

NSW Fish and Flow Management Framework Report

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Executive Summary

Fish need water to survive. However, different fish have different life history responses depending on the flow conditions in rivers, meaning that assuming any water will have positive outcomes for all fish is too simplistic. Management of water for fish needs to be targeted to support critical life history elements and key population processes to support ongoing viable populations. We know that restoring fish populations through smarter water delivery and protection of natural flows can be an effective way to manage river health.

Restoring components of natural flow regimes through the delivery of water for the environment has become a key aspect of riverine and wetland ecosystem management. However, effective flow restoration requires an understanding of the relationships between hydrology, and life history and population dynamics of biota, so that these can then be linked to management decisions. Ongoing research efforts are needed to continue to build understanding of the drivers that support healthy fish populations, to expand the range of species we can support, and to test and refine the conceptual models that underpin Environmental Water Requirements (EWRs). Improvements will not be achieved without continued concerted management efforts and the incorporation of recently generated knowledge (Koehn et. al. 2014a).

This updated Fish and Flow Management Framework (the Framework) summarises our current understanding of fish life history traits for native fish species in the NSW Murray-Darling Basin (MDB) and the associated EWRs that provide for them. The Framework is the culmination of several iterations of fish and flow frameworks, recent research and the accumulation of knowledge learned through adaptive management of flows for native fish outcomes. The guidance presented in this framework will enable flow management decisions that include the needs of additional aquatic biota such as mussels, prawns, shrimps, and crustaceans. New knowledge of the likely impacts of climate change can also be incorporated in flow management.

The Framework, in combination with more localised Fish and Flow reports, are key resources for NSW DPIRD Fisheries and water managers to guide management of water for the environment for systems over long-term planning timeframes. Ongoing adaptive water management will require coordinated efforts between jurisdictions within the MDB and with expert fish ecologists. It will also require ongoing consideration of antecedent and forecast conditions (climate and hydrology), water availability and prioritisation of ecologically significant flow components within and between systems both spatially and temporally.

Introduction

The importance of flow

Water is fundamental to fish, and the movement of water within and between waterbodies (i.e. flow) has a major influence on their life history and population processes. Flows promote productivity in aquatic ecosystems via nutrient exchange and cycling and create connectivity between aquatic habitats (e.g. rivers and floodplain habitats, valleys, or reaches within a valley). Individual fish species have particular habitat, food and lifecycle needs that are linked to the availability of water and the way it flows in the landscape. Different species also respond uniquely to changes in flow regimes. The biological rhythms of fish are often linked to flow so that opportunities for spawning, growth and dispersal are synchronised (Baumgartner et al. 2014). For example, survival of eggs and larvae may also be dependent on flow to transport them to suitable nursery habitat, or to maintain habitat while the eggs hatch and larvae develop. If there is an aim to protect and improve native fish populations, there is a need to cater for these differences across various spatial and temporal scales.

Fish life cycles are closely linked to the nature of water flow in rivers. Therefore, the particular flow regime of a river influences the health, long term status and viability of native fish populations. However, just assuming any water will have positive outcomes for all fish is overly simplistic. Historically, diversity and variability in flowing conditions was a natural feature of NSW MDB rivers. Native biota with life histories evolved in NSW river systems are specifically adapted to these natural hydrological regimes (Mallen-Cooper and Zampatti 2020). Human influences and the exploitation of freshwater resources have substantially altered flow regimes and reduced hydraulic complexity throughout much of the MDB in less than 200 years. The resulting impacts have had a direct impact on the ecology and life cycles of native fish.

Flow regulation and changes to the natural flow regime are only some of the threats implicated in the decline of native fish in the NSW MDB. A range of additional influences will impact on the health of the rivers and wetlands and therefore on the status of fish and fish communities. Dealing with the cumulative impacts on native fish populations arising from flow alteration and regulation therefore requires continued concerted management efforts that incorporates recently generated knowledge (Koehn et al. 2014a; Koehn et al. 2020a). The potential for achieving positive long-term ecological outcomes through water management is likely to be increased by undertaking parallel complementary actions that also address key threatening processes and evolving threats.

Managing flow for fish outcomes

Managing river health through the protection or re-instatement of key flow components can be an effective way to support protection and recovery of native fish populations. In recent years the process of restoring components of natural flow regimes, augmented by the delivery of water for the environment, has become a key aspect of ecosystem management in the MDB (Arthington 2012; Koehn et al. 2014b; Mallen-Cooper and Zampatti 2015c; Stewardson and Guarino 2018). However, managing riverine flows for consumptive and agricultural use while considering flow restoration for environmental purposes can be challenging and may lead to conflict (e.g. channel capacity constraints, potential for third party impacts (Arthington 2012; 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 water for the environment (Beesley et al. 2011; Koehn et al. 2014b).

Managing expectations surrounding the limitations of water for the environment in fish protection and recovery is important. For example, water managers often struggle to support ecologically meaningful baseflows for the required duration due to limited water availability. Managed flows could also potentially contribute to negative outcomes such as increased recruitment of non-native fishes (Stuart and Jones 2006; Beesley et al. 2012), hypoxic blackwater events (King et al. 2012) or sedimentation (Lyon and O'Connor 2008).

Regulating infrastructure purposefully constructed to facilitate environmental watering could also have unexpected outcomes. For example, regulators which artificially inundate floodplains by backing up water rather than delivery of a downstream pulse of floodwater, could also lead to negative impacts (e.g. increases in residency times, reduction in hydraulic variability, fish passage obstruction and proliferation of non-native species (Koehn et al. 2014b; Baumgartner et al. 2014)). To date, such initiatives have largely been implemented in the Southern Basin; but as our knowledge of system scale connectivity requirements for fish and the value of off-channel nursery habitat increases, similar initiatives may be progressed in the Northern Basin and it is important to consider lessons learnt from the south.

Effective flow management requires an understanding of the relationships between hydrology, life history and population dynamics of biota, which can then be linked to management actions (Arthington et al. 2006). To effectively manage fish populations, an understanding of the drivers that support healthy fish populations and communities, and the threats and pressures impacting them is required. Flows need to be managed at spatial scales that match the life history needs of fish. For example, floodplain specialists such as Olive Perchlet may benefit from localised management actions, while spawning and recruitment of flow pulse specialists like Golden Perch require flow management over much larger scales (100s to 1000s of km) over extended time periods (Mallen-Cooper and Zampatti 2015b; Stuart and Sharpe 2020).

NSW Murray-Darling Basin

The NSW MDB largely comprises two distinct regions based on differences in geography and hydrological character: the Northern Basin and the Southern Basin. While differences should not be overstated, there are some important distinguishing features that separate the two areas.

The northern NSW MDB covers over 500,000 km² and includes the river valleys of the Paroo, Warrego, Condamine-Balonne, Border Rivers, Gwydir, Namoi, Macquarie/Wambuul and the Barwon-Darling. Rivers flow to the Darling River and from there to the Murray River. The southern NSW MDB comprises the valleys of the Lachlan, Murrumbidgee, Lower Darling and Murray Rivers and water drains to the Murray River.

The landscape across much of the NSW MDB displays very low topographic relief, meaning that floods spread across large areas of the floodplain sometimes flowing into major wetlands in lower areas. Typically, the Northern Basin receives higher rainfall during summer and early autumn with most rainfall falling on the slopes of the eastern portion of the Border Rivers, Gwydir, Namoi, and Macquarie/Wambuul catchments and slowly flowing through the lower sections of the catchment. Evapotranspiration rates in the north are high, and inflow to rivers is variable and unreliable with only approximately 5% of rainfall being generated as runoff to rivers. This makes annual water

availability highly variable. In contrast, the Southern Basin has higher rainfall during the winter and spring, with significantly higher runoff and surface water availability (Chiew et al 2022).

Water temperatures in the Northern Basin are also often higher on average than for Southern Basin systems (Hutchison et al. 2011). Increased flows in Northern Basin systems may also coincide with higher water temperatures, creating optimum conditions for fish breeding (NSW DPI 2013). This is reflected in a slightly earlier spawning season for Murray Cod in some Northern Basin systems (e.g. the Border Rivers), where the species may spawn in August to September rather than mid to late spring spawning for Southern Basin systems (Wilson and Ellison 2010; Nichols et al. 2012; Butler et al 2022).

Much of the Northern Basin is sparsely populated and remote. The total population of the Northern Basin is estimated at around 660,000¹, compared to around 2.34 million in the Basin as a whole (ABS 2021).

Detailed descriptions of the fish and fish habitats of the Northern Basin and Southern Basins can be accessed in the following documents:

- Fish and Flows in the Northern Murray-Darling Basin (NSW DPI, 2015) and
- Fish and Flows in the Murray River Catchment (Ellis et al. 2016).

Purpose of this review

This report represents an updated Fish and Flow Management Framework for fisheries and water management practitioners to design, implement and monitor fish specific EWRs. EWRs are considered necessary to achieve the targets and objectives of NSW Long Term Water Plans (LTWPs), and subsequent long term environmental outcomes and targets as defined by the Basin-wide environmental Watering Strategy (BWS) and Basin Plan. The Framework builds on a series of technical reports, expert workshops and new science to reflect current and best available information to guide native fish protection and recovery in the NSW MDB through the management of water.

In 2023, a review of the Fish and Flows Framework was undertaken by 2rog Consulting (2rog Consulting 2023). The scope of the review was to:

- Synthesise recent relevant science and knowledge relating to native fish life history and the causal effects of flow on native fish outcomes and water quality in the MDB.
- Review and make recommendations as needed to update the existing fish functional groups.
- Make recommendations as needed to update the existing Fish and Flow Management Framework to reflect contemporary science and knowledge.
- Assess the extent to which current (or updated) fish functional group EWRs contribute to outcomes of freshwater mussels, freshwater snails and freshwater crustacea (shrimp, prawns, yabbies and crayfish) that occur throughout the NSW MDB, and making recommendations to better define related EWRs as needed.

¹ based on cumulative totals from specified catchments

(<https://www.mdba.gov.au/basin/catchments/northern-basin-catchments>, Accessed 15/04/2024)

- Make recommendations in relation to climate change associated risks, functional group susceptibility, and associated impediments to achieving LTWP and BWS native fish targets and objectives.

The review included a literature review as well as an expert workshop attended by relevant NSW DPIRD Fisheries staff. Recommendations from the 2rog Consulting (2023) review have been used as the basis for this report, along with the addition of cultural considerations, and information on the status of fish in the NSW MDB.

Culture as a part of Country

First Nations people do not just identify by their Nation, but by reference to water – saltwater people, freshwater people and river people. As water is essential for life, so it is essential for culture (Williams et al 2023). This necessitates the need to manage Country, and water, as a natural pattern of interconnected cycles. There is no distinction between water, land, air, plant, animals, people, living or non-living; all exist in this cycle as a part of Country (Moggridge and Thompson 2021).

These natural patterns and interconnected cycles are pivotal in safeguarding, preserving, and enhancing First Nations culture, but are also a catalyst for the seasonal calendar (Atkinson 2009). Listening to Country and the natural patterns of river flow trigger important cultural cues for First Nations people to practise cultural activities such as social gatherings or moving across Country for initiation or custodial duties (Moggridge and Thompson 2021). The symbiotic relationship between First Nations peoples and their Country bears a resemblance to the interdependence observed in native fish and river flow. The life history stages of native fish are intrinsically tied with the natural patterns and interconnected cycles of the flowing river. Any disruption or deviation to the balanced pattern results in profound impacts on Country and communities.

At the core of First Nations culture lies a knowledge system referred to in English as the Dreaming. The Dreaming explains the creation story of all things, with water as a prominent theme for all First Nations groups. Despite variations between different groups, the fundamental belief is that water is sacred, living and the life of us all (Moggridge and Thompson, 2021). The flow of water is vital to sustaining the natural patterns and interconnected cycles central to First Nations knowledge systems. It's understood that the rivers are the veins of Country, carrying water to sustain all parts of the landscape, connecting communities, ecosystems, economies, Lore, and culture together (MLDRIN et al. 2018).

Biame's Ngunnhu (fish traps) at Brewarrina is a Dreaming place intrinsically linked to water, Country and Culture. Biame's Ngunnhu is an ancient Dreaming place created by the ancestral Creator spirit Baiame. Ngemba (a First Nations group) Dreaming explains that the Ngunnhu were built by Baiame, and his two sons Booma-ooma-nowi and Ghindi-indi-mui, to save his people from starvation during a devastating drought. Baiame taught the Elders to call the rain through ceremony and as long-awaited rain fell it called the fish into the Ngunnhu and the Ngema people caught thousands of fish, saving them from starvation. Baiame appointed the Ngemba as custodians of the Ngunnuh in Lore, but also granted other groups such as Morowari, Paarkinji, Weilwan, Barabinja, Ualarai and Kamilaroi

permission to use the traps (Murdi Paaki Regional Assembly 2015). This Lore is still followed today and represents how the Dreaming has a physical presence that is intrinsically tied to water, and how these water-places are woven into the social fabric of First Nations culture.

First Nations people describe their role in interconnected cycles and delineate custodianship duties through the totem system. They may recognise, relate, and regulate plants or animals through the Dreaming as ‘totemic’ species, which are then assigned custodial obligations or rules that are maintained by specific individuals or kinships (Robinson and Raven 2019). Totems go beyond symbolic representations; they can be intricately linked to sacred sites and serve as foundational elements supporting the spiritual, emotional, physical, social, and environmental wellbeing of First Nations communities. The care and protection of totems and Country are inseparable, as the health of one directly influences the wellbeing of the other (Pattel, 2007). An example of totemic significance is observed in the Gambaal (Silver Perch), a totem for the Gomeroi Nation, exemplifying the deep connection between native fish species and the cultural fabric of First Nations communities.

Culture and Fish

Bioarchaeological investigations along the Lower Murray River have shed light on the dietary practices of First Nation peoples, revealing a significant reliance on freshwater fish and molluscs for sustenance. These aquatic resources contributed between 30-40% of the dietary protein among First Nations communities (Pate 2000). Similarly, a comprehensive examination of 216 open midden sites along the Barka River and associated lakes underscored the prevalence of molluscs, alongside common fish species such as Golden Perch, River Catfish, and Yabbies, with mammals and reptiles featuring less prominently (Balme 1995). This underscores the vital role of freshwater aquatic species in the diet and culture of First Nations groups.

Moreover, the significance of aquatic resources transcends mere sustenance, flowing into the realms of economy and cultural practices. Notably, Humphries (2007) highlights the utilization of aquatic plants and animal parts, including freshwater crayfish antennae and fish bones, for decorative purposes. Recent studies have further emphasized this connection, affirming the continued importance of freshwater crayfish and yabbies as food sources targeted by Aboriginal cultural fishers in certain basin areas (Nobel et al., 2016).

The Murray Cod (Pondi/Guduu) holds particular cultural reverence among many First Nations communities. Pondi/Guduu is deeply intertwined with the Dreaming creation story of the MDB and all native fish. The Dreaming varies between regions and Nations but can be summarised as follows. During a great hunt between Pondi/Guduu and a spiritual ancestor, Pondi/Guduu carved the rivers and waterways of the Basin. When Pondi/Guduu was finally caught, the great hunter cut him up into multiple pieces. As each piece was thrown back into the river, they took on the form of the native fish species we know today. The great hunter took the final piece of Pondi/Guduu and said “You keep being Pondi/Guduu” and threw him back into the river (Humphries 2023). This Dreaming tells how the Murray Cod created the Basin and all native fish species, which aligns with the western scientific narrative on genetic drift and natural selection. Here, it is considered that an ancestral species with a wide distribution in riverine environments may have become separated into two or

more populations by a chance event like an earthquake or volcanic eruption (or as seen in the Pondi/Guduu Dreaming, significant geomorphic changes from the hunt). Once isolated, different environmental conditions may have caused the populations to diversify through natural selection or genetic drift, which is how several Australian cod species (of the genus *Maccullochella*) split from the ancestral cod west of the Great Dividing Range (Humphries 2023). This showcases the strong correlation between First Nations cultural knowledge and contemporary western-science interpretations, further reinforcing the fact that First Nations people possess a deep understanding of their Country through their culture.

Another example of the significance the Murray Cod has in First Nations culture and as a part of Country is observed through the tree-like markings on the Murray Cod's swim-bladder. Some First Nations groups believe that the birthplace of the fish is imprinted on the swim-bladder, essentially marking the Country it belongs to into its physical form (G.P. Whitely 1941). This is a representation of the deep connection the Murray Cod has to the MDB, showcasing the First Nations cultural understanding of the role the Murray Cod has in the Dreaming and how the Dreaming can have physical representation in the physiology of the Murray Cod. Historically, it also constituted a substantial portion of the cultural catch across the basin, representing over 25% in certain areas (Noble et al., 2016). Beverage (1882) documented instances of First Nations individuals using Murray Cod fat for both decorative and insulating purposes, further underscoring its cultural significance and multifaceted utilization.

Culture and Molluscs

Freshwater mussels have a long history of human use in Australia as a food source, in fishing, as tools and in cultural practices, with virtually all rivers in the MDB showing evidence of First Nations occupation either through the presence of middens, scar trees or artefacts (Humphries 2007). Middens occur frequently across the rich cultural landscape, with the oldest in the Barka River region dating back to around 27,000 years ago (Balme 1995; Balme and Hope 1990; Mallen-Cooper and Zampatti 2020), and are an important indicator for First Nations occupation, diet and cultural practises. Middens are typically confined to areas close to contemporary river channels, tributaries or ancestral anabranches, which highlights the importance of water-places for First Nations culture. Middens can provide valuable insights about the local aquatic economy and the role molluscs have in First Nations culture (Garvey 2017).

First nations shell middens in the MDB are primarily dominated by freshwater mussel species (*Velesunio ambiguus* and *Alathyria jacksoni*) and freshwater river snails (*Notopala sublineata*) (Garvey 2017). While there are other terrestrial protein sources available to First Nations groups, cultural protocols dictate the division of nutritionally rich animal food sources, such as macropods, to favour the male hunters and/or Elders. Further to this, freshwater molluscs possess high levels of Polyunsaturated Fatty Acids (PUFAs), especially Omega 3 (n-3) Fatty Acids and Omega 6 (n-6) Fatty Acids which have important health benefits for the human diet and metabolic function, especially for cognitive processes (Gomez Pinilla 2008). Due to cultural protocols governing the distribution of food within a group and the high nutritional value of freshwater molluscs, it's evident that this species is culturally and nutritionally important for First Nations people, especially women and children (Garvey 2017). This is further reinforced by references of First Nations women digging for

mussels in the Barka, cooking mussels on their fires, and using mussels as bait, particularly for cod (Langloh-Parker 1905).

Freshwater molluscs also have cultural value through ceremony and tool-making practises. Mussel shells are used as substitute for stone tools, specifically as scrapers for processing plant fibres (which are then used to construct nets or baskets), processing animal skins, and in drawing blood or fat for anointment purposes such as insulation (Humphries 2007), with mussel shell tools from the Barka region dating back to 50,000 years ago (Weston et al. 2017). In ceremony, women and men both use the shell to lacerate their bodies for mourning or initiation purposes, and in decoration as hair and body ornaments (Roberts et al. 2022). The use of shell in contemporary cultural expression is also evident in Wiradjuri artist Jonathan Jones, who used mussel shells in his 2018 work entitled 'giran' which featured contemporary hand-made tools, including 'bindu-gaany' - freshwater mussel scrapers (Jones 2020). Furthermore, Barkandji artist Badger Bates has also used freshwater mussel shells in his 2018 exhibition 'Barka, the forgotten river' to highlight concerns over impacts of lack of flows on mussels (Volkofsky and Bates 2018).

The season for collecting mussels was short, typically occurring at the end of spring to the end of summer, with the mussels migrating into deep mud during winter (Garvey 2017). Even so, freshwater mollusc species maintained consistent use by First Nations groups as a reliable food source and as a tool with practical and ceremonial applications.

Managing Country with Culture

For a millennia, First Nations people have actively managed and shaped the landscape to sustainably harness resources (DSEWPC 2012). This stewardship is evident in the sophisticated fish trap technology found throughout the MDB, with each region showcasing unique variations in design, construction material and functionality (Roughley 1968; Rowland and Ulm 2011). Fish traps exhibit diverse fishing and construction techniques tailored to local resources, landscape knowledge and cultural practises. These can range from utilising reeds or fibre to create woven funnels/baskets, physical modification of banks or wetlands through earthworks, and using chemical extractions from plants such as the bark of the *Acacia* species or leaves of *Persciaria hydropiper*, to create fish poisons (Murrumbidgee CMA 2008).

An exemplary instance of landscape engineering is showcased at the Brewarrina Fish Traps on the Barwon River, known as 'Baime's Ngunnhu' to the Ngemba people (Humphries 2017). This complex network of dry-stone rock weirs and pens spans roughly 0.5 km, highlighting a profound understanding of dry-stone wall construction, river hydrology, and fish ecology. Crafted with an intimate knowledge of Country, these traps endure fluctuating river flows while enabling the herding and capture of large quantities of fish (DCCEEW 2005). These fishing activities were prevalent during spring rainfall and aligned with the seasonal migration of species like the Golden Perch. Baime's Ngunnhu once encompassed several hundred stone traps, managed by numerous kinship groups of neighbouring Nations, which required complex social organisation to manage the resource sustainably. This emphasises the importance of kinship and custodianship duties to the social fabric of First Nations culture. The intimate connection between Baime's Ngunnhu and the natural life

history of native fish also demonstrates First Nation people's intricate understanding of the natural patterns and interconnected cycles of Country and how this knowledge is used to enhance the cultural, economic and resource value of waterways in the MDB.

First Nations groups are known to alter the physical environment to enhance the survival and growth of fish species (Humphries 2007) which is evident at the Budj Bim Kooyang Traps (Eel Traps) in south-west Victoria. The Budj Bim Kooyang Traps are an ancient lava flow that has been engineered by the Gunditjmara people to provide a permanent supply for freshwater, eels, fish and aquatic plants at Lake Condah (DCCEEW 2004). The Budj Bim dates back 6600 years and is the oldest known aquaculture of eels. Smoked Kooyang (short-finned eel) is a treasured food source and an important resource for freshwater and saltwater economies (Noble et al 2016). Furthermore, First Nations people have been documented modifying riverbanks to facilitate fish passage into wetlands and billabongs. This allowed the easier capture of fish and provided fish passage into floodplain wetlands during dry periods without the reliance on high natural flow (Kirby 1895).

The known occupation of First Nations people on the MDB, combined with a landscape that has been engineered by cultural practises demonstrates that First Nations people were intimately aware of their role as custodians and developed cultural protocols to ensure their impact on Country was sustainable. The current poor condition of native fish and river health in the MDB as a whole shows the significance of First Nation people's absence from resource management in contemporary Australia (Humphries 2007).

NSW DPIRD Fisheries seeks to identify and reflect the intrinsic connection of First Nations culture to Country and adopt flow-related objectives reflecting the cultural vision, custodianship, and totemic duties that First Nations groups possess for native fish in the Fish and Flows Management Framework. To address these knowledge gaps, NSW DPIRD Fisheries commenced the Culture, Fish and Flows project in the Peel valley that aimed to pair Culture with the Fish and Flows Management Framework.

