Chapter 6 of the Basin Plan).
- Implementation of the SDL adjustment mechanism in the Southern Murray–Darling Basin (Chapter 7 of the Basin Plan; MDBA 2014e).
- Development and implementation of Basin Plan monitoring and evaluation frameworks (Chapter 13 of the Basin Plan).

Review of fish and flow relationships in the Southern Murray–Darling Basin

The Southern Murray–Darling Basin

The Murray–Darling Basin (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 Murray–Darling Basin (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 River from just upstream of the Menindee Lakes (Figure 1).

The Murray River catchment drains the south 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(MDBA 2010, MDBA 2011)(MDBA 2010, MDBA 2011). By comparison, the upper Darling River and its tributaries contribute around 42% of total inflows in the MDB (MDBA 2010). Tributaries in NSW include the lower Darling River (downstream of Menindee Lakes) and the Great Darling Anabranch, and the Murrumbidgee River (in NSW). The Edward and Wakool rivers are a major effluent system in NSW that re-enter the Murray River upstream of Euston. The Lachlan River only infrequently connects with the Southern MDB (i.e. the Murrumbidgee River). 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(MDBA 2015)(MDBA 2015).

The topography of the Southern MDB ranges from steep to gently undulating hills, low relief floodplains and flat plains (CSIRO 2008). 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 2011b). Although the lowland rivers of the Southern MDB (including the Lower Darling River) would have also periodically exhibited high velocities, since regulation they have been characterised by slower flows (MDBC 2006).

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). The Northern Basin is hotter, with higher evaporation and less predictable flow, and more frequent and longer periods of very low flow than the southern Basin (MDBA 2010). 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 (DPI 2015).

Aquatic habitats of the Southern Murray–Darling Basin

Rivers and creeks of the Southern MDB provide a variety of in-stream habitats, such as pools, riffles, and benches (Thoms and Walker 1993; Koehn et. al. 2004). Hydraulic complexity (i.e. velocity, depth and turbulence) within streams creates habitat heterogeneity, which in turn promotes biological diversity and creates areas for refuge, breeding, feeding and shelter for a variety of native fish species (and different life history stages)(Dyer & Thoms 2006).

The upper reaches of the Murray River system comprises fast-flowing streams originating in the Great Dividing Range that flow north into the Murray River Basin (e.g. the Goulburn, Ovens, Loddon and Campaspe rivers). These upland streams are important contributors of carbon and sediment to the MDB's lowland rivers (MDBA 2011b). Although the lowland rivers of the Southern MDB (including the Lower Darling River) would have also periodically exhibited high velocities, since regulation they have been characterised by slower flows (Mallen-Cooper and Zampatti 2015a).

Wetland habitats are another key feature of the Southern MDB, which provide important ecosystem functions, including filtering sediments and recycling of carbon and nutrients (Beesley et. al. 2012; Górski et. al. 2013). Wetlands also support an array of aquatic vegetation and provide diverse breeding and foraging habitat for a variety of organisms (e.g. Junk et. al. 1989; Balcombe & Arthington 2009). Wetlands also provided a specific habitat for fishes reliant on vegetated lentic habitats (MDBA 2010). A number of nationally important wetlands are located in the Southern MDB:

- Ramsar-listed wetlands including the Barmah-Millewa forest, Gunbower-Koondrook-Perricoota forests, the Hattah Lakes and the Chowilla and Lindsay–Wallpolla floodplain wetland systems (MDBA 2010) (MDBA 2011) (MDBA 2011).
- Wetlands listed on the Australian Directory of Important Wetlands located in the mid-Murrumbidgee (Mid-Bidgee Wetlands), the Lower Murrumbidgee floodplain and the Goulburn River Floodplain (Environment Australia 2001).

Fish in the Southern Murray–Darling Basin

The MDB has 46 species of native fish (although 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 expected to occur in the Southern MDB (see Appendix A, Table A1 and Table A2). The Southern MBD contains slightly different fish assemblages in upland, midland and lowland zones. Not included in Tables A1 and A2 are those species found only in the upper Victorian reaches of the Southern MDB (Barred Galaxias) and species found only in the Lower Murray SA and/or estuarine habitats (e.g. Small-mouthed Hardyhead, Yarra Pygmy Perch, Western Blue-spot Goby, Lagoon Goby, Tamar Goby). 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 are also excluded.

Since European settlement, human development and use of freshwater resources has contributed to the decline in native fish numbers in the MDB to an estimated 10% of pre-European levels (MDBC 2004; Koehn and Lintermans 2012). 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). Ten of these have been recorded in the Southern MBD (and other states) (see Table 1).

The aquatic ecological communities of the lowland Murray River are listed as an Endangered Ecological Community (EEC) in 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(DPI 2007)(DPI 2007). The Lower Darling catchment from Mungindi (to the convergence with the Murray is also listed as an EEC (DPI 2007b).

Reasons for decline

The poor condition of MBD fish communities are generally attributed to the following threats and stressors (adapted from Koehn and Lintermans 2012):

- Flow regulation: including reduced flow and hydraulic complexity, seasonal flow reversal, loss of small to medium floods, permanent inundation and altered connectivity.
- Habitat degradation: including damage to riparian zones, removal of in-stream habitat such as snags, and sedimentation.
- Lowered water quality: including impacts on nutrient concentrations, turbidity, sedimentation, salinity, dissolved oxygen (e.g. blackwater events), artificial changes in water temperature (especially cold water release from storages), pesticides and other contaminants.
- Barriers which impede fish passage: These include dams, weirs, levees, culverts and non-physical barriers such as high velocities, poor water quality, thermal pollution and loss of population connectivity.
- Entrainment and fish losses though irrigation diversions including pumping and gravity-fed channels during irrigation season.
- Competition and/or predation by non-native species (e.g. Carp, Gambusia, Trout and Redfin).
- Exploitation from recreational, illegal and (formerly) commercial fishing activities.
- Disease, such as Epizootic Haematopoietic Necrosis (EHN) virus and other viruses and parasites.
- Loss of genetic integrity caused by inappropriate stocking and translocation of native species.

Status of fish communities in the Southern Murray–Darling Basin

The Sustainable Rivers Audit (SRA) was a Basin-wide comparison of the status of biological communities (groups of species). The second round of the SRA (SRA2) assessed the status of the fish community throughout the majority of valleys in the Southern MDB to be in a 'Poor 'to 'Extremely poor 'condition (Davies 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 (DPI in prep.). The project provides delineation 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 will also document current threatened species distribution information for NSW listed species, which will help to inform the planning of recovery actions for threatened species.

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 2). Although the lower NSW Darling and Murray River region reaches were assessed to be in a 'Good' and 'Moderate' condition respectively, they also contain numerous Carp hotspots and will require careful management to avoid further degradation. Carp hotspots were identified through analysis of records from the NSW Freshwater Fish Research Database (DPI in prep.) and SRA2 information from the period 2008-2010 (Davies et. al. 2012).

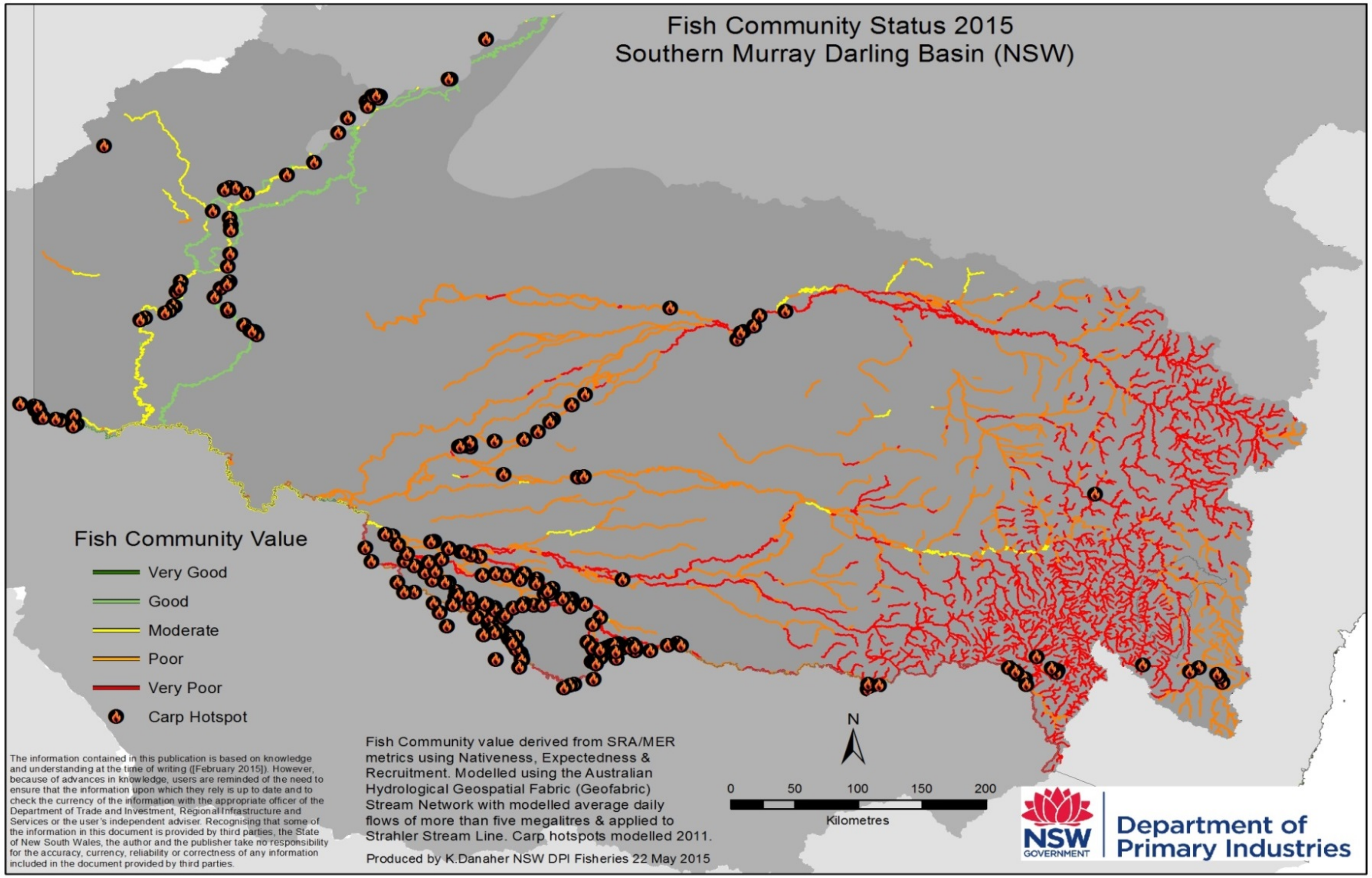

Figure 2. Fish community status and Carp Hotspots in the southern Murray–Darling Basin (DPI in prep.).

Fish and flow relationships

Flow is a major factor structuring freshwater fish communities, as it influences the range of physical habitats available to fish, as well as ecological processes and functions to which their life-history is linked. Biological rhythms are often linked to flow and optimised so that opportunities for spawning, growth and dispersal are synchronised (Baumgartner et. al. 2013). Historically, diversity and variability in flowing water conditions was a regular feature of the Murray River, to which fish and other aquatic biota are adapted (Humphries et. al. 1999). Hydrodynamic complexity (i.e. the distribution and change in velocity, depth, turbulence) has been significantly reduced in the MDB, through factors including weirs creating still-water habitats, removal of large wood, and increased sedimentation (Mallen-Cooper and Zampatti 2015a). 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 (e.g. Kingsford & Thomas 2004).

