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NSW Long Term Water Plans: Background Information

A description of the development of the 9 LTWPs in NSW

Part C: Environmental water requirements

Department of Planning and Environment

Cover photo: Surveying waterbird colonies in the Macquarie Marshes. John Spencer/DPE

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Overview of the background information document

NSW Long Term Water Plans (LTWPs) bring together information from a range of planning material, scientific literature and expert opinion. This varied and complex information has been interpreted and analysed to produce new information products and tools to support development of the plans. The purpose of this background information document is to:

- describe the information sources that informed the development of the LTWPs
- describe how this information was interpreted and analysed
- outline the rationale behind the analyses, methods, assumptions and decisions that have underpinned the LTWPs
- provide a reference for future revision of the LTWPs.

The background information document has been divided into 4 parts for ease of use:

Part A: Introduction

1. Background to the development of NSW Long Term Water Plans
2. Priority environmental assets

Part B: Objectives and targets

3. Introduction to Part B
4. Native fish objectives and targets
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9. Introduction to Part C

In order to achieve the objectives and targets set out in Part B, flow requirements to support those objectives need to be defined. Chapter 10 describes how the environmental water requirements to support those objectives and targets were developed.

10. Developing environmental water requirements

10.1. Background

Flow regimes determine the ecological characteristics of riverine ecosystems (Poff and Zimmermann 2010). The flow regime is the long-term sequence and pattern of flow events in the river over time. Individual flow events shape and maintain river channels, provide cues for key ecological processes such as breeding or migration, support dispersal of plants and animals and connect the river to its floodplain (Lytle and Poff 2004; Poff et al. 1997). Over the long term, it is the flow regime that dictates population stability and ecosystem resilience.

The inherent variability of flow regimes can be simplified by partitioning them into flow categories, such as baseflows, freshes, and overbank flows (Figure C.2). Flow categories characterise different types of flow events. Each flow category can support a range of ecological outcomes. For example, small freshes might inundate river benches that provide access to food for native fish and support in-channel vegetation. Similarly, overbank flows may support carbon and nutrient exchange between the river and its floodplain (increasing productivity) and improve river red gum condition.

Meeting the lifetime needs of an aquatic organism (plant or animal) might require a combination of several different flow categories over time. For example, a native fish species may require a ‘small fresh’ as a 10-day pulse in late winter to cue spawning, followed by a relatively stable flow for 2–4 weeks in early spring to support nesting. Frequent freshes and overbank events may be required to provide food resources, and once the fish reaches maturity (1–3 years) it may require a fast-flowing river in combination with ‘overbank’ flows to trigger dispersal and migration.

An environmental water requirement (EWR) for the purpose of NSW Long Term Water Plans (LTWPs), describes a set of recommended flow characteristics (flow threshold or volume, duration, timing, frequency, maximum inter-event period) for each flow category to meet a particular set of environmental objectives. For each flow category (e.g. baseflows or small freshes), there may be multiple different EWRs (small fresh 1, 2, etc.), each aimed at meeting specific objectives, and differing in duration, timing frequency, etc. The description of the flow regime[1] that water-dependent populations and communities require to ensure survival and persistence over the long term is found in Table 10 of Part A of the LTWPs. The complete set of EWRs for the catchment at individual river gauges are found in Part B of the LTWPs (in the relevant planning unit section).

[1] These are not EWRs and do not include flow rates or volumes. Tables in Part A of the LTWP should not be used to assess EWRs from hydrological model outputs.

While the EWRs attempt to define the critical elements of water flows in rivers and floodplain wetlands, they are a coarse representation of the water requirements of water-dependent species and functions, and resilient river and wetland ecosystems. EWRs capture the minimum water needed to support the environment and we would expect further enhancement of values with more water. However, more research is needed to better quantify the relationship between environmental outcomes and each of the metrics described in the EWRs. The NSW Department of Planning and Environment (the department) is currently collecting flow and environmental data that will be used to further refine EWRs as our knowledge and water management strategies improve over time.

Determining EWRs involved the assimilation of large amounts of contemporary information, including from:

- peer-reviewed scientific studies, grey literature and expert knowledge on the flow requirements of fauna and flora species
- data and mapping describing species distributions
- monitoring and evaluation data describing population condition and the outcomes of past flow events
- river operators and environmental water managers' knowledge and experience
- river channel cross-sections
- inundation and habitat mapping and modelling
- satellite imagery showing the spatial extent of inundation during specific events
- observed flow time series and outputs from river system models.

In assimilating this information to determine EWRs, the following 4 broad tasks were undertaken:

1. Determine Basin or regional-scale 'generic' EWRs for thematic groups to support ecological functions and water-dependent species and their lifecycle stages (Section 10.3).
2. Determine the broad flow regime for each catchment (integrating all water-dependent thematic groups: fish, waterbirds, vegetation, other species (namely frogs) and ecosystem functions) (Section 10.4).
3. Determine specific EWRs for each planning unit (Section 10.5).
4. Determine specific flow rates at a gauge for EWRs (Section 10.6).
5. Refine the specific flow rates through analysis of modelled and observed hydrological time series of flows (Section 10.7)

In addition to setting specific EWRs, recommendations were developed for catchments' unregulated water sharing plans (WSPs) to support ecologically important flow categories.

The methods described in this chapter for developing EWRs in the LTWPs were generally applied to all catchments in the NSW Murray–Darling Basin (MDB). A schedule for each catchment was developed to provide a detailed description of how the general method was applied to a specific catchment to inform decisions based on the unique information available.

10.2. General principles applied

The determination of EWRs has adopted the following principles:

a. EWRs identify the specific flows required to achieve environmental objectives

The EWRs focus on those components of the flow regime that are considered important for achieving the environmental objectives. Accordingly, the EWRs do not seek to restore flows to natural or pre-development conditions, rather they describe a targeted set of flow events and conditions required to achieve the environmental objectives established for the identified environmental assets.

b. EWRs reflect environmental needs

EWRs are not limited to current environmental water delivery constraints, rather they specify the flows required to achieve the environmental objectives. This will enable transparent identification of where delivery constraints are impacting on achieving environmental objectives and will inform future program delivery (e.g. the Constraints Management Strategy), monitoring and evaluation, and policy development. Constraints to delivery are noted and EWRs that cannot be achieved under current arrangements are clearly identified in most instances.

c. Multiple lines of evidence

Our knowledge of freshwater ecosystems and their flow or watering needs is imperfect. Consequently, the determination of EWRs has drawn upon best available information. This includes peer-reviewed scientific publications, management reports, topographic data, satellite imagery, monitoring data, river management experience and flow data (both observed/gauged and model outputs). Wherever possible, multiple sources of information have been used to improve confidence in the EWRs.

d. All water and all flows are important

A variety of water types will contribute to achieving the EWRs, including unregulated ('natural') flows, consumptive water in-transit, conveyance water, planned environmental water and held environmental water. Environmental water will make a significant contribution to achieving the EWRs; however, meeting many EWR targets will only be achieved through the contribution and coordination of multiple water types. EWRs therefore include the full range of flows and water types.

e. Achieving ecological objectives may require more than water

While the provision of the EWRs is considered essential in achieving the objectives and sustaining the assets, it is recognised that other actions such as land management, water quality management and pest plant or animal control may also be required to achieve the objectives and sustain the assets. Such complementary actions are typically noted in association with the EWR where specific knowledge is available.

f. Knowledge will improve over time

It is important to recognise that our understanding of freshwater ecosystems continues to develop including in response to monitoring, scientific research, observed outcomes from flow events and improved understanding of traditional and local knowledge. The EWRs specified in the LTWPs represent the state of our knowledge at the time the plans were written. As the plans are implemented and reviewed, and new knowledge becomes available and is shared, it will be considered when planning environmental watering events and in revising future LTWPs.

10.2.1. Basin Plan requirements

Chapter 8, Part 5 of the Basin Plan provides some requirements for determining EWRs. As specified in the Basin Plan 8.49 1I it is a requirement to 'determine the environmental watering requirements needed to meet the targets in order to achieve the objectives'.

This is to be done in accordance with Section 8.51 of the Basin Plan:

Section 8.51 Determination of environmental watering requirements of environmental assets and ecosystem functions

The environmental watering requirements referred to in paragraphs 8.49(1)(e) and 8.50(1)(e) must:

a. be supported by relevant information relating to the underlying physical geomorphic processes driving the flow-ecological relationship; and

b. include the following flow components that are relevant to the watering requirements:

   i. cease-to-flow events;

   ii. low-flow-season base flows;

   iii. high-flow-season base flows;

   iv. low-flow-season freshes;

   v. high-flow-season freshes;

   vi. bank-full flows;

   vii. over-bank flows; and

c. be determined having regard to:

   i. groundwater-derived base flows; and

   viii. groundwater recharge associated with groundwater resources that are highly connected to surface water resources; and

d. be within the range of natural flow variability and seasonality.

The environmental watering requirements must be expressed, where relevant, in the following terms:

a. a flow threshold or total flow volume;

b. the required duration for that flow threshold, or the duration over which the volume should be delivered (as the case requires);

c. the required timing of the flow event;

d. the required frequency of the flow event;

e. the maximum period between flow events;

f. the extent and thresholds for any groundwater dependency;

g. the required inundation depth at the site.

As identified in the Basin Plan requirements, EWRs are described by at least the following 5 variables: (1) flow magnitude or volume, (2) duration of flow event, (3) frequency of flow event, (4) timing of flow event, and (5) the maximum duration between flow events (Figure C.1). Other variables included where relevant or known include the rate of rise and fall, flow velocity and water temperature.

Specifically, EWRs are expressed using either a flow magnitude (typically megalitres per day) or total flow volume (typically megalitres), measured at a specific river gauge. In many cases, specific environmental objectives may be achieved for any flow that exceeds the specified threshold, so long as the other requirements such as duration are met. An example of this may be the watering of a vegetation community, where any flow that inundates the community may be beneficial. However, in other cases the achievement of specific environmental objectives may be compromised if flows are too high (e.g. a flow pulse may be required to trigger spawning of some fish species but flow rates that are too high may wash away fish eggs and larvae). In these cases, EWRs are expressed as a minimum and maximum flow magnitude.

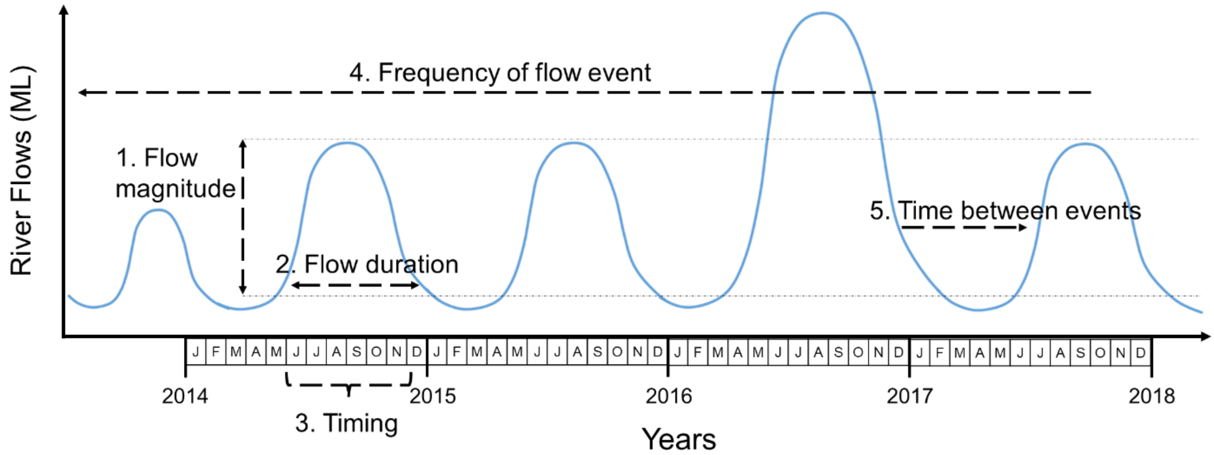

Figure C.1 **Visual representation of the 5 flow regime components used to describe EWRs**
1. Flow event magnitude (flow threshold (ML/day or total flow volume (ML)); 2. Flow event duration (days); 3. Timing of flow event (month); 4. Frequency of flow event (number of years in 10 and long-term average frequency); 5. Time (maximum) between flow events (days or years).

10.2.2. Flow categories

The term 'flow categories' describes the different parts of a hydrograph that are considered relevant in achieving environmental objectives and described as a flow magnitude (listed in the Basin Plan Section 8.51(1)(b) and illustrated in Figure C.2). Table C.1 defines the flow categories for the purposes of developing the LTWPs. Specific variations of these broad flow categories exist (e.g. nesting flows, anabranch connecting flows, etc.) and will be described in the catchment specific Schedules where relevant.