Culture, Fish and Flows Project

The Culture, Fish and Flows is a pilot project developed to understand how to represent First Nations culture in the Fish and Flows Management Framework.

The aim of this project is to identify Gomeri science, knowledge, values, experience, and perspectives about river flow and native fish ecology on the Peel River, and to work collaboratively with the Gomeri people to determine a way to reflect this information in the Framework.

The project will use a collaborative inquiry framework to investigate the following research question:

“What are Gomeri science, knowledge, values, experience and perspective about river flow and native fish ecology, and how to include that information within the Fish and Flows Management Framework?”

The project will develop:

- A culturally appropriate methodology to pair Gomeroi cultural knowledge, experience, perspective and values within the Fish and Flows Management Framework
- River flow related cultural objectives for native fish maintenance, conservation and recovery for a river reach of high cultural value.
- A final project report outlining how cultural information can be included in the Fish and Flows Management Framework and recommendations to implement.
- A Cultural Watering Place study for a site of cultural significance, which includes scientific information from the Fish and Flows Management Framework. The project will also facilitate inter-generational knowledge exchange between the Gomeroi community members through on-Country workshops.

The pilot project will take place along the Peel River part of the traditional Country of the Gomeroi Nation.

The Culture, Fish and Flows project uses the National Cultural Flows Research Project (NCFRP) Indigenous Research Methodologies (IRMs) and the Aboriginal Waterways Assessment tool developed by Murray Lower Darling Rivers Indigenous Nations (MLDRIN), Northern Australia Indigenous Land and Sea Management Alliance (NAILSMA) and the Northern Basin Aboriginal Nations (NBAN), as a process to incorporate Indigenous knowledge systems into an existing Western scientific framework.

NSW DPIRD Fisheries have developed relationships with Gomeroi representatives and organisations based in Tamworth. The project includes a Consultative Panel to provide high level advice on project design and engagement approaches, as well as Human Research Ethics Committee (HREC) review and approval by the Australian Institute of Aboriginal and Torres Strait Islander Studies (AIATSIS).

The intention is to progress related engagement, involvement, and assessments during 2024, with targeted outputs, including Cultural Watering Place case study, project methodology and recommended changes to the Fish and Flows Management Framework expected during 2025. Ongoing updates and engagement will continue beyond this time, with further opportunities explored to continue and expand on the project to other reaches and communities.

Background

Policy Context

The Commonwealth Water Act 2007 established the Murray-Darling Basin Authority (MDBA) and tasked it with the preparation of a Murray-Darling Basin Plan (Basin Plan) to provide for the integrated management of the MDB's water resources (Commonwealth of Australia 2012; MDBA 2010). The Basin Plan required the development of an Environmental Watering Plan (EWP) to ensure that the size, timing and nature of river flows maximise benefits to the environment (see Chapter 8 of the Basin Plan).

The intent for the EWP is to protect, enhance and nourish the rivers, wetlands, and floodplains of the MDB together with their plants and animals including native fish and other aquatic biota. At a local scale LTWPs and Water Resource Plans (WRPs) inform water for the environment management to ensure consistency in the implementation of the Basin Plan and EWP across the MDB (see Chapter 8 and Chapter 10 of the Basin Plan).

In developing the Basin Plan, indicator sites were used to model and assess water for the environment needs across the MDB and determine a proposed Environmentally Sustainable Level of Take (ESLT) (MDBA 2011). This work assessed the EWRs for major themes (waterbirds, vegetation, fish and ecosystem functions) at key Hydrologic Indicator Sites (HIS) across the MDB (MDBA 2011). EWRs were integral in developing an assessment framework for the Basin Plan using the best science available at the time (2009), and to provide a common language between the themes, and between environmental outcomes and hydrology.

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

It is important to note that in many cases, flow events of a higher magnitude will meet the requirement for lower magnitude events, but only if they are delivered in line with natural processes (e.g. not using works and measures to artificially inundate floodplains) and they are delivered at the right time. The EWRs originally developed to inform Basin Plan development were based on best available information at the time; however, do not necessarily reflect newer scientific advancements (i.e. those made post-2009). The BWS editions I and II (MDBA 2014; MDBA 2019) did incorporate more recent information regarding the responses of fish to flows.

In 2014, the then NSW Department of Primary Industries (NSW DPI) Fisheries embarked on a body of work referred to as the 'Fish and Flows' program to review and synthesise our understanding of the requirements of native fish in the MDB. Initially applied in the Northern MDB (NSW DPI 2015), the principles were transferred to the Southern MDB in a project titled 'Fish and Flows in the Southern Basin: A review of fish and flow relationships in the Southern Murray – Darling Basin conducted in 2015-16 (Ellis et al. 2016).

The framework informed the development of conceptual flow hydrographs to describe significant flow components which support the varied life -history requirements of the different functional groups of native fish.

Fish-specific EWRs that reflect the flow requirements of native fish were developed throughout valleys of the northern NSW Basin, namely the Border Rivers, Gwydir, Macquarie-Wambul and Namoi, and for indicator sites in the Southern Basin including:

Five sites 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 sites 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 site 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.

Native fish objectives and targets in LTWPs

Objectives and targets from the BWS were then transferred to individual NSW MDB valleys using the latest information on fish distribution to identify relevant broad fish community objectives and species-specific targets relating to improved fish outcomes. Valley based objectives and targets, and their links to BWS outcomes are presented in Table 1.

Fish specific EWRs developed by NSW DPIRD Fisheries were aggregated with EWRs that had been devised for waterbirds, vegetation and priority ecosystem functions. The process ensured that valley-scale objectives and targets for native fish had a direct line of sight to the overarching BWS outcomes whilst being ecologically relevant to the management and monitoring activities within the valley.

Fish specific EWRs assist water for the environment holders to systematically develop annual watering priorities and will contribute to future reviews of Basin Plan implementation. Fish specific EWRs also support state agencies in the periodic review of LTWPs, WRPs and annual priorities to reflect the objectives of the BWS. This will also inform the development of coordinated Basin scale watering opportunities.

Table 1 Existing BWS Outcomes and relative valley objectives, targets and priorities

BWS Outcome	Valley Objective	Valley Target	Priority systems
<i>No loss of native species currently present in the Basin</i>	No loss of native species present within the management zone.	Prevalence of all known species continually detected over 5, 10 and 20 year time frames, with an improvement in Fish Community Status (FCS) by one category over a 20-year time frame.	All management zones to include this objective.
<i>Restored distribution and abundance of short-lived species to levels recorded pre-2007</i>	Increased distribution and abundance of short-lived species relative to levels prior to Basin Plan implementation.	Increased distribution (measured as prevalence) and abundance (measured as Catch per unit effort or CPUE) from pre-Basin Plan for known short-lived species, with no more than one year between detection of immature size classes.	Management zones that contain relevant short-lived species in their asset lists and where standardised fish community data exists and/or will exist (i.e. monitoring sites located in management zone) for short-lived species across the nominated temporal scales (pre-Basin Plan and post-Basin Plan) will include this objective.
<i>^aImproved population structure (i.e. a range of size/age classes for all species and stable sex ratios where relevant) of moderate to long lived species in key sites.</i>	Improved population structure of moderate to long lived species driven by sufficient frequency and magnitude of recruitment events.	Population length-frequency data indicates presence of young of year, juveniles, and adult size classes within the population with no more than 2 consecutive years without recruitment for moderate lived species and no more than 4 consecutive years without recruitment for long lived species, with at least 1 significant recruitment event, indicated by a size/age cohort (Young of Year) representing greater than 30% of	Management zones that contain relevant moderate to long lived species in their asset lists and where standardised fish community data exists and/or will exist (i.e. monitoring sites located in management zone) for moderate to long lived species across the nominated temporal scales (pre-

BWS Outcome	Valley Objective	Valley Target	Priority systems
		numbers of the population from standardised sample.	Basin Plan and post-Basin Plan) will include this objective.
<i>A 10-15% increase of mature fish (of legal take size) for recreational target species (Murray Cod and Golden Perch) in key populations</i>	A 15% increase of mature fish (of legal take size) for recreational target species (Murray Cod and Golden Perch) in key populations detected over 5, 10 and 20 year time frames.	Population length-frequency data indicates presence of legal take size classes within the population, with an increased abundance (measured as CPUE) from pre-Basin Plan for key populations of Murray Cod and Golden Perch.	Management zones where a weighted average modelled distribution of Murray Cod and Golden Perch is greater than 50% probability of occurrence was used to identify priority systems and/or water management zones that could potentially include this objective; however assessment of this objective will need to consider the influence of angler take, which will require a separate focused project that may only be achievable in a reduced number of systems.
<i>Annual detection of species and life stages representative of the whole fish community through key fish passages, and increase in passage of targeted species through key fish passages to be</i>	Annual detection of species and life stages representative of the whole fish community through key fish passages and increase in passage of targeted species through key fish passages to be detected in 2019-2024 compared to passage rates detected in 2014-2019.	Increased movement of targeted species in 2019-2024 compared to passage rates detected in 2014-2019.	Management zones to be selected by identifying 'key fish passages', which may include fishways, tributary connectivity and/or floodplain connectivity, as part of an NSW MDB review that will also consider associated monitoring and research activities related to fish movement detection. If a management zone is identified as having a 'key fish passage'

BWS Outcome	Valley Objective	Valley Target	Priority systems
<i>detected in 2019-2024 compared to passage rates detected in 2014-2019</i>			and related fish movement monitoring activities, then relevant objective and targets will be included.
<i>Expand the range (or core range) of a nominated number of existing populations and/or establish a nominated number of an additional populations for identified key species at priority locations</i>	Increased prevalence and/or extent of occurrence (range) of key species driven by increased site prevalence and dispersal and establishment in additional locations.	Key species detected annually in priority systems, with an increase in distribution (measured as prevalence) and abundance (measured as CPUE), with no more than one year (short-lived)/two years (moderate-lived)/four years (long-lived) without detection of immature size classes.	

^a This will require annual recruitment events in at least eight out of 10 years at 80% of sites, with at least four of these being ‘strong’ recruitment events.

Environmental water requirements for fish

Native fish have evolved in a system that is characterised by highly variable, and at times extreme, environmental conditions. From diverse wetting and drying cycles, to fluctuating temperatures, these conditions provide important seasonal cues for native fish, with hydrological variability playing an integral role in influencing the structure and diversity of aquatic communities. A variety of life history and recruitment styles have been developed by different fish species in response to the range of environmental conditions experienced across the Basin. If there is an aim to protect and improve native fish populations, there is a need to cater for these differences across various spatial and temporal scales.

To account for differing watering requirements across the 51 native fish species of the MDB (Lintermans, 2023), species have been placed into 'functional groups'. Each of the four functional groups consist of species that have similar needs and responses to water:

Group 1: Flow Pulse Specialists

Group 2: River Specialists

Group 3: Floodplain Specialists

Group 4: Generalists

A fifth group (Group 5) has been developed for the Southern Basin of the Murray-Darling to account for the current list of 12 generalist non-native species that occur there (Ellis et al, 2016). This Framework does not include the water requirements for alien species - where possible watering actions should be carefully considered so that they do not inadvertently benefit the life cycles of these alien species.

A review of new information on freshwater species undertaken by 2rog Consulting (2023) has assembled information and knowledge on several non-fin fish species including native freshwater mussels, shrimps, prawns, yabbies, crayfish and snails. Where available, the flow requirements of these species have informed their inclusion into the existing Functional Groups. These species have had significantly less research focus than many of the fin fish species, however, their importance and contribution to river ecosystem productivity and health is considered to be significant. The lifecycles and water needs of the following species have fitted neatly into the existing functional groups:

- River Mussel (*Alathyria jacksoni*) and Freshwater Mussel (*Alathyria condola*) have been added to the River Specialist Group (2),
- Floodplain Mussel (*Velesunio ambiguous*) has been added to the Floodplain Specialists Group (3),
- Two prawn species (*Caridina mcculloch* and *Macrobrachium australiense*), Glass Shrimp/ Freshwater Shrimp (*Paratya australiensis*), Yabby (*Cherax destructor*) Murray Crayfish (*Euastacus armatus*) and Highland Cray (*Euastacus jagara*) were all added to the Generalists Group (4).

The Darling River Snail (*Notopala sublineata*) and Hanley's River Snail (*Notopala hanleyi*) were identified as not having enough available information to be included in an existing functional group, nor was there enough information to justify the creation of a new functional group. Therefore, they have been placed in an "Undefined functional group".

The use of these functional groups of freshwater fish in the Basin can assist with water for the environment planning to deliver native fish benefits and develop specific EWRs. When developing EWRs there are basic principles related to the biological and ecological criteria for native fish and inland waterways that need to be considered.

Fish and Flow Requirement Principles

Several principles have been applied to guide the development of functional groups and to determine their flow requirements, including:

1. Water is fundamental to fish; however, it is the interaction of the movement of water within and between waterbodies (i.e., flow) that influences fish life cycles, their survival and persistence.
2. Species respond uniquely to changes in flow regimes as different species have particular habitat, food and lifecycle needs that are linked to the availability of water and flow.
3. Historically, diversity and variability in flow conditions was a natural feature of the rivers in the Murray-Darling Basin. However, the development of river and wetland environments including abstraction and regulation of freshwater resources, have substantially reduced the volume of water available and altered flow regimes throughout much of the Basin. The resulting flow changes have contributed to a decline in the abundance and distribution of many native fish species, with some now absent throughout much of their former range and many persisting in fragmented populations.
4. Managing river health through the protection or re-instatement of more natural flow regimes can be an effective way to support native fish and help protect and recover their populations.
5. Principles specific to the EWRs developed within the Fish and Flows Framework include:
 - i. EWRs seek to reinstate key aspects of the natural flow regime or to retain aspects of the antecedent flow regime deemed critical to achieving native fish objectives by using all available water. To this point, to ensure optimal success of flow management for native fish species, providing sequences of flow that provide for a range of EWRs is required to cater for different life stages. Broadly, EWRs do not seek to restore flows to natural or pre-development conditions.
 - ii. EWRs identify the minimum flow requirements to achieve ecological and biological objectives relating to native fish, which includes ecosystem function, river productivity and water quality over the long term.
 - iii. A combination of EWRs is required to achieve ecological objectives: For example, to prevent the loss of native fish species (objective Native Fish 1) EWRs related to all flow components are needed to ensure species spawn, recruit, and have access to food and habitat that allow individual fish to contribute to the broader population and continue the cycle. Conversely, a single EWR (e.g., related to a baseflow) may contribute to achieving several objectives across multiple groups of species (e.g., access to habitat for native fish and waterbirds), and cumulatively for ecological functions.
6. EWRs are underpinned by eco-hydrological connectivity between EWRs, Planning Units and catchments, so that the associated Ecologically Significant Component (ESC) of the flow regime

and metrics cannot be treated as discrete units. Consideration has been given to determining appropriate flow-height and flow-velocity relationships in waterways of the Basin that account for connectivity and hydraulic requirements of native fish using the overarching principles below to guide the identification of flow rates:

- i. Requirement for very low flows for maintaining water quality by de-stratifying refuge pools is a flow velocity of 0.03-0.05m/s (Mitrovic et al. 2003).
 - ii. Minimum depth for small bodied and moderate bodied fish movement is 0.3m above Cease to Flow (Gippel 2013; O'Connor et al. 2015).
 - iii. Minimum depth for large-bodied fish movement is 0.5m above Cease to Flow (Fairfull and Witheridge 2003; Gippel 2013; O'Connor et al. 2015). Optimal transition of small fresh to large fresh events for the flow specialist spawning and movement response is 2m above Cease to Flow and/or velocity greater than or equal to 0.3-0.4m/s (Marshall et al. 2016; Mallen-Cooper and Zampatti 2015; Bice et al. 2017).
 - iv. Consideration of antecedent conditions is required when setting EWRs for native fish recovery following extreme events such as droughts, fires or hypoxic blackwater events.
 - v. Given the current restricted distribution of some species within the Basin, bespoke flow management may be required at some locations, to improve outcomes for those isolated populations.
7. Monitoring, evaluation and reporting to assess native fish outcomes should be ongoing at least at an annual frequency, with complementary hydrological analysis needed to assess outcomes against described EWRs.
 8. NSW DPIRD Fisheries seeks to identify and reflect the intrinsic connection of First Nations culture to Country and adopt flow-related objectives that reflect cultural perspectives, values, and objectives in relation to native fish, Country, and river flow.
 9. The management of water for the environment remains a relatively new concept, with flow related ecological knowledge still evolving. Periodic revision and updates should be undertaken over time to ensure the latest knowledge is being used to inform the development and implementation of the fish and flows framework. In updating the Fish and Flows Framework, information for both cultural and scientific perspectives, knowledge and values should be incorporated.

Coupled with the latest biological and ecological information for native fish, these principles have been used to develop EWRs for fish. It is important to note that EWRs represent minimum flow conditions needed to maximise opportunities to support improved native fish outcomes in a highly modified system. In most cases the EWRs reflect regular occurrence in historical flow datasets; however native fish populations have been significantly affected by a range of impacts across their historical distribution. To improve a population it may be necessary to implement aspects of the flow regime that do not necessarily reflect 'natural conditions' but seek to balance the impact of river regulation.

Life history of fishes

Life history refers to the sequence of events in an organism's lifetime related to survival and reproduction. Life history incorporates growth, spawning and movement (e.g. migration and dispersal). Native fish of the MDB have a variety of life history and reproductive styles developed in response to the range of environmental conditions experienced across the Basin (Mallen-Cooper and Zampatti 2015c). However, in general adults lay eggs which hatch into larvae; larvae develop into juveniles and ultimately to adults (Figure 1). Flow is a major factor for structuring freshwater fish communities as it influences the range of physical habitats available at each developmental stage for fish as well as ecological processes and functions to which their life history is linked. Modified hydrology within rivers can therefore result in detrimental impacts on life history elements and processes (Poff et al. 1997). Flows need to be managed at spatial scales that match the life history needs of fish.

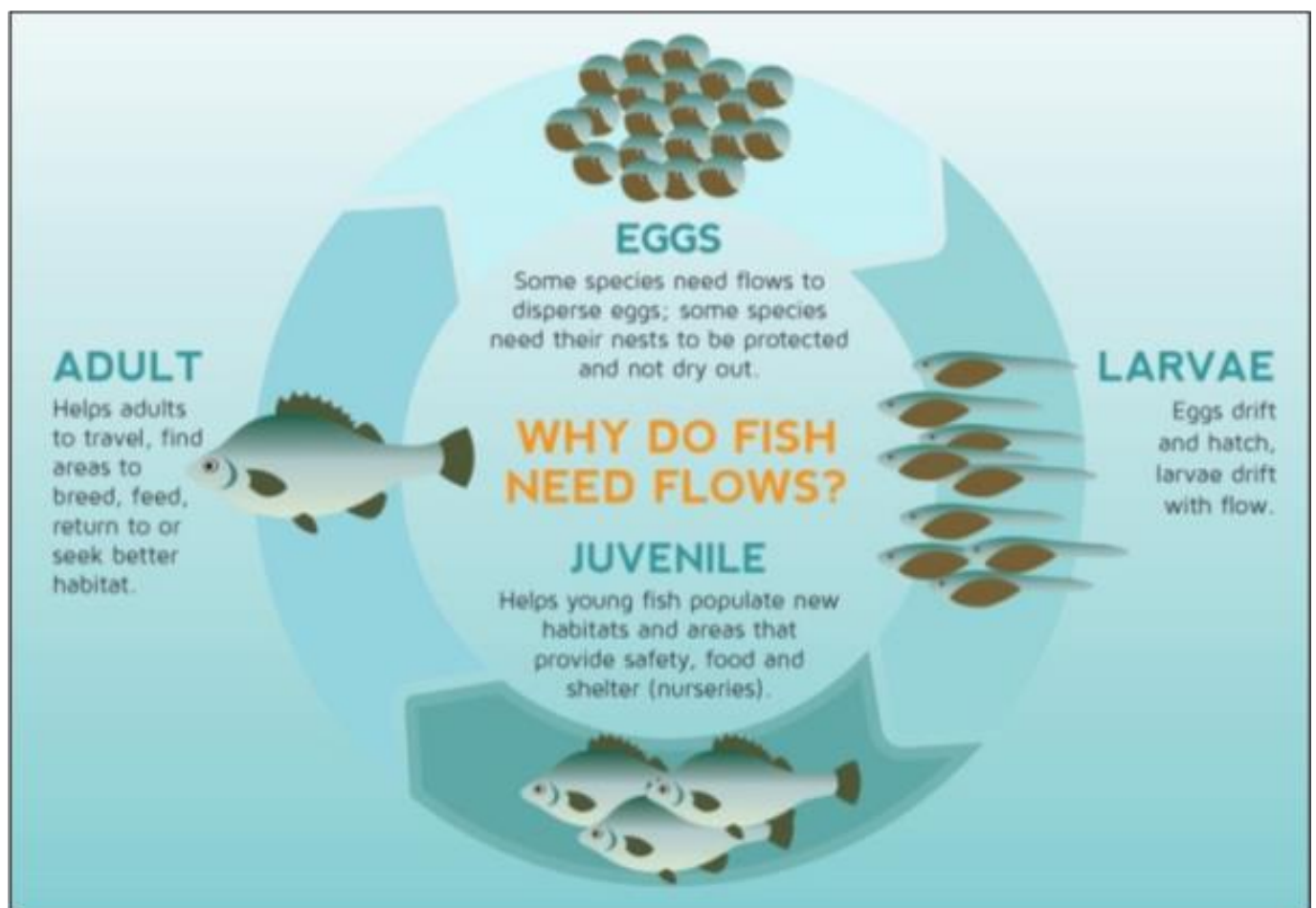


Figure 1 The influence of flow on the different life history stages of fish (NSW DPI 2018b)

Links between flow requirements and the different life history stages of fish are framed as having five life history elements and processes. Each element or process is regarded as being critical to the maintenance of self-sustaining fish populations and communities. These include: Habitat Access, Growth and Body Condition, Reproduction, Movement and Connectivity, and Maintenance and Survival.

Habitat Access

'Habitat' is a description of the type of waterbody a fish lives in (e.g. creeks, wetlands or rivers), the water quality and hydrology of the waterbody (e.g. flow, depth, seasonal water availability etc.), as well as its physical characteristics (e.g. Large Woody Habitat (LWH), aquatic and riparian vegetation, substrate). Different species of fish have different habitat needs and may select "patches" of suitable habitat ("micro habitats") which constitute a small proportion of all available habitats. These patches of habitat may overlap considerably with other species of fish (Koehn and Nicol 2013).

Aquatic habitats can be broadly categorised as lotic (flowing) or lentic (still). Different fish will prefer lotic or lentic habitats e.g. Golden Perch and Murray Cod prefer to live in faster flowing streams, while Olive Perchlet and Southern Pygmy Perch avoid flowing water, preferring still pools or wetlands (Lintermans 2023).