Altered flow regimes in the MDB are implicated in the demise of many native fishes as a result of impacts on physiology, spawning, recruitment, movement and habitat availability (Gehrke and Harris 2001; Koehn et. al. 2014b). 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). Maintaining natural rates of change in water level may be important for nesting species where river operations to meet irrigation demand cause rapid water level fluctuations which are out of sync with natural patterns and climatic cues. For example, data for the upper Yanco Creek demonstrate water level oscillation by more than 1.2 m (or at least half of the overall stream depth) in response to changes in irrigation demand over a few days (Sharpe and Stuart 2013). 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 lentic species (such as non-native Carp) (Walker 2006; Walker and Thoms 1993; Cheshire et. al. 2010).

In flow altered systems such as the MDB, restoring a natural flow regime is targeted for ecosystem recovery to encourage recruitment, dispersal and growth processes (Poff et. al. 1997). Restoring flow regimes with environmental water allocations has become a key aspect of ecosystem management in the MDB (Arthington 2012; Koehn et. al. 2014b). The management of ‘environmental flows’ for river restoration aims to mimic components of the river’s natural flow variability, including the magnitude, frequency, timing, duration, and rate of change of flow events (Arthington et. al. 2006; Mallen-Cooper and Zampatti 2015c).

Managing riverine flows for consumptive use while considering flow restoration for environmental purposes can be challenging (Arthington 2012; Koehn et. al. 2014b). Water managers are currently unable to return large volumes of water to mimic natural flooding cycles due to water availability and physical and operational constraints. Managed flows may also have negative outcomes, such as increased recruitment of non-native fishes (Stuart & Jones 2006; Beesley et. al. 2012), hypoxic blackwater events (King et. al. 2012; Beesley et. al. 2013; Leigh & Zampatti 2012), or high levels of sedimentation (Lyon & O’Connor 2008). Furthermore, environmental works and measures projects (such as regulators which artificially inundate floodplains) generally back up water from downstream rather than deliver a downstream pulse of flood-water, with many potential associated 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).

Competing demands in the MDB has also led to conflict over water buybacks and environmental water management (Koehn et. al. 2014b). As such the need to maximise environmental benefits and minimise risks of unwanted outcomes has increased the expectation for science to underpin and justify water management and the delivery of environmental flows (Beasley et. al. 2011; Koehn et. al. 2014b). Effective flow restoration requires an understanding of relationships between hydrology, life history and population dynamics of biota, which can then be linked to management decisions (Arthington et. al. 2006). Environmental watering is a relatively new management action, and as such our ecological knowledge is still evolving, particularly with regard to how different fish species may be affected by flows, including natural events, environmental watering and other water management actions.

Population dynamics

Management of freshwater fish populations requires knowledge of fish life histories and population dynamics across the relevant spatio-temporal scales at which population processes occur. In large and complex river systems, specific regions may act as sources and sinks of particular life stages and the connectivity between these locations may influence population structure at discrete locations. Understanding the sources and dispersal of early life stages as well as the presence (and movements) of adult spawning stock is necessary in preserving and recovering native fish populations.

In riverine ecosystems, where flow is a major determinant of physical and biological processes, fish recruitment, dispersal and population dynamics are intrinsically linked to hydrologic processes. Consequently, in regulated rivers, restoring flow regimes to benefit fish necessitates an understanding of relationships between hydrology and life history stages, and the subsequent population dynamics. Integrating biological information for all life stages with hydrological data is required in order to elucidate key relationships between flow and population processes.

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. For example, understanding the influence of hydrology on the population dynamics of golden perch is reliant on accurately determining the hydrological conditions at the time and place of crucial life history processes (Zampatti et. al. 2015). This may be the movement of adults prior to spawning, or the recolonisation of juveniles into mid reaches following the downstream drift of larvae. Furthermore these movements and processes may occur over large landscape scales (i.e. 1000s of kilometres) thus necessitating continuity or translucency of flow events at the same scales and unobstructed connectivity.

Population models could be used to predictively assess how populations of different species may be affected by flows. Population models provide a method by which the potential effects of water management options can be compared so that the benefits to fish populations can be maximised, and can also assess the impact of a range of other threats on a population. Fish population models for eight species of fish native to the MDB (Golden Perch, Silver Perch, Murray Cod, Trout cod, Macquarie Perch, Southern Pygmy Perch, Olive Perchlet and Murray Hardyhead) are currently being developed by the Arthur Rylah Institute for Environmental Research on behalf of the MDBA (ARI, in prep). These species are considered representative of a range of habitats and flow requirements. It is anticipated these models will provide a means to predictively assess population responses to flow management.

Ecologically Significant Components of a flow regime

Discrete components of a flow-regime (hydrograph) will have different influences on riverine functions and processes and consequently the elements fish life-cycles (Figure 3). These can be referred to as Ecologically Significant Components (ESCs) of the flow regime (Kennard *et al.* 2009; Matthews & Richter 2007; MDBA 2011b), and serve as a common reference to which flow management targets such as EWRs can be applied and gauged. These ESCs typically comprise a relevant combination of the following:

- Cease to flow periods;
- Baseflows (or low flows);
- Freshes;
- Large flows/Small floods;
- Bankfull flows;
- Overbank flows; and/or,
- Large floods.

Due to the importance of hydrodynamics for fish outcomes, DPI Fisheries, in consultation with leading fish ecologists, have included a separation of in channel flow pulses or freshes, to small and large, which recognises the shift from slow to fast flowing within channel flows (Figure 3). These different parts of the flow-regime (ESCs) will influence different processes and elements fish life-cycles. . The ESCs defined for water planning for MDB fish are therefore:

- **Cease to flows.** No-flow periods occasionally occur in intermittent streams where flows decrease so much that a series of disconnected pools eventuates. High food availability for predatory species at higher trophic levels may occur initially during cease to flow periods, with limited refuge habitat for prey. Ultimately, however, food supply and water quality would be expected to decrease in isolated pools as water levels contract. No-flow periods have been associated with poor body condition; particularly for species at lower trophic levels (Balcombe et. al. 2012). Cease to flow periods can play an important role in these streams by promoting growth of biofilms and productivity. Rates of wetting and drying are important. Cease to flow can also be useful in controlling Carp populations, and would generally occur annually in highly intermittent systems.

- **Base flows** are confined to deeper low lying part of the channel, and would typically inundate geomorphic units such as pools and riffle areas between pools. Base flows (and cease to flows) are also allow for the accumulation of allochthonous carbon and vegetation on benches and dry river channel sediments, which then contribute to ecosystem productivity during subsequent flow events. They would generally occur on an ongoing basis in perennial systems. They may be important in maintaining aquatic habitat for fish, plants and invertebrates when low inflow conditions prevail; retain longitudinal connectivity for small-bodied fish and maintain reasonable water quality. Base flows maintain drought refuges during dry periods and contribute to nutrient dilution during wet periods or after a flood event. Base flows may also support winter conditioning and oxygenation through riffle habitats, and historically may have benefited small-bodied native species in terminal wetlands. Base flows are commonly maintained by seepage from groundwater and low surface flows (MDBA, 2014a).

- **Small within-channel pulses (freshes)** are generally short increases in flow that provide 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 pulses would generally be considered to be relatively slow flowing (e.g. less than 0.3m/s). They can contribute to the maintenance of refugia and key aquatic habitat such as snags and aquatic vegetation, which supports diverse heterotrophic biofilm generation, with high nutritional value to higher organisms (Wallace et al. 2014). Small within-channel pulses would have generally occurred annually throughout the majority of the Basin, and potentially two to three times in a year for perennial systems.

- **Large within-channel pulses** are more substantial increases in flow that provide inundation of within-channel features such as benches and longitudinal connectivity, and may connect floodplain wetlands and anabranches with low commence to flow thresholds. Large within channel pulse are distict from small pulse in that they provide fast flowing in channel habitats (e.g. velocity greater than 0.3m/s). Large within-channel pulses enhance productivity and nutrient exchange, promote dispersal and recruitment for all species and can trigger spawning in flow dependent species (i.e. Golden Perch and Silver Perch). These flow events are also important for maintaining refuges and minimising geomorphological impacts of regulation (e.g. sedimentation). The shape of these events should reflect the natural rates of flow increase or decrease corresponding to position in the catchment. Maintaining natural rates of change in water level may be important for nesting species, such as Murray Cod, Freshwater Catfish and Purple Spotted Gudgeon, as water level fluctuations that are out of sync with natural patterns and climatic cues can have adverse impacts (e.g. rapid decreases in water levels over short time periods leading to nest abandonment). Large within-channel pulses would have generally occurred annually across most of the Basin, and up to two to three times a year in some systems.

- **Bankfull flows** are the flow rate at which overbank flows begin, or maximum regulated flow releases. Bankfull flows generate similar ecological benefits to large within-channel pulses, potentially at a greater magnitude depending on channel geomorphology. They are characterised by the inundation of low-lying ephemeral wetlands and floodplains. As with large within-channel pulses, the shape of these events should reflect the natural rates of flow increase or decrease corresponding to position in the catchment.

- **Overbank events** which inundate floodplain and off-channel habitats are important in providing lateral connectivity, provide large-scale nutrient and sediment cycling and increase productivity. 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. Overbank events generally would have occurred between 1-25 years (depending on the magnitude of the event) for both intermittent and perennial systems. These events are generally unregulated, although there may be scenarios where environmental water activities could augment within-channel flows to create overbank events in which cases the shape of these events should reflect the natural rates of flow increase or decrease corresponding to position in the catchment.

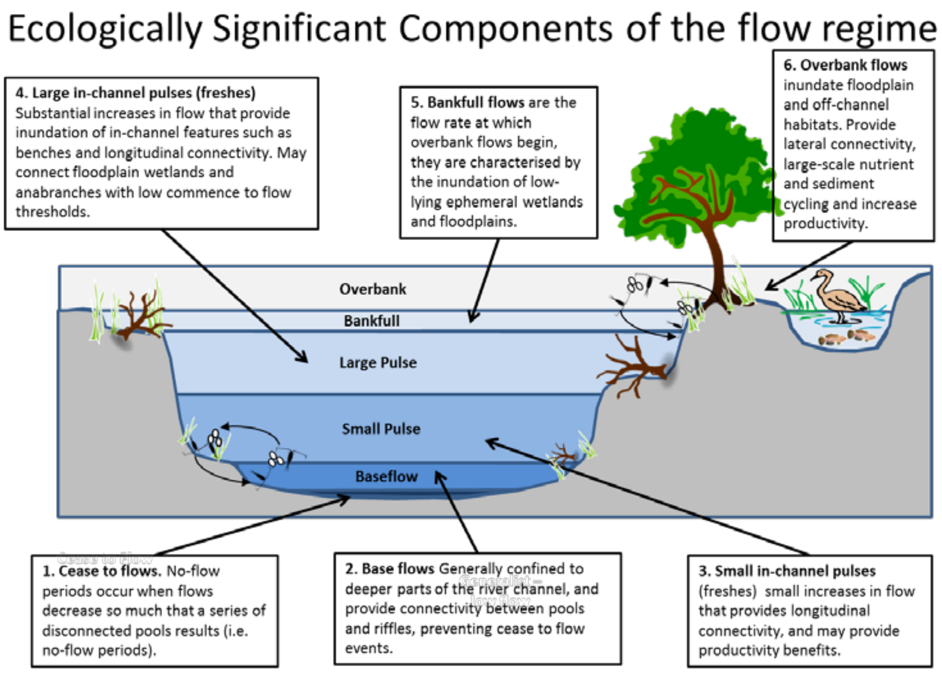

Figure 3. Components of the within-channel flow regime (cease to flows, base flows, small pulses, large pulses, bank full and overbank).