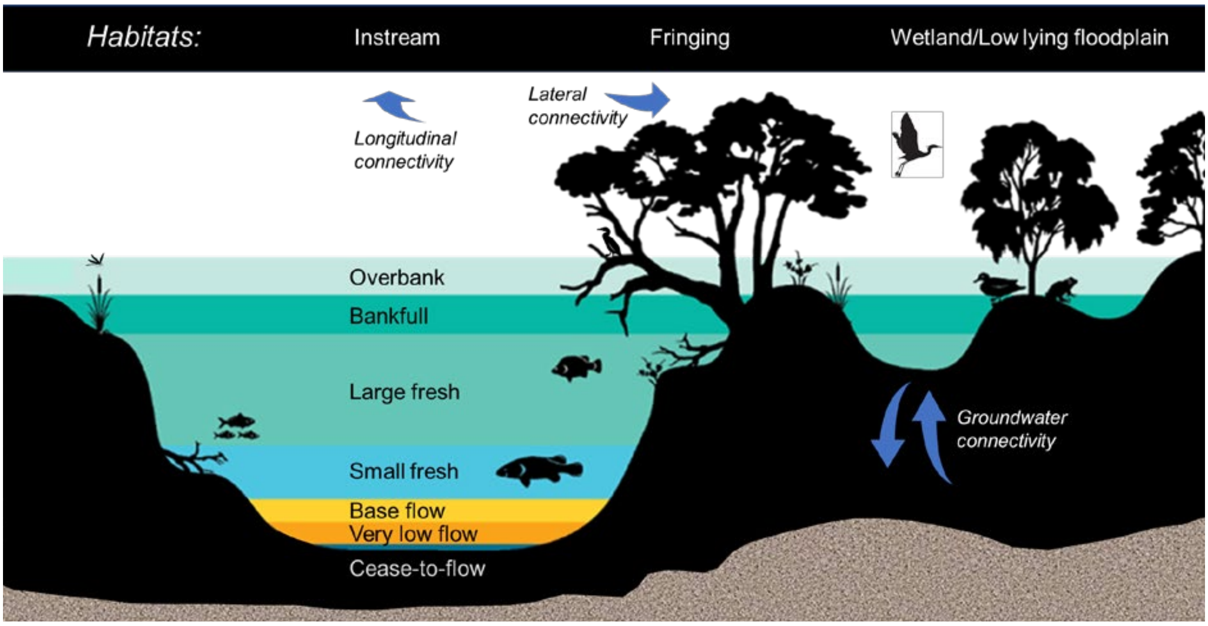

Figure C.2 Flow categories shown as river level stages on the cross-section of a river channel

The combined, long-term behaviour (frequency, duration, rates of rise and fall, persistence, or time between events) of the different components of a river's hydrograph determine the flow regime and each flow category serves important ecological functions.

Table C.1 Definitions of flow categories and ecological response for river and stream channels (adapted from Alluvium 2010 and Eco Logical Australia 2012)

Flow category	Flow characteristic	Ecological outcome
Cease-to-flow (CF)	Partial or total drying of the channel No surface flow Stream contracts to a series of isolated pools	Dries habitats and substrate Facilitates organic matter and carbon processing Disturbs lower channel features by exposure and drying Promotes successional change in community composition through ecological disturbance Maintains a diversity of ecological processes through wetting and drying This state places fish populations at risk, particularly if there are extended durations of disconnection (drying of pools), warm weather (reducing dissolved oxygen (DO), particularly if there are high nutrient inputs in the river reach, resulting in high biochemical oxygen demand) or active pumping of pools by people occurs Provides good food availability for higher trophic biota initially; however, food supply and water quality would be expected to decrease in isolated pools as water levels contract, with extended no flow periods associated with poor body condition in fish, especially lower trophic species CF can also be useful in controlling carp populations and would generally occur annually in highly intermittent systems
Very low flow (trickle flow or connection flow)	Small flow in the very low flow class that joins river pools thus providing partial or complete connectivity in a reach	Improves DO saturation in pools May help prevent thermal stratification in some pools. In many locations, higher flows are required to prevent and/or break stratification Protects pools from drying out during extended dry periods Prevents contraction of the river to discreet pools (i.e. minimises the duration of CF events)
Baseflow	Provides minimum continuous flow throughout the channel Confined to the low flow part of the channel. Typically inundates geomorphic units such as pools and riffle areas between pools	Allows accumulation and drying of organic matter in the higher areas of the channel such as benches Protects pools from drying out during extended dry periods. Maintains permanent pools with an adequate depth of water to provide habitat and support aquatic biota in the short term (i.e. drought refuges) Improves DO saturation in pools May help prevent thermal stratification in some pools. In many locations, higher flows are required to prevent and/or break stratification

Flow category	Flow characteristic	Ecological outcome
		Supports limited longitudinal connectivity at the reach scale for movement of aquatic biota. Unlikely to drown out any significant weirs, and flows between deeper pools may be very shallow Increases wetted habitat area in comparison to CF and very low flow May support recruitment for fish that spawn during low flow periods (e.g. generalist and river specialist fish species) Supports winter conditioning for fish through maintenance of ecosystem processes Supports condition of non-woody vegetation in the lower parts of river channels
Small fresh	Low magnitude flow pulse The duration of small freshes is typically short (one to several days) but may last up to 1–2 weeks in larger rivers and/or downstream river reaches. Event duration is also dependent on the ecological process linked to that fresh so there is no consistent duration that can be applied across all seasons and rivers Unlikely to drown out any significant weirs, so overall connectivity is still limited Rates of rise and fall should follow natural limitations to avoid stranding of fauna and excessive erosion of riverbanks	May be a trigger for movement by some aquatic fauna May provide fish breeding cues, predominantly for river specialists and generalist native fish species Supports condition of non-woody vegetation in the lower parts of river channels Improves DO saturation in pools May help prevent thermal stratification in some pools. In many locations, higher flows are required to prevent and/or break stratification May help to export salt and flush unnaturally high nutrient loads Supports temporary longitudinal connectivity between pools Enhances productivity and nutrient exchange through mobilising carbon and nutrients from snags, riverbanks and low-level benches Promotes hydraulic complexity within a reach, including fast and slow-moving habitats May support sediment transport by scouring fine sediment from riverbeds and pools Replenishes local groundwater, supporting condition of riparian vegetation in areas of high surface water – groundwater connectivity Provides small variations in flow throughout the year, which is part of a system's natural variability and helps to maintain productivity during periods of low flows or drought
Large fresh	High magnitude flow pulse (remaining in-channel) Event duration is typically longer than a small fresh (i.e. may last for a few weeks), but this is dependent on the ecological objective	Provides triggers for the movement of some aquatic biota (including the dispersal of adult, juveniles, larvae and eggs of some native fish species and the dispersal of propagules along banks) Supports longitudinal connectivity within aquatic systems, including drowning out some small in-channel barriers

Flow category	Flow characteristic	Ecological outcome
	May engage flood runners with the main channel and inundate low-lying wetlands and anabranches (depending on flow magnitude) Connects most in-channel habitats (inundation of snags, low and mid-level benches and banks) Partial longitudinal connectivity (some low-level weirs and other in-channel barriers may be drowned out) Rates of rise and fall should follow natural limitations to avoid stranding of fauna and excessive erosion of riverbanks	May provide fish breeding cues, predominantly for flow-dependent fish species (e.g. golden perch and silver perch) Enhances productivity and nutrient exchange through mobilising carbon and nutrients from snags, riverbanks, benches and low-lying wetlands (when connected) Maintains in-channel and fringing vegetation by wetting mid and higher channel banks and benches Removes terrestrial vegetation that has encroached down the bank during the low flow period, thinning out stands and improving the channel's capacity to convey flows (requires sufficient duration of inundation of vegetation; approximately 14 days) Increases habitat area, including access to large woody debris and other submerged structures for instream biota Improves DO saturation in pools Prevents thermal stratification in pools May help to export salt and flush unnaturally high nutrient loads Scours biofilms on submerged surfaces, enhancing biofilm structure and function Promotes hydraulic complexity within a reach, including fast and slow-moving habitats Supports sediment transport by scouring fine sediment from riverbeds and pools, turning over gravel and delivering sediment to benches and banks Supports longitudinal connectivity within aquatic systems, including drowning out some small in-channel barriers Replenishes local groundwater, supporting condition of riparian vegetation
Bankfull	Larger flow events that fill the channel with little spill onto the floodplain Inundates all in-channel habitats including all benches, snags and banks Engages the riparian zone, anabranches, flood runners, wetlands located within the meander train and in some cases, low parts of the floodplain	Provides important fish breeding cues Provides triggers for the movement of some aquatic biota (including the dispersal of adult, juveniles, larvae and eggs of some native fish species and the dispersal of propagules along banks) Supports longitudinal connectivity within aquatic systems, including drowning out most in-channel barriers Supports successional patterns for aquatic and riparian vegetation, and promotes and supports floodplain riparian woodland recruitment

Flow category	Flow characteristic	Ecological outcome
	Partial or full longitudinal connectivity; drowns out most small in-channel barriers (e.g. small weirs)	Removes terrestrial vegetation that has encroached down the bank during the low flow period, thinning out stands and improving the channel's capacity to convey flows (requires sufficient duration of inundation of vegetation; approximately 14 days) Enhances productivity and nutrient exchange through mobilising carbon and nutrients from snags, riverbanks, benches and some low-lying floodplain wetlands Scours biofilms on submerged surfaces, enhancing biofilm structure and function Supports sediment transport by scouring fine sediment from riverbeds and pools, turning over gravel and delivering sediment to benches and banks Increases habitat area, including access to large woody habitat, overhanging banks and low-lying parts of the floodplain for instream biota Replenishes local groundwater, supporting the condition of riparian and groundwater-dependent vegetation communities
Overbank and wetland inundating flows	Flows that spill out of the channel Inundate adjacent floodplain habitats Flow extends to floodplain surface flows	Supports lateral connectivity and inundates additional ephemeral habitats (e.g. low-lying flood runners, anabranches, wetlands, billabongs and floodplains) Replenishes soil moisture in riparian and floodplain zones Supports breeding and recruitment of floodplain wetland biota (including floodplain vegetation communities, waterbirds, native fish, frogs, turtles, etc.) Inundates the entire floodplain to improve wetland wetting and drying cycles Enhances productivity and nutrient exchange through mobilising carbon and nutrients from snags, riverbanks, benches and floodplain wetlands Replenishes local groundwater, supporting the condition of riparian and groundwater-dependent vegetation communities Increases habitat area, including access to anabranches, billabongs, floodplain wetlands, and reconnecting isolated wetlands with the main river channel for water-dependent biota

10.3. Determining Basin or regional-scale environmental water requirements to support water-dependent biota

The flow requirements of specific species are often consistent over broad spatial scales (e.g. the flow requirements of golden perch are reasonably consistent across the MDB). There is also often alignment in the flow requirements for different species. This allows the flow requirements to be grouped according to functional groups or ecological communities and represented as 'generic' EWRs that apply at a broad spatial scale.

Establishing generic EWRs involved:

1. placing species within each thematic group (i.e. fish, vegetation, waterbirds and frogs) into functional groupings that have similar flow requirements (e.g. floodplain specialist fish species that require overbank flows)
2. identifying the flow-dependent processes or lifecycle stages (e.g. fish spawning or dispersal) for each functional group or community
3. identifying the flow events required for each flow-dependent process or lifecycle stage. These describe the flow events required for the relevant lifecycle stage (e.g. freshes or overbank flows), and the required characteristics of those flow events (timing, duration, frequency)
4. identifying the important elements of the flow regime required to support priority ecosystem functions (PEFs), depending on where they are located in each catchment.

The generic EWRs for each thematic group (native fish, native vegetation, waterbirds, frogs and platypus) are provided in Part D of this document at Appendix 10.2, 10.3, 10.4, 10.5 and 10.6, respectively.

10.3.1. Flow requirements for native fish

Native fish have evolved in a highly variable system that is characterised by extreme environmental conditions (Baumgartner et al. 2014; Humphries et al. 1999). Hydrological variability (e.g. diverse wetting and drying cycles, fluctuating temperatures) plays an integral role in influencing the structure and diversity of aquatic communities (Baumgartner et al. 2014; Rolls et al. 2013).

Flows, habitat and hydrological connectivity are essential for healthy native fish populations, with flows playing a range of important roles (Figure C.3), including:

- creating the hydrodynamic diversity needed for fish habitat (particularly for species that rely on flowing habitats, such as Murray cod, golden perch, silver perch, trout cod and Macquarie perch)
- maintaining health of instream and emergent vegetation and other habitat features needed by many fish species
- influencing quality, size and persistence of refuge habitats in dry periods
- inundating in-channel benches and floodplains to support carbon and other nutrient cycling, which is important for system productivity and fish maintenance, recruitment and condition
- enabling access to a range of aquatic habitats
- providing cues that stimulate movement, such as for spawning or larval dispersal (movement may be longitudinal migration along the river, or lateral movement into off-channel habitats such as wetlands, billabongs and anabranches).