The quality of the water and the way it interacts with the environment also influences habitat for fish. For example, in the Northern Basin, Spangled Perch live in the warm water temperatures apparent across the slopes and lowland regions, while Mountain Galaxias are adapted for life in cooler upland streams. Barred Galaxias require low salinity, while Murray Hardyhead tolerate saline wetland habitats (Lintermans 2007).

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

Increasing the magnitude and duration of flows generally increases the amount of (and access to) in-channel and off-channel habitat. Off-channel floodplain habitats are critical for wetland specialist species like Olive Perchlet, Murray Hardyhead and Southern Pygmy Perch (Beesley et al. 2012; Whiterod et al. 2020). Early life stage flow pulse specialist species (e.g. Golden Perch and Silver Perch) may access off-channel or floodplain wetland habitat during elevated flows, resulting in high growth rates and increased survival rates (Sharpe 2011; Ellis et al. 2015; Stuart and Sharpe 2020). Other more generalist species access lentic floodplain habitats opportunistically to utilise submerged structure (vegetation and LWH) for spawning of adhesive eggs (e.g. Carp Gudgeon, Murray-Darling Rainbowfish). Connecting flows are needed following recruitment to promote dispersal. Reduced flooding isolates floodplain habitat and may result in reduced spawning and recruitment outcomes, stranding of individuals, and/or eventual extirpation.

Habitats differ in terms of physical characteristics such as shape, depth, roughness (e.g. rocks, LWH) and connectivity (Mallen-Cooper and Zampatti 2015b). Physical structure within flowing or still waterbodies may be important for survival and reproduction. For example, LWH in flowing rivers create sheltered areas in which Murray Cod often lay their eggs (nest).

Flow conditions that raise and maintain minimum river height over the spawning and nesting season for in-channel specialists will support improved spawning outcomes. For example, higher flows will increase the number of LWH available to Murray Cod. Maintaining minimum water levels over nests and avoiding water height reductions greater than 0.3m across the spawning season is essential in

preventing nest abandonment by Murray Cod and will avoid desiccation of Freshwater Catfish nests (Stuart 2019).

Growth and Body Condition

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

The increased productivity and habitat availability associated with higher flows and floods promotes food availability and enhances growth and body condition (Geddes and Puckridge 1989; Harris and Gehrke 1994; Sharpe 2011; Balcombe et al. 2012). High growth rates may also influence breeding and recruitment outcomes within a population. Good body condition is often associated with recent flow events while protracted low flow periods are associated with poor condition (Tonkin et al. 2011; Balcombe et al. 2012).

Reproduction

Most native MDB fish species synchronise their breeding to occur in warmer months, when there is likely to be more resources available to support survival. For some species (e.g. Silver Perch, Golden Perch) a rising hydrograph coinciding with warmer water temperatures is required to cue adult migration and spawning (Mallen-Cooper and Stuart 2003; Sharpe 2011; Cheshire et al. 2016). For other species, such as Freshwater Catfish, Bony Herring, and Murray Cod, spawning is principally linked to season and temperature and potentially day-length rather than high flow conditions (Cheshire et al. 2010; King et al. 2010). For these species, lower, relatively stable flow conditions within river channels (and the associated hydraulic variability) may provide opportunities for spawning and recruitment. Associated floodplain inundation provides increased productivity and habitat for fish, particularly early life history stages (Harris and Gehrke 1994; Sharpe 2011). Assessment of Golden Perch life history in the Barwon-Darling/Barka River system has demonstrated strong recruitment in large floodplain lakes following flood-cued spawning (Sharpe 2011). This may in turn be an important driver of Golden Perch populations throughout the Basin (Zampatti et al. 2015; Stuart and Sharpe 2017; Stuart 2019a; Stuart and Sharpe 2020), highlighting the need to consider macro or whole-of-system scale movements and water requirements for some species of native fish.

There is increasing evidence that recruitment for most species benefits from the improved environmental conditions and productivity resulting from flooding or elevated flows (King et al. 2009; Sharpe 2011; Stuart and Sharpe 2017). Higher flows also promote dispersal of early life stages from the breeding site, enhancing genetic diversity among reaches and catchments (Humphries and King 2004). Accordingly, sequences of flow events over one or more years may improve reproductive success.

Altered flow regimes can impact directly and indirectly on fish reproductive outputs. For nesting and substrate spawning species such as Murray Cod, River Blackfish and Freshwater Catfish, an unnatural rapid decrease in depth can cause abandonment of spawning sites or nests (Rowland

1998; Stuart et al. 2019) or disturbance/displacement of eggs and larvae (Tonkin et al. 2015). River operations to meet consumptive water demand can cause rapid fluctuations which are out of sync with natural patterns and climatic cues (Stuart and Sharpe 2013). Therefore, maintaining natural variability in height and natural rates of change in water levels during the breeding season is important for nesting species. Cold water releases (cold water pollution) from large weirs and dams can also inhibit spawning as well as disrupt the development of larvae in nests of fish that do spawn, given eggs are generally laid at a time of year when warm water is expected (Koehn, Todd and Wooten 2023; Butler et al 2022).

Movement and Connectivity

Movement between habitats is important for the completion of life cycles for many species including spawning, dispersal, foraging, and to seek refuge from threatening processes. Different fish may undertake large ‘macro-scale’ movements up to 100s or 1000s of km (e.g. Golden Perch), or smaller ‘meso-scale’ movements of 100s of meters to 10s of km within and between habitats in wetlands or river channels (e.g. Murray Cod and Southern Pygmy Perch). Some smaller species conduct movements over even smaller ‘micro-scales’ of less than one km (Mallen-Cooper and Zampatti 2015a; Ebner, Scholz, and Gawne, 2009; Thiem et al 2023).

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

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

Maintenance and survival

Changes to hydrology can affect fish survival directly with lethal or sub-lethal effects (e.g. changes to water quality parameters like temperature and dissolved oxygen, or the complete drying of water bodies). Flows contribute to the maintenance of fish populations by preserving longitudinal connectivity and habitat availability, which may in turn support higher population carrying capacity for density dependant species.

Another contribution to fish maintenance and survival are ecologically meaningful baseflows. These are flows that maintain habitat access and improve survivability following irrigation orders and over winter when conditions are typically very low flow. When flows drop below baseflow levels, fish can become stranded in channel pools. Provision of ecologically meaningful baseflows outside nesting/spawning season maintains longitudinal dispersal and habitat access and quality, over winter, following irrigation deliveries, and during drying and drought conditions. Protecting fish from

predation stress due to isolation in refuge pools increases survivability of adults and improves next season spawning outcomes.

Flows also contribute to sustaining suitable water quality by maintaining mixing within the water column preventing thermal stratification and by exporting salt and nutrients. Floodplain inundation following long dry periods, or drying of refuge pools, can mobilise large carbon loads resulting in the depletion of dissolved oxygen (which is absorbed by fish through their gills). This 'hypoxia' can result in fish deaths, particularly bigger fish which have higher oxygen demands or inflexible habitat requirements. Regular floodplain inundation via managed flow delivery (including water for the environment) can prevent unnatural build-up of floodplain carbon and in turn support fish populations by reducing the risk of hypoxic blackwater. Managed flows can also be delivered to try and dilute hypoxic blackwater (Watts et al. 2017).

Altered hydrology can also affect survival indirectly by reducing habitat availability and food resources. 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 which increases primary productivity and stimulates other aquatic productivity processes such as plant propagation and growth (Baldwin and Mitchell 2000). These processes may be important for maintaining key habitats and food sources for different life history stages of fish (Geddes and Puckridge 1989).

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

Identifying native fish assets

The BWS identified 28 priority environmental assets for native fish in NSW. Priority native fish assets were included in the first iteration of the NSW LTWPs (2015 – 2017). These 28 priority environmental assets were identified by collating and analysing information from sources including the NSW DPI Aquatic Ecosystem Research (AER) database² (), Australian Museum records (as cited in Morris et al. 2001), fish community status models, and threatened and common species distribution models. As such, native fish assets have been listed under Priority Environmental Assets for each catchment in each LTWP. Overall Fish Community Status (FCS) was derived from the three condition indicators of Expectedness, Nativeness and Recruitment, with outcomes partitioned into five equal bands to rate the condition of the fish community; Very Good, Good, Moderate, Poor, or Very Poor (NSW DPI, 2015b).

The Expectedness Indicator represents the proportion of native species that are now found within NSW, compared to that which was historically expected based on expert opinion. The Expectedness Indicator is derived from two input metrics; the observed native species richness over the expected species richness at each site, and the total native species richness observed within the zone over the total number of species predicted to have existed within the zone historically (NSW DPI, 2015b). The

² AER database includes a range of site specific data and information from various fish related projects in NSW from 1970s through to the present depending on the project and location.

Nativeness Indicator represents the proportion of native versus alien fishes within the river and is derived from three input metrics: proportion native biomass, proportion native abundance and proportion native species (NSW DPI, 2015b). The Recruitment Indicator represents the recent reproductive activity of the native fish community within each altitude zone. The Recruitment Indicator is derived from three input metrics; the proportion of native species showing evidence of recruitment at a minimum of one site within a zone, the average proportion of sites within a zone at which each species captured was recruiting, and the average proportion of total abundance of each species that are new recruits (NSW DPI, 2015b).

To improve understanding of the distribution of native fish species across the NSW MDB, it was necessary to eliminate any potential issues associated with over reliance on singular site record data. It was also necessary to strengthen the spatial identification of native fish assets. To this end, Generalised Additive Modelling (GAM) analysis was used to model relationships between the fish assemblage metrics/indicators/index with environmental and River Style® attributes of stream segments (NSW DPI, 2015b). Modelling the geographic distribution of each listed threatened freshwater fish species or population was undertaken using MaxEnt 3.3.3. MaxEnt is a widely used species distribution modelling program that utilises presence records to generate probabilities of occurrence based on a suite of environmental variables quantified across the area of interest. A greater than 33% probability of occurrence was used to predict presence of threatened species for the FCS&TSD project (NSW DPI, 2015b; Appendix 3). This work was extended to common species of the NSW MDB to model the current geographic distribution of each native fish species (NSW DPI, unpublished data).

All of this information, including AER database records, threatened fish species or population modelled distribution (greater than 33% probability of occurrence), and common species modelled distribution (greater than 33% probability of occurrence) was compiled to determine native fish asset lists for management zones across the NSW MDB. The AER database was again interrogated in 2023 to inform updated species distribution information for the current (January 2024) update of the NSW LTWPs.

For key species with range expansion outcomes listed in the BWS, the AER database was interrogated to determine valleys with existing core populations, relative to other valleys across the NSW MDB and where range extension targets should be prioritised. Historical records and expert opinion were also used to identify potential valleys where additional population targets should be prioritised (Table 2). To further refine range expansion outcomes and related targets at the valley scale, a weighted average modelled distribution of key species greater than 50% probability of occurrence was used to identify priority systems and/or water management zones. The refinement of this range expansion outcome meant that even though a key species identified for a valley may not necessarily have an associated range expansion outcome. Targets were designed so that the most effective outcomes for native fish at a valley scale would also contribute to the broader Basin scale outcome.

Table 2 Priority valleys and related targeted BWS key species for range expansion targets based on AER database records, threatened species distribution modelling, and expert opinion.

Priority Valley	Targeted BWS key species
Barwon-Darling/Baaka	Freshwater Catfish; Silver Perch
Border Rivers	Freshwater Catfish; Olive Perchlet; Purple Spotted Gudgeon
Gwydir	Freshwater Catfish; Olive Perchlet; Purple Spotted Gudgeon
Lachlan/Galari	Flathead Galaxias; Macquarie Perch; Olive Perchlet; Southern Pygmy Perch; Trout Cod
Macquarie-Castlereagh /Wambul - Warrumbungle	Flathead Galaxias; Freshwater Catfish; Olive Perchlet; Purple Spotted Gudgeon; River Blackfish; Trout Cod
Murray-Lower Darling/Baaka	Flathead Galaxias; Freshwater Catfish; Murray Hardyhead; Olive Perchlet; Purple Spotted Gudgeon; Silver Perch; Southern Pygmy Perch; Trout Cod
Murrumbidgee	Flathead Galaxias; Macquarie Perch; Olive Perchlet; Purple Spotted Gudgeon; River Blackfish; Silver Perch; Southern Pygmy Perch; Trout Cod
Namoi	Freshwater Catfish; River Blackfish; Silver Perch

Status of native fish in the NSW MDB

An estimate of the extent of native fish decline in the MDB was undertaken by the Murray Darling Basin Commission (MBC) in 2002. At that time, it was estimated that changes to river flows and habitats had led to a >90% decline in native fish populations over the previous 150 years (Kohen et al 2020).

Fish and other aquatic biota have adapted over millennia to the diversity and variability in flow conditions that are a natural feature of the NSW MDB. Human influences and the exploitation of freshwater resources have significantly altered NSW MDB flow regimes in less than 200 years.

Flow related impacts include reduced water volume, reduced flow variability and hydraulic complexity, seasonal flow reversal, loss of small to medium in-channel flow components along with small to medium sized floods, the development of more frequent and longer cease to flow events, permanent inundation of some areas, permanent diversion of water from others and altered connectivity for many components of the system.

Flow regulation and changes to the natural flow regime are only one of the threats implicated in the decline of native fish in the NSW MDB. A range of additional influences impact on the health and status of fish and fish communities. These include:

- Riparian and in-stream habitat degradation and loss, including loss of access to habitat.
- Reduced water quality.
- Barriers which impede fish movement.
- Cold water releases from large weirs and dams that can severely impact breeding cycles, recruitment and survival of fish downstream of storages.
- Loss from the system, injury and death of fish in pumping and diversion infrastructure.
- Competition and/or predation by non-native species.
- Recreational fishing pressure.
- Disease, loss of genetic integrity and fitness.
- Climate change.
- Extreme events including bushfires.

Today, the NSW MDB has eight native fin fish species with a threatened species designation (one with restricted historical distribution above a major headwater storage), and two endangered population listings, the MDB population of Freshwater Catfish and the western population of Olive Perchlet (Fisheries Management Act 1994). Eight of the species and populations listed as threatened are small bodied species and the range of species listed represents all flow guilds.

In addition to fin fish, the Darling and Hanley's river snails are both listed as 'Critically Endangered', Murray Crayfish are listed as 'Vulnerable', and another 'Critically Endangered' crayfish species, the Cudgegong Giant Spiny Crayfish, occurs in the MDB above Windemere dam on the Cudgegong River. The NSW MDB is also home to three aquatic Endangered Ecological Communities (Lower Murray, Lower Darling-Barka and the Lower Lachlan).

Other fish species are persisting in increasingly fragmented populations (Crook 2023 and Lintermans 2023). Some species are persisting naturally in only one or two highly restricted river reaches or wetland sites. For example, within mainstem regulated river systems there is only one confirmed naturally recruiting population of Silver Perch remaining in the state along the mid-Murray. Scientific understanding of the extent to which other populations are self-sustaining has not progressed from the initial Fisheries Scientific Committee listing in 2002. The presence of Silver Perch elsewhere in the NSW MDB is believed to be heavily reliant on conservation stocking. NSW has not recorded any extinctions, however there is concern for Flat-headed Galaxias which was last detected in NSW in 2003 (DCCEEW 2024 In Prep).

A significant factor influencing the condition of native fish is the emergence of large-scale climatic events as drivers of fish recruitment and assemblage condition. For example, periodic fish kills have a devastating negative impact on fish assemblages. Stocks et al (2020) report that fish kills along the Darling-Barka near Menindee from June 2019 – March 2020 led to significantly lower abundances of Murray Cod, Bony Herring, Carp Gudgeon and Freshwater Prawns than nearby

unaffected areas. Ongoing fish kills in the region have further impacted fish populations. River mussels suffered significant mass deaths in the Darling-Barka and tributary valleys during the summer of 2019 – 2020 (Sheldon et al 2020). The ability of individual native fish species to recover from ecological shock events is determined by a series of factors including reproductive responses and the hydrological conditions following events.

Ecological fragmentation increases vulnerability, further exposing surviving populations to the impacts of threats and risks (Lintermans 2023). In many cases isolated and remnant populations will require ongoing management intervention to persist (DCCEEW 2024 In Prep).

In 2023 NSW DPIRD Fisheries researchers began multi-decadal (1994 – 2023) analysis of records in the DPIRD Fisheries Fish Survey Database to examine temporal trends in abundance, biomass, population size structure, recruitment, movement and changes in native fish assemblages. The DPIRD Fisheries data set has been built primarily from electrofishing survey data collected through projects funded by the Commonwealth and NSW governments. In 2022/2023 DPIRD Fisheries introduced eDNA metabarcoding through the Basin Plan Environmental Outcomes Environmental Monitoring-Fish program (BPEOM-Fish). Analysis of the dataset has focused on medium to large bodied natives that are well represented in electrofishing data.

Crook et al (2023; DCCEEW 2024 in prep) report the following key learnings regarding long term trends in native fish population behaviour:

Distribution, abundance, and biomass

At the NSW MDB scale, the relative abundance of native fish has been stable since the 1990s with peaks and dips in abundance that correspond to periods of wet conditions and dry/drought conditions respectively. Overall, native fish biomass shows a slight increase from the 1990s and has been stable over the past 10 years.

The following trends can be seen for specific species:

- Over the last 30 years, Murray Cod and Golden Perch have maintained widespread distribution. Murray Cod populations are well structured with recruits in most years. Across the time series, the relative abundance of Murray Cod has increased in the Murrumbidgee, Namoi and Border Rivers. However, Lintermans (2003) notes that Murray Cod are no longer caught in the Paroo.
- There is evidence that Golden Perch have retained sufficient ecological resilience to enable large scale spawning and recruitment responses when climatic conditions are favourable.
- The distribution of Freshwater Catfish has not changed appreciably over the past 30 years.
- There are no consistent trends in the relative abundance of Freshwater Catfish, Silver Perch and Macquarie Perch. Low sample sizes for these species affect models at the NSW MDB and valley scale. Silver Perch did illustrate improvements in abundance in response to wet conditions in 2009, however these gains have been recently lost. Over the past 30 years Silver Perch have experienced severe contraction of their distributions and are now restricted to isolated locations in the southern basin and upper reaches of some northern tributaries.

- The distribution of Spangled Perch has shown substantial variation over the past 30 years. There have been southward expansions during large flood events, followed by contractions during drier periods. This variability demonstrates that species distributions can be highly dynamic, and trajectories may not be unidirectional over time.

Recruitment and Population structure

Trends in recruitment and population structure are again non-linear with a high degree of inter-annual variability at a valley and Basin scale.

- Over the last 30 years, poor recruitment has been a limiting factor for the recovery of most key BWS species, with BWS recruitment targets not being achieved for all species across the full time series (1994 – 2023).
- There is evidence that recruitment improves with improved antecedent conditions, including where water for the environment is delivered.
- Recruitment for Golden Perch is more episodic with strong recruitment responses associated with major flooding across the NSW MDB 2010 – 2011.

Initial long-term analysis of the DPIRD Fisheries database indicates that trends in abundance, distribution, biomass, recruitment are often not linear, with strong inter-annual variation in abundance, distribution, population structure and biomass for the species examined. In addition, trends are highly variable between valleys. This variability reflects species population status, and species-specific responses to stressors and interventions at local and regional scales. Researchers observe that a combination of favourable climate, targeted watering and flow protection efforts, together with complementary activities supports improvements in these trends.

Efforts to conserve and restore native fish populations at the NSW MDB and valley scale are ongoing. Supported by a range of management interventions, including captive breeding, species such as Trout Cod, Macquarie Perch, and Murray Hardyhead have been successfully reintroduced to river and wetland environments within their historical range.

Managing river health through the provision of more natural flow regimes can be an effective way to support native fish and help protect and recover their populations. However, water deliveries to support native fish outcomes need to be combined with the continued remediation of barriers to fish passage and cold-water pollution; habitat restoration and protection; threatened species conservation, captive breeding, and stocking and translocation programs.

Finally, monitoring, evaluation and reporting to assess native fish outcomes should be ongoing at least at an annual frequency, with complementary hydrological analysis needed to assess outcomes against described EWRs.

Fish functional groups

The range of life history strategies and movement behaviours exhibited by native fish of the NSW Basin means a single flow regime cannot provide equal benefits for the whole fish community (King et al. 2010; Baumgartner et al. 2013). Allocating species of fish into functional groups based on similarities in reproductive strategies, movement capabilities and habitat requirements, helps

simplify the development of fish specific EWRs and flow related management actions, as they can be developed for groups of species rather than individual species (NSW DPI 2015a; NSW DPI 2015b). A hybrid approach to deriving fish functional groups was applied by combining elements of the reproductive spawning-movement as presented in Baumgartner et al. (2013), eco-hydraulic groupings as presented in Mallen-Cooper and Zampatti (2015b), as per a review undertaken by 2rog Consulting in 2023. The life history elements considered are:

- Cues for migration (dispersal and recolonisation) and spawning (temperature and/or flow).
- Spatial scales of adult/juvenile spawning and dispersal movements (10s – 100s of m; 100s of m – 10s 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.

A detailed description of each function group along with example species and key life history elements and processes is presented below and in Appendix A. While it's acknowledged the groupings presented here represent a simplistic interpretation of fish requirements, they nevertheless enabled the subsequent design of conceptual (theoretical) flow regimes that meet the needs of multiple fish species. We recommend consultation with regional fish ecologists is conducted when using the groupings and conceptual hydrograph in water planning, to fully ensure species requirements are addressed.

Information relating to the life history elements of non-fish species including freshwater mussels, snails and crustacea is sparse in comparison to the body of information available for native fin fish. Nevertheless, for some species, adequate information exists to allow for the placement of species into existing fish functional groups. Freshwater snails lack enough information currently to be included in the existing functional groups and not enough evidence to justify the formation of an additional functional group so are placed in an 'undefined' group (2rog Consulting 2023; Appendix A).

Group 1 - Flow pulse specialists

Flow pulses (within or overbank) coinciding with warmer water temperatures are generally required to generate a spawning response for these species, although instances of winter spawning have been documented in recent years (Stuart and Sharpe 2017; Stuart 2019a; Stuart 2019b, Koehn et al. 2020b). Adults of this group are highly fecund and may make long migrations in response to flow. Spawning can be delayed if appropriate flow conditions are not experienced. Flow pulses are required to cue movements and provide longitudinal connectivity for upstream re-colonisation. Eggs and larvae drift for weeks potentially dispersing over long distances.

Growth and recruitment success for flow pulse specialists are enhanced by flows that transport young into inundated off-channel habitat and ephemeral wetlands which may offer productive and sheltered floodplain 'nursery' habitat (Sharpe 2011; Ellis et al. 2014; Stuart and Sharpe 2017; Stuart and Sharpe 2020).

These species are medium to long-lived. In healthy self-sustaining populations, spawning and recruitment is not required every year to maintain a viable population. healthy populations consist of multiple year classes and demonstrate some recruitment in most years (e.g. Golden Perch, Silver Perch).