Modelled within-channel flow threshold estimates

In developing the ESLT for the Basin Plan the MDBA focussed on the water needs of floodplains and wetlands (overbank and bankfull flows) with less attention was given to within-channel environmental water needs (Wallace et. al. 2014a). To address this information gap, the Environmental Water Requirements developed by MDBA under the Basin Plan require refinement to include targets for within-channel ecological outcomes.

The MDBA's Eco-hydrology Analysis Branch conducted hydrological analysis to estimate flow thresholds (discharge rates) that distinguish ecologically significant components of the in-stream flow regime at ten hydrologic indicator sites in the Murray River catchment (nine gauging locations, see Figure 1)(MDBA in prep.). The following threshold estimates were provided courtesy of the MDBA.

The flow thresholds estimates (Table 1) were derived using a multiple lines of evidence approach including modelled "without development" data, channel capacity data (adopted by river operators), environmental flows data (adopted by Environmental Water Managers), Flood Inundation Models (incorporating LandSat imagery of flood events and Digital Elevation Models) and, Bankfull / Overbank flows applied by the ESLT.

Flood Inundation models and maps were the primary information source used to determine over bank and bank full flow thresholds with bankfull thresholds validated by comparison with hydrologic studies where available (the lower Murrumbidgee) and through consultation with regional water managers. Due to the influence of geomorphological characterises, main floodways through the Barmah-Millewa forests were included within the bankfull flow threshold. Small and large within-channel pulse thresholds were derived through analysis of hydrological modelling of without development flows to identify flow thresholds consistent with the natural flow regime (Figure 4).

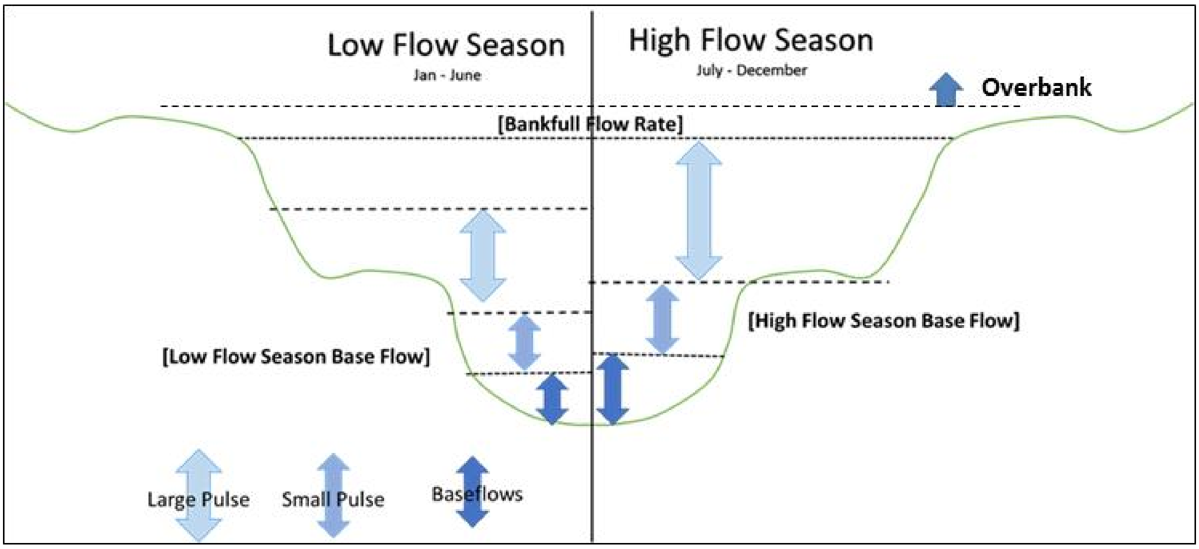

Figure 4. Diagrammatic representation of ecologically significant components of the in-stream flow regime (base flows, small pulses, large pulses and bank full) (courtesy of the MDBA).

To incorporate seasonal variation in flows, thresholds for low and high flow seasons (Jan-May and June – Dec, respectively) are presented. Flow thresholds are conservative in order for them to be operationally achievable flow rates. These flow thresholds provide an indication of the hydrology associated with within-channel flows to inform on environmental flow planning in high and low flow seasons.

Appendix 1. Flow thresholds estimates for the ecologically significant components of the in-stream flow regime for nine HIS in the Murray River catchment (courtesy of the MDBA).

Indicator Site	Overbank Flow	Bankfull	High Flow Season		Low Flow Season		High Flow Season	Low Flow Season
			Fresh (lrg)	Fresh(sml)	Fresh (lrg)	Fresh(sml)	Baseflow	Baseflow
Murray River @ D/S Yarrawonga	15,000	12,000	12,000	7,000	9,000	4,000	3,000	2,000
Murray River @ Torrumbarry	12,000	9,000	9,000	5,500	7,500	4,500	4,000	3,000
Edward Wakool @ Deniliquin	5,000	4,000	4,000	3,000	3,000	2,500	2,000	1,500
Murray River @ Euston	40,000	34,000	17,000	8,500	14,000	7,000	6,000	4,000
Murray River @ SA border	45,000	40,000	26,000	14,000	20,000	10,000	7,000	3,000
Murrumbidgee River @ Narrandera	38,220	26,850	26,850	17,500	20,500	7,700	4,000	2,000
Murrumbidgee River @ Maude	>20,000	20,000	20,000	10,000	13,000	8,500	3,000	1,500
Murrumbidgee River @ Balranald	11,000	9,735	7,500	4,500	5,000	3,500	2,500	1,500
Goulburn Shepparton	19,000	15,000	7,700	4,500	6,600	3,000	940	540

Life history of fishes

Life history refers to the sequence of key events in an organism's lifetime related to survival and reproduction including growth, spawning and movements (e.g. migration and dispersal of young). Fish in the MDB have a variety of life history and reproductive styles developed in response to the range of environmental conditions experienced across the MDB (Mallen-Cooper and Zampatti 2015c). For example, the Flood-Recruitment Model suggests that a rising hydrograph cues movement and spawning in some species, and that floodplain inundation provides increased productivity and habitat for fish which enhances growth and condition, particularly early life-history stages (Harris and Gehrke 1994). Conversely, the Low-Flow Recruitment Model suggests that low flow periods provide opportunities for growth, spawning and recruitment of species which are able to recruit under non-flood conditions within the main river channel (e.g. Australian Smelt, Bony Herring and Carp Gudgeon) (Humphries et. al. 1999). For each life history style, flow, habitat and connectivity are fundamental and inseparable requirements to healthy fish populations (Figure 5).

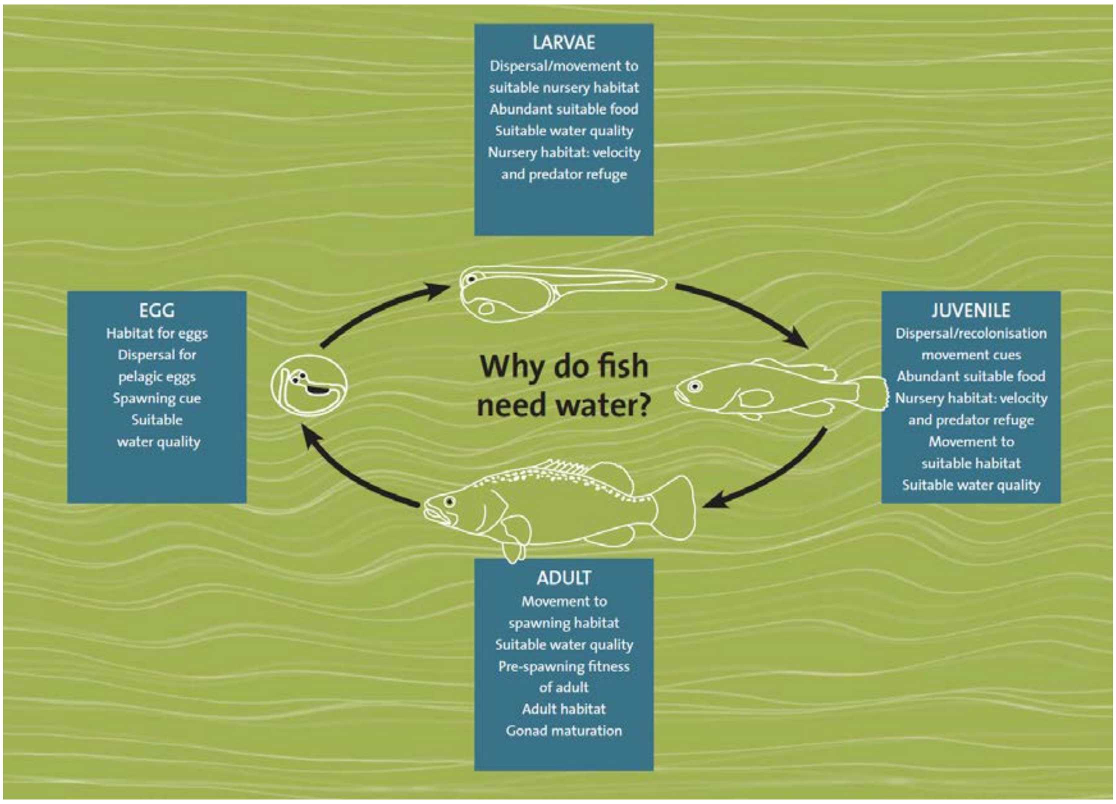

Figure 5. The influence of flows on the different stages within the life-cycle of fish (reproduced from MDBA 2014, courtesy of the Arthur Rylah Institute).

The linkages between flow requirements and the different life history stages of fish are framed here using five life history elements and processes which are each critical to the maintenance of self-sustaining populations and communities. These five critical life history elements and processes are (i) Habitat Access, (ii) Growth and Body Condition, (iii) Reproduction, (iv) Movement and Connectivity, and (v) Maintenance (Survival). Modification of the hydrology within rivers can have a range of detrimental impacts on these life history elements and processes, including changes to water quality, energy sources, physical habitat and biotic interactions, which result in a reduced ecological integrity (Poff et. al. 1997)

Habitat Access:

A fishes habitat is made up by the type of waterbody it lives in (e.g. lakes, wetlands or rivers), hydrology within this waterbody (flow, depth, seasonal water availability etc.), the physical characteristics, such as woody debris or plants that can be found around them, and water quality. Different species of fish in the Southern MDB 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). Water influences habitat availability or suitability in a number of ways:

- Aquatic habitats can be broadly categorized as lotic (flowing) or lentic (still). Different fish will have a preference for fast (lotic) or slow flowing (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.
- Historically, diversity and variability in flow (hydraulic complexity) was a regular feature of the Murray River. Hydraulic complexity promotes habitat heterogeneity, which in turn promotes biological diversity (Mallen-Cooper and Zampatti 2015a)
- Flow regulation creates lentic (flowing), stable weir pool environments, impacting species which require lotic (flowing) habitats during parts of their lifecycle (e.g. Murray Cod, Trout Cod).