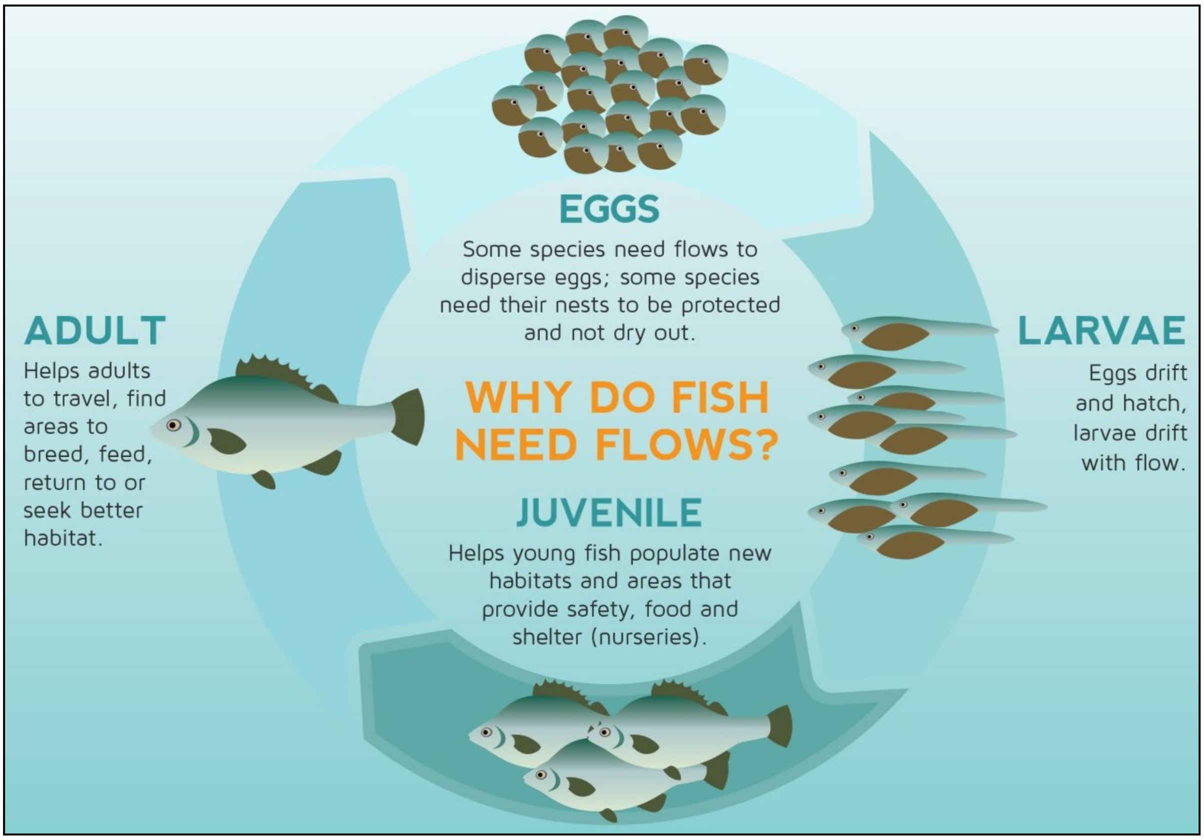

Figure C.3 The influence of flows on different lifecycle stages of native fish (adapted from MDBA 2014)

While flow management has often focused on hydrology (water volume or threshold, duration, seasonality and timing), the hydrodynamics of flow is equally important (Mallen-Cooper and Zampatti 2015). This includes parameters such as flow depth, width, velocity, direction and turbulence. River regulation is particularly detrimental to flow hydrodynamics, often producing still or slow-flowing aquatic environments (Schmutz and Moog 2018). In addition to this, water quality is as important as water quantity, including appropriate water temperature, levels of oxygen, pH, salinity, chemical cues and food content, and is equally influenced by river regulation (MDBA 2014, p.41; Mallen-Cooper and Zampatti 2015). It is possible to establish relationships between hydrology and hydraulics based on gauged stream flow data and stream cross-sectional data (e.g. what type of flow results in velocities >0.3 m/s and weir drown out flow rates for stretches of rivers) (Mitrovic et al. 2010).

Fish use flows at a variety of scales, from the 'micro-level' (<100 m) to medium-scale (100s of metres to 10s of kilometres) and macro-scale (from 10s of kilometres to 100s of kilometres, e.g. across the whole MDB) (Mallen-Cooper and Zampatti 2015). Effective flow management for native fish therefore requires consideration of flow aspects at different spatial scales, as well as the consideration of flow variability, with different parts of the hydrograph playing important roles for fish lifecycles (Appendix 10.1, Table C.2 and Appendix 10.2).

The range of spawning and recruitment behaviours exhibited by native fish species of the MDB means it is highly unlikely a single flow regime will provide optimal benefits for the entire fish community in a system (Baumgartner et al. 2014; DPI 2013). To optimise native fish outcomes from water management decisions, it may be more effective to form hydro-ecological functional groups of fishes based on certain flow-related attributes (Baumgartner et al. 2014; Baumgartner 2011; DPI 2013; Humphries et al. 1999; Lloyd et al. 1991; Mallen-Cooper and Zampatti 2015). The approach of classifying fish species into functional groups is a valid way of simplifying flow requirements for fish and maximising environmental benefits from water use (DPI 2013; Growns 2004; Humphries et al. 1999; Mallen-Cooper and Zampatti 2015).

Native fish functional groups were developed using the latest scientific knowledge and expert opinion (DPI 2015; Ellis et al. 2016). Criteria for classification were:

- cues for migration, dispersal and spawning (temperature and/or flow)
- scale of spawning migration (10s to 100s of metres; 100s of metres to 10s of kilometres; 10s to 100s of kilometres)
- whether it is a nesting species or not
- whether it spawns in still/slow-flowing water or in fast-flowing habitats
- egg incubation time (short 1–3 days; medium 3–10 days; long >10 days) and egg morphology
- temporal and spatial scales of larval drift and recruitment.

Based on these physiological and behavioural traits for freshwater fishes in the MDB, 5 functional groups of native fish were developed and linked to flow characteristics (Figure C.4). It is important to note that, while these functional groups have differing flow requirements, it is still possible to design a flow regime that meets the needs of multiple fish groups.

These functional groups of freshwater fish can be used to assist with environmental water planning to develop specific EWRs that benefit native fish. There are a number of basic principles[2] to be considered when developing EWRs for native fish:

1. **The natural flow regime is one of the most important principles underpinning the development of conceptual flow models for native fish in the MDB.**
    - The natural flow regime provides a strong foundation for the rehabilitation of flows; however, impacts of river regulation that have affected connectivity, access to habitat and altered fluvial geomorphology also need to be considered in specific planning objectives (Mallen-Cooper and Zampatti 2015).
2. **Water quality, and not just water quantity, needs to be considered when developing and delivering water requirements for native fish.**
    - Water temperature drives life history responses for most native species, whilst water clarity, DO and productivity (related to chemical, nutrient and plankton composition) also play an important role in maximising benefits to species (Górski et al. 2013; Jenkins and Boulton 2003; Mallen-Cooper and Zampatti 2015; Zampatti and Leigh 2013).
    - The influence of water quality parameters, such as temperature, on guiding flows for fish outcomes means that management actions will primarily occur in the warmer spring and summer months. Nevertheless, the importance of replenishing critical refugia and supporting base flows throughout the year, and late-winter high flow events, will need to be considered given their importance for water quality maintenance and riverine productivity (Robertson et al. 2001).

[2] These basic principles were applied where possible and where information existed to support them. Specific application and information used for each catchment can be found in the relevant Schedules.

3. **The importance and interdependency of the fundamental riverine elements of flow, habitat and connectivity for the dynamics and response of native fish populations, need to be considered when making flow management decisions and actions (Mallen-Cooper and Zampatti 2015).**
   - These 3 key factors determine the need for still water or flowing environments, the spatial scale at which connectivity and hydraulic complexity needs to be maintained, and the variation in flow needed to allow access to habitat and completion of lifecycles (Mallen-Cooper and Zampatti 2015).
4. **Appropriate flow height and flow velocity relationships in waterways of the MDB should be determined based on the connectivity and hydraulic requirements of native fish.**
   - These relationships may be guided by overarching principles related to:
     - maintaining water quality by preventing stratification of refuge pools (Mitrovic et al. 2003)
     - providing minimum depths for movement of species (Fairfull and Witheridge 2003; Gippel 2013; O'Connor et al. 2015)
     - changes in height or velocity to trigger native fish responses, noting the need to adapt flow height and velocity relationships to specific systems, species and spatial and temporal scales (Bice, Zampatti and Mallen-Cooper 2017; Mallen-Cooper and Zampatti 2015; Marshall et al. 2016).

Group 1: Flow pulse specialist
- Flow pulses during warm temperatures generally required for spawning
- Growth and recruitment success potentially enhanced by flows
- Lots of eggs, broadcast spawning
- Eggs and larvae drift in flow
- Move long distances in response to flow
- Medium–large bodied, long lived
- Golden perch, Silver perch

Group 2a: Riverine specialist (lotic)
- Prefer faster flowing riverine habitats
- Spawn annually in response to temperature, independent of flow
- Growth and recruitment success potentially enhanced by flows
- Moderate numbers of eggs, nesting species
- Move moderate distances for spawning
- Large bodied, long lived
- Murray cod, Trout cod, Macquarie perch

Group 2b: Riverine specialist (lentic)
- Prefer slower flowing river habitats: anabranches and lakes
- Spawn annually in response to temperature, independent of flow
- Growth and recruitment success potentially enhanced by flows
- Medium numbers of eggs, nesting species
- Move shorter distances for spawning
- Range of body sizes and life spans
- Freshwater catfish, Purple-spotted gudgeon

Group 3: Floodplain specialist
- Slow flowing well vegetated streams and wetlands, may have unique water quality needs
- Overbank flows may inundate required habitats and provide access or dispersal
- Spawn annually, may repeat spawn, in response to temperature, independent of flow
- Low numbers of eggs, may have spawning substrate preferences
- Small bodied, short lived
- Southern pygmy perch, Murray hardyhead, Olive perchlet, Flat-headed galaxias
- Gambusia – non native

Group 4: Generalists
- Able to occupy a range of streams and waterbody types
- Flexible spawning and recruitment strategies
- Spawn annually, may repeat, in response to temperature, independent of flow
- Low numbers of eggs
- Move short distances
- Small–medium bodied, short–medium lived
- Australian smelt, Carp gudgeon, Flat-headed gudgeon, Bony herring, Murray River rainbowfish, Unspecked hardyhead, Mountain galaxias, Spotted galaxias, Climbing galaxias

Figure C.4 Details of fish functional groups developed to assist with water management activities (adapted from DPI 2015 and Ellis et al. 2016)

These principles, as well as consideration of responses of native fish to flow categories, reproductive biology, recruitment ecology, habitat requirements, spatial scales and geographic distributions were used to develop EWRs for fish. It is important to note that these EWRs represent ideal flow conditions needed to maximise the opportunities for native fish populations in a highly modified ecosystem. In most cases the EWRs should occur regularly in the historical flow record; however, native fish populations have been significantly affected by a range of impacts across the MDB. To improve these populations, it may be necessary to implement aspects of flow regimes that do not necessarily reflect 'natural conditions' but seek to balance the impact of river regulation in a working MDB.

The general ideal native fish EWRs found in Appendix 10.2 were adapted to Basin Plan implementation activities, including LTWPs, to help define what can be achieved for the protection and improvement of native fish populations with improved hydrological regimes. The EWRs may be used for examination of historical conditions (both modelled and observed) to inform the likelihood of the requirements being met; however, this analysis should not change the minimum requirements identified, which should be adapted as needed as part of planning and implementation activities. It is anticipated that the implementation of these EWRs will contribute to the achievement of overarching Basin Plan outcomes and catchment specific objectives and targets for native fish. Table C.2 describes the flow regime required to support native fish objectives in the LTWP.

Table C.2 Important flow regime characteristics required to deliver LTWP native fish objectives

Ecological objective	Important flow regime characteristics
NF1: No loss of native fish species	CF periods that are not longer than the persistence of water of sufficient volume and quality in key larger river pool refuges is vital for survival of native fish populations. Alternative watering actions (e.g. pumping) may be required to support floodplain habitats under very dry, dry and moderate scenarios to ensure no loss of species (e.g. to prevent wetlands with threatened fish species from drying out).
	Very low flows and baseflows are required for the survival and maintenance of native fish condition as these flows maintain adequate water quality (DO, salinity and temperature) in refuge pools and sufficient flow depth along the whole channel to allow fish movement (Gippel 2013; O'Conner et al. 2015).
	A baseflow preferably between September and March with an annual or biannual frequency is required to enhance recruitment outcomes.
	Small freshes supports movement and dispersal opportunities for large-bodied fish (Fairfull and Witheridge 2003; Gippel 2013; O'Conner et al. 2015).
	A large fresh of at least 5 days duration and occurring ideally between July and September (but can occur at any time) is required to promote dispersal and pre-spawning condition for all native fish species in 5–10 years in 10. The large fresh should trigger some primary productivity that will provide food resources and hence improve fish condition prior to the spring/summer spawning season.
	Moderate overbank and wetland inundating flows, ideally from September to February, for at least 5 days and occurring in 2–3 years in 10 (with a maximum inter-event period of 5 years) are also required to support condition and movement/dispersal outcomes of all native fish groups. Larger flows that inundate off-stream habitat can also promote growth and recruitment through increased floodplain productivity and habitat availability. Larger flows that connect low-lying wetlands provide important habitat to support strong survivorship and growth of juveniles.