Group 2 - River specialists (with either lotic or lentic preferences)

River specialists prefer hydraulically complex river habitat with submerged structure (e.g., rocks or woody debris). Adults may make short migrations to spawn in response to increased temperature. River specialists are moderately fecund, some spawn in nests or have specific spawning substrate preferences. Fish species of this group often provide parental care for 14 days or more. Several species need flowing water for successful spawning and hatching (Macquarie Perch, River Blackfish). Emerging evidence suggests adults may ‘invest’ more strongly into reproductive outputs during years in which exceptional flow cues are apparent or following long periods in which sub-optimal breeding conditions prevailed. For example, when flows recommence following protracted cease to flow conditions spanning multiple breeding seasons (Stuart and Sharpe 2017).

Maintaining water levels during breeding season 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 fluctuations in water levels over short time periods). River discharge is important in lower-order streams to allow adults to disperse to locate spawning sites and mates (Koehn et al. 2020). On leaving nests, larvae ‘drift’ semi passively over short to moderate distances for dispersal. Recruitment success for this group is enhanced by perennial flows and flow pulses (i.e. increased floodplain productivity and connectivity). Periodic, within-channel pulses provide connectivity for upstream recolonisation movements by juveniles. Healthy self-sustaining populations of river specialist species would not necessarily require large scale recruitment every year to maintain a viable population. Healthy populations of river specialists consist of multiple year classes and demonstrate some recruitment in most years.

River specialists can be further categorised as preferring either lotic habitat (e.g. Murray Cod, River Blackfish, and Macquarie Perch) or lentic habitat (Freshwater Catfish, Southern Purple Spotted Gudgeon (SPSG)). In the Northern Basin, SPSG and Olive Perchlet may also be considered Floodplain Specialists depending on the geomorphology and biophysical features of the sub-catchment. As such they may fall in to either this category or the Floodplain Specialists category depending on local expert opinion and historical habitat preferences. New knowledge of Darling River Hardyhead life history (Moy et al. 2018) has resulted in this species being reclassified as a Riverine (lotic) Specialist (Appendix A).

Of the non-fish species, River and Freshwater Mussels (*Alathyria jacksoni*, *Alathyria condola*) other than Floodplain Mussels (*Velesunio ambiguous*), are considered as River Specialists. These species are intolerant of drying and display spring/autumn breeding which is temperature cued but independent of flow.

Group 3 - Floodplain specialists

Floodplain specialists prefer off-channel wetland habitats, usually containing submerged vegetation or complex submerged structure (e.g., woody debris, rocks, or inundated terrestrial material). Adults may make short migrations to spawn in response to increased temperature, into or

within lentic (or slow-flowing) off-channel habitats. Individual species of this group may have specific spawning substrate preferences (e.g. broad-leafed submerged aquatic plants, rocks), increases in inundation extent can therefore enhance breeding opportunities by creating additional spawning habitat as well as floodplain productivity benefits.

These species are relatively short-lived with low fecundity and most require spawning and recruitment events every 1-2 years for the population to persist. Overbank flooding is required (although not necessarily annually) to facilitate dispersal for re-colonisation, mixing between populations and to establish new populations (e.g. Olive Perchlet, Flathead Galaxias, SPSG, Murray Hardyhead).

In the Northern Basin, SPSG and Olive Perchlet may also be considered Riverine (lentic) specialists depending on the geomorphology and biophysical features of the sub-catchment. As such they may fall in to either this category or the Riverine Specialist (b) category depending on local expert opinion and historical habitat preferences (Appendix A).

Floodplain Mussels (*Velesunio ambiguus*) falls into Group 3 Floodplain Specialists, given they inhabit floodplain habitats, display an increased tolerance for drying and show enhanced spawning with overbank flows.

Group 4 - Generalists

Group 4 Generalists occupy a range of streams and waterbody types. Spawning is generally linked to increased temperature but species in this functional group exhibit greater flexibility in spawning strategies than other functional groups (Appendix A). They 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 and short periods of larval drift may occur. Small flow pulses may enhance dispersal of these species by inundating in-stream habitat and connecting drought refuges. Larger flows that inundate off-stream habitat can also promote growth and recruitment (i.e. increased floodplain productivity and habitat availability). Generally short-lived with low fecundity requiring regular (ideally annual) spawning and recruitment events for persistence (e.g. Australian Smelt, Bony Herring, Carp Gudgeon, Mountain Galaxias, Un-specked Hardyhead).

The Generalist functional group include some non-fish species such as shrimps (*Paratya australiensis*), prawns (*Caridina mccullochi*, *Macrobrachium australiense*), yabbies (*Cherax destructor*) and crayfish (*Euastacus armatus*, *Euastacus jagara*). These species are known to occupy a wide range of habitats and show a general spring-summer breeding preference.

Undefined species

Whilst some habitat criteria for these species are available, freshwater snails currently lack sufficient information to be included in an existing functional group or to suggest an alternate grouping. The available information on flow ecology for these species is included in Appendix A.

Ecologically Significant Components of the flow regime

Restoring flow regimes to benefit fish necessitates an understanding of the relationship between hydrology and life history, along with the subsequent population dynamics. This can be done by considering the specific components of a rivers flow regime that may influence population outcomes such as spawning, recruitment and movement (e.g. migration). These are referred to here as Ecologically Significant Components (ESCs) of the flow regime (MDBA 2011) and serve as a common reference to which flow management targets such as EWRs can be applied and gauged (Figure 2). The recommended flow regime requirements for each fish functional group are summarised in Table 3 and Table 4 summarises the degree to which each flow component will support the key life history elements and processes for each functional group of fishes.

Cease to flow – under natural flow conditions, cease to flow (CTF) periods occasionally occur in intermittent streams. In perennial flowing rivers CTF conditions are considered to have been rare. Prolonged CTF conditions may eventuate in a series of disconnected pools. The onset of disconnected pools associated with CTF conditions is geographically variable and dependant on local geomorphology and biophysical attributes. CTF periods can play an important role in promoting growth of biofilms and productivity although they can also be associated with poor body condition; particularly for species at lower trophic levels (Balcombe et al. 2012). High food availability for predatory species at higher trophic levels may occur initially during cease to flow periods, as refuge habitat for prey becomes limited. Ultimately however, food supply and water quality would be expected to diminish in refuge pools as water levels contract during protracted CTF events. In some cases, CTF can also be useful in limiting Carp breeding. The timing and rates of wetting and drying are likely to be important given the potential for non-flowing refuge pools to become thermally stratified in warmer climates with a related potential for de-oxygenation of deeper water layers. “Turn over” of stratified refuge pools upon recommencement to flow, or due to rapid temperate change (decrease) and high wind, can mix poor quality water throughout the entire pool which carries a risk of fish deaths (Ellis and Meredith 2004; Vertessy et al. 2019).

Very low flows – Very low flow (VLF) corresponds to exceptionally low flows at the lower end of the hydrographic range that would normally occur in an unmodified perennial river (Stewardson and Guarino 2017). Productivity, movement and spawning of native fish are restricted under VLF conditions. However, VLFs are a critical component of the flow regime to maintain water quality (temperature, dissolved oxygen) in refuge pools. The velocity of VLFs is particularly important. Flows with velocities of 0.03 – 0.05 m/s have been identified as the ideal to prevent the development of persistent thermal stratification and suppression of nuisance cyanobacterial growth in lowland systems (Mitrovic et al. 2003). Rapid turnover of stratified refuge pools and dissolved oxygen deficiencies associated with cyanobacterial blooms have been attributed to fish deaths within the MDB (Ellis and Meredith 2004; NSW DPI 2011; Vertessy et al 2019). Interaction and competition between native and introduced fish increases during VLF conditions.

Ecologically meaningful base flows – Ecologically meaningful base flows (BFs) provide connectivity between pools and riffles, preventing VLF and CTF conditions. BFs would generally occur on an ongoing basis in perennial systems and in many cases maintain longitudinal connectivity and associated dispersal opportunities. BFs are important in maintaining aquatic habitat or drought refuges for fish, plants and invertebrates when low flow conditions prevail, and help maintain water

quality (e.g. oxygenation through riffle habitats or refuge pools prone to thermal stratification). By maintaining the condition of individuals, BF can support a larger population carrying capacity for density dependant species in stream systems or reaches during low flow periods, thereby increasing the likelihood of successful spawning and recruitment in subsequent breeding events. BFs may also benefit small-bodied native species with preference for low velocity habitats (in-channel or terminal wetlands). Small variations in flow within the BF band (Figure 2) mimic natural variability and promote productivity during base flow periods. Ecologically meaningful BF are distinguished from baseflow targets outlined in Water Sharing Plans on the basis of their ecological relevance.

Small within-channel freshes – Small short-term increases in flow above BF that provide longitudinal connectivity. The small fresh (SF) ESC 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. Generally, SFs are relatively slow flowing (e.g. less than 0.3m/s). Rates of rise and fall are typically fast and should mimic natural duration and rates of change in each reach. Spawning and recruitment in nesting River Specialists (e.g. Murray Cod, Freshwater Catfish) may be supported by prolonged and continuous within-channel rises during the predictable breeding season in spring (i.e. avoiding rapid drops in water level that may lead to nest abandonment).

Large within-channel freshes – Substantial increases in flow that provide inundation of within-channel features such as benches. Large freshes (LF) can provide large scale longitudinal connectivity. LFs generally provide fast flowing within-channel habitats (e.g. velocity greater than 0.3m/s) and may connect floodplain wetlands and anabranches with low commence to flow thresholds. Rates of rise and fall should mimic natural durations and rates of change in each reach. Opportunities to include a priming ‘spike’ at the start of event could be considered (in managed events) as a cue to trigger breeding preparation by flow pulse specialists. Protracted recession can assist with larval dispersal.

Spring nesting component – The spring-nesting component (SN) applies to lowland floodplain river environments. Represents a seasonal period of flow during which unnaturally rapid decreases in water levels are absent during the predictable spring breeding season for nesting River Specialists (e.g. Murray Cod, Freshwater Catfish), thus avoiding stranding or abandonment of nests. Minimum event duration of 14 days should be maintained within natural rates of variability to allow eggs to hatch and for larvae to leave nest sites. Daily height variation in flows has been suggested as no more than 0.15m (Stuart 2019) but this is partially based on River operator tolerance rather than ecological evidence (S McCaffrey pers. comm). River height should not decrease by more than 0.3m from the beginning to the end of the event. There are currently no guidelines for the impacts of rapid rises on breeding success; the assumption is that a rapid rise in water level would not cause harm. Larger/longer duration for spring nesting components (30-50 days from early October through to late November in the southern Basin, or September – November in the northern Basin) may enhance breeding outcomes by increasing the period of time within the spawning season that individuals can spawn, improving productivity, inundating additional nesting/spawning sites and dispersing drifting young to productive nursery habitat. Depending on location, nesting could be supported at flow magnitude representative of ecologically meaningful Base Flow levels through to Large Fresh levels. A short increase in flow at the end of the spring nesting component is recommended to inundate additional in-stream habitat and further enhance productivity and food generation (Sharpe and Stuart 2018).

Bankfull – Flow rates which, for the purposes of this project, are defined as flows greater in magnitude than LF that wet the upper channel perimeter to the point where overbank spilling occurs (Figure 2). May include flow into lateral channels and wetlands with low commence to flow levels.

Overbank flows – Flows that overtop the defined channel bank and inundate floodplain and off-channel habitats. Overbank flows typically occur between spring and autumn in the Northern Basin and in spring and summer in the Southern Basin.

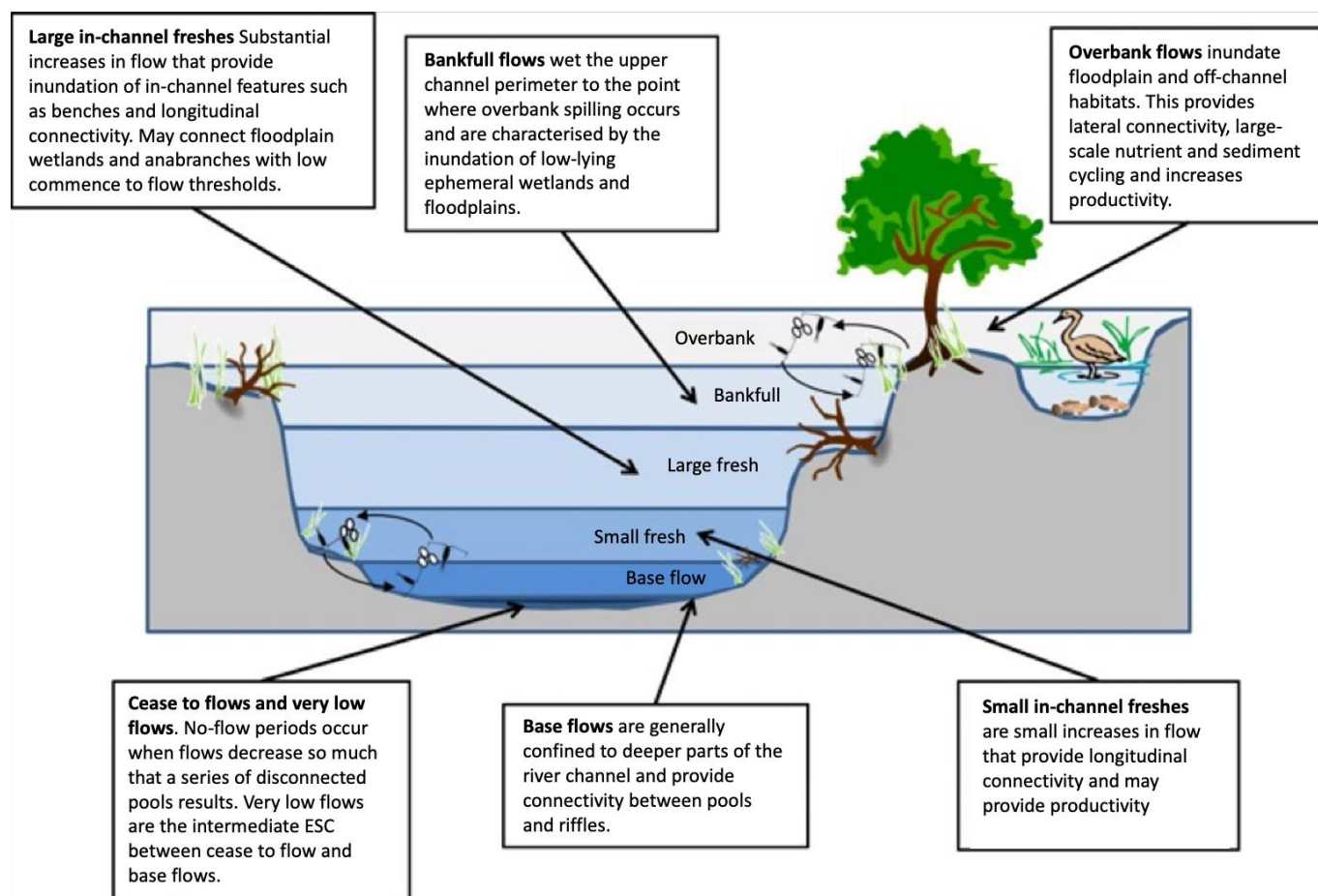


Figure 2 ESCs of the flow regime (adapted from Ellis et al. 2016).

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

Flow component	Functional Group	Seasonal requirements	Annual return interval (years)	Duration (days)	Max period between events (years)
Overbank flows	Group 1: Flow Pulse Specialists	spring to summer (Sep-Feb, NB); (Aug-Feb, SB)	3-5	>5	5
	Group 2: River Specialists	spring to summer (Sep-Feb ¹ , NB); spring (Oct-Nov ¹ , SB)	3-5 (NB) 5 (SB)	>5	5
	Group 3: Floodplain Specialists	spring to autumn (Oct-Apr, NB); spring to summer (Aug-Feb, SB)	2 ¹ (NB) 1 ² (SB)	>10 (NB) >10 ² (SB)	4 ⁶ (NB) 1 ² (SB)
	Group 4: Generalists	spring to summer (Sep-Feb, NB); (Aug-Feb, SB)	3-5 (NB) 5 ⁵ (SB)	>5	5
Large Fresh	Group 1: Flow Pulse Specialists	spring to autumn (Oct-Apr, NB); spring to summer (SB)	2-3 (NB) 1 - 2 (SB)	>5	4 (NB) 2 (SB)
	Group 2: River Specialists	ideally winter to spring but can occur any time (Jul-Sep, NB); spring (Oct-Nov ¹ , SB)	1 - 2	>5 (NB) >14 ^{3,4} (SB)	2

Flow component	Functional Group	Seasonal requirements	Annual return interval (years)	Duration (days)	Max period between events (years)
	Group 3: Floodplain Specialists	winter to spring (Jul-Sep ideally but can occur at any time, NB); spring to summer (SB)	1-2 (NB) 1 ² (SB)	>5 (NB) >10 ² (SB)	2 ⁶ (NB) 1 ² (SB)
	Group 4: Generalists	winter to spring (Jul-Sep ideally but can occur at any time, NB); spring to autumn (SB)	1-2 (NB) 2 (SB)	>5	2
Spring nesting (SB)	Group 1: Flow Pulse Specialists	- (SB)	- (SB)	- (SB)	- (SB)
	Group 2: River Specialists	spring (Oct-Nov) 1 (SB)	1-2 (SB)	>14 ^{3,4} (SB)	2 (SB)
	Group 3: Floodplain Specialists	- (SB)	1 ² (SB)	>10 ² (SB)	1 ² (SB)
	Group 4: Generalists	any time (SB)	- (SB)	- (SB)	- (SB)
Small Fresh	Group 1: Flow Pulse Specialists	spring to autumn (ideally Oct-Apr but can occur any time, NB); any time (SB)	1 (NB) 0.5 (SB)	>10 (NB & SB)	1 (NB) 0.5 (SB)
	Group 2: River Specialists	spring to autumn (Sep-Apr, NB); at	1-2 (NB) 0.5 (SB)	>14 (NB) >10 ^{3,4} (SB)	2 (NB) 0.5 (SB)

Flow component	Functional Group	Seasonal requirements	Annual return interval (years)	Duration (days)	Max period between events (years)
		least 1 in spring (SB)			
	Group 3: Floodplain Specialists	spring to autumn (ideally Oct-Apr but can occur anytime, NB); any time (SB)	1 (NB) 0.5 (SB)	>10 (NB & SB)	1 (NB) 0.5 (SB)
	Group 4: Generalists	Spring to autumn (Sep-Apr, NB); anytime (SB)	1-2 (NB) 0.5 (SB)	>14 (NB) >10 (SB)	2 (NB) 0.5 (SB)
Ecologically meaningful Base flow (NB) Variable base flow (SB)	Group 1: Flow Pulse Specialists	anytime (NB); all season (SB)	No less than modelled natural (NB) - (SB)	Sufficient to maintain refuge habitat and support connectivity (NB) - (SB)	As required during dry periods (NB) - (SB)
	Group 2: River Specialists	spring to autumn (Sep-Mar, NB); all season (SB)	1-2 (NB) - (SB)	Maintained throughout spawning season (NB) - (SB)	2 (NB) - (SB)
	Group 3: Floodplain Specialists	anytime (NB); all season (SB)	No less than modelled natural (NB) - (SB)	Sufficient to maintain refuge habitat and support connectivity (NB) - (SB)	As required during dry periods (NB) - (SB)
	Group 4: Generalists	spring to autumn (Sep-	1-2 (NB) - (SB)	Maintained throughout	2 (NB) - (SB)

Flow component	Functional Group	Seasonal requirements	Annual return interval (years)	Duration (days)	Max period between events (years)
		Mar, NB); all season (SB)		spawning season (NB) - (SB)	
Very Low Flows (NB)	All native fish groups		No less than modelled natural (NB)	In line with natural, unless key refuges endangered (NB)	No greater than modelled natural (NB)
Cease to flow (NB)	All native fish groups		No less than modelled natural (NB)	No less than modelled natural (NB)	

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

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

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

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

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

⁶ may require complementary actions.

Table 4. Degree to which each flow component is expected to support key life-history elements and processes for each functional group of fishes in the Northern Basin (NB) and the Southern Basin (SB)

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

	Reproduction	Good	Good	Good ² (SB)	Moderate	Moderate
	Movement	Good	Good	Good ² (SB)	Moderate	Moderate
	Maintenance	Good	Good	Good (SB)	Good	Moderate

Site specific EWRs

For each valley, fish specific EWRs are developed targeting fish outcomes in regulated and unregulated river systems. EWRs include recommended magnitude, duration, timing (i.e. season) for each flow component. Each EWR is expressed as the ideal minimum duration (number of days flow) that the proposed target threshold is suggested to maintain or exceed, timing (seasonality) and frequency. Rates of rise and fall around the peak should reflect natural rates of change for the sites and any operational requirements.

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

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

It is important to note that these EWRs represent ideal flow conditions to maximise the opportunities for targeted native fish outcomes in a largely modified system. Native fish populations have been significantly affected by a range of impacts across the Basin. To improve these populations, it may be necessary to implement flow regimes that do not necessarily reflect ‘natural conditions’ but seek to balance the impact of river regulation in a working Basin.

By helping to define what can be achieved for native fish with improved hydrological regimes, it is anticipated that implementation of fish specific EWRs will contribute to the achievement of overarching Basin Plan and BWS outcomes for native fish, including:

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

Responsible Application of EWRs

The conceptual hydrograph and EWRs underpinned by the Framework are by no means prescriptive. Responsible water management and manipulation of the flow regime will require coordinated efforts between water for the environment managers, water users and river operators across the NSW Basin, as well as other Basin jurisdictions. It will also require 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.

Furthermore, the flow elements we present here for one functional group of fishes may not necessarily provide benefits for another. As such adaptive management, flexibility, and a long-term commitment to deliver benefits to native fish and river health will be required (Baumgartner et al. 2013; NSW DPI 2015a). The conceptual flow hydrograph presented was constructed with the capacity to be updated or expanded to multiple hydrographs, where water management events require flexibility to be modified and as additional information comes to hand. In practice, this responsiveness means the on-ground delivery of desired flow components can also be adapted in 'real time' to accommodate or adapt to changing hydraulic conditions, water quality, or other real-time observations.

There are many considerations for flow management that need to be considered when developing and delivering flows for fish outcomes. These include:

Timing

A conceptual hydrograph should consider generalised natural flow regimes for the region (e.g. northern Basin/southern Basin, altitudinal zone (e.g. upland, slopes, lowland)). Watering events are likely to be guided by natural flow cues most of the time. This hydrograph is by no means a recipe for success. Given the complexity and variability in ecological systems across the NSW MDB, different ESCs could occur anytime within a year, although the productivity response may differ between seasons (see Robertson et al. 2001). Thus, for wholly managed watering events:

- The timing of other reproductively significant flow components (i.e. bankfull flows, large freshes) may be implemented at any stage during the breeding season window for functional groups in attempting to generate reproductive outcomes. Note however, the potential perverse outcomes that may impact nesting species (see below); where possible efforts should be made to avoid disruption to nesting species and may be informed by local knowledge and observations.
- Small freshes can occur anytime of the year but may be deliberately applied at a certain time to target outcomes. For example, to maintain water quality, to facilitate/cue movements or spawning in River Specialist nesting species (such as Murray Cod and Freshwater Catfish).
- The provision of variable base flows that prevent streams from contracting to lentic pools between flow events will provide refuge habitat and maintain appropriate water quality.