Alternatively, high velocity, highly fluctuating flows at inappropriate times (such as during spawning periods for nesting species) may also be damaging in some areas.

- Increasing flows generally increase the amount of (and access to) off-channel floodplain habitats which are critical for a number of 'wetland-dependent' (Beesley et. al. 2012). Other species access lentic floodplain habitats to utilise submerged structure (vegetation and snags) for spawning of adhesive eggs (e.g. Carp Gudgeon, Murray–Darling Rainbowfish).
- 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 structure within flowing or still waterbodies can also be important for survival and reproductions. Snags in flowing rivers create sheltered nests in which Murray cod often lay their eggs.
- Early life stages of some species (e.g. Golden Perch and Silver Perch) may access off-channel habitat during elevated flows, resulting in high growth rates and low mortality (Sharpe 2011; Ellis et. al. 2015).
- Higher flows can also provide access to additional instream habitat (such as inundation of woody structure and benches) and to floodplain anabranches (Koehn 2009).
- The quality of the water and the way it interacts with the environment are also very important to providing fish with suitable habitats. Spangled perch live in the warm water temperatures apparent across the north of the MDB, while Barred Galaxias are adapted for life in cooler mountain streams. Barred Galaxias habitat also needs to be low in salinity, while the Murray Hardyhead prefers salty habitats, such as saline wetlands.

Growth and Body Condition:

Fish also need a reliable food supply to support growth and good body condition. Historically, natural flow cycles in the MDB promoted diverse aquatic food webs, which in turn supported healthy fish communities. Without natural flow variability nutrients and resources become depleted and food webs are compromised.

- Large flows that inundate floodplains and intermediate flows inundating within-channel benches trigger a pulse of productivity and promote the exchange nutrients and carbon between rivers and their floodplains (Junk et. al. 1989; Baldwin & Mitchell 2000). This in turn promotes food and breeding opportunities for within-channel fish assemblages (Geddes and Puckridge 1989; Balcombe et. al. 2012; Beesley et. al. 2011).
- Body condition is strongly linked to recruitment success for some species (Balcombe et. al. 2012). Some fish species access inundated food-rich floodplains to improve body condition and growth (e.g. Bony Herring, Golden Perch and Carp Gudgeon) (Beesley et. al. 2012), while others benefit from return of floodwaters to lotic habitats (e.g. Murray Cod and Australian Smelt) (King et. al. 2009; Tonkin et. al. 2011).
- High growth rates may influence subsequent recruitment within a population. For example, high growth of Golden Perch and strong recruitment aligned with years in which high river discharges were experienced (Zampatti and Leigh 2013a; Zampatti et. al. 2015), and growth of Trout Cod, Murray Cod and Golden Perch is positively related to discharge and flow variability in the Ovens and Murray Rivers (Tonkin et. al. 2014).
- Antecedent hydrological characteristics influence fish assemblages and hence their response to subsequent flows. Good body condition is often associated with recent flow conditions, while protracted low flow periods are associated with poor condition (Tonkin et. al. 2011; Balcombe et. al. 2012).
- Growth and condition may develop occur over several years. Sequential flows may therefore be required to sustain robust populations.

Reproduction:

Each fish species in the MDB has a preference for where and how it breeds. For fish in the MDB there are some basic differences in life cycle strategies that are related to water – most obvious is that some are dependent on intermittent high flow pulses to spawn, whereas others require specific habitats to spawn in or on and others again can complete their life cycle in almost any conditions, including low flows. Most native fish species synchronise their breeding to occur in warmer months, when there is likely to be more resources available to support survival. Changes to habitat availability and flow patterns impact directly and indirectly on fish reproductive outputs.

- For most native fish species spawning is principally linked to season and temperature, and is not dependent on high flow conditions (Cheshire et. al. 2015; King et. al. 2015). However, recruitment for many species may benefit from improved environmental conditions resulting from flooding or elevated flows (King et. al. 2009).
- Flow pulses (within channel or overbank) coinciding with warmer water temperatures are considered important in triggering spawning and facilitating dispersal of Silver Perch and Golden Perch (Mallen-Cooper and Stuart 2003; Cheshire et. al. 2015; Zampatti et. al. 2015). Although both species appear to spawn under a range of flow conditions if the temperatures are sutibale. Floods may augment recruitment, infrequent flooding interspersed with within-channel increases in discharge may result in more frequent spawning and recruitment and more robust population structure (Zampatti and Leigh 2013a).
- Many species are able to spawn and recruit under low flow conditions within the main river channel (e.g. Australian Smelt, Carp Gudgeon) (Humphries et. al. 1999; Cheshire et. al. 2015). Historically, low flow conditions (and associated hydraulic variability) were a regular feature of the Murray River and its tributaries.
- 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/or over extended time period, for example Golden Perch (Zampatti et. al. 2015)
- For nesting and / or substrate spawning species such as Murray Cod, River Blackfish, Macquarie perch and Freshwater Catfish (also referred to as Eel-tailed Catfish) removal of snags and flow variability reduces the “patchiness” of habitats in a waterbody, thus reducing its suitability to a variety of fish. Furthermore, unnaturally rapid variations in depth and discharge can result in poor recruitment. This is most likely due to abandonment of spawning sites or nests (Rowland 1998); or disturbance / displacement of eggs and larvae (Tonkin et. al. 2015). Maintaining water levels may be particularly important for nesting species 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) (Sharpe and Stuart 2013). Rapid variation in flows due to irrigation flow management is an example of where unnatural rates of change in flow may impact on within nest egg and larval development.
- Reduced flooding isolates wetland habitat needed by floodplain fish like Murray Hardyhead and Southern Pygmy Perch.
- Cold water releases from the depths of reservoirs behind large dams in spring can disrupt the development of tiny Murray cod in nests, given eggs are laid at a time of year when warm water is expected (unlike us, Murray cod can’t throw another blanket on to keep their babies warm).
- Flow pulses can promote dispersal of early life stages for a range of species from the breeding site and promote genetic diversity among catchments (Humphries and King 2004).
- Flows need to be managed at spatial scales that match the life cycles of fish. While wetland specialists like Southern Pygmy Perch or Murray Hardyhead may benefit from micro-scale (10’s of m) or meso-scale (100s m to 10s km) management actions, spawning and recruitment of flow

pulse specialists like Silver Perch require flow management over macro- or river-scales (100s of km) (Mallen-Cooper and Zampatti, 2015b).

Movement and Connectivity:

Connectivity which facilitates movement between habitats is often important for the completion of life-cycles. Longitudinal connectivity along the length of the river or between catchments may be critical for completion of life-cycles by 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 that are critical for many species like Southern Pygmy Perch.

- Flows that support movement are critical to a variety of life-stages for fish, with movements occurring for the purposes of spawning, dispersal, foraging, and to seek refuge from threatening processes (Mallen-Cooper and Zampatti 2015b).
- Different fish may undertake large 'macro-scale' movements up to 100's or 1000's of km (e.g. Golden Perch), or smaller 'meso-scale' movements of 100's of meters to 10's of kilometers within and between habitats in wetlands or river channels (e.g. Southern Pygmy Perch). Some smaller species conduct movements over smaller 'micro -scales' of less than one kilometer (Mallen-Cooper and Zampatti 2015a).
- For many species flows can be important for the dispersal movements of eggs and early life stages from breeding sites to suitable nursery habitats, to increase distribution and to promote genetic mixing (Humphries and King 2004).
- 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.
- Lateral connectivity between the river and floodplain is particularly important for those species and life history stages that utilise floodplain wetlands and anabranches for refuge, feeding or reproduction opportunities (Jones & Stuart 2008; Lyon et. al. 2010).

Maintenance/Survival:

Fish need water to survive – it's the medium in which they live. Changes to hydrology can affect fish survival directly, having lethal and sub-lethal effects, and indirectly through reducing habitat availability and food resources. Direct lethal affects can include alterations to water quality parameters like temperature, salinity and dissolved oxygen (which fish absorb by 'breathing' through their gills) (McNeil and Closs 2007) or the complete drying of water bodies.

- Base flows maintain fish populations by preserving habitat and longitudinal connectivity. Base flows and small pulses also contribute to maintaining water quality (e.g. dilution of potential hypoxic blackwater events).
- Larger flows that inundate benches, exposed sediments and low-lying off channel wetlands can trigger the release of a pulse of carbon, phosphorous and nitrogen into the water column, increasing primary productivity and stimulating other aquatic productivity processes such as plant propagation and growth (Baldwin and Mitchell 2000). These processes may be important for supporting higher trophic levels, and hence in maintaining food sources for all life-history stages of fish (Geddes and Puckridge 1989).
- Floodplain inundation or drying of refuge pools can cause hypoxic black water events - the depletion of dissolved oxygen (which fish absorb though their gills) which can result in fish deaths – particularly bigger fish which have higher oxygen demands.
- Flows can also provide broader ecological outcomes essential for the viability of fish assemblages such as the preservation of channel morphology, structural habitat and the transport of sediment (Robison 2007; Nilsson 2008; Brierley 2013).
- For nesting species with parental care such as Murray Cod, Trout Cod and Freshwater Catfish, maintenance flows might avoid unnaturally rapid variations in depth and discharge during

spawning periods to protect adhesive eggs and nests (Rowland 1998; King et. al. 2009; Koster et. al. 2014).

- Flow regimes influence fish growth and condition which are important factors to recruitment outcomes. As these factors may occur over several years sequential flows may be critical in supporting healthy populations.

Complementary Actions

Fish are one part of a riverine ecosystem, therefore to support healthy fish populations we need to aim to support healthy rivers and wetlands, which requires more than just water. The five critical life history elements and processes for fish (habitat, growth and condition, reproduction, movement and connectivity, and maintenance/survival) are also supported by a range of biotic processes that are not limited to the interaction with flows. A range of other external influences will impact of the health of the rivers and wetlands and therefore, the status of fish communities. As outlined previously 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. These additional threats may include: riparian and instream habitat degradation, lowered water quality, barriers which impede fish passage, 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 and regional climate change.

Complementary actions are opportunities to support flow management through the direct management of these additional threats and pressures, and include (not exclusively):

- Improving fish habitat through restoration and enhancement (e.g. re-snagging, instream and riparian zone management). This is likely to require detailed habitat mapping (woody snags, benches, macrophytes, deep pools and lateral connections) to improve our understanding of flow, habitat and connectivity requirements;
- Protection and rehabilitation of riparian and instream vegetation communities: for example, restoration of native vegetation, fencing of riparian zones, control of exotic/invasive plant species;
- Protection and rehabilitation of bank erosion: for example, restoration of riparian habitats and vegetation communities, bank and channel stabilisation;
- Alleviating impacts of poor water quality: for example, mitigating cold water pollution, diversion of saline intrusions, managing hypoxic blackwater events;
- Improvements to connectivity through fish friendly infrastructure design: for example, installing fishways (see Barrett and Mallen-Cooper 2006) making road crossings and culverts more fish friendly, removing weirs and actively managing floodgates).
- Diversion screening to minimise fish entrainment: the installation of screening technologies on irrigation pump offtakes to prevent native fish and other debris entering irrigation offtakes;
- Invasive species control: for example, through wetland screening, biological controls such as Koi Herpes Virus, daughterless Carp;
- Conservation stocking or translocations; this will often need to be conducted following habitat restoration through both physical and water management controls;

Native fish populations in the MDB remain in a poor state and improvements will not be achieved without continued concerted management efforts and the incorporation of recently generated knowledge (Koehn et. al. 2014a). The potential for achieving long-term ecological outcomes through environmental water management is likely to be increased by undertaking parallel complementary actions. This was a focus of the Native Fish Strategy through the demonstration reaches which aimed to provide a coordinated attempt to concurrently address the major fish community and environmental degradation issues of an individual reach. Many rehabilitation programs are already underway across the MDB, however these need to be expanded to make the most of the current water management.