Ecological objective	Important flow regime characteristics
NF2: Increase the distribution and abundance of **short to moderate-lived generalist** native fish species	In addition to the flows listed above for all native fish species (see NF1 objective), other important aspects of the flow regime for generalists are listed below.
	Regular (ideally annual) spawning and recruitment events are required for the persistence of short-lived species. Although generalist species can spawn independent of flow events, spawning is enhanced by small freshes during the warmer months of October to April in southern catchments and September to April in northern catchments. Events should occur in 5–10 years in 10 with a minimum event duration of 14 days for egg development and hatching. Multiple freshes during the spawning season provide flexibility in species response and opportunities for multiple spawning events.
	Large freshes occurring 2–3 weeks after spawning will enhance recruitment of larvae and juveniles by aiding dispersal and access to habitat and suitable prey. Larger flows that inundate off-stream habitat can also promote growth and recruitment (i.e. increased floodplain productivity and habitat availability).
NF3: Increase the distribution and abundance of **short to moderate-lived floodplain specialist** native fish species	In addition to the flows listed above for all native fish species (see NF1 objective), other important aspects of the flow regime for floodplain specialists are listed below.
	Overbank and wetland inundating flows during the warmer months of October to April provide spawning habitat and floodplain productivity benefits to support fish growth. Overbank and wetland flows should inundate floodplain habitats for at least 10 days to allow for egg development and occur in at least 5 years in 10, with a maximum inter-event period of 4 years in the northern catchments, and 2 years in the southern catchments. This period will depend on the persistence of floodplain habitats and time between reconnection to mainstem waterways. The critically endangered flathead galaxias (found in the Murray catchment), require wetland-connecting flows in August to September for breeding. These flows are required in at least 7–8 years in 10 to support population viability. Flows should be of a long enough duration to support isolated populations. Water temperatures should be above 22°C.
	Recruitment is enhanced by subsequent flows events 2–4 weeks after spawning flows. Most floodplain specialist species require spawning and recruitment every 1–2 years for population survival.
NF4: Improve native fish population structure for **moderate to long-lived flow pulse specialist** native fish species	In addition to the flows listed above for all native fish species (see NF1 objective), other important aspects of the flow regime for flow pulse specialists are listed below. Spawning of flow pulse specialists is triggered by a rapid rise or fall in flow (relative to natural rates) between spring and summer when temperatures are >17°C. In lowland systems, spawning responses are enhanced by substantial flow depths to cover instream features and high flow velocities. A large fresh between October and April for a minimum of 5 days and a rapid rate of rise should meet these spawning requirements. This is needed in 3–5 years in 10 (or 6–8 years in 10 where recovery is required), with a maximum inter-event period of 4 years. Integrity of flow events needs to be maintained over long distances (10s to 100s of kilometres) to maximise the capacity for instream spawning, downstream dispersal by drifting eggs and larvae and movements by adults and juveniles.

Ecological objective	Important flow regime characteristics
NF5: Improve native fish population structure for **moderate to long-lived riverine specialist** native fish species	In addition to the flows listed above for all native fish species (see NF1 objective), other important aspects of the flow regime for riverine specialists are listed below.
	Spawning of riverine specialists usually occurs annually, independent of flow; however, spawning may be enhanced by a small fresh between October and April (from September for trout cod) to promote ecosystem productivity and inundate additional spawning habitat. Event duration should be a minimum of 14 days with an average frequency of 5–10 years in 10 and maximum inter-event period of 2 years. Water temperatures should be >20°C. River blackfish may spawn in lower water temperatures of >16°C and Murray cod in >18°C. Murray cod generally have a narrower spawning window, usually from September to December. For nesting species (e.g. Murray cod and freshwater catfish) preventing rapid drops in water levels (that exceed natural rates of fall) during, and for a minimum of 14 days after spawning is important for preventing fish nests from drying.
	Overall, riverine specialists prefer hydraulically complex flowing streams containing submerged structures (snags and benches) that provides cover and spawning habitat. Flow variability through the delivery of small and large freshes, bankfull and overbank flows enhances the availability of diverse habitat, enhances growth and condition of larvae and juveniles and provides connectivity for dispersal between habitats. Recruitment is also enhanced by a larger secondary flow pulse for dispersal and access to nursery habitat in low-lying wetland habitats.
NF6: A 25% increase in abundance of mature (harvestable sized) golden perch and Murray cod	The flow requirement of golden perch (flow pulse specialist) and Murray cod (riverine specialist) are outlined above under NF4 and NF5, respectively. An increase in mature (harvestable size) fish is strongly dependent on recruitment success and supporting improved population structure.
	Baseflows support the maintenance of populations.
	Recruitment for both species benefits from fresh events and larger flows that inundate ephemeral wetlands. Such large events provide dispersal opportunities and access to sheltered and productive nursery habitat.
NF7: Increase the prevalence and/or expand the population of key **short to moderate-lived floodplain specialist** native fish species into new areas (within historical range)	In addition to the flows listed above for floodplain specialist species (see NF3 objective), important aspects of the flow regime for increasing their prevalence and/or expanding their population are listed below.
	Expanding populations into new areas will be especially dependent on dispersal flows, particularly large freshes and overbank and wetland inundating flows. Complementary actions such as conservation stocking and/or translocation may be required to support these watering actions. Infrastructure-based watering actions (e.g. pumping) may also be required to support floodplain habitats under very dry, dry and moderate scenarios to ensure no loss of species for floodplain specialists (e.g. to prevent wetlands with threatened fish species from drying out).

Ecological objective	Important flow regime characteristics
NF8: Increase the prevalence and/or expand the population of key **moderate to long-lived riverine specialist** native fish species into new areas (within historical range)	In addition to the flows listed above for riverine specialist species (see NF5 objective), important aspects of the flow regime for increasing their prevalence and/or expanding their population are listed below. Expanding populations into new areas will be especially dependent on dispersal flows, particularly large freshes and overbank and wetland inundating flows. Complementary actions such as conservation stocking and/or translocation may be required to support these watering actions.
NF9: Increase the prevalence and/or expand the population of key **moderate to long-lived flow pulse specialist** native fish species into new areas (within historical range)	In addition to the flows listed above for flow pulse specialist species (see NF4 objective), important aspects of the flow regime for increasing their prevalence and/or expanding their population are listed below. Expanding populations into new areas will be especially dependent on dispersal flows, particularly large freshes and overbank and wetland inundating flows. Complementary actions such as conservation stocking and/or translocation may be required to support these watering actions.
NF10: Increase the prevalence and/or expand the population of key **moderate to long-lived diadromous** native fish species into new areas	Large freshes, bankfull or overbank flows are required in the River Murray in winter to early spring to cue upstream migration of lamprey from the sea to upstream spawning sites. Lamprey are likely to continue to migrate upstream throughout spring so multiple large freshes or higher flows are required during winter and spring to support them. Maintaining longitudinal connectivity of flows (from source to sea) is important for supporting long-distance migrations and preserving biochemical signatures from flow sources that may provide olfactory migratory cues. This includes protecting large flow pulses from tributaries such as the Goulburn and Murrumbidgee rivers during winter and spring. Diversions of flows (e.g. to Lake Victoria or major irrigation areas) may disrupt migration. Very low flows, baseflows and small and large freshes are required during other times of the year to support survival and recruitment and to allow mature fish to return to the sea.

10.3.2. Flow requirements for water-dependent vegetation

Riparian, wetland and floodplain vegetation communities are integral components of freshwater ecosystems (Naiman et al. 2010), mediating geomorphic processes and modifying landform dynamics (Brierley and Fryirs 2005), runoff and water quality (Tabacchi et al. 2000). Vegetation is important in nutrient cycling and transformation and contributes organic matter to riverine ecosystems (Wolfenden et al. 2004). Healthy vegetation communities provide valuable habitat, drought refuges and movement corridors for many plants and animals in the MDB (Catterall et al. 2006; Johnson et al. 2007; McGuinness et al. 2010; Tzaros et al. 2014; Woinarski et al. 2000).

The riverine, wetland and floodplain habitats of the MDB support a mosaic of different vegetation communities ranging from woody forests, woodlands and shrublands to herbaceous communities and understoreys of high plant species diversity (Roberts et al. 2016). The availability of water in the landscape (both shallow groundwater and surface water) and local inundation regimes, combined with climatic conditions, influences plant germination, survival and reproduction, and ultimately determines the position of species in the landscape (Casanova 2015). The water regime (the short and long-term pattern of wetting and drying) is a major determinant of the composition of riparian, wetland and floodplain vegetation communities (Figure C.5) (Reid and Capon 2011; Roberts and Marston 2011). Floods drive short-term floodplain vegetation production (Thapa et al. 2016) whilst the inundation regime is a key determinant of floodplain vegetation communities (Barrett et al. 2010). However, water resource development has grossly altered flow regimes in MDB rivers, reducing flow volumes, inundation extent, longitudinal and lateral connectivity, inundation frequency, and flow variability (Kingsford 2000; Maheshwari et al. 1995; Ren et al. 2011; Thoms and Sheldon 2000). In combination with agricultural development, this has reduced the extent of floodplain vegetation and has been detrimental to vegetation condition (Ballinger and Mac Nally 2006; Bowen and Simpson 2010a,b; Cunningham et al. 2007; Kingsford and Thomas 2004; Mac Nally et al. 2011). In many wetlands reduced inundation frequency and duration has been followed by a transition from wetland communities to terrestrial vegetation types (Bino et al. 2015; Bowen and Simpson 2010b; Thomas et al. 2010; Thomas et al. 2011). However, in other parts of the river system, river regulation and the construction of weirs has stabilised water levels and created permanent waterbodies, which has altered the aquatic and littoral plant communities (Blanch et al. 2000).

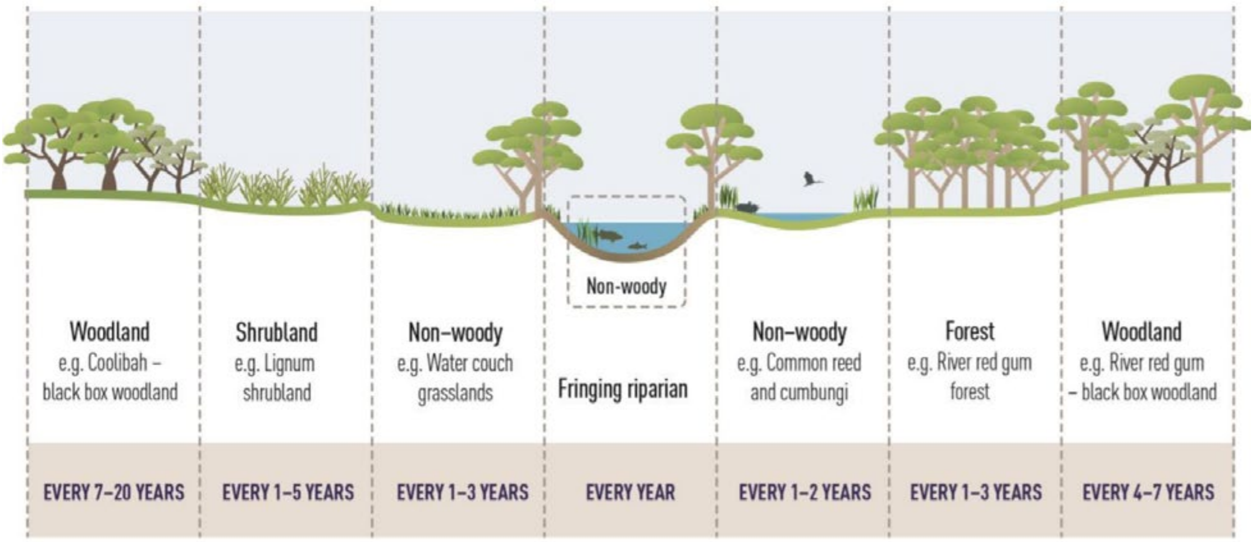

Figure C.5 Stylised example of hydro-ecological groups of native vegetation, their position on the floodplain and their watering frequency (from MDBA 2014)

To better manage for the water requirements of particular species or functional groups of wetland and floodplain plants, we need to understand the variability of the inundation regime in terms of frequency, duration and timing, as well as the water depth and tolerance to submersion, and how long species can tolerate dry periods (termed the inter-event or dry spell duration) for plants to remain healthy (Roberts and Marston 2011). The duration and inundation frequency required for growth and regeneration can vary widely within and between species. In response to variable water availability, wetland vegetation communities will naturally transition between wet and dry adapted species. During the recession of inundated areas, species diversity may increase as the conditions change to suit both amphibious and dry adapted species. Prolonged dry periods between inundation events can inhibit regrowth of non-woody vegetation when rewetted, an important consideration for water planning for wetland recovery.