Achieving multiple outcomes

Where possible the conceptual hydrographs and EWRs presented attempt to benefit multiple functional groups to provide efficiency in flow delivery. For example, large within-channel freshes in

spring may primarily target spawning in Flow Pulse Specialists but will also support spawning by Generalist species while promoting larval and adult dispersal for all groups (except Floodplain Specialists). Large and small freshes also promote hydraulic variability within riverine habitats (location dependant) and can support ecological processes such as biofilm complexity and productivity, or the dispersal and establishment of aquatic vegetation (habitat for many fish).

For flexibility in the application of managed flows, individual flow components should not necessarily be considered as discreet flow events. In many cases flow components of a higher magnitude will also meet the requirement for lower events. For example, a managed small fresh may be disrupted by a natural increase in flow which extends into the large fresh flow band in a stream or reach. In this instance the attempted delivery of a small fresh should not be considered to have failed but rather it deferred to a large fresh (so long as the flow rate at that site is exceeded for the recommended duration of a large fresh event).

The achievement of ecological outcomes from delivering a particular flow component will be influenced by antecedent conditions and may depend on cumulative outcomes from multiple events within a year and over successive years. For example:

- Spawning cues provided by a large fresh or bankfull flow are best followed by flows conducive to recruitment and subsequent dispersal of larvae and juveniles (i.e. small freshes or sequences of large freshes).
- Large freshes delivered in late-winter or spring could be ‘blended’ into a small fresh in which rapid drops in flow are avoided (September through April) to support breeding by nesting River Specialists. Conversely, a small fresh could be followed by increases in flow which blend in to a large fresh to potentially induce a spawning response from Flow Pulse Specialists at the completion of the breeding season for River Specialists.
- End of system connectivity (dispersal) objectives, triggered by a preceding spawning event in an upstream tributary (NSW or Qld), may require late winter high flow events to account for travel times. As such, multiple benefits (productivity and end of system connectivity/recruitment) may be achieved during the low-risk cooler months prior to onset of thermal stratification in storages.

Natural flow protection and enhancement

In the unregulated main-stem channels and tributaries, natural flows and cues (e.g. tributary inflows) should be protected, and where possible complemented with environmental water to achieve in-channel flow variability, overbank flows that connect floodplains (where appropriate) and support in-stream functions. This will preserve many of the critical flow elements such as timing and longitudinal connectivity. It will also assist in delivering biological, chemical and climatic cues that support key ecosystem functions.

Flow augmentation

There may be opportunities to modify or enhance the delivery of consumptive water orders or operational deliveries to achieve desired fish outcomes. These flows (e.g. consumptive water delivery and bulk water transfers (between storages) may be shaped or augmented with environmental water to modify or prolong flow components that support native fish outcomes. There

may also be opportunities to facilitate bankfull or small overbank flows to key floodplain wetlands that support floodplain specialist species (where constraints permit) either via connectivity or by simplifying logistical requirements for complementary watering actions (such as pumping). These types of flow augmentation opportunities are being incorporated into the day-to-day river operations in some valleys and are likely to continue to do so as the Basin Plan progresses and water managers adaptively 'learn by doing'.

Water quality

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

Natural flooding

An assumption is made that, during very wet periods natural flood events which are unable to be regulated will result in substantial overbank flooding throughout the NSW Basin. Minor through to major floods are vital for the long-term ecological integrity of the MDB. They promote floodplain productivity and nutrient cycling, mobilise and flush salt, deliver water to ephemeral habitats high on the floodplain and increase the extent of inundation of delta/terminal wetlands than can be achieved under regulated conditions. These larger flood events are not considered achievable using environmental water reserves due to the volumes required and current constraints within the system. However, the important aspects of floods (unregulated events) that contribute to ecological outcomes may be protected through policy measures and environmental water holders calling on supplementary entitlements, for example, and enhanced via the management of water for the environment.

Perverse outcomes

The NSW Basin is a highly regulated system. Water managers need to be mindful of potential perverse impacts on native fish communities arising from management of water for the environment and adopt a cautious approach. Responsible water management also considers the use of environmental flows to mitigate negative impacts.

In recent decades river regulation and drought has increased the frequency and duration of in-channel CTF events and reduced floodplain inundation frequency increasing the risk and occurrence of hypoxic blackwater events. Longer dry phases reduce flushing and allows for extensive accumulation of carbon sources between flow/wetting events. Whilst the dissolved carbon which gives blackwater its name is ordinarily beneficial to aquatic food webs, excessive dissolved carbon concentration results in very high biological oxygen demand upon re-inundation, which can cause extensive fish deaths.

Occasionally, streams or river reaches will cease to flow and may contract to refuge pools. Non-flowing pools have the potential to thermally stratify during warmer months, with a related potential for de-oxygenation of deeper water layers. “Turn over” of these pools upon recommencement to flow can mix poor quality water (potentially hypoxic) throughout the refuge pool which carries a risk of fish deaths (Ellis and Meredith 2004; Vertessy et al 2019). Similarly, hypoxic blackwater may manifest upon river restart following prolonged cease to flow conditions; risk of occurrence is compounded when restart occurs at very low flow magnitude during hot conditions.

In warmer months lentic water bodies may experience blue-green algal blooms (particularly in association with thermally stratified water columns rich in nutrients). Environmental flows have been utilised to prevent the development or mitigate the impacts, of widespread blue-green algal blooms.

Benefits to invasive species may occur when inundating floodplain habitat and providing access to spawning substrate for Carp, which can in turn result in unwanted population increases (Koehn et al 2017; Rayner et al 2015). Unfortunately, the breeding season of Carp overlaps with many native fish species (and other non-fish water dependant environmental assets) in the MDB, so avoiding provision of water for the environment to minimise Carp recruitment may also preclude positive native fish outcomes. As such, although minimising Carp recruitment during water for the environment delivery is an important consideration in the planning of environmental flows, it may not be the primary watering objective.

Mozambique Tilapia (*Oreochromis mossambicus*) is possibly the most imminent (known) aquatic biosecurity threat to native fish in the MDB. All other Non-native fish species known within the NSW Basin are naturalised and have a broad distribution. In the event of a Tilapia incursion, the use of water for the environment must be carefully considered so as not to unnecessarily aid its dispersal. This is especially relevant during the early stages of an incursion, should it occur, when emergency response activities may be underway. Water managers and river operations staff should consult with NSW DPIRD Aquatic Biosecurity with regard to supporting the implementation of the NSW DPIRD Mozambique Tilapia Incursion Response Plan (NSW DPI 2018).

Water delivered from large water storages to meet consumptive or environmental demand is often significantly colder in comparison to natural flows. In summer, when stratification of water storages is most pronounced, water temperature can be more than 10°C lower than natural river flows immediately downstream of some dams. Suppressed river temperatures may persist for hundreds of kilometres.

The impact of cold water pollution (CWP) on native fish and river health is well documented. CWP primarily impacts the life histories of fish in four ways: changes the range and distribution of species; reduces the opportunity for effective reproduction; reduces body growth and condition; and reduces recruitment success (Lugg 1999; Sherman 2000; Preece and Jones 2002; MDBC 2004; Preece 2004; Todd et al 2005; Boys et al 2009; Rutherford et al 2009; NSW CWPIAG 2012; Lugg and Copeland 2014). The severity and extent of CWP varies across valleys. The impact CWP can have on native aquatic biota downstream of storages must be considered during the planning of water management actions.

Prioritising hydrograph components

The prioritisation of EWRs in any given season will be guided by the required frequency of particular flow components. Flow components that are not met in one or more years will inform prioritisation

and planning in subsequent years. Recommended annual return interval (ARI; years), duration (days) and maximum period between events for EWRs relative to each functional group of fish are presented in Table 5. The degree to which EWRs, achieved wholly through the management of stored/held water for the environment is expected to attain ecologically significant flow components, and therefore support key life history elements for the NSW Basin functional fish groups, is presented in Table 5.

Table 5 Native fish EWRs as described in the LTWPs (adapted from NSW DPI, 2015; Ellis et al. 2016).

Flow component	Fish Group	Overarching primary ecological objective ¹	Ideal EWRs					
			Timing ²	Duration ³	Frequency ⁴	Max inter-flow period ⁵	Other requirements/ comments	
Cease to flow								
Cease to flow	All native fish groups	Maintenance/Survival	In line with natural	In line with natural, unless key refuges endangered			When restarting flows avoid harmful water quality impacts, such as de-oxygenating refuge pools	
Very Low flow								
Very Low Flow	All native fish groups	Maintenance/Survival	Any time	No less than modelled natural	No less than modelled natural	No greater than natural	Flow of 0.03 to 0.05 m/s velocity to de-stratify refuge pools	
Baseflow								
Base Flow 1	All native fish groups	Maintenance/Survival	Any time	Maintain refuge habitat and support connectivity	No less than modelled natural	As required during dry periods	Minimum depth of 0.3 metres to allow fish passage	
Base Flow 2	River specialists Generalists	Recruitment	Sept - March	Maintained throughout spawning season	1:1-2	2 years	Minimum depth of 0.3 metres to allow fish passage	
Small Fresh								
Small Fresh 1	All native fish groups	Dispersal Productivity/condition	Ideally Oct - April, but can occur anytime	10 days minimum	1:1	1 year	•>20°C for Oct to April •Australian smelt >11°C •Minimum depth of 0.5 metres to allow movement of large fish •Can follow Large Fresh 2 for increased likelihood of successful recruitment of fish, productivity and dispersal •Flow ideally up to 0.3 to 0.4 m/s (depending on channel form)	

Flow component	Fish Group	Overarching primary ecological objective ¹	Ideal EWRs				
			Timing ²	Duration ³	Frequency ⁴	Max inter-flow period ⁵	Other requirements/ comments
Small Fresh 2	River specialists Generalists	Spawning	Sept – April (Northern Basin) Oct – April (Southern Basin)	14 days minimum	1:1-2	2 years	• >20°C; for river blackfish >16°C; for Murray cod Sept to Dec >18°C • Minimum depth of 0.5 metres to allow movement of large fish • Flow ideally up to 0.3 to 0.4 m/s (depending on channel form)
Large Fresh							
Large Fresh 1	All native fish groups	Dispersal Productivity/condition	Ideally July to Sept (but can occur anytime)	5 days minimum	1:1-2	2 years	• Flow for pre-spawning condition • Minimum depth of 2 m to cover in-stream features and trigger response from fish • Flow ideally 0.3 to 0.4 m/s (depending on channel form)
Large Fresh 2	Flow specialists	Spawning	Oct - April	5 days minimum	1:2-3	4 years	• Rapid rise (comparative to natural rates) • >17°C • Can be followed by 'Small Fresh 1' for increased likelihood of successful recruitment of fish, productivity and dispersal • Minimum depth of 2 m to cover in-stream features and trigger response from fish • Flow ideally 0.3 to 0.4 m/s (depending on channel form)
Overbank/Wetland							
Overbank/ Wetland 1	Floodplain specialists	Spawning	Oct - April	10 days minimum	1:2	2 years (South) 4 years (North)	• >22°C • Ideally, recruitment flow 2-4 weeks after spawning flow

Flow component	Fish Group	Overarching primary ecological objective ¹	Ideal EWRs				
			Timing ²	Duration ³	Frequency ⁴	Max inter-flow period ⁵	Other requirements/ comments
Overbank/ Wetland 2	All native fish groups	Dispersal Productivity/condition	Ideally Sept - Feb but can occur anytime	5 days minimum	1:3-5 years	5 years	For enhanced productivity and movement opportunities for fish

¹Objectives related to spawning of in channel specialists in the Northern Basin (i.e. Small Fresh 2) should be assessed based on the determined rates for the specific flow component (i.e. within the associated flow thresholds). Objectives related to spawning of in channel specialists in the Southern Basin may be able to be assessed based on exceedance of flow rates (i.e. above the associated minimum flow threshold) due to the different hydrological conditions that prevail in the extensive lowland systems of the Southern Basin (i.e. increases in discharge generally do not result in substantial increases in water velocity, posing less of a potential impact on disrupting spawning outcomes when compared to the more dynamic mid and upland systems commonly found in the Northern Basin). All other objectives, including those related to spawning of flow specialists, recruitment, dispersal and/or productivity may be able to be assessed based on exceedance of flow rates (i.e. above the associated minimum flow threshold), as the associated outcomes would still be expected from native fish.

²Recommended ideal timing is linked to maximising spawning and recruitment outcomes based on known spawning seasons for native fish. Ideal timing for objectives related to dispersal and/or productivity have also been recommended; however, these may occur anytime with a movement and/or condition outcome still expected from native fish.

³Recommended minimum duration is linked to maximising spawning and recruitment outcomes based on known egg hatch time and morphology; these may be able to be increased based on flow data analysis and/or real time monitoring of fish larval presence, but they should not be reduced (e.g. extending the Small Fresh 2 duration would reduce the likelihood of nests being disturbed or abandoned during the critical 14 day incubation period). The duration for objectives related to dispersal and/or productivity may be able to be adjusted based on flow data analysis.

⁴Recommended ideal frequency is linked to providing conditions that protect and improve native fish populations in heavily impacted systems. To achieve this recovery more frequent events that maximise native fish outcomes may be required.

⁵Recommended ideal period between events for spawning and recruitment objectives is linked to the longevity of species, providing a guide to the maximum period between these outcomes before risk of significant population decline. For short-lived Floodplain Specialists species in the Southern MDB (e.g. Murray Hardyhead) additional activities such as pumping to remnant wetlands may be required to maintain habitat and support recruitment in intervening years between floodplain connectivity events. Objectives related to in channel dispersal and/or productivity have been set at annual frequencies to provide conditions that protect and improve native fish populations in heavily impacted systems.

Climate change impacts

Improving outcomes for native fish within water management frameworks must be considered within the context of ongoing changes to climate and associated increasing pressure on all available water resources.

Overview climate change trends for the NSW MDB

Australia has warmed on average by $1.47 \pm 0.24^{\circ}\text{C}$ from records began in 1910 with most of that warming occurring since the 1950s, with the period from 1980 being the warmest (BOM 2020). Every decade since 1980 has been warmer than the preceding. Australia's warmest year on record was 2019, and the eight years between 2013 – 2020 rank among the ten warmest years on record. Warming is observed across Australia in all months, with both day and night-time temperatures increasing. There is an increase in the number of heat events across all months, including greater frequency of very hot days in summer. There is also a corresponding increase in the frequency of months that are much warmer than usual: very high monthly maximum temperatures now occur >11% of the time (up from 2% 1960 – 1989). Very high night-time temperatures now occur 10% of the time (up from 2% 1960 – 1989). Night time minimum temperatures have not changed in southeast Australia (BOM 2022).

Rainfall in NSW MDB is highly variable and influenced by global drivers such as El Nino, La Nina, the Indian Ocean Dipole and Southern Annular Mode. Even so, there is a clear trend towards drier conditions with more frequent years of below-average rainfall especially in the cool-season (April – October). For 19 of 22 years between 2000 – 2021, April to October rainfall in southern Australia has been below the 1961-90 average and 10% lower than the 1990-99 period (BOM 2022). The Millennium Drought was a major influence on this, affecting rainfall totals across the region from 1997–2009. However, cool season rainfall totals are still 7% below the 1900–99 average in the years since 2010. Over the last two decades, above average cool season rainfall has only been experienced in 2010, 2016 and 2020. These occurred during the La Niña events of 2010–12 and 2020–22, and the strong negative Indian Ocean Dipole event of 2016 (BOM 2022).

Streamflow in the MDB shows significant inter-annual and inter-decadal variability. The period 1895 – 1945 was dry, followed by relatively wet years in the 1950s and 1970s, the period from 1995 has been relatively dry and includes two drought periods from 1997 – 2009 (the Millennium Drought) and 2017 – 2020 (Chiew et al 2022). Cool season rainfall is more effective at generating runoff. However, long term trends for declining rainfall April – October are reflected in declining streamflow; nearly half of the long-term streamflow gauges in the Murray Darling Basin show a declining trend since records began in 1970.

In the northern Basin catchments, where these trends are strongly evident, there are statistically significant declining trends in the headwaters, including the Namoi, Border Rivers, Condamine–Culgoa and Gwydir River catchments. In the Murrumbidgee, Lachlan, Goulburn and Loddon River catchments of the southern Basin, the majority of streamflow gauges show declining trends. In the Darling River region, declining trends were observed at almost all gauges (BOM 2022).

While declining stream flow trends are clear, there is a large range in the projected future changes in mean annual runoff, ranging between – 40% and +10% in the southern MDB and between – 45%

to +30% in the northern MDB. The median projection is for streamflow in the MDB to reduce by ~20% under 2°C global average warming by 2060 (relative to 1976 – 2005) (Prosser et al 2021). This is likely to result in a less reliable winter filling season, especially in the southern MDB (Hope et al 2017).

There has been an increase in the intensity of heavy rainfall events in Australia that occur on timescales of less than 24 hours. Daily rainfall totals associated with thunderstorms have increased since 1979. This is primarily due to an increase in the intensity of rainfall per storm. Warmer air can hold more water than cooler air, as the climate warms atmospheric moisture increases by 7% for every 1°C of warming, increasing the likelihood of heavy rainfall events (BOM 2022). The degree to which any potential increase in warm season rainfall and runoff might offset expected declines in the cool season remains largely unknown (Post et al 2014).

With the intensity of heavy rainfall events set to increase with climate change, an increase in the flashiness of flows especially during summer months, would be likely. This has implications for flood and erosion risk (BOM 2022).

Climate change is contributing to a change in fire weather through impacts on temperature and relative humidity and associated changes to fuel moisture content. The frequency of dangerous fire weather days has increased across NSW the fire season also has an earlier onset (BOM 2022).

Within a dry climate scenario, there will be an increased risk of natural disasters caused by extreme weather including ‘compound extremes’ where multiple extreme events occur close together, exacerbating their impacts (BOM 2022).

It is noted that there remains interannual variability in short term patterns and some variation in predictions of climate change models. However, the majority of models indicate continued warming and declines in cool season rainfall, with more frequent intense rainfall events even where average rainfall decreases or stays the same. This is matched with an indication of longer periods of drought and a longer fire season (BOM 2022). These changes will continue to effect streamflows and the biota that rely on them.

The 2023 review of the Framework (2rog Consulting 2023) summarised the forecast climate change considerations for fisheries and water managers into the future and ranked native fish functional groups in terms of risk, based on forecast climate and life history/flow relationships.

Implications for native fish

Research on climate change and fish communities within the MDB predicts potentially severe impacts on both the fish community and individual species within it. Modelling work undertaken by Galego de Oliveira et al (2019) suggests that local extirpation of fish populations is likely with climate change, with associated declines in species distribution. Under modelled conditions, five species (Common Galaxias, Obscure Galaxias, Trout Cod, Hyrtl’s Catfish, Flathead Gudgeon) were predicted to lose 100% of suitable habitat within the MDB by the end of the century. Loss of Obscure Galaxias and Trout Cod would represent global extinctions given that both species are endemic to the MDB. Other species such as Silver Perch and Dwarf Flathead Gudgeon are predicted to only be found in one localised area of the MDB under the most pessimistic scenario assessed (~3.5°C increase in temperature by 2100 compared to the 20th century average), by 2080 (Galego de Oliveira et al 2019). It was suggested that the persistence of species in their original ranges will be

dependent on the degree of genetic diversity, physiological and phenotypic plasticity (Fuller et al 2010, Ingram, Gooley and Giri, 2022).

In addition to habitat and range changes, it appears that climate change will directly affect fish in three ways:

1. Reduced streamflow will impact habitat quality and quantity, especially over hot summers (Wright et al 2022). Periods of extreme dry and drought are likely to increase, putting native fish populations under increased stress during these times. In addition, reduced streamflow will limit lateral and longitudinal connectivity and movement opportunities for fish to seek out suitable habitat and to undertake important life cycle elements such as spawning.
2. Water and ambient temperatures are rising. The temperature in the MDB has increased by approx. $1.47 \pm 0.24^{\circ}\text{C}$ over the past 114 years, with most of the increase occurring after 1980 (BOM 2020). Continued increases in water temperature may widen the spawning window for temperature sensitive species but may also occur outside seasonal spawning windows, potentially leading to decoupling of spawning cues and day-length relationships. Increasing temperature is likely to have an uneven effect on fish species, with species that prefer lower spawning temperatures such as Australian Smelt (King et al 2016), potentially more impacted. The spawning of Murray Cod is predicted to occur up to four weeks earlier by 2090 in response to future temperature projections in the MDB (Ingram, Gooley and Giri, 2022). This may have broader implications for the management of this species such as recreational fishing closed seasons (Ingram, Gooley and Giri, 2022). In addition, increases in temperature may rise to such a degree as to exceed some species lethal limits (Galego de Oliveira et al 2019). While increases in temperature are likely to have an overall negative impact on native fish, there may be some positive implications such as a potential increase in the range of some temperature tolerant species into new areas (such as Spangled Perch; Balcombe et al 2011).
3. Increased storm intensity and associated flooding with climate change has the potential to increase erosion risk (BOM 2022), influencing habitat stability and quality. Increased flashiness of flows may also disrupt spawning for species that require low or steady flows to spawn and may also increase the chance of nest abandonment for nesting species.

Climate change has and will present a range of risks to all native fish populations across the MDB. These risks are not likely to be uniform across all species from a functional perspective. Table 6 summarises an assessment of the consequences of these risks across functional groups along with an attempt to rank them in order of climate change impact. Floodplain Specialist species (Group 3) are likely to be the most impacted by climate change for several reasons. Reductions in river-floodplain connectivity and off channel habitat persistence and quality will directly impact on the ability of this species to survive and reproduce. In addition, many of these species are short lived, with low fecundity, so any restriction in their ability to access breeding habitat may have a significant influence on their populations. Their small size and limited movement capability will also limit their ability to move throughout the MDB to more suitable habitats in the longer term.

River Specialist species (Group 2) will likely be the next most impacted by climate change, as reductions in flow rate may limit access to suitable breeding habitats. Increases in the variability or 'flashiness' in flows during the breeding season may impact on flow stability required by these species for successful reproduction.

It is expected that Generalist species (Group 4) will potentially be less effected by climate change given their wide-ranging habitat and spawning preferences. The low to moderate ability of these species to move larger distances may restrict their movement throughout the MDB to more suitable habitats in the longer term.

Flow Pulse Specialist species (Group 1) will likely be least impacted by climate change, given their increased ability to migrate throughout the MDB, their preference for in channel habitats, and their high fecundity and long lifespan, noting however that impacts described above will affect these species, especially those related to changes to flow regimes, temperatures and extreme events.

Impacts on native fish guilds from a changing climate will take place in the context of continuing cumulative impacts that affect river health and native fish communities now. This includes river regulation and water management, including likely changed volumes and timing of Planned Environmental Water (PEW) in regulated and unregulated systems. Under drying conditions, reliance on Held Environmental Water (HEW) to achieve environmental outcomes is likely to increase while the efficacy of that water use, volumes and quality may diminish.