Fish functional groups

For most fish species in the MDB, hydrology is linked to recruitment and population health via its influence on productivity (growth and condition), habitat availability (both physical and hydraulic) and connectivity (facilitating dispersal to appropriate habitats) and recruitment. 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. 2013a). Classifying fish species into functional groups based on flow related attributes (e.g. spawning, recruitment or movement) can assist with simplifying flow requirements for fish, to inform flow management decision making and enhance fish outcomes (Baumgartner et. al. 2013a; Mallen-Cooper and Zampatti 2015b).

Humphries et. al. (1999) proposed four categories for Murray–Darling fishes based on reproductive life history traits (e.g. spawning style, egg attributes, larval development and the occurrence of parental care):

1. (Mode 1) Large-bodied species that spawn the same time annually regardless of flow, with parental care or eggs and early larvae. (e.g. Murray Cod, Freshwater Catfish, River Blackfish).
2. (Mode 2) Large-bodied species that can delay spawning until appropriate conditions occur, with no parental care (e.g. Golden Perch, Silver Perch).
3. (Mode 3a) Small-bodied species, protracted serial or repeat spawning unrelated to flow; there may be parental care of eggs only (e.g. Australian Smelt, Flat-headed Gudgeon).
4. (Mode 3b) Small-bodied species, single spawning at the same time annually regardless of flow, with no parental care (e.g. Murray–Darling Rainbowfish, Un-specked Hardyhead).

Given species from within the same reproductive guild may respond differently under the same environmental conditions, Baumgartner et. al. (2013) grouped Murray–Darling fishes into flow guilds using reproductive characteristics and movement ecology (responses to flow). These guilds were then used to design managed flow hydrographs that would benefit each guild.

1. Long-lived apex predators – Moderately fecund nesting species known to spawn over a predictable temporal period in response to increasing temperature irrespective of flow. Recruitment may be enhanced by higher flows which inundates more spawning habitat, facilitate movement to productive floodplain nursery habitat, and subsequent recolonization of river channels. Long-lived so although small-scale annual recruitment is likely, populations do not require successful recruitment every year (e.g. Murray Cod, Trout Cod).
2. Flow dependent specialist – Highly fecund, flow pulses are needed to generate a spawning response. Undertake large-scale migrations in response to flow increases both for spawning and dispersal (e.g. Golden Perch, Silver Perch).
3. Foraging generalists – Low to moderately fecund, generally resilient to prolonged low flow conditions, may have more flexible spawning and recruitment strategies, may also spawn more than once annually (e.g. Australian Smelt, Un-specked Hardyhead, Carp Gudgeons, Freshwater Catfish).
4. Floodplain specialists – Generally low fecundity, requiring access to floodplain habitats to complete essential life history stages. Often short lived and hence susceptible to disturbance (e.g. Purple-spotted Gudgeon, Southern Pygmy Perch, Murray Hardyhead).

Mallen-Cooper and Zampatti (2015b) developed ‘Ecohydraulic recruitment guilds’ based on the characteristics of the river to which fish respond (i.e. hydrodynamics, spatial scale and habitat) rather than reproductive characteristics. This approach considered the hydrodynamics of habitats where recruitment occurs (i.e. lotic or lentic) and the spatial scales over which spawning and recruitment occur (micro = 10’s of m, meso = 100’s m to 10’s km and macro = 100s of km).

1. Macro-lotic, channel specialists - Spawn and recruit in lotic habitats and the minimum scale over which spawning movements and recruitment occurs is 100s of km (e.g. Golden Perch, Silver Perch).

2. Meso-lotic, channel specialists - Spawn and recruit in lotic habitats and the minimum scale over which spawning movements and recruitment occurs is 10s to 100s of km (e.g. Murray Cod, Macquarie perch).
3. Meso-Lotic-lentic, habitat generalists with flexible recruitment strategies - Spawn and recruit in a wide range of lentic and lotic habitats including river channels, weir-pools, and wetlands of varying sizes and the minimum scale over which spawning movements and recruitment occurs is 10s to 100s of km (e.g. Bony Herring, Unspecked Hardyhead, Carp).
4. Micro-Lotic-lentic, habitat generalists with flexible recruitment strategies - Spawn and recruit in a wide range of lentic and lotic habitats including river channels, weir-pools, and wetlands of varying sizes and the minimum scale over which spawning movements and recruitment occurs is less than 100 m (Australian Smelt, Carp Gudgeon).
5. Micro-lentic can be divided into two sub-guilds based on habitat use - The first are the wetland specialists, which spawn and recruit in lentic habitats and have specific requirements for wetland size, aquatic vegetation, turbidity, salinity and connectivity (e.g. Southern Pygmy Perch, Murray Hardyhead, Gambusia). The second is arid river specialists; these spawn and recruit in arid rivers with intermittent flow and frequent periods of zero flow with lentic conditions, but also in flow pulses or floods over 100s of km (e.g. Desert Rainbowfish, Hyrtl’s Tandan).

Southern MDB Functional Groups

A hybrid approach to fish functional groups, combining elements of the reproductive spawning-movement and eco-hydraulic groups summarised above, was applied to the fish of the Southern MDB by DPI Fisheries to assign each species to a functional group. These functional groups were established in consultation with experts to assist in development of specific long term environmental watering requirements and flow related management actions. Elements considered included:

- Cues for migration (dispersal and recolonization) and spawning (temperature and/or flow).
- Spatial scales of 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 habitats 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 and recruitment.

Five functional groups were identified based on key life-history traits that can be linked to flow characteristics:

1. **Flow pulse specialists -** Flow pulses (within or overbank) coinciding with warmer water temperatures are generally required to generate a spawning response. Adults are highly fecund and may make long migrations in response to flow (but can delay spawning). Eggs and larvae drift for weeks, potentially dispersing over long distances. Growth and recruitment success potentially enhanced by flows that inundate and transport drifting young to off-channel habitat (i.e. increased connectivity and ecosystem productivity). Flow pulses are also required to cue movements and provide connectivity for upstream recolonisation movements by juveniles. Medium to long-lived fish not necessarily requiring spawning and recruitment every year, but healthy populations consist of multiple year classes and demonstrate some recruitment in the majority of years (e.g. Golden Perch, Silver Perch). Although floods may augment recruitment, infrequent flooding interspersed with within-channel increases in discharge may result in more frequent spawning and recruitment and more robust population structure.
2. **River specialists** (with lotic or lentic preferences) - Adults may make short migrations to spawn in response to increased temperature. Moderately fecund, spawn in nests or have specific spawning substrate preferences, often with parental care. Maintaining water levels (or rates of increase/decrease) may be important for nesting species 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). On leaving nests larvae drift over short to moderate distances for dispersal, with recruitment success potentially enhanced by flow pulses (i.e. increased floodplain productivity and connectivity). Periodic within-channel pulses provide connectivity for upstream recolonization movements by juveniles. Not necessarily requiring large scale recruitment every year, but healthy populations consist of multiple year classes and demonstrate some recruitment in the majority of years. River specialists can be further categorises as having a preference for either lotic habitat (e.g. Murray Cod, Macquarie perch) or lentic habitat (Freshwater Catfish, Purple-spotted Gudgeon).
3. **Floodplain specialists** – 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, hence increases in inundation extent can enhance breeding opportunities by creating additional spawning habitat and floodplain productivity benefits. Relatively short-lived with low fecundity, with most species requiring annual spawning and recruitment events for survival of populations. Overbank flooding is required (not annually) to facilitate dispersal for recolonisation and establishment of new populations, and mixing between populations (e.g. Southern Pygmy Perch, Olive Perchlet, Murray Hardyhead and the non-native Gambusia).

4. **Generalists (native)** – Display flexible spawning strategies, but generally 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 occur, and small flow pulses 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, Carp Gudgeon, Mountain Galaxias, Un-specked Hardyhead).
5. **Generalists (non-native)** - Adults may make short migrations to spawn in response to increased temperature. 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).

Figure 6. Functional groups for the Southern MDB Fish with descriptions of the defining characteristics

A description of the key life history elements and processes for each group and the implication of these are presented in Table 2. The flow regime requirements for each functional group are summarised in Table 3. This functional grouping of fish enables the subsequent design of conceptual (theoretical) flow regimes that meets the needs of multiple fish guilds despite their differing flow requirements. However we acknowledge the groupings presented represent a simplistic interpretation of fish requirements. We recommend consultation with fish ecologists at a regional level be conducted to fully consider particular key species requirements in a region (e.g. threatened populations) when applying the above groupings during water planning.

Appendix 2. 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.	**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). The timing and operation of floodplain regulators can deny drifting early life history stages access to floodplain 'nursery habitat', thereby impacting on recruitment (Sharpe 2011). **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**: 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. Floods or within-channel flow pulses coupled with warmer water temperature may generate adult spawning migrations (Mallen-Cooper & Stuart 2003; Zampatti and Leigh 2013a). Although floods may augment recruitment, infrequent flooding interspersed with within-channel increases in discharge may result in more frequent spawning and recruitment and more robust population structure (Zampatti et. al. 2015; Ebner et . 2009). **MOVEMENT**: May undertake large seasonal migrations associated with an increase in flow where connectivity permits. Undertake moderate to large scale 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 distances. Flow pulses required to cue upstream recolonization movements by juveniles. Connectivity over large spatial scales is critical for these species. **MAINTENANCE**: 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. 2014). Populations are 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, 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 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. **CONDITION**: Adult fish gain condition with increasing water temperature usually between spring and autumn. Flow pulses may increase growth and condition when the inundation of benches or off-channel habitat contributes to ecosystem productivity. **REPRODUCTION**: Nesting species, or have specific spawning substrate preferences. 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 inundating additional spawning habitat and dispersing drifting young to productive nursery habitat. **MOVEMENT**: 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 pulses that transport drifting young to productive off-channel nursery habitat. Periodic pulses provide connectivity for upstream recolonization movements by juveniles. **MAINTENANCE**: 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.**

Functional group	Species	Key life history elements
Group 3: Floodplain specialists	Southern Pygmy Perch, , Murray Hardyhead, Olive Perchlet, Flat-headed Galaxias, Gambusia (non-native)	**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). **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**: 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**: 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**: Relatively short-lived and have low fecundities, requiring regular spawning and recruitment events. For some species this implies reliance on large overbank flows 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 flows.**
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.	**HABITAT**: Able to occupy a range of streams and waterbody types. Generally persist in 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. **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**: 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. **MOVEMENT**: 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**: 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.**