Variability in the size and duration of flows (across the range of baseflows, freshes, bankfull and overbank flows) throughout the year will promote diverse plant communities. Regular inundation of wetlands will also encourage a dominance of native species over exotic species, as the latter tend to be intolerant of inundation (Catford et al. 2011), although there are exceptions (e.g. lippia) (Roberts and Marston 2011). Increasing the groundcover of flood-dependent non-woody vegetation will stabilise riverbanks, reduce erosion risk and help to improve water quality.

To determine the water requirements for native water-dependent flora in the NSW portion of the MDB, a comprehensive list of the vegetation communities within each catchment was compiled from all available spatial datasets. Each vegetation community was aligned with the plant community types (PCTs) listed under the department's Environment and Heritage Group (DPE–EHG) Vegetation Classification (OEH 2014, 2017).

PCTs were then allocated to water-dependent vegetation types defined in the BWS (MDBA 2019), based on the dominant species of the community and the water dependency of the community. The BWS groups were found to be too broad for informing water management, so hydro-ecological functional groups were developed by grouping PCTs based on the dominant plant species with similar life forms, habitats (riverine, wetland, floodplain) and inundation frequency requirements (Table C.3).

Table C.3 Native vegetation hydro-ecological functional groups developed for the LTWPs and their known range of inundation frequency required to maintain the vegetation state (expressed as an average recurrence interval (ARI))

See Appendix 10.3 for more details on watering requirements for maintenance, recruitment and recovery.

Hydro-ecological functional group	Example PCT numbers	Example dominant species	BWS group	Inundation frequency (ARI)
Non-woody (within and closely fringing channels)	23, 53, 166, 181, 182, 205, 238, 242, 336	common reed; cumbungi and submerged aquatic macrophytes (e.g. ribbonweed)	non-woody water-dependent vegetation	1 in 1–2 years
Non-woody (wetlands and floodplains)	204, 50, 160	common reed; cumbungi; water couch; moira grass; nardoo; milfoils	non-woody water-dependent vegetation	1 in 1–2 years to 1 in 2–7 years[3]

[3] Frequency depends on where in the catchment the PCT is located. More frequent flows are required for PCTs that are found in lower parts of the channel or in low-lying floodplains, and longer frequencies are sufficient for PCTs that are located higher up on the floodplain or in ephemeral reaches and wetlands.

Hydro-ecological functional group	Example PCT numbers	Example dominant species	BWS group	Inundation frequency (ARI)
Flood-dependent shrublands	25, 39, 247, 241, 63, 375	lignum; nitre goosefoot; coolibah wetland woodland	shrublands	1 in 1–3 years to 1 in 7–10 years[3]
Flood-dependent forests	2, 5, 7, 11, 36	river red gum	forest and woodlands (river red gum)	1 in 1–3 years
Flood-dependent woodlands	8, 9, 10, 71, 74, 78, 208, 249, 454	river red gum	forest and woodlands (river red gum)	1 in 2–4 years
	13, 15, 16, 37, 38	black box	forest and woodlands (black box)	1 in 3–7 years to 1 in 5–10 years[3]
	40, 87	coolibah	forest and woodlands (coolibah)	1 in 10 years
Floodplain vegetation	27, 43, 49, 52, 55, 62, 87, 115, 161, 198, 214, 1324, 55, 115, 206, 207	weeping myall; belah; chenopod species; poplar box	N/A	N/A

The water requirements (including frequency, duration, seasonality and maximum inter-event period) for each of the dominant species in the PCT was further defined using published literature sources where available (Casanova 2015; Roberts and Marston 2011; Rogers 2011) and the water requirements of vegetation communities collated for the Murray–Darling Basin Authority (MDBA) assessment of EWRs for the proposed Basin Plan (MDBA 2012a,b). Published literature describing water requirements was not available for all PCTs. In those cases, PCTs were assumed to be supported by the flows described for vegetation communities in their corresponding hydro-ecological functional group. The information presented in Appendix 10.4 provides a summary of the water requirements to support the maintenance, recruitment, recovery and improvement (and/or vegetative expansion) for some of the main PCTs in each hydro-ecological functional group, and was used to define the specific EWRs needed to support the objectives in different catchments across NSW. Table C.4 describes the flow regime required to support flood-dependent vegetation objectives in the LTWP.

Table C.4 Important flow regime characteristics required to deliver LTWP native water-dependent vegetation objectives

Ecological objective	Important flow regime characteristics
NV1: Maintain the extent and viability of **non-woody vegetation communities occurring within and closely fringing channels**	Non-woody, inundation tolerant plants occurring on the channel bed, banks, bars and benches require regular wetting and drying to complete lifecycles. Partial dry phases in summer and autumn for 1–4 months encourage recruitment. Regular inundation will also encourage a dominance of native species over exotic species, which are mostly adapted to dry environments.

Ecological objective	Important flow regime characteristics
	Prolonged submergence of some amphibious species (e.g. especially if there are continuous high flows during the irrigation season) may have detrimental impacts on survival.[4]
	Small freshes in summer and autumn are important for replenishing soil moisture in riverbanks to ensure survival and maintenance.
	Inundation of banks during late winter and early spring by freshes and bankfull flows is required to replenish soil moisture to promote growth during spring. Frequent (near annual) inundation through baseflows, bankfull flows, weir pool surcharges (where relevant) and large freshes for 7–12 months will promote vigorous growth and expansion of tall emergent aquatic species (such as cumbungi, common reed and giant rush) within and closely fringing channels. Frequent, but shorter duration flows may reduce vigour, but encourage more diverse communities.
NV2: Maintain the extent and viability of **non-woody vegetation communities occurring in wetlands and on floodplains**	Submerged aquatic species, such as pondweed and tall, emergent aquatic species such as cumbungi, common reed and giant rush require inundation for 7–12 months duration, for 8–10 years in 10 to promote vigorous growth and expansion with a maximum period between events of 18 months. If establishing from dry, some species, such as ribbonweed, may require the inundation duration to cover 2 growing seasons.
	Large freshes, bankfull flows and wetland inundating flows will support non-woody wetland vegetation in some low-lying wetlands with low commence-to-flow (CTF) thresholds.
	Overbank and wetland inundating flows that inundate wetlands and floodplains for 2–8 months between August and April are required to support non-woody, inundation tolerant vegetation.
	Small but frequent overbank and wetland inundating events will be important for maintaining the extent and viability of these species. The required duration and frequency varies widely by species. Highly water-dependent, amphibious species such as water couch, spike-rush, and cumbungi require inundation for 5–8 months, 8–10 years in 10. The maximum period between events is 2 years.
	Larger overbank and wetland inundating flows will support amphibious damp species such as floodplain herbs, grasses and sedges that require less frequent (3–10 years in 10) and shorter duration (2–4 months) inundation.
NV3: Maintain the extent and maintain or improve the condition of **river red gum and river cooba communities closely fringing river channels**	Large freshes and bankfull flows that recharge alluvial aquifers and soil moisture in the riparian zone are also important for maintaining deep rooted vegetation between inundation events. The general condition of riparian vegetation will benefit from inundation or groundwater recharge anytime of the year, with an ideal frequency of inundation of 4–10 years in 10 to maintain good condition.
	River red gum and river cooba fringing river channels will be supported by a range of flows including, most importantly, bankfull flows, which inundate the tops of banks, overbank flows and larger wetland inundating flows that inundate the fringing riparian zone.

[4] Increased cover of non-woody, inundation tolerant vegetation on banks is likely to stabilise bank material and therefore reduce the risk of excessive bank erosion.

Ecological objective	Important flow regime characteristics	
NV4: Maintain the extent and maintain or improve the condition of native **woodland and shrubland communities** on floodplains[5]	River red gum forest and woodland	Maintaining the condition of river red gum forests and woodlands on the floodplain requires overbank flows that inundate vegetation for 2–7 months during September to February. For river red gum communities located on lower parts of the floodplain, inundation needs to occur 4–10 years in 10 with a maximum period between events of 3 years.
		Maintenance of river red gum communities located higher on the floodplain requires larger overbank and wetland inundating events but these can occur less frequently: on average 3–5 years in 10, with a maximum inter-event period of 5 years. Regeneration of river red gum communities will require additional, shorter duration (1–2 months) inundation during August to November. These events would ideally occur the year following a maintenance flow to support the survival of seedlings from the previous year in areas where recruitment is desired.
	Lignum shrubland	Maintenance of lignum shrublands requires inundation by overbank or wetland inundating flows for 3–7 months at a frequency of 5–10 years in 10 and a maximum period between events of 5 years. Regeneration requires more frequent inundation (ideally annual), for 1–12 months between August and March (September to February for vegetative expansion).
		Overbank and wetland inundating events that occur more frequently will support regeneration and maintenance of lignum on lower parts of the floodplain.
		Large overbank events and wetland inundating events will support maintenance of lignum located higher on the floodplain.
	Black box woodland	Large overbank flows are required to maintain and improve condition of black box woodland communities, which tend to be located on higher parts of the floodplain. Maintenance requires inundation for 2–6 months, at a frequency of 2–4 years in 10 and a maximum period between events of 5–7 years. An interval >5–7 years may result in a reduction in condition.
		Regeneration and improvement of condition will require additional inundation for 1–2 months on an annual basis (maximum inter-event period of 2 years).

[5] Individual LTWPs may have other vegetation communities not listed here, e.g. Coolibah woodlands

10.3.3. Flow requirements for waterbirds

At least 102 species of waterbirds have been recorded in the NSW portion of the MDB. These species can be split into functional groups with similar habitat requirements (Figure C.6). The numbers of waterbird species and total number of individuals can change rapidly in response to inundation, specifically increases in total wetland area and the diversity of inundated floodplain wetland habitats. When inundated, floodplain habitats provide feeding and breeding habitat for a range of waterbird species.

Waterbird species richness is greatest when there are varying water depths across a range of wetland types (Taft et al. 2002). Deeper wetlands provide habitat for fish-eating waterbirds and diving ducks, whilst shallow, vegetated wetlands provide feeding habitat for dabbling ducks and large waders. Emergent aquatic vegetation at the margins of waterbodies provides habitat for cryptic crakes, rails and bitterns. As wetlands dry, exposed mudflats provides feeding habitat for resident and migratory shorebirds (Figure C.8).

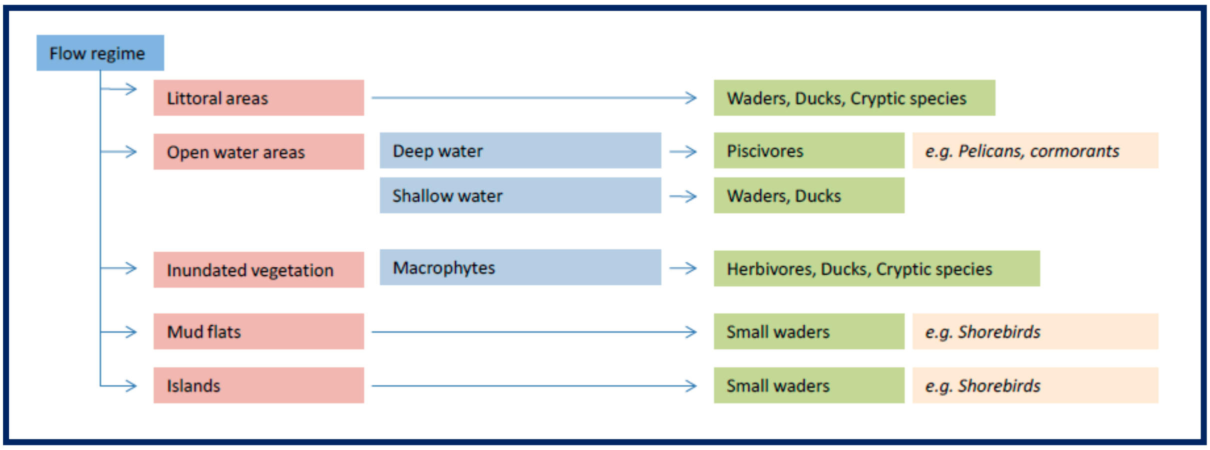

Figure C.6 Waterbird species can be grouped according to their habitat requirements, which are influenced by the flow regime (reproduced from Brandis et al. 2009)

For example, large waders such as spoonbills feed in shallow vegetated wetlands, while many piscivores, including pelicans and cormorants, feed in deeper more open waterbodies, and shorebirds (or small waders) prefer open waterbodies with shallow muddy shorelines.