Table 6 Potential general impacts and risks of Climate Change on native fish functional groups in the MDB. Note that any vulnerabilities that arise due to threatened species status have not been considered.

Functional Group	Key Species	Potential climate change impacts	Order of relative greatest Risk (1-highest, 4 lowest)
All	All native fish	Under drying conditions, continued reduction in frequency of small – medium sized flows may impact system productivity with implications for conditioning, spawning and recruitment success. Prolonged hot and drying conditions are associated with declining water quality. Poor water quality will impact habitat quality, while prolonged exposure to poor water quality conditions will have a series of physiological implications for native fish. Increases in water temperature may exceed some species lethal limits. Increased water temperatures may lengthen spawning windows, but also impact on spawning if temperatures become too high. Increased storm intensity may increase erosion risk, reducing habitat stability and quality.	
Group 1: Flow Pulse Specialists	Golden Perch, Silver Perch, Spangled Perch	In addition to all native fish impacts: Changing rainfall patterns (timing, volume) may change timing, frequency and duration of flow pulse events relied upon to cue spawning and migration.	4 High ability to migrate to more suitable conditions if required. In-channel species so increased access to habitat compared to Floodplain Specialist species. Long lived species and highly fecund.

Functional Group	Key Species	Potential climate change impacts	Order of relative greatest Risk (1-highest, 4 lowest)
		Reduced in-channel flow will reduce accessibility to tributaries and off-channel wetlands that act as spawning and nursery environments for Golden Perch. Prolonged periods of low flows may reduce availability of lotic habitat critical for Silver Perch. Recovery opportunities may diminish in long/frequent periods of dry conditions.	
Group 2: River Specialists	(a) Lotic preference: Murray Cod, Trout Cod, Macquarie Perch, River Blackfish, Two-spined Blackfish, Darling River Hardyhead (b) Lentic preference: Freshwater Catfish, Southern Purple Spotted Gudgeon, Olive Perchlet. River and Freshwater Mussels	In addition to all native fish impacts: Reduced flow in rivers may restrict access to off-channel habitats and suitable in-channel spawning sites. Under prolonged low-flow conditions, water quality and longevity of preferred habitats may be reduced. Increase in floods and flow variability during breeding season may impact on breeding success and increase nest abandonment.	2 Mainly longer-lived and highly fecund species, which can move moderate distances to find suitable habitat. Reductions in flows may limit access to off-channel habitats and to suitable spawning habitat. Increase in flood frequency may impact on flow stability required for reproduction.

Functional Group	Key Species	Potential climate change impacts	Order of relative greatest Risk (1-highest, 4 lowest)
Group 3: Floodplain Specialists	Olive Perchlet, Southern Purple Spotted Gudgeon, Flathead Galaxias, Southern Pygmy Perch, Murray Hardyhead. Floodplain Mussels	In addition to all native fish impacts: Reduced flow may limit opportunity to access off channel habitats. Reduced floodplain connection would likely reduce the availability and quality of off-channel habitats.	1 Lower flows likely to impact quality of and access to floodplain habitats. Occupy smaller ranges limiting opportunity to move to suitable habitats. Shorter lifespan, low fecundity means higher impact if they fail to spawn. Floodplain Mussels are 'well adapted' to drought conditions (Sheldon 2020). Given this adaptation, Floodplain Mussels may not be as vulnerable as other species in this Group.
Group 4: Generalists	Australian Smelt, Carp Gudgeon, Flat-headed Gudgeon, Dwarf Flat-headed Gudgeon, Bony Herring, Murray-Darling Rainbowfish, Unspecked Hardyhead, Mountain Galaxias, Obscure Galaxias, Spotted Galaxias, and Climbing Galaxias.	In addition to all native fish impacts: Reduction in suitable habitat and opportunity to move through landscape. Increased water temperatures may impact on suitable water quality.	3 Generalist in their habitat and spawning preference. However, species occupy relatively small home ranges limiting their ability to move and reach suitable alternative habitat under drying conditions.

Monitoring, Evaluation and Review

Since development of the original Framework in 2017 (NSW DPI, 2017), knowledge of fish life history and causal effects of water management on fish protection and recovery outcomes has improved. Therefore, it is necessary to update the Fish and Flow Management Framework to reflect current science and best available information. This will inform various program/plan reviews (e.g. five yearly technical reviews of NSW LTWPs and BWS reviews) and assist with annual water planning. The Framework will also continue to be used in the development of fish intervention monitoring hypotheses, and policy relating to infrastructure development and assessment.

The Monitoring, Evaluation, and Review (MER) process plays a fundamental role in ensuring the effectiveness and accountability of management initiatives. Evaluation activities rigorously assess the outcomes and effectiveness of management interventions, providing valuable insights into successes and areas for improvement. By offering a structured framework for ongoing assessment and reflection, MER supports evidence-based decision-making, fosters transparency, and promotes accountability.

Integration of the proposed framework for fish and flow management with existing water management strategies is crucial. This integration should consider regional variations in breeding seasons, channel capacity, and discharge values, with collaboration among stakeholders encouraged for effective implementation across scales.

Recognising the inherent variability in flow characteristics within the MDB, adopting an adaptive management approach is recommended. This approach allows for flexible adjustments based on regional specifics and evolving understanding of fish-flow dynamics, ensuring optimized outcomes for fish populations and habitat health. Robust monitoring protocols are necessary to assess ecological outcomes, including fish populations, habitat conditions, and flow regimes, facilitating adaptive decision-making.

Targeted research projects are essential to address knowledge gaps, fostering collaboration between researchers, agencies, and stakeholders for comprehensive data analysis.

Capacity-building initiatives, such as training programs and knowledge exchange platforms, are vital for enhancing stakeholder skills and fostering a culture of reciprocity and feedback within the MER framework.

Regular updates to the framework based on new research and evolving priorities support continuous improvement, enabling adaptive management practices to effectively respond to changing environmental conditions and stakeholder needs.

Conclusion

The current report represents a contemporary synthesis of knowledge and conceptual understanding of how flow may be managed to benefit fish. Together with the associated DPIRD Fisheries Basin valley-scale reports, this Framework improves the understanding of water requirements for fish and other key aquatic biota, helping to ensure that the science underpinning the EWRs for fish species in the NSW Basin is current and based on best available knowledge. Targeted valley scale assessments across the Basin have helped describe flow-related attributes of each valley, including fish barriers and connectivity issues, aquatic habitat condition, fish community status, system scale connectivity requirements, improving and consolidating the understanding of hydrological and ecological information for each valley.

Individual Fish and Flow valley reports identify regionally relevant future opportunities for managing water to achieve fish outcomes. These include but are not limited to collaborative water management and operations, key threatening processes, monitoring and research requirements, constraints and complementary measures.

Considering the DPIRD Fisheries' commitment to adaptive management, valley reports also identify data deficiencies and knowledge gaps that if overcome, would improve definition and implementation of EWRs for fish. Generally, these include a requirement to increase the extent of habitat mapping initiatives, undertake field assessments of HIS (channel and landscape/floodplain survey), calculate ecologically informative in-stream fish barrier drown-out thresholds; and improving understanding of fish life history (especially rare and cryptic species such as Darling River Hardyhead), as well as fish population dynamics and limnological response to hydrology. Further research on non-fish species will enhance our understanding of the flow requirements of these species.

There are additional opportunities to build on this recent review work of the Framework by undertaking future priority actions, including:

- Revise the Fish and Flows Management Framework in line with recommendations from the Culture, Fish and Flows project.
- Undertake further work to define the life history traits and EWRs for the snail species that are currently placed in the unidentified functional group.
- Continue review of EWRs with focus on:
 - Revised assessment regarding 'risk of achieving' considering climate change and water availability risks.
 - Update System Scale Connectivity knowledge based on case studies and practice.

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Appendix A: Key species, life history elements and attributes and flow management implications for Functional Groups of the NSW MDB.

Functional group	Key Species	Key life history element	Attributes and implications on flow management
Group 1: Flow pulse specialists	Fish Species: Golden Perch Hyrtl's Tandan Silver Perch Spangled Perch	General	Species are medium to long-lived and spawning and recruitment are not required every year to maintain a viable population, however healthy populations consist of multiple year classes and demonstrate some recruitment in most years (Golden Perch, Silver Perch). Flow pulses (within or overbank) coinciding with warmer water temperatures are generally required to generate a spawning response, although instances of winter spawning have been documented in recent years. Adults are highly fecund and may make long migrations in response to flow. Flow pulses are required to cue movements and provide longitudinal connectivity for upstream re-colonisation (DPI 2020 unpub.). While Silver Perch do fit into this Group, they are functionally different to other species in the Group, and there is still limited information about some aspects of their life history (e.g., dietary requirement) (2rog Consulting 2023).
		Habitat	Adults use deeper hydraulically complex habitats with a preference for submerged structure (Koehn and Nicol 2014). Recruitment success may be enhanced by flows that inundate and transport drifting young to off-channel habitat (i.e. increased connectivity and ecosystem productivity) (Sharpe 2011). The timing and operation of floodplain regulators can deny drifting early life history stages access to floodplain 'nursery habitat', thereby impacting recruitment (Sharp 2011).

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			Silver Perch: High affinity to emergent vegetation in the northern Basin (2rog Consulting 2023); Water clarity a key component for macrophyte growth but also predator evasion (2rog Consulting 2023). Golden Perch: Habitat preferences vary seasonally and between different life stages; Research has shown preferences for rocky habitat over emergent plants (Hutchinson 2020), woody habitat in late summer, deeper habitats in late winter in weir pools (Koster et al 2020); Use of inundated floodplain habitats as nurseries also varies between populations (Zampatti et al 2021a); Research has shown strong site fidelity and occupy restricted home ranges (Crook 2004). Spangled Perch: Preference for a mix of structure and sandy substrates (2rog Consulting 2023).
		Condition	Adult fish gain condition with increasing water temperature usually between spring and autumn. The first post-winter flow fresh 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. Silver Perch: Different dietary requirements than others in this guild (eat algae and specific macroinvertebrates) (2rog Consulting 2023); Condition response linked to both floodplain inundation and in-channel flows. Multiple years of flow important (Bice et al 2021). Golden Perch: Optimal temperature for survival is higher in the northern Basin (23-27.8 °C) than in the southern Basin (19.8 °C) (Koehn et al 2020); Higher survival of juvenile fish is associated with increased temperatures and food densities (24 – 28 °C) (Price et al 2019); Growth variation from otolith analysis showed sensitivity to environmental parameters, with depression during the Millennium Drought and positive responses to higher river flows and flow pulses (Izzo et al 2016b in Koehn et al 2020).

Functional group	Key Species	Key life history element	Attributes and implications on flow management
		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 freshes, coupled with warmer water temperature may generate adult spawning migrations (Mallen-Cooper and Stuart 2003; Zampatti and Leigh 2013; Stuart and Sharpe 2020). Eggs and larvae drift for weeks potentially dispersing over long distances. Growth and recruitment success is enhanced by flows that transport young into inundated off-channel 'nursery' habitat. Ephemeral wetlands may offer productive and sheltered floodplain 'nursery' habitat which supports strong survivorship and growth of juveniles (Sharpe 2011; Ellis et al 2014; Stuart and Sharpe 2020). 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 (Ebner et al 2009; Zampatti et al 2015; Stuart and Sharpe 2017). Adult fish prepare for spawning in response to increasing water temperatures usually between spring and autumn, with research in the Northern Basin suggesting that the first post-winter flow pulse may be important for pre-spawning condition and migration in some northern systems (Marshall, et al. in press), but timing is not predictable. Adult fish can undertake moderate to large scale migrations (100s of m to over 100s of km) in response to increased flows and temperature, but can delay spawning if conditions are not suitable, with species being medium to long-lived and not necessarily requiring annual spawning and recruitment events. Flow events do not have to be large pulses, with small, sharp rises in flow also providing benefits and eliciting responses from species (Marshall et al. in press).). Larvae drift downstream over long distances for up to 20 days post spawning in perennial and intermittent systems (potentially

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			shorter in highly intermittent systems with smaller flow pulses), with recruitment relying on flows for dispersal and conditioning (DPI, 2015). Silver Perch: Spawning can occur without floods or flow pulses if temperatures are suitable, but spawning intensity increased exponentially with increased flows (King et al 2016). Juveniles subsequently move upstream. Strongest year class recruitment is associated with extended high flows and widespread flooding in the following year that promotes survival of age 1+ juvenile fish (Tonkin et al 2019). Water temperature critical for spawning (22 °C optimal) and best when preceded by a period of limited flooding (2rog Consulting 2023, King et al 2016). Follow up flows that allow access to food and habitat critical for recruitment (2rog Consulting 2023). Southern populations in the Murray River spawning and recruiting well, but not going on to 2,3,4-year age classes (2rog Consulting 2023). Golden Perch: Flow pulses or floods constitute obligate cue for mass spawning and strong recruitment occurs when floods transport larvae and early juveniles into optimal nursery habitat such as Menindee Lakes (Koehn et al 2020). Golden Perch recruitment is generally associated with periods of increased flow through spring and summer (Zampatti et al 2021a). May spawn on the rising or falling limb of the hydrograph if water temperature is in range (Optimal temperature of 19°C in southern Basin (King et al 2016), higher in the northern Basin (23-27.8 °C); Kohen et al 2020). Nursery habitats such as Menindee Lakes in the northern Basin and large, 'slow travel' flows that promote high productivity have been suggested to enhance recruitment rates (Stuart and Sharpe 2020). Larvae underwent full transition to fully scaled fingerlings during downstream drift or dispersal of 1,600 km down the Darling River (Stuart and Sharpe 2020).

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			Spangled Perch: In the southern MDB able to breed in edge habitat in wetlands/lakes/floodplains and backwaters off the main channel (2rog Consulting 2023).
		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. Freshes required to cue upstream recolonisation movements by juveniles. Connectivity over large spatial scales is critical for these species. Larvae drift downstream over long distances for up to 20 days post spawning in perennial and intermittent systems (potentially shorter in highly intermittent systems with smaller flow pulses), with recruitment relying on flows for dispersal and conditioning. Silver Perch: Migration often cued by flow increases. Recorded movement of up to 1,200 km, often associated with bankfull and overbank flows (Koehn et al 2020). High tributary flows, compared to main stem flows, may increase probability of movement into tributaries (Koster et al 2020). Flow regime to provide floodplain and lateral habitat connection important for supporting post larval fish (Tonkin et al 2019). Golden Perch: Preservation of even low-magnitude flow events in tributaries may confer improved population resilience to main-stem fish populations, if tributaries are hydrologically and physically connected to the main river (Zampatti et al 2021a). Some indication that rainfall induced flow events are a prime cue for fish migration and spawning rather than river rises from stored/impounded water. This may be due to different micro-chemical cues where rainfall flows across dry ground, as originally proposed by Lake (1967). Stored water from Copeton Dam (Gwydir River) is an example of poor water quality (Stuart. I 2019).

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			Spangled Perch: Depth of passage (0.3 m) not a constraint for this species. Migrating juveniles will jump at least 0.3 m (2rog Consulting 2023). May disperse rapidly and over extensive areas during floods (Ellis et al 2015).
		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. 2015; Stuart 2019b; Stuart and Sharpe 2020). Populations may be maintained by low levels of regular (usually annual) recruitment and larger less frequent flood-enhanced recruitment events. Key difference to other functional groups: long lived and move over large (macro-scale) distances. Require Flow Pulses to generate spawning response and facilitate dispersal. Silver Perch: The strongest year classes were associated with a combination of low to average river discharge (i.e., within channel) and high water temperatures over the peak spawning period, followed in the next year by extended high flows and widespread flooding that promoted survival of age-1p juvenile fish (Tonkin et al 2019). Annual recruitment in large-scale lotic habitats is an essential part of the life history strategy of Silver Perch, and hence a requirement for a resilient population (Tonkin et al 2019).
Group 2 River Specialists (Lentic and Lotic)	Fish species: (a) Lotic preference: Murray Cod, Trout Cod,	General	River specialists can be further categorised as preferring either lotic habitat (e.g. Murray Cod, River Blackfish) or lentic habitat (Freshwater Catfish, SPSG). In the Northern Basin, SPSG and Olive Perchlet may also be considered Floodplain Specialists depending on the geomorphology and biophysical features of the sub-catchment. As such they may fall in to either this category or the Floodplain Specialists category depending on local expert opinion and historical habitat preferences. New knowledge of Darling River Hardyhead life history (Moy et al. 2018) has resulted

Functional group	Key Species	Key life history element	Attributes and implications on flow management
	Macquarie Perch, River Blackfish (RB), Two-spined Blackfish (TSB), Darling River Hardyhead (b) Lentic preference: Freshwater Catfish, SPSG (SPSG), Olive Perchlet. Mussels: River Mussel (<i>Alathyria jacksoni</i>) Freshwater Mussel		in this species being reclassified as a Riverine (lotic) Specialist. River specialist species do not necessarily require large scale recruitment every year to maintain a viable population. However, healthy populations consist of multiple year classes and demonstrate some recruitment in most years (DPI 2020, unpub.). Murray Cod: Can spawn in lotic habitats but survival from egg to larvae to juvenile doesn't happen in static water environments (2rog Consulting 2023). Macquarie Perch: Need to concentrate on flows in upland settings (2rog Consulting 2023). Olive Perchlet: Seems to persist in areas of higher salinity because it helps to control Carp (2rog Consulting 2023). River Blackfish: Life cycle and habitat use different to other species in this guild – no larval drift (2rog Consulting 2023). Two-spined Blackfish: Antagonistic relationship between Two-spined Blackfish and salmonoids is well documented (2rog Consulting 2023). Mussels: River and Freshwater Mussels (<i>Alathyria jacksoni</i>, <i>Alathyria condola</i>) fit in Group 2 River Specialists; these species are intolerant of drying and display spring/autumn breeding which is temperature cued but independent of flow. There are few Australian studies on Freshwater Mussel reproductive biology. Juvenile survival and growth of mussels in the northern Murray-Darling Basin is unknown and represents a large knowledge gap (Sheldon et al 2020). Limited information on the growth of Australian Freshwater Mussels from metamorphosis to adult. Most field surveys have noted very few juveniles and small mussels in shoals; whether this is the result of poor recruitment or specific growth patterns is unknown (Sheldon et al 2020). As filter

Functional group	Key Species	Key life history element	Attributes and implications on flow management
	<i>(Alathyria condola)</i>		feeders the impact of higher flows (increasing sediment load) is a knowledge gap (2rog Consulting 2023).
		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 2013; Koehn et al 2020b), except for Darling River Hardyhead which are typically associated with open, slow flowing channel environments <1 m deep (Moy et al 2018). SPSG are generally associated with tributaries or slow flowing anabranches and backwaters off main channels (particularly for breeding purposes) but are detected in flowing habitats. Often susceptible to cold water pollution. Macquarie Perch: This is now an upland species, but juveniles can be swept into a lowland context (2rog Consulting 2023). Freshwater Catfish: Found in both lentic and lotic habitats. Preference for off channel habitats in the southern Basin, but flowing water in the north (2rog Consulting 2023). Habitat generalists found in a range of habitats (Kohen et al 2020). Require complex habitat to live, submerged macrophytes key for juveniles to live and hide from predators. Able to exist in complex root masses (2rog Consulting 2023). Olive Perchlet and SPSG: Olive Perchlet and SPSG share similar habitat niche (2rog Consulting 2023), showing a preference for submergent macrophyte forests (Hutchinson, Morris and Nixon 2020). Although in an upland context SPSG prefer cobble boulder and bedrock, but dependant on species assemblage (2rog Consulting 2023).

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			Water visibility important for these species, for both macrophyte growth and to escape predators (2rog Consulting 2023). SPSG considered a floodplain species but can be found in small streams, often in conditions that would not seem suitable for any fish (2rog Consulting 2023). SPSG predominantly occur in small streams (<10 m wide and 0.4 m deep) with moderate to low current velocity in association with structure (submerged veg, undercut banks, exposed roots) (Kerr, Fawcett and Prior 2017). RB and TSB: RB found in upland areas only, but some below major dams (2rog Consulting 2023). RB have a heavy reliance on undercut banks in the southern Basin especially, with shaded banks, woody debris and overhanging veg also forming key habitat in the north (2rog Consulting 2023). RB have been shown to use inundated riparian areas during flooding with large movements coinciding with times of elevated flows (Koster 2008). TSB show less association with woody debris and undercut banks, preferring cobble boulder streams (2rog Consulting 2023). TSB show smaller range of movement than RB and can do well in reservoirs even in the presence of salmonoids (2rog Consulting 2023). Darling River Hardyhead: Preference was shown for pool habitats with sand or cobble substrate, increased channel depth and width and distance from the bank, and reduced flow velocity. Overhanging exotic riparian vegetation and in-stream woody debris were non-preferred (Moy et al 2018). Mussels: Micro-habitat requirements of mussels are unknown as they are locally restricted to specific regions of the channel based on substrate or localised flow conditions (Walker 2017). River Mussel: Have capacity to persist in isolated water holes, despite lack of water flow and low water quality. Species however is unable to withstand drying (Sheldon et al 2020). Distribution

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			positively associated with availability and permeance of water across the landscape (Sheldon et al 2020). Freshwater Mussel: Has a geographically restricted distribution and is likely only found in river channels with relatively strong flow conditions (Walker 1981 in Sheldon et al 2020). Freshwater Mussels are considered rare.
		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. Murray Cod: Growth of Murray Cod positively correlated with river discharge and flow variability, especially spring discharge (Tonkin et al 2017). Growth of adults highest in years with flooding, whereas younger juveniles (1+ and 2+ years) showed peak growth during median annual discharge years. Growth suppressed in years with very low annual discharge (Stossel et al 2020) Trout Cod: Similar patterns to Murray Cod. In addition, years with increased flow variability during both spring and summer-autumn were associated with increased Trout Cod growth in the Murray River (Tonkin et al 2017a) River Mussel: A study undertaken in the River Murray showed growth and age varied widely in populations over several locations with adults over 30 years old in some populations (Sheldon et al 2020).
		Reproduction	Adults may make short migrations to spawn in response to increased temperature. Moderately fecund, spawn in nests or have specific spawning substrate preferences. Fish species of this

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			group often provide parental care. Emerging evidence suggests adults may ‘invest’ more strongly into reproductive outputs during years in which exceptional flow-cued productivity cues are apparent or following long periods in which sub-optimal breeding conditions prevailed. Adults may make short migrations to spawn in response to increased temperature (DPI 2020, unpub.). Nesting species, or have specific spawning substrate preferences, except for Darling River Hardyhead where relatively little is known of spawning traits. On leaving nests, larvae ‘drift’ semi passively over short to moderate distances for dispersal with recruitment success potentially enhanced by perennial flows and flow pulses (i.e. increased floodplain productivity and connectivity). Periodic, within-channel, pulses provide connectivity for upstream recolonisation movements by juveniles (DPI 2020, unpub.). Have a predictable spawning period from mid-winter to the end of autumn, but most commonly between spring and summer independent of flow, except for Darling River Hardy Head where size structures suggested a single annual spawning season in late September or early October (Moy et al 2018). 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; except Darling River Hardyhead where relatively little is known of the reproductive biology of the species other than eggs are usually be deposited amongst aquatic vegetation (NSW DPI 2014) and flow cues are potentially a less significant spawning trigger than parameters such as photoperiod or water temperature (Moy et al. 2018). Higher flows may increase recruitment success by inundating additional spawning habitat and dispersing drifting young to productive nursery habitat.