Functional group	Species	Key life history elements
Group 4b: Generalists (non-native species)	Carp, Goldfish, Redfin Perch, Oriental Weatherloach, Rainbow Trout, Brown Trout	**HABITAT**: Most species occupy streams and impoundments, with particular preferences (flow, temperature, substrate) demonstrated by each species. Carp, Goldfish, Oriental Weatherloach, Redfin Perch and Tench prefer slow-flowing or still streams and wetlands over a wide geographic range. Rainbow Trout and Brown Trout tend to be confined to cooler upland streams and lakes. **CONDITION**: Adult fish generally prepare for spawning in response to increasing water temperature. Increases in flow may enhance breeding opportunities by inundating additional spawning habitat and contributing to ecosystem productivity. **REPRODUCTION**: Recruit under low flows all year round; however spawning is most common between spring and summer. High fecundity and may spawn more than once during the year. Eggs are sticky and demersal, with a hatch time of up to 14 days (but can be as low as 6 days). **MOVEMENT**: Adult and juveniles may move short to moderate distances (100s of m to 10s of km) over a wide range of hydrological conditions. Larval drift is exhibited by some species over short to moderate scales, with recruitment relying on flows for dispersal and conditioning. **MAINTENANCE**: Persist in channel during extended low flow conditions, but able to take advantage of floodplain inundation due to high concentrations of food and habitat. For Carp, floodplain inundation for an extended period of time provide greatest spawning response, while low to moderate flow events that inundate within-channel habitat produce reduced spawning outcomes (Koehn et. al. in prep.). **Key difference to other functional groups – Exotic species with flexible spawning and recruitment strategies. Do not require flow pulses to generate spawning response, dispersal and recruitment enhanced by flows.**

Appendix 3. Flow regime influences on life history for functional fish groups. Capitalised letters denote ecologically significant components of the annual hydrograph (A = Overbank flow, B = Large within-channel pulse, C = Small within-channel pulse, D = Base flows) which may support key life history elements and processes (i.e. Habitat, Condition, Reproduction, Movement, Maintenance). Flow scenarios are based on the simulation of natural flow regimes for Southern MDB systems, and are consequently assumed to be the same for all functional groups.

Functional group	Flow regime influence on life history
Group 1. Flow pulse specialists (Silver Perch, Golden 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 (overbank or large within-channel pulse) may be significant for enhancing pre-spawning condition (i.e. increases ecosystem productivity) and in facilitating long distant movements. <u>This flow pulse will generally coincide with increased irrigation demand, hence could present an opportunity for environmental water to enhance flow magnitudes</u>. • A rapid rise or fall in flow (corresponding to natural rates of variability at a given reach in the catchment) between spring and autumn, is required to cue spawning. The entire pulse should span a minimum of 5 days (including rise and fall) at a given location and will occur annually. Overbank flow are recommended to occur at least every 3-4 years (A) to promote large scale recruitment, with large within-channel pulse to occur every 1-2 years otherwise to support small scale recruitment (B). <u>These flows may generally coincide with increased irrigation demand, hence could present an opportunity for environmental water to enhance flow magnitudes</u>. • Recession of flow after peak event (within natural rates of variability corresponding to the position within a catchment) can assist with egg dispersal and may also induce subsequent spawning (Sharpe 2011). • Integrity of flow pulses 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. • Subsequent flow variability (i.e. large or small flow pulses) (B and C) 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. A late summer – autumn pulse can promote juvenile dispersal movements. Small pulses would occur two to three times per year in perennial systems, with large pulses experienced every one-two years in intermittent systems. • 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 (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, 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 occurs annually, independent of flow; however response may be enhanced by increase in flow during spring which inundates additional spawning habitat and promote ecosystem productivity (A and B). • Maintaining water levels may be important for nesting species 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 (B). Where this is not an a critical limiting factor for fish populations (e.g. the Lower Murray) water management should instead focus on returning the natural shape of events as they correspond to position in catchment. • Recruitment of larvae and juveniles enhanced from secondary peak event for dispersal and access to habitat and suitable prey sources (C). • Integrity of flow pulses needs to be maintained over moderate distances (10s to 100s of m) 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 pulses (B). Larger scale flood-enhanced events (i.e. overbank flows) to support spawning and recruitment will ideally occur two to three times per decade (A). • Subsequent flow variability (i.e. large or small flow pulses) 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 pulses would occur two to three times per year in perennial systems, with large pulses experienced every one-two years in intermittent systems (B and C). • 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 (D). • 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 flowing conditions for short to moderate scale fish movement and dispersal throughout the system away from spawning and refuge sites.

Functional group	Flow regime influence on life history
Group 3. Floodplain specialists (Southern Pygmy Perch, , Murray Hardyhead, Olive Perchlet, Flat-headed Galaxias, Gambusia (non-native))	• 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 (A). Modified flow regimes increase the potential for isolation and extirpation of floodplain population. • 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 is required for dispersal, recolonisation, and mixing between populations. This need not occur annually, but need to occur frequently enough to prevent extirpation of isolated populations. These flood-enhanced events will ideally occur two to three times per decade. <u>Complementary action in the form of water delivery (e.g. pumping) may be necessary to prevent desiccation and maintain habitat for isolated populations in the absence of connecting overbank flows (location dependant).</u> • Recruitment of larvae and juveniles enhanced by subsequent flow pulses 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 (A, B, and C in some cases, location dependant). • 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 (D). • For some species autumn spawning events may occur, supported by small and large flow pulses which connect habitats and create additional spawning habitat (B and C) in some cases, location dependant. • Relatively short-lived with low fecundity, with most species requiring annual spawning and recruitment events for survival of populations, particularly fragmented floodplain populations (e.g. Murray Hardyhead). • 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 and maintenance through hydrodynamic complexity; improved productivity throughout the system from flow pulses which inundate benches and floodplain.

Functional group	Flow regime influence on life history
Group 4. Generalists (native and non-native)	• 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) (A and B). • Multiple peak events during spawning season provide flexibility in species response, as well as opportunities for multiple spawning events from serial spawning species (A and B). • Flow peak needs 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 pulses for dispersal and access to habitat and suitable prey sources (B and C). • 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 (D). • 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.

Conceptual flow hydrographs

The use of functional groups for freshwater fishes can simplify environmental water planning to deliver native fish benefits by developing environmental water targets for groups of species rather than individual species. However, each functional group has unique flow requirements related to their life history (i.e. spawning, recruitment, condition and movement, see Table 2). Furthermore, the habitat, connectivity and spatial scale requirements that influence these life history outcomes also differ across functional groups and species (Mallen-Cooper and Zampatti 2015b). Consequently the development of watering and hydrological requirements for one group may not necessarily provide benefits for another, requiring flexibility and a long term commitment to deliver benefits to native fish and river health (Baumgartner et. al. 2013; DPI 2015). The development of conceptual flow models which highlight the ecologically significant components of the flow regime required by functional groups can assist with the environmental water planning process.

Conceptual flow models use defined biological assumptions and ecological objectives to develop flow regime requirements and theoretical hydrographs for functional groups of fish (DPI 2015). Some basic principles for flow management related to the biological and ecological criteria that need to be considered when developing and implementing conceptual flow models for fish outcomes are:

- The natural flow regime - the natural flow regime provides a strong foundation for the rehabilitation of flows; however the impacts of river regulation, including connectivity, access to habitat, and changes to geomorphology, need to be considered and incorporated into specific planning objectives (Mallen-Cooper and Zampatti 2015a). Hydrology (e.g. timing and magnitude) and hydraulics (variability in depth, width, velocity and turbulence) in different valleys in the Southern MDB are likely to differ in (both historically and post regulation), and thus need to be considered independently.
- Flow enhancement - although few unregulated streams remain in the Southern MDB, where possible, natural flows (e.g. tributary inflows, rainfall rejection events) should be protected and complimented with environmental water. This will preserve many of the critical elements such as timing, longitudinal connectivity and biological and climatic cues that support key ecosystem functions. Environmental water can then contribute to freshers or overbank flows, connecting rivers and floodplains and support in-stream functions. There is also significant opportunity to modify the delivery of irrigation water orders to achieve desired flow hydrographs.
- Water quality - Water temperature drives life history responses for the majority of 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; Zampatti and Leigh 2013b; Mallen-Cooper and Zampatti 2015c). The influence of water quality on fish will generally result in management actions primarily occurring in the warmer spring and summer months. However, the importance of base flows to maintain water quality, and late-winter high flow events for to enhance productivity (Robertson 2001) still need to be considered.
- Fundamental riverine elements and processes – the influence of flow, habitat and connectivity on the dynamics and response of fish populations are inseparable and need to be considered in flow management decisions and actions (Mallen-Cooper and Zampatti 2015c). These three factors will influence the need for still or flowing environments, the spatial scale that connectivity and hydraulic complexity needs to be maintained, and the variation in flow needed for habitat access and completion of life history aspects(Mallen-Cooper 2015)(Mallen-Cooper 2015).

Marrying these principles with known biological and ecological information for fish when developing flow scenarios and EWRs will assist with:

1. defining what can realistically be achieved through improved hydrological regimes, and
2. establishing specific and measureable objectives that can achieve multiple outcomes through variable and flexible delivery plans that consider the needs of multiple water users (Baumgartner et. al. 2013; DPI 2015).

Conceptual hydrographs Murray River Catchment

Ecologically significant components (ESC's) of a hydrograph which promote key life history elements and processes for fish were identified previously as:

A. **Overbank flows** - flows that inundate low lying floodplain and off-channel habitats. Most commonly experienced in spring and summer in the Southern MDB.

B. **Large within-channel pulses** - Substantial increases in flow that provide inundation of within-channel features such as benches and longitudinal connectivity. May connect floodplain wetlands and anabranches with low commence to flow thresholds. Rates of rise and fall are fast and should mimic natural durations and rates of change in a given reach.

C. **Small within-channel pulses** - Small increases in flow that provides longitudinal connectivity, and may provide productivity benefits. Rates of rise and fall are fast and should mimic natural duration and rates of change for in a given reach.

D. **Base flows** – Generally confined to deeper parts of the river channel, and provide connectivity between pools and riffles, preventing cease to flow events. Small variations in flow (e.g. ±50% of median base flow magnitude for the reach) mimic natural variability and promote productivity during base flow periods.