The 5 waterbird functional groups described by Bino et al. (2014) and used in the BWS are: ducks and grebes, herbivores, piscivores (fish-eating waterbirds), large waders, and shorebirds (or small waders). Waterbirds may also be grouped according to their breeding requirements as non-colonial or colonially-nesting species. Non-colonial waterbird species include waterfowl (ducks, geese and swans), grebes, crakes, rails and waterhens, and resident shorebirds. These species generally do not congregate in large numbers to breed but they are still dependent on wetlands for nesting and feeding habitat to raise their young. Colonially-nesting waterbirds can gather in very large numbers (100s to 1000s of individuals) at some sites, called colonies, when their breeding and feeding habitats are inundated (Figure C.7). They include pelicans, cormorants, darters, ibis, egrets, herons and spoonbills. These waterbird groupings are used to describe the objectives and targets in the LTWPs.

Figure C.7 Large colonies of waterbird species including ibis (left) and pelicans (right) can form in floodplain wetlands when conditions are suitable for breeding (Photos: Paul Packard/DPIE, December 2016)

More than 60% of colonial waterbird breeding events in Australia have been recorded in the MDB (Brandis 2010) and breeding at some of these sites can be supported with environmental water (Bino et al. 2014; Spencer 2017). Colonially-nesting species such as egrets and ibis require appropriately timed flows of sufficient duration, depth and extent to allow birds to pair-up, build nests, lay eggs, and raise and fledge their young successfully (Kingsford and Auld 2005; Scott 1997). Breeding is initiated once floods reach a certain magnitude and the overall size of breeding response is determined by the extent of inundation, with larger and longer floods associated with a greater number of colonies overall and the presence of large (>5,000 nests) colonies (Spencer 2017).

The total duration of the nesting period varies greatly among species, as some adults continue to feed their young for several weeks until they reach independence (Figure C.8). For most colonially-nesting waterbird species a minimum of 90–120 days is required to encompass the pre-, during and post-nesting periods (Brandis and Bino 2016). Some colonial species, such as straw-necked ibis, are particularly sensitive to falling water levels in their colony sites and surrounding habitats, which can cause adults to abandon their nests (Brandis et al. 2011; Carrick 1962; Magrath 1991).

Flows also need to inundate foraging grounds adjoining key colony sites to support successful waterbird breeding. For open-water, fish-eating species such as cormorants and pelicans, proximity to large deep waterbodies that sustain large fish populations is important, while for large waders such as egrets and ibis, proximity to flooded marshlands and croplands is likely to be important (Platteeuw et al. 2004). There are also other non flow-related factors that can influence waterbird breeding including loss of suitable habitat through vegetation clearing, predation by feral animals and outbreaks of avian diseases (Brandis 2017; Brandis et al. 2020, McGinness et al. 2019; Spencer 2010).

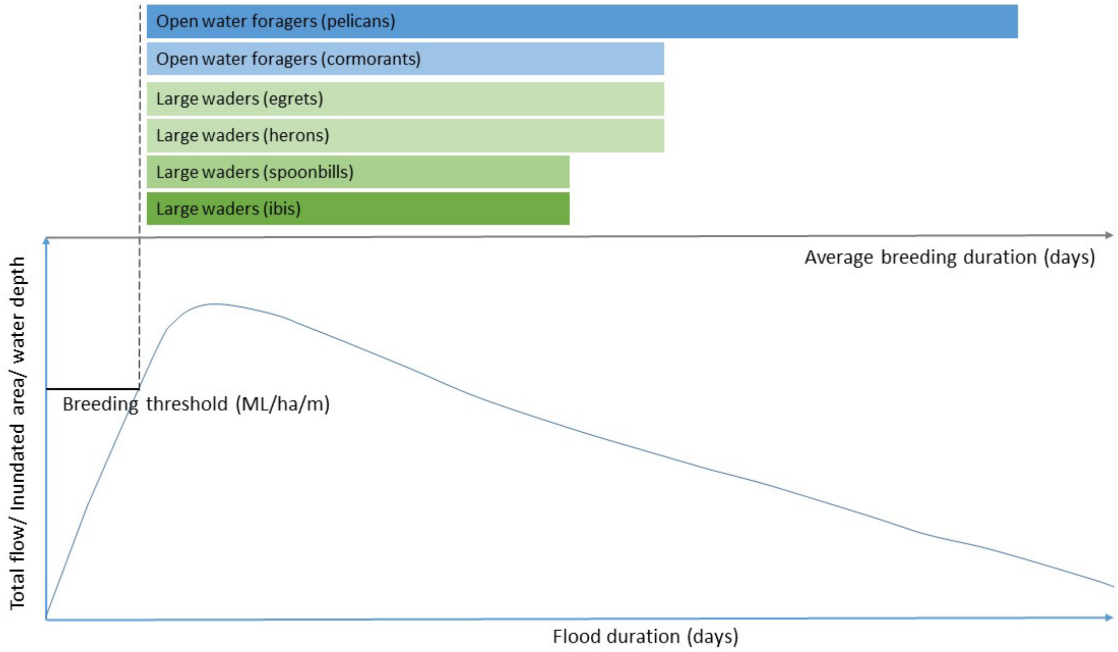

Figure C.8 **Representation of how key flow parameters (total river flow, inundated area, water depth and inundation duration) influence colonial waterbird breeding (adapted from Brandis and Bino 2016)**[6]

Knowledge of the water requirements of different waterbird species informs watering strategies and can be used to evaluate whether these strategies have met the timing, duration and frequency requirements for different waterbird groups. For the purposes of LTWP development, 7 hydro-ecological waterbird groups were developed through consultation with the department's water managers. These 'hydro-ecological groups' are similar to the BWS waterbird groups described above, except they are more explicitly linked to habitat types that can be targeted with water management. They include open waterbodies (open water foragers), wetlands with emergent vegetation including reedbeds *Phragmites australis* (emergent-vegetation dependent), flooded grasslands (herbivores), shallow wading habitat (large waders and small waders) and broad wetland types (wetland generalists).

The shorebird (or small wader) groups included a resident species group (e.g. stilts, avocets and dotterels) that are resident in Australia and may breed in wetlands in the MDB, and a separate migratory shorebird group for species recognised on international bilateral agreements that Australia has signed with Japan (JAMBA), China (CAMBA) and the Republic of Korea (RoKAMBA). Migratory shorebirds spend their breeding season in the Northern Hemisphere and use wetlands in the MDB during their non-breeding season (September–April).

To collate information on water requirements we allocated each of the waterbird species recorded in the NSW MDB to a hydro-ecological group. Our list contained 102 waterbird species, including 16 species listed as vulnerable or endangered in NSW (NSW *Biodiversity Conservation Act 2016*), 7 species listed as nationally endangered or critically endangered (Commonwealth *Environment Protection and Biodiversity Act 1999*),

[6] Once nesting begins the duration of flooding and water depth needs to be sufficient to meet total breeding duration requirements (laying and incubation of eggs through to raising of offspring through the nesting and post-fledgling dependent period), which vary among species.

27 species listed on one or more migratory bird agreements (JAMBA, CAMBA or RoKAMBA) and 6 vagrant species not typically found in Australia. Information on waterbird habitat requirements was collated from unpublished reports, scientific literature and previous reviews by Marchant and Higgins (1990,1993), Higgins and Davies (1996), Brandis et al. (2009), Brandis and Bino (2016) and Rogers (2011). We identified information that related to water management including the timing, duration, frequency, rate of fall and maximum inter-event period (Appendix 10.4).

There are considerable knowledge gaps around life history aspects of most waterbird species including information on site fidelity, longevity, age at sexual maturity or how the age of adult birds influences breeding success. This reduces confidence in determining the ideal frequency of small, medium and large overbank flows as well as the maximum inter-event period. In this context, the information in Appendix 10.4 is a broad guide only. Table C.5 describes the flow regime required to support waterbird objectives in the LTWP.

Table C.5 Important flow regime characteristics required to deliver LTWP waterbird objectives (adapted from NSW LTWPs)

Ecological objective	Important flow regime characteristics
WB1: Maintain the number and type of waterbird species	Maintaining waterbird species richness in the waterbird areas will require a range of large freshes, bankfull flows, and wetland inundating and overbank flows to support feeding and breeding habitat (see WB2, 3, 4) and maintain habitat condition (see WB5). Overbank flows, preferably delivered in spring–summer, that inundate a mosaic of floodplain habitats including non-woody floodplain vegetation, open shallow waterbodies and deep lakes and lagoons, will provide feeding habitat for a range of waterbird species including open-water foragers, herbivores, emergent vegetation-dependent species, large waders, wetland generalists and small waders (including migratory shorebird species). Where there is gradual draw-down of habitats over late summer–autumn this can extend feeding habitat available for migratory and resident shorebird species (small waders).
WB2: Increase total waterbird abundance across all functional groups	As in WB1, provide seasonal (spring–summer) flooding with gradual draw-down over summer into autumn to provide feeding habitat for waterbird species and maintain the condition of waterbird breeding and feeding habitats (WB5). Increasing waterbird abundance in the waterbird areas will require increased breeding opportunities for both colonial and non-colonial waterbirds across many waterbird areas. Where possible this should be maximised through large overbank flows in the waterbird areas from September to March with inundation duration maintained into May for colonies in some waterbird areas that commence in late summer. Small and medium overbank events will provide foraging habitat for waterbirds and may support small-scale non-colonial waterbird breeding. For some active colony sites managed flows can be delivered to extend the duration of large overbank flows to maintain the duration of inundation in colony sites and maintain adequate water depths under nesting birds. These events need to be of sufficient duration (3–6 months, species-dependent) to ensure successful completion of colonial waterbird breeding (from egg laying through to fledging including post-fledgling care) and access to key foraging habitats to enhance breeding success and the survival of young. Where possible, large freshes, bankfull flows, and wetland inundating and overbank flows that inundate floodplain wetlands should be

Ecological objective	Important flow regime characteristics
	delivered at the same time as neighbouring catchments to provide benefits to waterbird populations by providing habitat across a larger area of the MDB. Follow-up overbank flows in years following large breeding events in each waterbird area and neighbouring catchments in the MDB will also promote the survival of juvenile birds and contribute to increasing waterbird populations. Increasing total waterbird abundance will also rely on maintaining (and in some cases) improving the condition of key native vegetation types that provide breeding and foraging habitats (see WB5 and flows for native vegetation objectives in Appendix 10.3). This includes colony sites comprised of common reed, river red gum, river cooba, coolibah, lignum and cumbungi. Overbank flows are needed to maintain the extent and condition of these nesting habitats (see WB5 for more details).
WB3: Increase opportunities for non-colonial waterbird breeding	Providing opportunities for non-colonial waterbird breeding will include the provision of seasonal flows (September–March) to inundate floodplain habitats for more than 2–3 months. Spring–summer is the ideal season for non-colonial species, with opportunistic breeding occurring in autumn and winter. Habitat availability for non-colonial species will increase with increasing magnitude (both extent and duration of inundation) of overbank flows. Providing opportunities for breeding in non-colonial species and contributing to increased numbers of non-colonial species will also depend on maintaining (and in some cases) improving the condition of key native vegetation types that provide breeding and foraging habitats (see WB5).
WB4: Increase opportunities for colonial waterbird breeding	Supporting breeding in active waterbird colonies in the waterbird areas identified as colonial waterbird breeding sites requires overbank flows (or smaller flows that can inundate lower-lying sites) during September–March. The minimum duration of inundation of active colony sites and surrounding foraging habitat is 3–4 months to ensure successful completion of colonial waterbird breeding (from egg laying through to fledging including post-fledgling care) and access to key foraging habitats to enhance breeding success and the survival of young. Larger overbank events will support larger colonies and a broader range of breeding species (non-colonial and colonial species) with greater benefits to breeding success and the total abundance of waterbirds (WB2, WB3). These large overbank events are required on average 2–3 years in 10, with a maximum inter-event period of 4–5 years.
WB5: Maintain the extent and improve condition of waterbird habitats	Waterbirds depend on a wide variety of breeding and foraging habitats, which are maintained through a range of overbank flows. Colonial waterbird species are dependent on relatively few sites across the major wetlands of the MDB. These include sites that provide nesting habitat consisting of common reed, river red gum, river cooba, coolibah, lignum and/or cumbungi. Large freshes, bankfull and overbank or wetland inundating flows of sufficient duration are needed to maintain the extent and condition of these vegetation communities in these discrete wetland sites. This ensures that sites are in event-ready condition when large overbank events initiate large-scale colonial waterbird breeding events. These flows will also support a broader range of foraging habitats in the waterbird areas, including spike-rush sedgelands, marsh grasslands, lignum shrublands, open lagoons and lakes. The required duration and frequency of inundating flows to support these habitat types are outlined in Appendix 10.3.