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			Murray Cod: Temperature cued spawners (15-21 °C water temps; Stocks et al 2021) but nesting linked to week of year and spawning linked to moon phase in the northern Basin (Butler et al 2022). Timing predictably mid-October to at least December in the southern Basin, earlier in the north, from September to mid-October (Koehn et al 2020). Dispersal is active or by drift, depending on water velocity, and in some cases drift distance can be minimal (Stuart et al 2019), especially in isolated pools in the northern Basin (S. Balcombe, Griffith University, pers. obs. in Koehn et al 2020). Larval dispersal in low-velocity waterholes and weir pools is suggested to be achieved through active movement rather than drift (Stuart et al 2019 in Koehn et al 2020). At moderate and relatively high discharges, Murray Cod larvae can determine whether they stay or move through a reach (Price et al 2019). Survival rates of larvae once external feeding commenced (9-15 days) were higher at colder temperatures (16 °C) than warmer temperatures (>19 °C). Survival was significantly influenced by food density at higher temperatures but not at 16 °C. In contrast, growth was extremely low at 16 °C and much higher at 22 – 25 °C once food densities reached 1,000 zooplankton per litre. (Price et al 2019). Although spawning occurs in impoundments, little or no recruitment is evident (Forbes et al 2016 in Koehn et al 2020). Trout Cod: Abundance of larvae greatest at 28 °C (King et al 2016 in Koehn et al 2020). Macquarie Perch: Temperature cued spawners, with spawning beginning when spring water temperatures exceed 16 °C. Greatest abundance of eggs recorded in Victorian rivers when mean daily water temperatures exceeded 18.8 °C. (Tonkin et al 2015). High-sloping riffles, associated with larger deeper pools containing complex habitat, appear to be the most favoured for spawning (Tonkin et al 2016 in Koehn et al 2020). Low flows suggested to impact population size by restricting access to spawning habitat (Koehn et al 2020).

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			Freshwater Catfish: Availability of suitable nesting habitat (pebble and cobble substrate) probably more important than flow for this species (2rog Consulting 2023). Primary spawning period between November and February. Water temps reaching approximately 22 °C and moderate stable discharges (~300 – 1,200 ML/d). Want stable moderate flows within lotic habitats, these are likely beneficial to their demersal nesting behaviours. Flows before and after spawning seasons may boost primary production, which may facilitate successful recruitment (Stocks et al 2021). While they will spawn in dams, study on the Nymbioda River north-eastern NSW found more abundant nesting below a weir than in the impounded section above. Maybe related to sedimentation in suitable areas above the weir (Carpenter-Bundhoo, 2019). Follow up connection flows post spawning may be important for allowing dispersal throughout the system (2rog Consulting 2023). SPSG: Displays an idiosyncratic distribution pattern of being a widespread species with a very limited dispersal ability (Sasaki et al 2016). In northern Basin breeds within channel with stable flows (2rog Consulting 2023). Needs a hard clean surface to spawn. Can spawn on the base of typha where freshly inundated surfaces can be utilised (2rog Consulting 2023). Darling River Hardyhead: Little known about reproductive life history characteristics (2rog Consulting 2023). Size structures suggested a single annual spawning season in late September or early October (Moy et al 2018) River Mussel: Sexual maturity attained at about four years of age (Walker 2017). Lower River Murray study showed seasonal glochidia production, brooding embryos in the spring and releasing in the spring and summer. Likely that a temperature related season signal in reproduction in northern MDB would occur too (Sheldon et al 2020). Breeding season is spring to autumn, critical temperature threshold is greater than 12 °C (Jones 2011).

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			Specialised lifecycle which involves a parasitic stage where fertilised eggs develop into glochidium, are released and attached to a vertebrate host, typically fish. The glochidium then begins an approximate three-week metamorphosis into a juvenile mussel and is released to the riverbed (Sheldon 2020). Appear to be host fish ‘generalists’ with most fish species (including several introduced species) able to support metamorphosis of glochidia to free-living juvenile mussels; however, some studies have shown introduced Carp (<i>Cyprinus carpio</i>) and Goldfish (<i>Carassius auratus</i>) consistently rejecting Australian glochidia across a wide geographic range in several species of mussel (Walker 2017). The proportion of actively reproducing individuals of River and Floodplain Mussels varied in the River Murray. Here, populations were influenced by variations in discharge (Walker 2017). Freshwater Mussel: Life cycle of this species has not been reported, but presumably larvae (glochidia) are brooded in marsupia in the gills of the female and, when released, attach to fish gills or fins where they undergo metamorphosis before detaching from the fish and dropping to the sediment as free-living juveniles (Ponder 2022).
		Movement	Adults may undertake short to moderate scale migrations (100s of m to 10s of km) to spawn. Larvae drift over short to moderate distances for dispersal. Recruitment success potentially enhanced by flow freshes that transport drifting young to productive off-channel nursery habitat. Periodic pulses provide connectivity for upstream recolonisation movements by juveniles. Mussels will move around locally. Some larger scale movement may occur with flooding, otherwise dependent on recovery and movement of native fish in the area as their host (Sheldon et al 2020). Murray Cod: Generally, have restricted home ranges and high site fidelity for most of the year, but can undertake large-scale movements (120 km), with homing behaviour common (Koehn et al

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			2009; Leigh and Zampatti 2013; Llewellyn 2014; Koehn and Nicol 2016; Carpenter-Bundhoo et al 2020a; Koster et al 2020 in Koehn et al 2020). River discharge is important in lower-order streams to allow adults to disperse to locate spawning sites and mates (G. Butler, NSW DPI, pers. obs. in Koehn et al 2020). Otolith microchemistry confirms residency within broad geographic regions (hundreds of kilometres), and limited movements between regions over their lifespan (Zampatti et al 2019 in Koehn et al 2020). River discharge had a significant effect on the activity of Murray Cod, with activity peaking at discharge rate of ~400 ML/d and declining up until 520 ML/d (the maximum discharge experienced in this study) (Thiem et al 2018). 50 – 100 km of flowing river habitat would support entire life cycle (2rog Consulting 2023). Macquarie Perch: A study found that Macquarie Perch occupied restricted home ranges for most of the year but undertook more extensive upstream and downstream movements of several kilometres coinciding with variations in river discharge. Following these larger movements, some fish established new home ranges in different locations, whereas others returned to areas previously occupied. Unlike impoundment populations, Koster et al 2013a in Koster, 2017) found no evidence of synchronised migratory behaviour during the spawning season in the Yarra River population. Studies of the movements of Macquarie Perch provide evidence of strong intraspecific variation in movement behaviour among environments (i.e., rivers v. impoundments), and demonstrate that movement and migration are not necessarily fixed traits but may be strongly influenced by environmental conditions (Chapman et al 2006; Barthel et al 2008 in Koster and Crook, 2017). Likely movement is from upland to lowland during connectivity events (2rog Consulting 2023). Freshwater Catfish: Traditionally freshwater catfish have been thought to display limited ranges. For example, Koster et al 2015 showed limited ranges (< 600 m) within a lagoon of the Goulburn catchment, with some individuals occasionally moving more extensively (up to 1.5 km) between

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			floodplain and riverine habitats. More recent studies in the northern Basin suggest larger movements (movements of up to 31 km per day in the Gwydir catchment (Carpenter-Bundhoo et al 2023) and movement of up to 78 km over several days in the Moonie River (Marshall et al 2016). In the Goulburn River catchment, fish moved over much greater areas at night compared with during the day. There was also evidence of sex-specific variation in movement, with a trend for greater movement of female fish at night compared with males (Koster et al 2015). Freshwater Catfish were found to use rising and peak limbs of the hydrograph to move and showed an increased likelihood of movement in the breeding season (Carpenter-Bundhoo, 2019). Fish movement behaviours can vary within a species, or genus, among flow regimes and among rivers and suggests that individuals in perennial, highly connected habitats may not need to move as frequently as they may in more variable environments (Carpenter-Bundhoo 2019). SPSG: Dispersal is flow mediated. Between large connecting events that allow for meta population mixing they probably need flow to help keep fish alive in certain areas until reconnection (2rog Consulting 2023). RB: Although RB movement was very localised most of the time, longitudinal movements up to 350 m, as well as lateral movements onto inundated riparian areas, were also exhibited by some fish during or following periods of elevated river discharge (Koster and Crook 2008 in Koster and Crook 2017). Movement tends to be significantly greater at night than during the day (Koster 2008). Freshwater Mussels: Some larger scale movement may occur with flooding, otherwise dependent on recovery and movement of native fish in the area as their host (Sheldon et al 2020).

Functional group	Key Species	Key life history element	Attributes and implications on flow management
		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; except Darling River Hardyhead which are short lived (Moy et al 2018) and require regular spawning and recruitment events. It may take many years for noticeable population improvements due to low or moderate fecundity. Mussels are sedentary, long-lived organisms (Sheldon 2022). Murray Cod: Winter is considered a critical period for young of year (YOY) survival, and recruitment may be greatly reduced where winter base flows are low and permanent lotic conditions have been lost (Sharpe and Stuart 2018 in Koehn et al 2020). Recruitment success in the lower Darling/Barka River in relation to the 2016 - 17 environmental flow plan was evaluated by a census survey of fish populations in the Lower Darling in June 2017 and showed YOY Murray Cod less than 12 months old at each site and these represented a significant proportion (~10 per cent) of the population. This finding provides evidence that the goal of promoting Murray Cod YOY recruitment with targeted environmental flows was achieved (Sharpe and Stewart, 2018). The release of water for the environment in the Severn and Dumaresq rivers during late winter/early spring in 2017 also contributed to specific responses from target species, including Increased numbers of Murray Cod YOY in both the Macintyre and Dumaresq systems (DoEE, 2019). Trout Cod: Population growth is driven primarily by larval and juvenile survival, with a positive relationship with higher growth rates provided by higher summer and autumn flow variability and spring discharge (Tonkin et al 2017b in Koehn et al 2020). Macquarie Perch: Based on long-term assessments of the Lake Dartmouth population, it is suggested that a healthy spawning stock structure consists of a stable number of large fish and a broad age distribution (Tonkin et al 2018 in Koehn et al 2020). Tonkin et al (2017a) also reported

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			positive associations between year class strength and the abundance of adult fish and, to a lesser degree, temperature during the spawning period (Koehn et al 2020). River Mussels: Species is medium to long lived and reaches sexual maturity at four years. Successful recruitment relies on minimal flow requirements required for native host fish for that period (Walker 2017). Northern MDB populations show the capacity to persist in isolated water holes, despite the lack of water flow, and often poor water quality of these refugia. This suggests that <i>A. jacksoni</i> may be more resilient to low flow conditions than perhaps has been appreciated to date. This study confirmed the inability of this species to withstand drying (Sheldon et al 2020)
Group 3: Floodplain Specialists	Fish Species: Olive Perchlet, SPSG, Flathead Galaxias, Southern Pygmy Perch, Murray Hardyhead. Mussels: Floodplain Mussel	General	Adults may make short migrations to spawn in response to increased temperature, into or within lentic (or slow-flowing) off-channel habitats. Individual species of this group may have specific spawning substrate preferences (e.g. broad-leafed submerged aquatic plants, rocks). Increases in inundation extent can therefore enhance breeding opportunities by creating additional spawning habitat as well as floodplain productivity benefits. Species are relatively short-lived with low fecundity. Most species require spawning and recruitment events every 1-2 years for the population to persist. Overbank flooding is required (although not necessarily annually) to facilitate dispersal for re-colonisation, mixing between populations and to establish new populations (e.g. Olive Perchlet, Flathead Galaxias, SPSG) (DPI 2020, Unpub.) Given the reliance of species in this Group on macrophytes, EWRs to support macrophyte health are important, especially low and base flows (2rog Consulting 2023).

Functional group	Key Species	Key life history element	Attributes and implications on flow management
	(Velesunio ambiguous)		SPSG: This species does well in upland small tributaries with low species diversity. They are an in-channel specialist in that context (2rog Consulting 2023) Southern Pygmy Perch: Similar requirements to SPSG (2rog Consulting 2023). Primarily found in the southeast sections of the MDB (2rog Consulting 2023). Predation by Redfin a key interaction and threat (2rog Consulting 2023) Murray Hardyhead: Appears to persist in areas with high salinity as it helps to control Carp numbers (2rog Consulting 2023). Lowland floodplain specialist which also occurs in estuaries. Primarily found in the southwest MDB (2rog Consulting 2023). May require bespoke flow management at the wetland scale. need to identify unique conditions where it can be managed to persist, across the landscape at multiple places. Then use flows to facilitate connectivity between those sites so they can act as nodes for dispersal. Their high salinity tolerance provides a management tool at the wetland scale (2rog Consulting 2023) Flathead Galaxias: Historically existed in floodplain sections of the Murrumbidgee and Murray, now a southeast MDB species (2rog Consulting 2023). Have been observed in Victoria in low quality back lakes and wetlands (2rog Consulting 2023). Potentially decimated by Redfin. More susceptible than Southern Pygmy Perch (2rog Consulting 2023)
		Habitat	Have specific spawning substrate preferences (often aquatic macrophytes). Some have water quality requirements unique to off-channel habitats (e.g. cooler temperatures for Flathead Galaxias). Olive Perchlet and SPSG: As in Group 2 above

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			Flathead Galaxias: South Eastern MDB lowland species (2rog Consulting 2023) Southern Pygmy Perch: Needs dense submerged, fringing and riparian structure (2rog Consulting 2023) Murray Hardyhead: Research has determined salinity tolerance at various life stages (Stoessel et al 2020) Floodplain Mussel: Occupies a wide range of habitats, frequently in the lower floodplain wetland regions. Uncommon in major river channels (Sheldon et al 2020). Habitats include temporary flowing creeks, backwaters, billabongs and artificial environments such as farm dams and irrigation channels (Jones 2011).
		Condition	Adult fish gain condition with increasing water temperature usually between spring and autumn, except Flathead Galaxias (Aug – Sept). Increases in flow may enhance breeding opportunities by inundating additional spawning habitat and contributing to ecosystem productivity.
		Reproduction	Spawning between spring and autumn (except Flathead 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. Recruitment and dispersal rely critically on flows that reconnect the channel to the floodplain, with large flow events required post spawning (DPI 2015) Olive Perchlet: Breeding season may be longer than previously thought – influence of temperature (2rog Consulting 2023). Signs of recruitment in Queensland in last few years. Occurring in areas with lots of macrophytes (2rog Consulting 2023). Hatchery spawning showed

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			high activity in late spring early summer, with lower activity later in summer (2rog Consulting 2023) Floodplain Mussel: Breeding season is spring to autumn; critical temperature threshold is greater than 12 °C (Jones 2011). Specialised lifecycle which involves a parasitic stage where fertilised eggs develop into glochidium, are released and attached to a vertebrate host, typically fish. The glochidium then begins an approximate three-week metamorphosis into a juvenile mussel and is released to the riverbed (Sheldon 2020). Appear to be host fish ‘generalists’ with most fish species (including several introduced species) able to support metamorphosis of glochidia to free-living juvenile mussels; however, some studies have shown introduced Carp (<i>Cyprinus carpio</i>) and Goldfish (<i>Carassius auratus</i>) consistently rejecting Australian glochidia across a wide geographic range in several species of mussel (Walker 2017). The proportion of actively reproducing individuals of River and Floodplain Mussels varied in the River Murray where populations were influenced by variations in discharge (Walker 2017). Lower River Murray study showed presence of glochidia most of the year with peak releases in spring and summer (Sheldon et al 2020), Glochidia parasitise a range of native fish including Australian Smelt, Bony Bream, Golden Perch, Silver Perch, Freshwater Catfish, Murray Cod, Flat Headed Gudgeon, Western Carp Gudgeon, Mitchellian Hardyhead and Congolli (Jones 2011).
		Movement	Adult fish undertake micro (< 100 m; Olive Perchlet, SPSG), or meso scale movements (100s m to 10s km; Flathead Galaxias) 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.

Functional group	Key Species	Key life history element	Attributes and implications on flow management
		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). Floodplain Mussel: Regulates oxygen consumption and may aestivate for more than a year buried in sediment (Jones 2007)
Group 4: Generalists	Fish species: Australian Smelt, Carp Gudgeon, Flat-headed Gudgeon, Dwarf Flat-headed Gudgeon, Bony Herring, Murray-Darling Rainbowfish, Unspecked Hardyhead, Mountain Galaxias, Obscure Galaxias, Spotted	General	These species are generally more resilient to extended low flow conditions having developed more flexible spawning strategies, and as such may be poor indicators of environmental flow effectiveness (MDBA, 2015); however, these species provide an important component of productivity in a system and food source for medium and large bodied species. 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 (DPI 2015). However, these species provide an important component of productivity in a system and food source for larger bodied fish. Generally, have low fecundity requiring regular (ideally annual) spawning and recruitment events for persistence (e.g. Australian Smelt, Bony Herring, Carp Gudgeon, Mountain Galaxias, Un-specked Hardyhead) (DPI 2020, unpub.).
		Habitat	Able to occupy a range of streams and waterbody types. Generally persist within-channel during extended low flow conditions but do access floodplains. Generally resilient to extended low flow conditions having developed flexible spawning strategies, and as such may be poor indicators of environmental flow effectiveness. Adult fish move short distances (10s of m to 100s of m) over a wide range of hydrological conditions and are known to recruit under low flows all year round; however, spawning is most common between spring and summer. They survive within-channel during low flows or on floodplains during overbank inundation. Adults move short distances and may spawn more than once in a year. Short periods of larval drift may occur, and small flow pulses

Functional group	Key Species	Key life history element	Attributes and implications on flow management
	Galaxias, and Climbing Galaxias. Shrimp: Glass Shrimp/ Freshwater Shrimp (<i>Paratya australiensis</i>) <i>Caridina mccullochi</i> Long Armed Shrimp (<i>Macrobrachium australiense</i>) Yabbies and Crayfish: <i>Cherax destructor</i>		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). Flat-headed Gudgeon: Fairly generalist (2rog Consulting 2023) Dwarf Flat headed Gudgeon: Whilst generalist, live in the edge of the wetland, becoming more prevalent in lower reaches (2rog Consulting 2023). Prefer lots of vegetation and sticks (2rog Consulting 2023). Murray-Darling Rainbowfish: Macquarie River study showed peaks in recruitment occur primarily in spring and summer during increasing water temperatures and moderate stable discharge, although some recruitment observed throughout winter. Water temperatures exceeding 20 °C. Attach their eggs to aquatic vegetation. (Stocks et al 2021). Unspecked Hardyhead: The abundance of Unspecked Hardyhead and Murray-Darling Rainbowfish generally increased following the release of water for the environment (DoEE 2019). Mountain Galaxias: Mostly occurs in smaller streams at high elevations with steep valley slopes and high stream gradients downstream (Cook et al 2019). Lowland specialists, upland only in the southern MDB (2rog Consulting 2023). Obscure Galaxias: mostly occurs in larger downstream waterways with higher magnitude and variability of stream flow (Cook et al 2019). Glass/Freshwater Shrimp and <i>Caridina mccullochi</i>: Habitat generalists, prefers slow-flowing water at all life stages (Richardson and Humphries, 2010). Common in the slackwater zone of slow-flowing rivers and streams, backwaters, billabongs and anabranches where it is associated

Functional group	Key Species	Key life history element	Attributes and implications on flow management
	Murray Crayfish (<i>Euastacus armatus</i>) Highland Cray (<i>Euastacus jagara</i>)		with aquatic plants and snags (Humphries et al 2006, Richardson and Cook, 2006; Sheldon and Walker 1998; Williams, 1997 in Jones, 2011). Freshwater Prawn (<i>Macrobrachium australiense</i>): Prefers still water as larvae but flowing as adult (2rog Consulting 2023). Yabbies (<i>Cherax destructor</i>): Semi aquatic generalist, occupying all habitats and avoiding clear water (Chessman et al 2010). Murray Crayfish: Inhabits a wide variety of permanent rivers and large streams, some lake environments. Clay banks appear to be important for constructing burrows. In the ACT region boulder/cobble substrate along with other structure such as snags (ACT Government 2018). Prefers intermediate flow velocities, deeper pools and glide with overhanging vegetation for shading (ACT Government 2018). Highland Cray: Highland, headwater reaches of five small first order streams in two different drainage divisions – Condamine River and Brisbane River catchments (McCormack et al 2010).
		Condition	Adult fish gain condition with increasing water temperature usually between spring and autumn, and benefit from access to floodplain habitats where there is high prey abundance. Low to moderate flow events that inundate within-channel habitat enhances spawning conditions and connectivity of drought refuge. There is a relationship between shrimp biomass and diet (2rog Consulting 2023). Glass/Freshwater Shrimp: Opportunistic traits (small body size, small eggs and high fecundity) (Richardson and Humphries 2010). Breeding initiated in late winter to spring and continues as water temperature increases until mid-summer. Life expectancy varies geographically between 1

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			- 2 years. Usually, will breed once in a season but may breed twice, producing 50-1,000 eggs (Jones, 2011). <i>Caridina mccullochi</i>: Intermediate, having neither high fecundity nor large size, and has limited swimming ability when young (Richardson and Humphries, 2010). Reproduction occurs in spring and summer with females producing 30-60 eggs (Jones 2011). Freshwater Prawn: ‘equilibrium’ traits (larger body size, larger eggs and moderate fecundity (Richardson and Humphries, 2010). Larvae prefer still water; adults prefer flowing water (2rog Consulting 2023). Life expectancy typically more than two years (Lee and Fielder (1984) in Richardson and Humphries, (2010)). <i>Cherax destructor</i>: Can survive temperatures of 1 – 36 °C but activity, growth and reproduction cease below 15-16 °C (Jones 2011). Murray Crayfish: Likely to be polytrophic, cannibalism can occur when food ability is scarce (Gilligan et al 2007).
		Reproduction	Spawning is generally linked to increased temperature but species in this functional group exhibit greater flexibility in spawning strategies than other functional groups. Adult fish prepare for spawning in response to increasing water temperature (generally spring-summer). May spawn more than once during the year with low to moderate flow events that inundate in-channel habitat enhancing spawning conditions and connectivity of drought refuge, providing the greatest benefits to these species, eggs are sticky and demersal with a hatch time of up to 10 days. Larval drift is exhibited by some species over short to moderate scales, with recruitment relying on flows for dispersal and conditioning (DPI 2015).