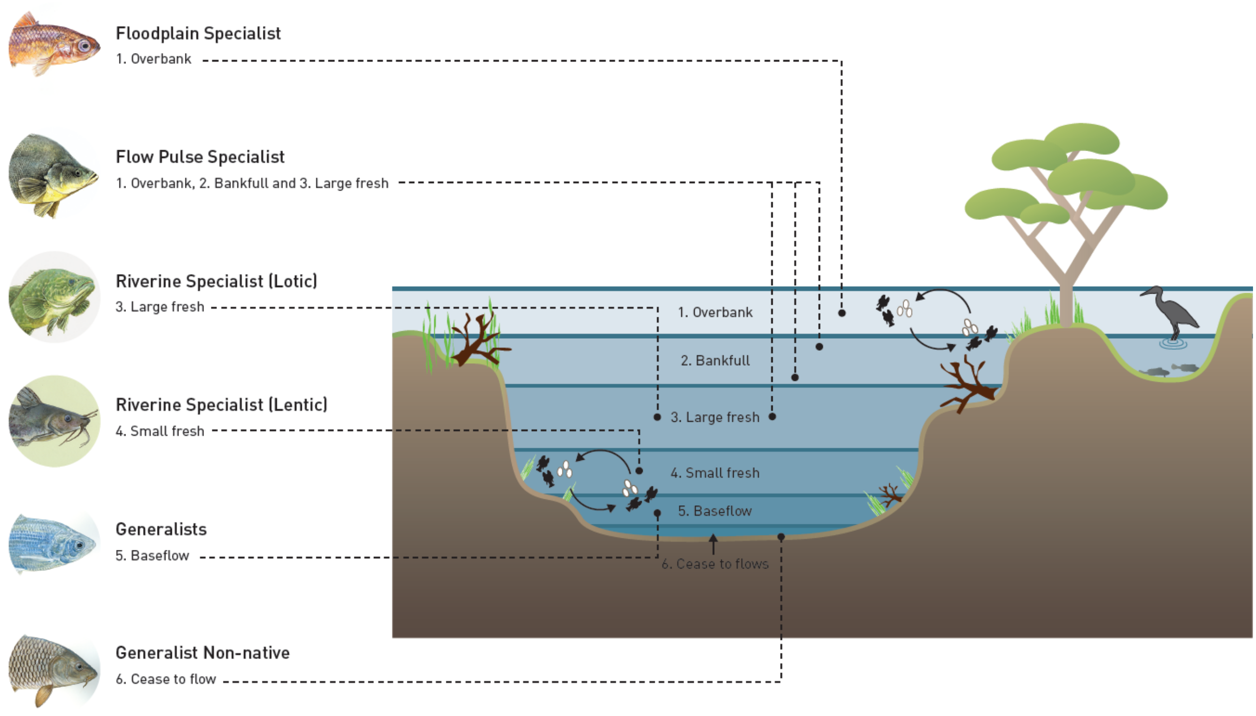

Figure 7. Ecologically significant components (ESC's) of a hydrograph which promote key life history elements and processes for functional groups.

Optimal annual flow hydrographs which conceptualise these components are presented in Figure 6 for three water availability scenarios in the Southern MDB (High, Moderate, and Low), with the known breeding season 'window' for each functional group of Southern MDB fishes included. The conceptual hydrographs presented here attempt to benefit different functional groups simultaneously (where possible) to simplify flow delivery planning (see Baumgartner et. al. 2013). Forexample, large within-channel pulses in spring may cue the spawning of flow-pulse specialists. The subsequent provision of decreasing flows in line with natural rates of change through October and early November (corresponding to position in the catchment) will maximise nesting habitat inundation, may triggering additional spawning by flow pulse specialists, and will promote larval and adult dispersal in both groups. In high water availability scenario years, there may be capacity for augmenting these large within-channel pulses with environmental allocations to facilitate overbank flows. Similarly, irrigation flows may be augmented with environmental water to achieve higher levels of inundation. Such cases could provide opportunities for water delivery to floodplain wetlands which support floodplain specialists either through direct connectivity with river flows, or by simplifying logistical requirements for complementary actions necessary to deliver water (such as pumping). Connection between these floodplain habitats and river channel flows would also promote dispersal and re-distribution of floodplain specialists.

Whilst many generalists species will also benefit from spring flow pulses (in terms habitat availability, spawning and recruitment and overall river productivity), the delivery of multiple small within-channel pulses throughout the year (Figure 6) should provide opportunity for dispersal movements and spawning by a range of generalist species, including species that can benefit from low-flow (see Baumgartner et. al. 2014; Humphries et. al. 1999). The provision of variable base flows (i.e. within the range of base flows derived at a given HIS) during periods between within-channel pulses (Figure 6) will preserve refuge habitat and maintain longitudinal connectivity, and will contribute to the maintenance of suitable water quality.

We make the assumption that during very wet years large flood events will be unregulated and hence will result in uncontained flooding throughout the MDB. These events are vital for the long term ecological integrity of the MDB (due for example to their capacity for influencing floodplain productivity, nutrient cycling, mobilisation and flushing of salt and delivery of water to habitats high on the floodplain) but are not considered as achievable using environmental water reserves due to the large volumes required and constraints within the system.

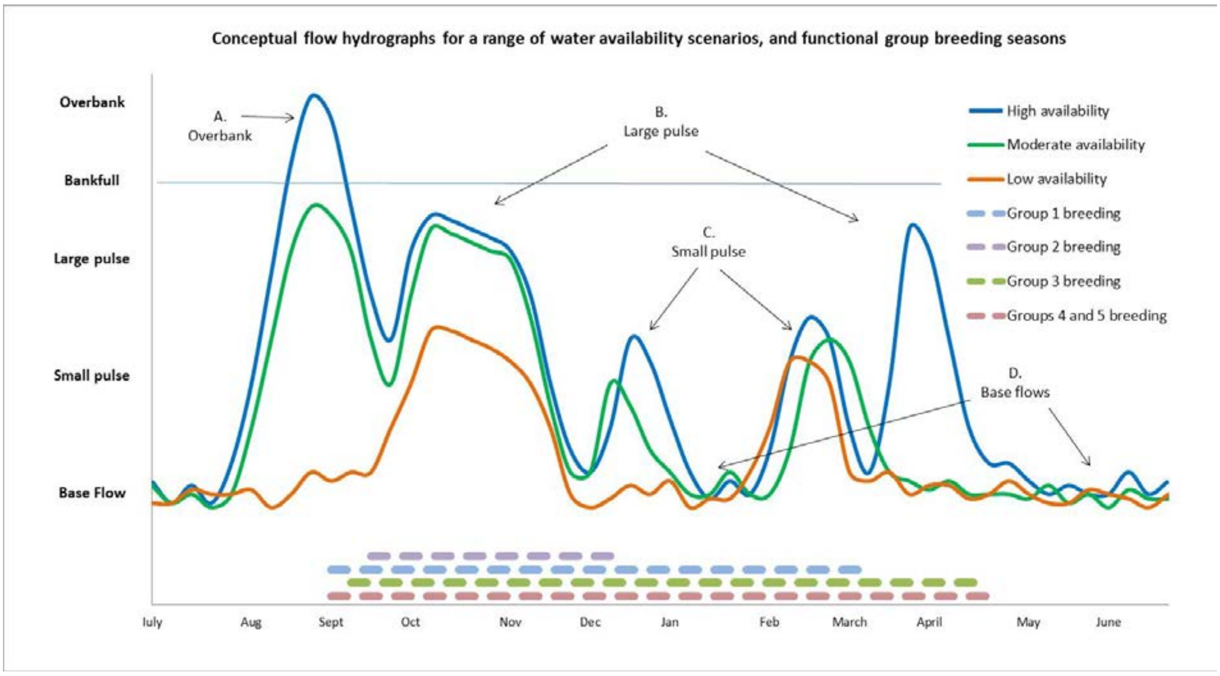

Figure 8. Conceptual flow hydrographs for three water availability scenarios (High, Moderate, and Low) and breeding season windows for each functional group of Southern MDB fishes (dashed lines). Ecologically significant components of each hydrograph which may promote key life history elements for fish such as movement, spawning and condition are indicated.

The theoretical flow scenarios presented are based on generalised natural flow regimes for Southern MDB systems. The seasonal timing of managed small and large within-channel pulses can be varied, although the productivity response may differ between seasons (see Robertson et. al. 2001). Similarly, the reproductively significant components for each hydrograph (i.e. over bank flows, small or large pulses) could be implemented at any point during the 'breeding season' window indicated to achieve reproductive outcomes where desirable for given functional groups. It is however important to note that the breeding window for a species may vary across catchments or streams in the Southern MDB. For example the breeding window for Golden perch in the cooler upper reaches of the Southern MDB tends to be narrower than depicted in Figure 6.

Regionally specific details such as the timing of breeding seasons, channel capacities and inundation values for critical habitat features (which influence spawning, recruitment and movement) must be considered applying these conceptual models. The natural variation in flow magnitude, timing and duration across the Southern MDB will also necessitate adaptation of these conceptual hydrographs to suit different geographic locations.

The prioritisation of required hydrograph components in any given season will to a large extent be based on the required return frequency of hydrograph ESC's. For example, those components that are not met in one year can then inform water management prioritisation and planning in subsequent years. A summary of the recommended annual return period (ARI; years), duration (days) and maximum period between events for each ESC are presented in Table 4.

Appendix 4. Recommended Frequency (annual return interval in years), duration (days) and maximum period between events for ESC's required to maintain each functional group. * Regional consideration should be given to critical temperature windows in which flow components must align with reproductive processes for key species. ** may require complementary action.

Functional Group	Annual return interval (years)	Duration (days)	Max period between events (years)	Seasonal requirements
	Overbank flows (A)			
Group 1: Flow pulse specialists	3	>7	5	spring to summer
Group 2: River specialists	5	>15	5	spring *
Group 3: Floodplain specialists	1*	>15	1**	spring to summer
Group 4: Generalists	5	>7	5	spring to autumn
Group 5: Generalists (alien)	5	>7	5	spring to autumn
	Large in-channel pulses (B)			
Group 1: Flow pulse specialists	1 to 2	>7	2	spring to summer
Group 2: River specialists	1 to 2	>15	2	spring *
Group 3: Floodplain specialists	1*	>15	1**	spring to summer
Group 4: Generalists	2	>7	2	spring to autumn
Group 5: Generalists (alien)	2	>7	2	spring to autumn
	Small in-channel pulses (C)			
Group 1: Flow pulse specialists	0.5	>7	0.5	variable
Group 2: River specialists	0.5	>7	0.5	variable
Group 3: Floodplain specialists	0.5	>7	0.5	variable
Group 4: Generalists	0.5	>7	0.5	variable
Group 5: Generalists (alien)	0.5	>7	0.5	variable
	Base Flows (D)			
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: Generalists (alien)	-	-	-	all season

The degree to which the three conceptual annual flow hydrographs is expected to attain each ESC (A. overbank flows, B. large pulses, C. small pulses and D. base flows), and therefore supports the key life history elements and processes (Habitat, Condition, Reproduction, Movement and Maintenance) for the four Southern MDB functional fish groups is presented in Table 5.

Table 5. Degree to which each flow component would be expected to support key life-history elements and processes for each functional group of fishes; and likelihood of achieving support for each element/process under different water availability scenarios. * Indicates circumstances where complementary action may be required to deliver water.

Functional Group	Life History element/process	Degree to which flow regime component supports life history element/process				Lilklihood of supporting life history element/process under different water availability scenarios		
		Overbank flow	Large in-channel pulse	Small in-channel pulse	Base flow	High availability	Moderate availability	Low availability
Group 1: Flow pulse specialists	Habitat	Good	Good	Modrate	Modrate	High	High	Modrate
	Condition	Good	Good	Modrate	Modrate	High	High	Modrate
	Reproduction	Good	Modrate	Poor	Poor	High	Modrate	Unlkiely
	Movement	Good	Good	Modrate	Modrate	High	Modrate	Low
	Maintenance	Good	Good	Modrate	Modrate	High	High	Modrate
Group 2:River specialists	Habitat	Good	Good	Good	Modrate	High	High	Modrate
	Condition	Good	Good	Modrate	Modrate	High	High	Modrate
	Reproduction	Good	Good	Poor	Poor	High	Modrate	Low
	Movement	Good	Good	Modrate	Modrate	High	Modrate	Modrate
	Maintenance	Good	Good	Modrate	Modrate	High	High	Modrate
Group 3: Floodplain specialists	Habitat	Good	Modrate*	Nil*	Nil*	Modrate*	Unlkiely*	Unlkiely*
	Condition	Good	Modrate*	Nil*	Nil*	Modrate*	Unlkiely*	Unlkiely*
	Reproduction	Good	Modrate*	Nil*	Nil*	Modrate*	Unlkiely*	Unlkiely*
	Movement	Good	Modrate*	Nil*	Nil*	Modrate*	Unlkiely*	Unlkiely*
	Maintenance	Good	Modrate*	Nil*	Nil*	Modrate*	Unlkiely*	Unlkiely*
Group 4 and 5: Generalists	Habitat	Good	Good	Good	Modrate	High	High	Modrate
	Condition	Good	Good	Good	Modrate	High	High	Modrate
	Reproduction	Good	Good	Modrate	Modrate	High	High	Modrate
	Movement	Good	Good	Modrate	Modrate	High	High	Modrate
	Maintenance	Good	Good	Good	Modrate	High	High	Modrate

Importantly, the conceptual flow hydrographs presented here can be updated as additional information comes to hand. Managers can use additional information (where available) to identify that in a given year, they will be able to meet certain ecologically significant components for each functional group (and thus the benefits they expect to see when they deliver them). They can also use this process to document outcomes achieved in a given timeframe.