10.3.4. Flow requirements for PEFs

Ecosystem functions are the physical, geochemical and biological exchanges and processes that contribute to the state, integrity and regulation of an ecosystem (Odum 1953). In river and floodplain wetland ecosystems, flow and inundation regimes drive their ecological characteristics (Overton et al. 2009; Poff et al. 1997). Flow regimes determine and maintain river channel form and wetland formation and configuration, and control the patterns of wetting and drying and the intervals between inundation of floodplain habitats. They also prompt key ecological processes such as nutrient cycling and energy flow, breeding and migration, and dispersal of plants and animals.

Different components of the flow regime provide for a range of ecological functions over a broad range of spatio-temporal scales (Table C.6). Overbank flows replenish the soil moisture profile on floodplains leading to a surge in terrestrial and wetland vegetation production, and revive and reconnect floodplain habitats to the main river channel (Baldwin et al. 2013), while at the same time liberating large quantities of dissolved organic carbon (DOC) and nutrients from floodplain sediments and coarse particulate organic matter (CPOM) stored on the floodplain (Baldwin et al. 2016; Ballinger and Lake 2006). However, such events are infrequent whereas the more frequent freshes that are retained within the channel regularly wet inset-benches, releasing smaller pulses of DOC and nutrients that supports in-channel biota (Sheldon and Thoms 2006; Southwell and Thoms 2011).

Lateral and longitudinal connectivity is fundamental in supporting many of the key ecosystem functions in riverine environments. Improved hydrological connectivity along river systems and between rivers and their floodplains is pivotal for moving nutrients, carbon and sediments, enhancing productivity, allowing organisms to disperse and improving water quality (MDBA 2014).

Refugia

Refugia can occur within the main river channels, such as instream pools, or in off-channel habitat where water persists after disconnection from the channel, such as in billabongs and anabranches. The refugia can contain different types of habitat, such as logs, wet undercut banks, riffles, subsurface stream sediments, and riparian or wetland vegetation (Boulton 2003). Minimum flows that can inundate these areas and maintain water quality or vegetation communities (e.g. very low flows, baseflow, and in some instances freshes and small wetland inundating flows) are critical to the survival of many aquatic species during dry spells and drought, and act as source populations for subsequent recolonisation and population growth (Adams and Warren 2005; Arthington et al. 2005). Refugia should be the highest priority for protection, especially during drought.

Quality instream habitat

The physical form of instream habitats, including the location of riparian and instream vegetation, channel shape and bed sediment, is sculpted by river flow (Bunn and Arthington 2002). Flow pulses (freshes) and bankfull flows with sufficient velocity are required to maintain pool depth and riffles by scouring out bed material and initiating material transportation downstream (Davie and Mitrovic 2014). Changes to the rates of rise and fall of river levels can also impact the quality of instream habitat by increasing riverbank erosion through bank collapse (Walker and Thoms 1993).

Variable flows and water levels (in the case of reaches affected by weirs) are also important for providing a diverse range of hydraulic environments for aquatic biota. These include slackwater (slow-flowing) zones at channel margins and areas of fast-flowing water to support native fish movement and spawning.

Another aspect of habitat quality is appropriate wetting–drying regimes of wetlands and channel margins to allow aquatic macrophytes to complete lifecycles and to support nutrient cycling. Variable flows and water levels also affect the area of woody habitat (snags) that is available to aquatic biota and the quality of epixylic biofilms that grow on them (Burns and Walker 2000; Ryder 2004). A key focus of LTWP targets is to ensure appropriate wetting–drying regimes. These are especially relevant in the middle and lower sections of rivers affected by weir pools or that receive extended periods of stable, elevated in-channel flows during the irrigation season.

Movement and dispersal opportunities for aquatic biota

Longitudinal and lateral connectivity allows organisms to move and disperse between environments. It can be essential for maintaining population viability by allowing individuals to move to different habitat types for breeding and conditioning, and by permitting recolonisation following disturbances like flood and drought (Amtstaetter et al. 2016). Flow pulses promote dispersal from the breeding site of early life stages for a range of species and maintain genetic diversity among catchments (Humphries and King 2004).

LTWP targets focus on maintaining longitudinal connectivity and integrity (timing, duration, magnitude and rate of rise and fall) of flow pulses along the entire length of rivers, including pulses originating from major tributaries and flows that connect with other catchments. Of equal importance in the LTWPs is maximising lateral connectivity between rivers and floodplain habitats including anabranches, billabongs, wetlands and floodplains.

Instream and floodplain productivity, and sediment, carbon and nutrient exchange

The supply of organic material underpins all food webs in aquatic environments by providing the energy needed to drive life. Productivity of a river, creek or wetland is influenced by the type of organic material, how much, and how often waterways connect with parts of the channel, riverbank and floodplain that store organic material. The sources of organic material, the timing of its delivery, and how long it remains in a section of river depend closely on the flow regime and the nature of the riparian and floodplain vegetation.

River flow management can be used to increase productivity by increasing the frequency of flows that connect and inundate river channels, benches, banks and floodplains. Re-wetting habitats (e.g. flood runners and creeks, in-channel benches, floodplains) following drying provides a pulse of terrestrial carbon available for potential use by consumers (Langhans and Tockner 2006). The flow of water enhances the physical breakdown of leaves, branches and other terrestrial detritus to support micro-organisms (e.g. protozoa, copepods) and biofilms that in turn support invertebrates such as shrimp, juvenile fish, large fish and water birds (Mora-Gomez et al. 2015). Furthermore, mimicking the natural flooding and drying regimes in wetlands is likely to conserve and enhance macroinvertebrate assemblages (NOW 2011).

The reduction of lateral connectivity between rivers and floodplains has affected the transport of sediment, nutrients, carbon and biota to and from the river (Baldwin et al. 2016). Consequently, the amount of DOC entering the main channels is reduced because of less frequent wetting of benches, flood runners and floodplains (Westhorpe et al. 2010). Longitudinal connectivity is equally important and fulfils the important environmental function of transporting nutrients and sediments between environments (MDBA 2014).

Groundwater-dependent biota

Groundwater and surface water resources are inextricably linked and connections between surface and groundwater systems can vary considerably between systems (Stanford and Ward 1993). GDEs are natural ecosystems that are occasionally or wholly reliant on access to groundwater to maintain plant and animal communities (e.g. coolibah and black box woodlands) and ecosystem processes and services (Doody et al. 2017). Additionally, a unique and biodiverse stygofauna occupies the hyporheic and parafluvial zones connected with river channels and the alluvial aquifers that are dependent on surface water for recharge (Hancock and Boulton 2008; Hose et al. 2015; Humphreys 2006).

In some rivers of the MDB, groundwater plays an important ecological role in supporting terrestrial and aquatic ecosystems, particularly during extended dry periods when groundwater can be critical for maintaining refuges (pools) and floodplain vegetation (Amoros and Bornette 2002; Hancock et al. 2005). Instream pools and floodplain wetlands and lakes are extremely valuable refugia in riverine landscapes and groundwater plays a critical role in maintaining these during droughts.

Describing the EWRs needed to support PEFs involved reviewing peer-reviewed papers and reports, as well as incorporating input from subject matter experts. Scientific researchers and experts from government departments, private consultancies and universities provided input throughout the process by reviewing draft material developed by the LTWP planning team and contributing to a series of workshops[7]. Some of the outcomes from these workshops are captured in Appendix 10.7 and contributed to defining PEF EWRs. The main steps involved were:

1. describing the specific ecosystem processes that support each PEF
2. identifying where in a catchment the PEF is likely to occur (e.g. channels, floodplains, wetlands, etc.), the scale at which it operates and whether adjacent landscape units need to be connected for PEF outcomes to be supported
3. linking PEFs with the relevant flow categories and the optimal timing of those flows needed to support them, taking into account where in the catchment they are likely to exist. This step was largely informed by the Alluvium (2010) report
4. determining which LTWP objectives are supported by the PEF. Many of the other theme group objectives and targets are reliant on ecosystem functions and so their EWRs are intrinsically linked with EWRs to support ecosystem functions (e.g. EWRs to support native fish incorporate flows that support in-channel refugia, water quality, lateral and longitudinal connectivity, and productivity) (Table C.1, Table C.2, Table C.4, Table C.5)
5. developing the required flow regime to support each PEF in a catchment (Table C.6)
6. refining the specific EWRs required to support a PEF in a specific planning unit or catchment:
    a. informed by specific monitoring reports (including the Long Term Intervention Monitoring project (LTIM)), expert input or peer-reviewed papers that are location specific
    b. important hydrological triggers for flows between catchments were informed by the timing and frequency of connectivity requirements for native fish and flow magnitudes required to support fish movement (e.g. weir drown out) (Appendix 10.2).

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[7] Workshops were held in Sydney in February 2017.

Table C.6 Important flow regime characteristics required to deliver LTWP PEF objectives

Ecological objective	Important flow regime characteristics
EF1: Provide and protect a diversity of refugia across the landscape	CF periods that are not longer than the persistence of water of sufficient volume and quality in key larger river pool refuges is vital for survival of native plants and animals.
	Very low flows and baseflows are required to maintain in-channel pools as refugia for native fish and other biota. These flows need to be of sufficient magnitude to prevent stratification of pools that can lead to de-oxygenation of the water column and subsequent fish deaths. They are required every year for most of the year (no less than natural) and are especially important during dry times.
	When restarting flows after a CF event, larger magnitude flows may be required to prevent detrimental water quality outcomes (as poor quality water from the bottom of pools is mixed through the water column).
	Core wetland areas can hold water for many months to years and provide an important refuge for waterbirds and other aquatic fauna during dry times. Regular overbank and wetland inundating flows are required to maintain the condition of wetland and vegetation in floodplains and wetlands to ensure they can function as refuges during dry times.
EF2: Create quality instream and floodplain and wetland habitat	The full range of in-channel and overbank flows are required to maintain quality instream and floodplain habitat. Variable in-channel flows (baseflows – bankfull flows) will provide a diversity of physical and hydraulic habitats. With increasing magnitude of flows, greater areas of the channel are inundated (e.g. benches, bars, snags and banks at different elevations in the channel). Bank notching can be avoided by varying flows (avoiding holding flows constant for too many consecutive days) and targeting different peak heights for freshes. To protect banks from excessive erosion it is important to maintain rates of fall that do not exceed natural rates of fall for ALL regulated deliveries. Slow rates of fall allow water to drain from the bank slowly, preventing mass failure of the banks.
	Baseflows and small freshes provide areas of slackwater (slow-flowing) habitat. Small freshes are also important for flushing fine sediment from pools, de-stratifying pools and maintaining geomorphic features such as benches and bars. Maintaining slow rates of fall is particularly important when flows are in the lower third of the channel, to protect the 'toe' of the bank, which supports the rest of the bank above.
	Large freshes provide deeper and faster-flowing habitats. Bankfull flows are important for geomorphic maintenance of all channel features. Large freshes are also important for flushing fine sediment from pools, de-stratifying pools and maintaining geomorphic features such as benches and bars.
	Overbank and wetland inundating flows are required to provide essential floodplain and wetland habitat for native fish, waterbirds and other aquatic fauna.

Ecological objective	Important flow regime characteristics	
EF3: Provide movement and dispersal opportunities within and between catchments for water-dependent biota to complete lifecycles and disperse into new habitats	Within catchment	Providing longitudinal connectivity is critical for migration, recolonisation following disturbance events, allowing species to cross shallow areas, and dispersal of larvae to downstream habitats. In-channel flows of adequate depth and duration (base-flows and freshes) are important to allow for the movement of aquatic and riparian fauna and flora along rivers and creeks. For example, flows of at least 0.3 m are needed to allow medium-sized native fish to move along a channel.
		Physical barriers, such as dams and weirs, have introduced additional barriers throughout the Lachlan, make large freshes, bankfull flows, and occasionally small overbank flows important for overcoming these man-made structures where fishways are not present.
	Between catchments	End of system flows occasionally provides connections between catchments, providing dispersal opportunities for native fish.
EF4: Support instream and floodplain productivity	Large freshes, bankfull flows and small wetland inundating flows may drive small pulses of productivity. Overbank and wetland inundating flows that inundate the floodplain for several months are the most critical flow categories for supporting large-scale productivity, which in turn drives aquatic food webs both on the floodplain and instream. Primary productivity includes growth of algae, macrophytes, biofilms and phytoplankton, which in turn drives secondary productivity (zooplankton, macroinvertebrates, fish larvae etc.).	
EF5: Support nutrient, carbon and sediment transport along channels, and between channels and floodplains/wetland s	Freshes and bankfull flows are important for mobilising organic matter and sediment from in-channel surfaces (e.g. leaf litter that has accumulated on bars, benches and banks during low flows). This material is transported downstream or deposited in other parts of the channel where it is utilised, in the case of nutrients and carbon, to drive primary productivity, or in the case of sediment, for channel maintenance (e.g. to replenish banks and benches). Overbank and wetland inundating flows are essential for transferring nutrients and carbon from the floodplain to the channel.	
EF6: Support groundwater conditions to sustain groundwater-dependent biota	Large freshes, bankfull flows, overbank, and wetland inundating flows will contribute to recharging shallow groundwater aquifers in areas where there is a surface–groundwater connection. This recharge can reduce the salinity of shallow aquifers and raise water tables, providing critical soil moisture for deep-rooted vegetation in the riparian zone and on low-lying floodplains.	
EF7: Increase the contribution of flows into the Barwon–Darling and the lower Murray River	The coordination of flows between catchments to provide movement and dispersal opportunities for water-dependent biota to complete lifecycles will also contribute to important EWRs in the Barwon–Darling and River Murray catchments. The full range of flows (baseflows, freshes, bankfull and overbank flows) is required to meet the EWRs in downstream areas, such as the Barwon–Darling River, the Coorong, Lower Lakes and Murray Mouth, including barrage outflows to support the Coorong and Murray Mouth throughout the year, with peak barrage outflows. Protecting larger overbank flows will provide important flows, connectivity and movement events, and transfer nutrients and carbon from floodplains to downstream river channels.	