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			Australian Smelt: Supports a window of opportunity hypothesis, where although the species has a protracted spawning period, temperature and discharge play a key role in the timing and magnitude of successful recruitment (Stocks et al 2021). A study in the Macquarie River showed highest recruitment during rising river levels of higher discharge periods. Temperature change did not affect recruitment rates, nor did number of flood days in the two weeks preceding hatch date (Stocks et al 2021). Bony Herring: A study in the Macquarie River showed backdated hatch date occurring through all seasons, suggesting their spawning window is much wider than previously thought (Stocks et al 2021). In the same study, recruitment events generally coincided with moderate 'in-channel' flows on the receding tail of flow events, with water temperature ranging from approximately 8 °C to 30 °C. Studies within the Gwydir River system found that hatch dates of Bony Bream coincided with a period of declining flow levels throughout February and March, although they peaked at the time of a brief late February flow pulse (Southwell et al 2015). Murray-Darling Rainbowfish: Macquarie River study showed peaks in recruitment occur primarily in spring and summer during increasing water temperatures and moderate stable discharge, although some recruitment observed throughout winter. Water temperatures exceeding 20 °C. Attach their eggs to aquatic vegetation (Stocks et al 2021). Glass/Freshwater Shrimp: Opportunistic traits (small body size, small eggs and high fecundity) (Richardson and Humphries 2010). Breeding initiated in late winter to spring and continues as water temperature increases until mid-summer. Life expectancy varies geographically between 1 - 2 years. Usually, will breed once in a season but may breed twice, producing 50-1,000 eggs (Jones, 2011).

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			<i>Caridina mccullochi</i>: Intermediate, having neither high fecundity nor large size, and has limited swimming ability when young (Richardson and Humphries, 2010). Reproduction occurs in spring and summer with females producing 30-60 eggs (Jones 2011). Freshwater Prawn: Show 'equilibrium' traits (larger body size, larger eggs and moderate fecundity (Richardson and Humphries, 2010). Larvae prefer still water; adults prefer flowing water (2rog Consulting 2023). Life expectancy typically more than two years (Lee and Fielder (1984) in Richardson and Humphries, (2010)). <i>Cherax destructor</i>: Breeding commences in spring as water temperature reaches 15 °C and flooding is not a breeding stimulus (Jones 2011). Breeding season may continue from spring to the entire year if water temperature remains warm enough (NSW DPI, nd.). May reproduce two to four times per breeding season (Jones 2011, NSW DPI, nd.). Egg numbers range from fewer than 100 to a maximum of 1200 per female depending on female size, nutrition, environmental factors, genetic variability (Jones 2011). Murray Crayfish: Mating in May and release of juveniles in late spring to early summer (Jones 2011). Attains sexual maturity at 5-9 years female and around 4 years for male, fecundity dependent on female size, carries from 300-1200 eggs per year but low recruitment rate (Jones 2011). Reproduction and growth are temperature dependent, so reduced water temperatures from dam release is a key threatening process (Jones 2011). Highland Cray: Evidence suggests low fecundity and larger egg size (McCormack et al 2010).
		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.

Functional group	Key Species	Key life history element	Attributes and implications on flow management
			Mountain Galaxias: In foothills and lowland areas where hydrological variability is greater, populations of both Mountain Galaxias and Obscure Galaxias persist using dispersal over larger geographical distances. It is likely that metapopulation dynamics enable persistence of Mountain Galaxias in streams with high hydrological variability, and possibly in stream segments with introduced salmonids (Cook et al 2019). Obscure Galaxias: Undertake upstream migrations prior to spawning, with larvae and post-larvae drifting downstream from spawning locations. Juveniles have successfully ascended fishways, indicating that juveniles also migrate upstream once active swimming abilities have developed (Cook et al 2019). Glass/Freshwater Shrimp: Juveniles and adults can swim against flow (Richardson and Humphries 2010). Caridina mccullochi: Largely confined to slow-flowing and still habitats in lowland rivers through its life, suggesting poor swimming ability (although not studied) (Richardson and Humphries 2010). Freshwater Prawn: Known to swim against considerable current velocities during freshes and floods to compensate for downstream displacement (Jones 2007). Cherax destructor: Not much knowledge about movement and dispersal (CABI 2011). Migrate upstream in huge numbers during flows, walk upstream (2rog Consulting 2023). Will abandon habitat when conditions become too stressful. Murray Crayfish: Southern MDB dispersal events and home ranges are likely to be restricted to distances less than 50 km (Whiterod, et al 2016). Mean home ranges in the Murrumbidgee of 1,800–2,000 m² have been documented (ACT Government 2018).

Functional group	Key Species	Key life history element	Attributes and implications on flow management
		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. Carp Gudgeon: Spawning and recruitment responses were observed following water for the environment flow events (DoEE 2019). Bony Herring: Recruitment of Bony Herring and Common Carp occurred over a broad thermal range in comparison to Golden Perch (Stocks et al 2021). Mountain Galaxias: Suggested that upland populations may be extremely isolated and dependent on relatively stable hydrological conditions (i.e. high perennial and low interannual variability of flows) for persistence (Cook et al 2019). Glass/Freshwater Shrimp: Mature at a relatively small size, produces large numbers of relatively small young that probably experience high mortality at times during the breeding season when conditions are not favourable (Richardson and Humphries, 2010). <i>Caridina mccullochi</i>: Life span of about 12 months. Intermediate, having neither high fecundity nor large size, and has limited swimming ability when young (Richardson et al 2004 in Jones 2011). Freshwater Prawn: Lifespan of two years, moderate fecundity (Price and Humphries 2010). Due to greater size and propensity for movement when young it is possible to find more suitable conditions. May be able to persist in altered environment (Richardson and Humphries 2010). <i>Cherax destructor</i>: The life span is at least 3 years and possibly up to 6 years (CABI, 2011). Murray Crayfish: Long lived from 30 – 50 years (ACT Government, 2018).

Functional group	Key Species	Key life history element	Attributes and implications on flow management
		Flow Requirements	Glass/Freshwater Shrimp: While adults can swim strongly against water currents, large numbers of larvae may be displaced by floods and strong flows (Hancock and Bunn 1997, 1999 in Jones 2011). Therefore, maintaining some areas of slack water through the summer period should be a management target for this species. Caridina mccullochi: Given the strong association of both larval and adults life stages with slow-flowing or still water habitats, the timing of low flows to coincide with critical stages in the life cycle over summer and autumn may be vital for the maintenance of shrimp populations. In the Campaspe River, this species was absent from sections of the river with high summer irrigations flows, probably because of the reduction of slack water habitats disrupting larval development and recruitment (Richardson and Cook 2006 in Jones, 2011). Freshwater Prawn: Onset of breeding is related to water temperature rather than flow and there is evidence that cold water releases below dams delay the onset of breeding (Richardson et al 2004 in Jones 2011). Cherax destructor: No specific flow requirements linked to life history but can benefit from boosted productivity after floodplain inundation. (Jones 2011). Murray Crayfish: Prefer cool flowing water of intermediate velocities, which maintains a well oxygenated environment (Noble and Fulton 2016 in Whiterod et al. 2016, Jones 2011). Species is intolerant of low dissolved oxygen (NSW DPI n.d.) and has been occasionally observed leaving the water (crawling onto riverbanks or snags) during periods of low dissolved oxygen (ACT Government 2018).
		Habitat	Darling River Snail: Once occurred in flowing rivers throughout the Murray-Darling system, where it was found along the banks attached to logs and rocks or crawling in the mud (NSW DPI 2007).

Functional group	Key Species	Key life history element	Attributes and implications on flow management
Undefined Functional Group¹ Freshwater Snails	Darling River Snail (<i>Notopala sublineata</i>) Hanley's River Snail (<i>Notopala hanleyi</i>)		Now found solely in an irrigation pipeline off the lower Murray River (Mitchell 2022). Rocky structures, off-channel habitat, holes and grooves in snags (2rog Consulting 2023). Study has shown a preference change from lotic systems to lentic systems (Mitchell 2022). Hanley's River Snail: The species once occurred in flowing, well oxygenated waters throughout the Murray River catchment. Artificially introduced hard surfaces now provide habitat for the species with populations being recorded as surviving in irrigation pipelines (DPI 2018).
		Condition	Darling River Snail: Nutritional value of altered biofilms may no longer be sufficient to sustain the high energetic requirements of the Darling River Snail's ovoviviparous reproductive strategy (Jones 2007). Hanley's River Snail: The pipeline environment is thought to promote microbial production and organic accumulation, which is a highly nutritious food source for the species. Changes in the nature of the periphyton (biofilm) community because of altered flow regimes (principally weir and dam building) have impacted this species. Hanley's River Snail is not able to thrive on the relatively low nutrient content provided by algae that results from reduced flow variability (DPI 2018).
		Reproduction	Females of both species are sexually mature at 15-16 mm. Fertilisation is internal, and the young remain with the female until they are large enough to survive independently (DPI 2018). Ovoviviparous breeders, brood eggs and have a relatively small number of live young (Jones 2011). High energetic cost of reproduction resulting in more developed but fewer offspring (Jones 2011).
		Movement	Limited dispersal ability for both Darling and Hanley's River Snail (Jones 2011, DPI 2018).
		Maintenance	No information available.

Functional group	Key Species	Key life history element	Attributes and implications on flow management
		Flow requirements	Flow requirements of both species are unknown. Both species have disappeared from their natural lotic habitat. This has coincided with predation from Common Carp and increased regulation in the MDB (Jones 2011).

1 info not available to assign to an existing functional group yet not enough evidence to justify forming a new group for them (2rog Consulting 2023)

Appendix B: Fish and Flow Review Report Recommendations

The following recommendations are made with respect to updating the Fish and Flow Management Framework principles, existing fish functional groups, and EWRs based on advances in information and knowledge gained through this project.

Recommendations as needed to update the Fish and Flow Management Framework principles.

Establish a principle concerning the consideration of antecedent conditions in the setting of EWRs for native fish recovery. This would include focussing on EWRs that support recruitment and emigrations rather than other life history elements following extreme events such as droughts, fires or hypoxic blackwater events. At a broader scale, providing guidance around the EWR sequencing that should be targeted within different Resource Availability States (very dry, dry, moderate etc) would assist water managers to obtain the best results for native fish populations using water for the environment.

Establish a principle that considers the current distribution of species within the Basin, and the need for bespoke flow management at some locations. The patchy distribution of some species across the Basin was identified in the workshop as being important to how fish species are managed in the future, especially for threatened species or those of high concern. Critical reaches/wetlands could be identified for some lower abundance species, and flows could be targeted in those reaches to improve population/stocks there. For example, wetland water levels could be manipulated to inundate specific macrophyte beds to provide breeding and rearing habitat for small, bodied wetland species like Southern Purple Spotted Gudgeon. Then connectivity flows could be used to allow dispersal.

Establish a principle that highlights achievement of all EWR parameters along with the sequences of flows that are required to cater for different life stages, to ensure optimal success.

Recommendations for updates to existing Functional Groups

General

Explicitly note in the functional group descriptions that differences in fish life history traits exist between southern and northern Basin and upland and lowland settings. Consideration should be given to the fact that some species population status/life history preferences differ between the southern and northern Basin, and between upland and lowland systems. Therefore, while a species fits into a broad functional group, EWRs to target the same species may differ between settings. Rather than split functional groups further, these differences could be noted explicitly in the functional group descriptions, so practitioners applying the framework are aware of it. This point also highlights the importance of local knowledge in applying the fish and flow information when defining EWRs for fish.

Specific

Group 1 Flow Specialists

We recommend placing Silver Perch in an additional subgroup to highlight their differences from other species in this Group. While Silver Perch fit in this Group, they are functionally different from the other two species within it. Silver Perch display different dietary preferences; they have spatially restricted populations and show a high susceptibility to negative impacts from Carp (workshop).

Group 2 River Specialists

We recommend maintaining the structure and name of this Group. In addition, we would recommend leaving River Blackfish in this Group, but highlighting the differences with this and other species in the Group description. There was discussion at the workshop about the name of this Group not fully reflecting the species within it. Options presented were splitting the Group into two flow guilds rather than lentic and lotic, or renaming to 'channel utilisers' and 'off-channel utilisers'. Workshop participants did not reach consensus on the best approach. It was also identified that some species such as Freshwater Catfish, Southern Purple Spotted Gudgeon and Olive Perchlet do fit in both subgroups, however, River Blackfish habitat and life cycle do not match other species within the guild (e.g., no larval drift like other species). Given the overlap of some species in both subgroups, we would recommend leaving the structure of the Group as is (i.e., 2 subgroups) and maintaining the same names for them (lotic and lentic).

Group 4 Generalists

We recommend following up with galaxias expert Dr Tarmo Raadik for further advice as to the requirements of species within the Galaxias genus. Workshop participants discussed the appropriateness of this Group for galaxias species given their variation in requirements between species and between different populations. No consensus was reached.

Assessment of Fish Functional Group EWRs

General

We consider the current methodology for developing EWRs outlined in the Fish and Flow Management Framework sufficient and fit for purpose.

We recommend adding more commentary to highlight the added benefits of existing EWRs on supporting fish species in general, rather than just providing for specific life history traits. There was discussion in the workshop that more emphasis was needed on supporting flows, not just for specific life history elements. Examples included providing flows to support progression of Silver Perch from larvae to 1+ individuals through providing resources to support recruits, but also to provide movement opportunities not just to promote spawning. Another example presented was setting EWRs to provide for the maintenance of habitat (macrophytes) that individuals rely on (particularly important for small-bodied wetland/lotic species such as Olive Perchlet and Southern Purple Spotted Gudgeon). Given the framework does provide EWRs to support maintenance/survival and dispersal, productivity/condition, which would be considered supporting flows, we would not recommend any additional EWRs be developed. Instead, more commentary could be placed around the existing flows to highlight the added benefits these flows have on supporting fish species in general.

We recommend the addition of some 'generalised' flows sequence examples into the framework to provide guidance on flow sequencing. The importance of sequencing of flows to cater for different life stages (spawning to recruits to juveniles to adults) for best results was also discussed at the workshop. While the sequence of flows is likely to be site and species specific, we would recommend the addition of some 'generalised' flows sequence examples into the framework to provide guidance on flow sequencing.

Specific

Group 2 River Specialists

We recommend the addition of the following comments in the EWR flow table:

In the large fresh category, ideal magnitudes for G2 species would provide connection to off-channel habitats.

For small fresh 2, river rises do not have to be large to promote G2 species spawning, the key consideration is that new clean substrate is inundated, then flows are held there for at least 10 days.

Group 3 Floodplain Specialists

Based on discussion at the workshop, we would recommend reviewing the 10-day minimum duration for the overbank/wetland 1 EWR. The 10-day duration is based on the time required to allow for spawning and egg development for floodplain specialist species. However, water will likely persist in off channel habitats once connection to the river has finished, facilitating spawning and egg development. For floodplain connection flows, it is likely that the magnitude and frequency of the flow will be the critical aspects of the flow that maintain a mosaic of habitats promoting floodplain specialist species. In addition, in valleys that display a flashy hydrograph, stipulating a 10-day duration is likely to describe an overbank flow that is much larger than that intended by the EWR that inundates critical off channel habitats. These larger flows are also likely to occur less frequently than the 1:2 year frequency specified for this EWR.

Appendix C: First Nations Language

Common Name	Aboriginal Name	Nation	Reference
Macquarie River	Wambuul	Wiradjuri	Geographic Names Board
Dumaresq River	Karaula	Bigambul	Geographic Names Board
Lachlan River	Galari, Galiyarr	Wiradjuri, Ngiyambaa	
Murray River	Dhungala	Yorta Yorta, Wamba Wamba, Barapa Barapa	
Edward River	Kolety	Wamba Wamba, Barapa Barapa	Geographic Names Board
Barwon River	Barwum, Bawon	Kamilaroi	
Darling River	Barka	Barkinji	
Namoi River	Namoi	Kamilaroi	Thematic History of Parry Shire
Mooki	Mukai	Kamilaroi	Thematic History of Parry Shire
Manilla	Munila	Kamilaroi	Thematic History of Parry Shire
Castlereagh River	Warrumbungle	Kamilaroi	Geographic Names Board
Peel River	Calala	Kamilaroi	The Aboriginal Names of Rivers in Australia Philologically Examined. P. MacPherson.
Water	Gayini	Nari Nari	WCC Nari Nari Dictionary

Common Name	Aboriginal Name	Nation	Reference
	Wala, Dhethogana	Yorta Yorta	WCC Yorta Yorta Dictionary
	Galing, guugu, ngadyan	Wiradjuri	WCC Wiradjuri Dictionary
	Gabi, Gawoo	Barngarla	WCC Barngarla Dictionary
	Katen	Wemba Wemba/ Wamba Wamba	WCC Wurrekangurr Dictionary
Fish General	Guya	Kamilaroi	B. Moggridge
	Wina or Guya	Bidjara	M. Hobbs: Bidjara and Gungabula grammar and vocabulary
	Guya	Wiradjuri	S. Grant snr & J. Rudder: A New Wiradjuri Dictionary
	Maniga, burnanga (large), Djawa (minnow)	Yorta Yorta	WCC Yorta Yorta Dictionary
Golden Perch	Thagaay, Dhagaay	Gamilaroi	P. Duncan / Living on the lower Namoi
	Gangupka	Yorta Yorta	WCC Yorta Yorta
	Gardi	Bidjara	M. Hobbs: Bidjara and Gungabula grammar and vocabulary
	Gagalin, Bidyin	Wiradjuri	S. Grant snr & J. Rudder: A New Wiradjuri Dictionary
	Wirrenggal	Wemba Wemba / Wamba Wamba	Wemba Wemba / Wamba Wamba

Common Name	Aboriginal Name	Nation	Reference
			Language Resource website
	Pilalki, pila:ki	Ngarrindjeri	Ngarrindjeri Dictionary
	Dhinnjur	Ngunnawal	Ngarigo and Ngunnawal wordlists
Macquarie Perch	Gubir	Wiradjuri	S. Grant snr & J. Rudder: A New Wiradjuri Dictionary
	Gubay	Ngunnawal	Winnagay Ngunnawal language group
Murray Cod	Guduu, Gugabul, Munyaa	Gamilaroi, Wiradjuri	P. Duncan S. Grant snr & J. Rudder: A New Wiradjuri Dictionary
	Pandyil	Wemba Wemba / Wamba Wamba	Wemba Wemba / Wamba Wamba Language Resource website
	Pondi	Ngarrindjeri	Ngarrindjeri Dictionary
	Wabalgan	Bidjara	M. Hobbs: Bidjara and Gungabula grammar and vocabulary
	Mangi	Ngunnawal	Winnagay Ngunnawal language group
Silver Perch / Black Bream	Dungay	Gamilaroi	P. Duncan
	Gambaal, Banngala	Kamilaroi	Living on the Lower Namoi

Common Name	Aboriginal Name	Nation	Reference
	Baawan, Gargalany	Wiradjuri	S. Grant snr & J. Rudder: A New Wiradjuri Dictionary
	Tji:ri	Ngarrindjeri	Ngarrindjeri Dictionary
	Badhunyn	Bidjara	M. Hobbs: Bidjara and Gungabula grammar and vocabulary
	Purrekonek	Wemba Wemba/ Wamba Wamba	Wemba Wemba / Wamba Wamba Language Resource website
	Tulari	Ngarrindjeri	Ngarrindjeri Dictionary
	Warthamarra, danela	Yorta Yorta	WCC Yorta Yorta
Bony Herring/Bream	Baraa	Kamilaroi	B. Moggridge
	Biirnga	Gamilaroi	Living on the lower Namoi
	Burilburil	Wiradjuri	WCC Wiradjuri Dictionary
	Berrumbunnun	Ngunnawal	Ngarigo and Ngunnawal wordlists
	Thukeri	Ngarrindjeri	Ngarrindjeri Dictionary
	Payipang, Ngeti Maren	Wemba Wemba/ Wamba Wamba	Wemba Wemba / Wamba Wamba Language Resource website

Common Name	Aboriginal Name	Nation	Reference
Two-spined Blackfish	Wagar	Ngunnawal	Winnagay Ngunnawal language group
	Mandja	Ngarigo	Ngarigo and Ngunnawal wordlists
River Blackfish	Wuggar	Ngunnawal	Ngarigo and Ngunnawal wordlists
	Wurrunak	Wemba Wemba/ Wamba Wamba	WCC Wurrekangurr Dictionary
Spangled Perch	Mulgu	Bidjara	M. Hobbs: Bidjara and Gungabula grammar and vocabulary
	Bobby Cod	Gamilaroi	Living on the lower Namoi
Freshwater Catfish	Gaygay	Gamilaroi	P. Duncan
	Puldupinyeri	Ngarrindjeri	Ngarrindjeri Dictionary
	Dhandhaang, dangur, Dandang	Wiradjuri	S. Grant snr & J. Rudder: A New Wiradjuri Dictionary
	Wanyakyi, Pirre-wil	Wemba Wemba/ Wamba Wamba	Wemba Wemba / Wamba Wamba Language Resource website
	Gaguda	Bidjara	M. Hobbs: Bidjara and Gungabula grammar and vocabulary

Common Name	Aboriginal Name	Nation	Reference
Purple-spotted gudgeon	Budan	Ngunnawal	Ngarigo and Ngunnawal word lists
Congollii	Kugguldehi	Ngarrindjeri	Ngarrindjeri Dictionary
Blue-spot Goby	Takaraki	Ngarrindjeri	Ngarrindjeri Dictionary
Common Galaxias	Terukurar	Ngarrindjeri	Ngarrindjeri Dictionary
Mulloway	Malawi	Ngarrindjeri	Ngarrindjeri Dictionary
Freshwater Mussel/River Mussel	Dhandyurigan, dhandjuri	Wiradjuri	S. Grant snr & J. Rudder: A New Wiradjuri Dictionary
	Dhunggal (large), gimbai (small)	Gamilaroi	Gamilaroi Fire and Seasons Calender
	Nangerr	Wemba Wemba/ Wamba Wamba	Wemba Wemba / Wamba Wamba Language Resource website
	Dhuliny	Bidjara	M. Hobbs: Bidjara and Gungabula grammar and vocabulary
	Bindugan	Ngunnawal	Ngarigo and Ngunnawal wordlists
	Didlinga, ratju	Yorta Yorta	WCC Yorta Yorta
Crayfish (possibly Murray cray)	Lip-Lip-Wil	Wemba Wemba/ Wamba Wamba	Wemba Wemba / Wamba Wamba Language Resource website

Common Name	Aboriginal Name	Nation	Reference
	Borpa	Yorta Yorta	WCC Yorta Yorta Dictionary
Spiny Crayfish	Dhagamang		WCC Wiradjuri Dictionary
	Marrumin	Wiradjuri	WCC Wiradjuri Dictionary
Prawns/Shrimp	Marramin	Wiradjuri	WCC Wiradjuri Dictionary
	Gando	Yorta Yorta	WCC Yorta Yorta Dictionary
Yabby	Yingaa	Wiradjuri	S. Grant snr & J. Rudder: A New Wiradjuri Dictionary
	Crawbob, Giirray	Kamilaroi	Living on the lower Namoi
	Bugili	Bidjara	M. Hobbs: Bidjara and Gungabula grammar and vocabulary
	Ngathang	Wemba Wemba/ Wamba Wamba	Wemba Wemba / Wamba Wamba Language Resource website