The conceptual hydrographs proposed are by no means prescriptive. Responsible water management and manipulation of the flow regime will require coordinated efforts between jurisdictions across both the Southern and Northern MDB, sustained consultation with expert fish ecologists, and ongoing consideration of antecedent hydrology, forecast water availability and prioritisation of hydraulic requirements within and between systems both spatially and temporally. Thorough monitoring of the ecological outcomes or impacts resulting from application of the framework we present will be critical to allow future adaptation and optimisation of this process.

Site-specific Environmental Water Requirements (EWRs)

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 environmental water requirements (EWRs) for 24 Hydrologic indicator sites (HIS) in the MDB that are considered to be 'key environmental assets' (MDBA 2011b). 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 sites it passes through, both upstream and downstream. EWRs also provide for a common language between environmental outcomes and hydrology.

The EWRs originally developed to inform Basin Plan development did not reflect newer (post-2009) scientific advancements. The Basin-wide Watering Strategy (BWS; MDBA 2014b) <u>does</u> however incorporate more recent information regarding the responses of fish to flows. Given Basin and State-wide Long-Term Watering Plans (LTWPs) and WRP currently being developed are required to "have regard" to the objectives of the BWS, the Basin Plan EWRs should be reviewed to also reflect best available science if they are to be used to support Basin Plan implementation.

The EWRs developed for each HIS under the Basin Plan (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 channel, area or floodplain feature). At a site level the combination of these flow indicators were considered indicative of the required long-term flow regime and therefore the EWRs of the site. The original EWRs can be viewed through the respective '*Assessments of Environmental Water Requirements for the Proposed Basin Plan published by the Murray Darling–Basin Authority' in 2012*' (MDBA 2012 a – k).

The 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, banks 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, the in channel flows required to support ecosystem function, 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.

It is proposed that the original EWRs are reviewed and that fish specific EWRs which reflect the objectives of the BWS and functional guilds and conceptual hydrographs developed for this project. Revision of these EWRs would support the MDBA in more systematically assessing annual priorities, state Long Term Watering Plans (LTWPs) and Water Resource Plans (WRPs), and in future reviews of effectiveness of Basin Plan implementation. This would also support the MDB States in the development of their LTWPs, WRP and annual priorities to reflect the objectives of the BWS. Revision of EWRs across key sites in the Southern-connected system will also support the coordinated development of LTWPs across the MDB, and importantly consider how to support connectivity and multi-site watering.

Discussion

The Sustainable Diversion Limits (SDLs) presented in the Basin Plan are intended to reflect an environmentally sustainable level of take (ESLT). To inform the ESLT, the MDBA developed environmental water requirements (EWRs) at a suite of Hydrologic Indicator Sites (HIS) spread across the MDB which represented the broader environmental flow needs of the MDB. In developing the ESLT for the Basin Plan in 2009, the MDBA focussed on the water needs of floodplains and wetlands (overbank and bankfull flows). Due to availability of information on casual relationships flow indicators 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. Consequently any consideration of within-channel flow-ecology relationships for fish in riverine habitats was limited, and this overlooked the key requirements and population processes that may be needed to support viable fish populations.

Significant advancement of our understanding of fish and flow relationships has occurred since the original development of water requirements in 2009. To incorporate this new knowledge and address the deficiency of within-channel flow requirements, DPI Fisheries (NSW) in partnership with the Arthur Rylah Institute (ARI) undertook an updated review of the water requirements of fish in the Southern Murray–Darling Basin, particularly in relation to flow (Section 1 of this report). The synthesised Information was used to develop refined EWRs specifically targeting fish outcomes at nine HIS in the Murray River catchment (Section 2 of this report). The refined EWRs are based on conceptualised annual hydrographs for each HIS and describe the key components of the flow regime required by native fishes in the surrounding river reach

It is important to note that the delivery of water is the 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, weir pool manipulations, improvements to fish passage, conservation stocking or translocations, screening of irrigation pump offtakes to minimise fish entrainment, pest fish control (e.g. wetland screening or removal programs), riparian restoration and coordinated watering strategies (between States, jurisdictions and sites).

Next Steps

The outputs of this project are intended to assist the MDBA and other agencies with their environmental water management responsibilities in the implementation of the Murray–Darling Basin Plan, including the delivery of the Basin-wide Watering Strategy and the Basin states Long term Environmental Watering Plans.

Addressing knowledge gaps

This project represents a contemporary synthesis of knowledge and conceptual understanding 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 condition and survival
- flow influences on reproduction and movement by some species
- regional flow influences or requirements, and
- the importance of flow translucency, supplementary flows, and multi-year flow sequences

Targeted research and thorough monitoring of the ecological outcomes or impacts resulting from application of the framework 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 consideration. Importantly, the outputs presented in this report can be updated as additional information comes to hand. We anticipate that over the next five years (and beyond) the outputs included in this report will be refined in support of the LTWPs and BWS. As knowledge gaps are addressed our understanding will increase and management options will be refined.

Adjoining catchments

It is recommended that the applicability of the framework developed here (for the Murray River catchments) be considered in subsequent projects for adjoining tributaries and valleys in the Southern MDB. These include the Lower Darling River, the Coorong, Lower Lakes and Murray Mouth, the Lachlan River and Victorian tributaries of the Murray River.

The Darling River historically provided regular summer flows to the lower Murray River, creating variability in terms of hydrology and source water. The Coorong, Lower Lakes and Murray Mouth region includes a diverse range of freshwater, estuarine and marine habitats and is listed under the Ramsar Convention. Both of these regions are vitally linked to ecosystem processes throughout the rest of the MDB, however, to keep the scope of the current project manageable neither is included in this review of EWRs. The Lachlan River is not included here given the infrequency of connection between its streams and the Southern MDB (i.e. the Murrumbidgee River).

Additional indicator sites

There are likely to be limitations in the capacity for the current HIS method to represent the flow-related requirements of all of the native fish within a region, particularly those inhabiting floodplain channels and wetland habitats between indicator site locations (Wallace et. al. 2014a). Application and testing of the framework described in this document may highlight the need for finer resolution with regard to indicator site location. For example, the Lower River Murray HIS located at the NSW –South Australia border does not generally represent flow 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. Similar inadequacies may become apparent within other assets of the MDB. Additional flow gauging sites located within minor tributaries or floodplain anabranches may improve the potential for conceptual hydrographs to reflect native fish requirements at a finer scale.

Development of fish specific Environmental Water Requirements

It is proposed that the Basin Plan Environmental Water Requirements (EWRs) are reviewed and that fish specific EWRs which reflect the objectives of the BWS and functional guilds and conceptual hydrographs developed for this project. Revision of these EWRs would support the MDBA in more systematically assessing annual priorities, state Long Term Watering Plans (LTWPs) and Water Resource Plans (WRPs), and in future reviews of effectiveness of Basin Plan implementation. This would also support the MDB States in the development of their LTWPs, WRP and annual priorities to reflect the objectives of the BWS. Revision of EWRs across key sites in the Southern-connected system will also support the coordinated development of LTWPs across the MDB, and importantly consider how to support connectivity and multi-site watering.

Comparison of conceptual and actual historical hydrographs

There is an opportunity for the development of a hydrological model which overlays the prescribed conceptual hydrographs on historical hydrographs. This would enable the volumes of environmental water that would have been required to achieve key elements of the conceptual hydrographs presented here under actual high, moderate and low water availability scenarios to be calculated. In turn, this would support refinement of the conceptual hydrographs presented here to reflect their achievability, and help determine the volumes of future environmental water that would be necessary to achieve key hydrograph features in a given valley under different water availability scenarios.

Comparison of conceptual and actual modelled historical 'without development' hydrographs

A comparison of the conceptual hydrographs with modelled 'without development' hydrographs for key HIS in the Southern MDB would allow refinement of the conceptual hydrographs and fish specific EWRs presented here. In particular, rates of rise and fall for environmental flow events could be matched to the variability in flows to which native fish have adapted.

Coordinated management

Most of the HIS in the Murray–Darling Basin are hydrologically connected and therefore interdependent. To be effective, manipulation of the flow regime to target fish objectives should aim to achieve cumulative benefits within and across catchments. This will require coordinated efforts by jurisdictions across both the Southern and Northern MDB in order to provide longitudinal connectivity that elicits natural spawning or movement cues. To maximise fish outcomes, flows should undertake ongoing consultation with fish ecologists, and ensure that consideration of antecedent hydrology and forecasts of water availability informs the prioritisation of hydraulic requirements, both within and between systems.

The framework presented here together with monitoring and evaluation of Basin Plan and knowledge gained through adaptive management will improve the prospects for the rehabilitation of native fish populations into the future.

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Appendix A: Fish of the Southern MDB

Appendix A1:Fish species recorded or expected in the Southern NSW Murray–Darling Basin including the conservation status of each species internationally (IUCN 2015), in the Commonwealth, in each MDB state and inclusion in NSW Endangered Ecological Communities is presented. Non-native species do not have conservation listing.

STATUS	International	Commonwealth	New South Wales		Victoria		South Australia	A.C.T.
Species/population	**International Union for Conservation of Nature (IUCN 2015)**	**Commonwealth (EPBC 2004)**	**NSW Fisheries Management Act (FM Act 1994)**	**NSW Endangered Ecological Community (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
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
Short-headed Lamprey (1)	Not listed	Not listed	Not listed	Lower Murray	Not listed	Not listed	Not Protected	Not listed
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 (icl. 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

STATUS	International	Commonwealth	New South Wales		Victoria		South Australia	A.C.T.
Species/population	**International Union for Conservation of Nature (IUCN 2015)**	**Commonwealth (EPBC 2004)**	**NSW Fisheries Management Act (FM Act 1994)**	**NSW Endangered Ecological Community (DPI 2007a)**	**Flora and Fauna Guarantee Act 1988 (DELWP 2015)**	**DSE Advisory List of Threatened Fauna**	**SA Fisheries Management Act 2007**	**Nature Conservation Act**
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) (western NSW population)	Data deficient	Not listed	Endangered	Lower Murray	Threatened	Regionally extinct	Protected	Not listed
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
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
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
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 A2: Biological information for fish species recorded or expected in the Murray River catchment (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) (Mallen-Cooper and Zampatti 2015b).

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
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
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 (5-6 yr.)	Macro	Aug-Nov	Serial (multiple events per year)	3,800 - 13,400	No
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

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
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
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
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
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
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