10.3.5. Flow requirements for frogs

Frogs occur in all aquatic habitats of the NSW MDB, from alpine meadows and rocky streams to ephemeral billabongs and vast floodplain wetlands. While all require water at some stage of their lifecycle, not all species have the same water requirements due to different behavioural and physiological adaptations. To describe the water requirements of frogs in the NSW MDB, similar species were grouped into hydro-ecological functional groups according to their habitat use, physiological adaptations and breeding requirements, based on the approach in Ocock et al. (2016)

The occurrences of all 60 frog species recorded in the NSW portion of the MDB since 1980 were reviewed first (NSW BioNet 2016). Of these 60 species, 19 were excluded from the LTWP process because <10% of their entire range occurred in the NSW MDB ('edge of their range' species) or they were considered no longer present there (based on Anstis 2017).

Each of the remaining 41 frog species were assigned to a group based on information in Amos (2017), Anstis (2017), Ocock (2013), Ocock et al. (2016) and Wassens (2010), and unpublished reports and observations from long-term monitoring in Murray River wetlands. The groupings in Ocock et al. (2016) were expanded to account for stream-associated species located in mid and upper catchment reaches of each water resource plan area (WRPA). The 4 hydro-ecological groups were defined as flow-dependent, flow-stream, flow-ambivalent and flow-oblivious (Appendix 8.1, Table C.7).

Table C.7 Descriptions of the 4 different hydro-ecological groups for frogs

Frog hydro-ecological group	Description of water-dependence
Flow-ambivalent	Frog species with a higher resistance to water loss and that occupy a wider variety of habitat, often at greater distances from wetlands or waterbodies. Local weather patterns, particularly rainfall and warmer temperatures, tend to have a stronger influence on movement and breeding, than wetland inundation.
Flow-dependent	Non-burrowing ground or marsh frogs that have limited ability to withstand drying. They are reliant on floodplain habitats for refuge, including wetlands, waterholes and creeks, and prefer to breed in recently inundated areas.
Flow-oblivious	Large-scale weather patterns that bring heavy localised rain are considered the most significant driver for the frog species' ecology and breeding responses. They may use and occasionally breed in floodplain wetland habitats.
Flow-stream	Frog species that are highly reliant on water but are separated from flow-dependent species because they are strongly associated with small, rocky streams only, and do not occur widely in lowland floodplain wetlands.

The key difference between the 4 groups was their reliance on free-standing water for survival and reproduction. Flow-dependent species are typically non-burrowing ground or marsh frogs that have limited ability to withstand drying. They are reliant on floodplain habitats for refuge, including wetlands, waterholes and creeks, and prefer to breed in recently inundated areas (Figure C.9) (Ocock et al. 2016; Wassens and Maher 2011). Movement is generally restricted to within flooded areas and short distances (a maximum of 1 km) across land around the edge of regularly inundated wetlands or floodplains (Ocock et al. 2016). This group of species tends to have the strongest activity and breeding response to inundation of wetland habitat.

Environmental water delivery has been shown to provide opportunities for breeding in flow-dependent frogs. Managed flows can influence the timing, extent, duration and depth of inundation, to provide favourable conditions that match the refuge and breeding requirements of flow-dependent frog species. For example, as most flow-dependent tadpoles require at least 3 months to complete development, water delivery can be managed to help ensure the duration of wetland inundation exceeds this development period, increasing the success of frog breeding. This approach has underpinned efforts to support the NSW endangered and nationally vulnerable flow-dependent southern bell frog in the Murrumbidgee and NSW Murray–Lower Darling catchments (Wassens et al. 2019; Waudby et al. 2020).

The seasonality of breeding for each flow-dependent frog species is also described in Appendix 8.1 for some species where needed, to distinguish them from other flow-dependent species that had flexible timing for breeding. This is important as threatened frog species such as the Sloane's froglet and southern bell frog, have specific seasonal breeding requirements and flow timings can influence the achievement of targets for specific threatened species objectives.

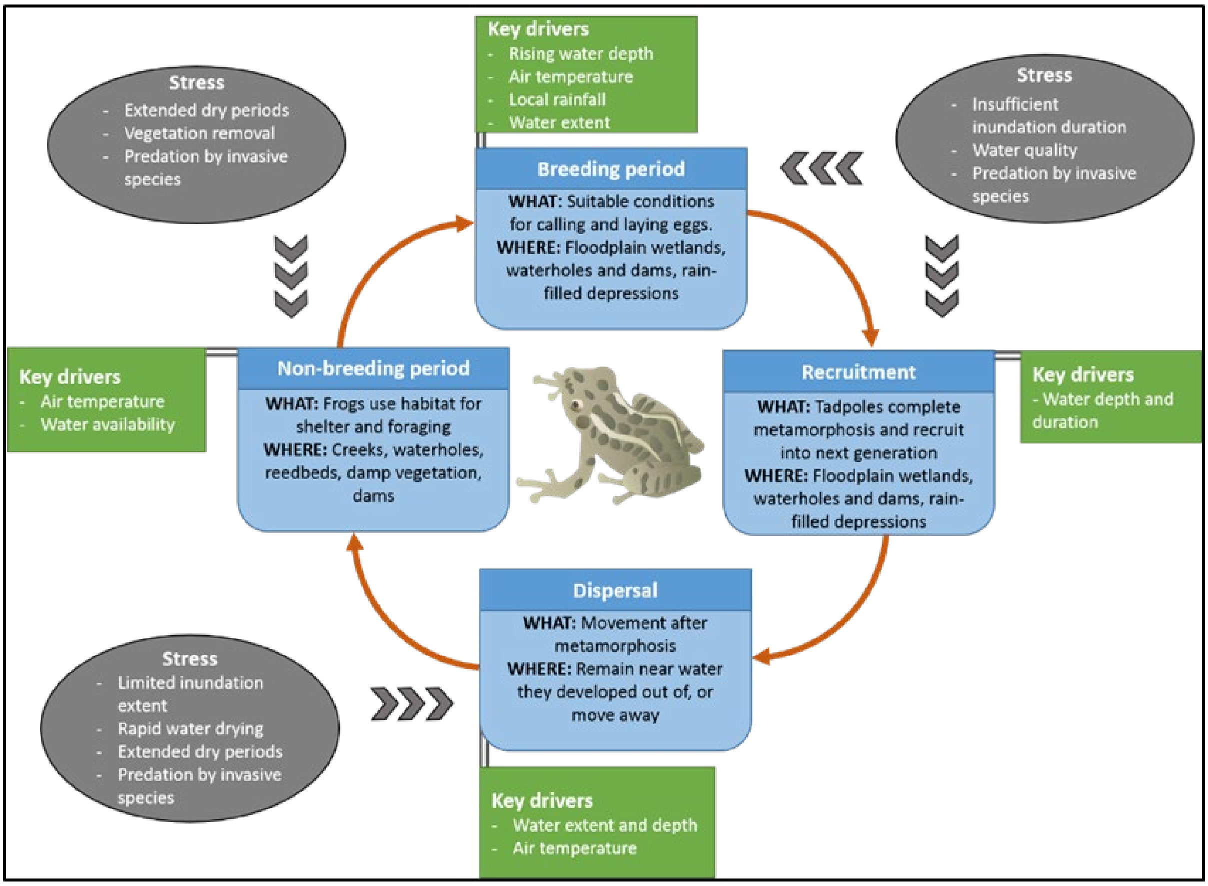

Figure C.9 Conceptual diagram of the life-stages of flow-dependent frog species, showing the key drivers and stresses for each life stage (from Ocock et al. 2018)

Frog species classified as 'flow-stream' are also highly reliant on water but are separated from flow-dependent species because they are strongly associated with small, rocky streams only, and do not occur widely in lowland floodplain wetlands. The breeding activity and successful tadpole metamorphosis of flow-stream species relies on sufficient flows in small creeks and streams, primarily in the mid and upper catchments, most of which are unregulated and not able to be targeted with managed water deliveries. Most of these locations also fall outside the defined spatial boundaries for frog objectives and targets (DPIE–EES 2020).

The flow-ambivalent species have a higher resistance to water-loss than the flow-dependent due to physiological and behavioural adaptations such as moderate resistance to loss of water through the skin and adopting water-conserving positions (Warburg 1965; Young et al. 2005). They also occupy a wider variety of habitat, often at greater distances from wetlands or waterbodies. Most arboreal tree frogs fit this category. For these species local weather patterns, particularly rainfall and warmer temperatures, have a stronger influence on movement and breeding than wetland inundation (Ocock et al. 2014). Similarly, burrowing frogs that dig into the soil and remain underground are closely associated with localised rainfall. Rain cues the emergence of these species and nearly all breeding takes place in temporary, shallow rain-filled depressions and waterholes. These species were categorised as flow-oblivious. While these species may use and occasionally breed in floodplain wetland habitats, large-scale weather patterns that bring heavy localised rain are considered the most significant driver of flow-ambivalent and flow-oblivious species' ecology and breeding responses. Therefore, while the EWRs compiled for the flow-ambivalent and flow-oblivious species outline the flow conditions required for the species to use floodplain wetlands, their use of wetland habitat will mostly be due to coinciding rainfall and warm temperatures (Appendix 10.5).

LTWP targets and objectives were developed for the flow-dependent frog species only. Water management decisions will seldom directly influence or affect the refuge and reproductive outcomes of the other 3 frog groups. While they comprise an important component of the overall native frog community, they are not strongly associated with the flow regimes of wetland habitat in the WRPA used in developing NSW LTWPs.

Table C.8 Important flow regime characteristics required to deliver LTWP frog objectives

Ecological objective	Important flow regime characteristics[8]
OS1: Maintain species richness and distribution of flow-dependent frog communities	The duration of CF events should not persist longer than what occurred naturally to protect sufficient water volumes and quality in key larger river pool refuges. Very low flows and baseflows can help maintain adequate water quantity and quality (DO, salinity and temperature) in refuge pools. Wetland inundating events and small overbanks maintain core wetlands, including off-channel waterholes for refuge. Larger flows maintain frog condition and habitat, allow dispersal and support breeding.
OS2: Maintain successful breeding opportunities for flow-dependent frog species	Wetland inundating events and overbank flows provide opportunities for breeding and recruitment (i.e. laying eggs and tadpole metamorphosis). To support successful breeding opportunities, these flows should ideally occur every 1–2 years and inundate their habitat for 6 or more months (with a minimum of 4 months). Spring–summer breeders require flows ideally from October to March, while species with more flexible breeding are likely to benefit from flows arriving between July and April. A gradual rise and fall is likely to improve recruitment outcomes.

[8] Important flow regime characteristics from Wassens (2010) and J Spenser and J Ocock (DPIE–Biodiversity and Conservation Division (DPIE–BCD), pers. comm. 2018)

Ecological objective	Important flow regime characteristics[8]
OS3a: Maintain and increase the number of wetland sites occupied by the threatened southern bell frog	Wetland inundating and overbank flows provide opportunities for breeding and recruitment (i.e. laying eggs and tadpole metamorphosis). Ideally every 1–2 years for 3[9] or more months. Unlike other species, it is believed the southern bell frog requires access to permanent water. Events to support breeding need to occur in late spring–summer months (ideally ephemeral wetlands between October and February). Events to support refuge in autumn–winter (can be wetlands or rivers, ideally March–August).
OS3b: Maintain and increase the number of wetland sites occupied by the threatened Sloane's froglet	Wetland inundating and overbank flows needed to provide opportunities for breeding and recruitment (i.e. laying eggs and tadpole metamorphosis). Ideally every 1–2 years for 3[9] or more months. Events to support breeding need to occur in the winter months (between June and August).

10.3.6. Flow requirements for other water-dependent species

Other water-dependent species, such as woodland birds, some bats and snakes can often inhabit areas that are farther away from wetlands or waterbodies compared to frogs. While they may use and breed in riverine, riparian and floodplain wetland habitats, there is limited information available that describes these species' responses to flows to be able to quantify specific EWRs at this time. Further work is needed to determine how much influence water management has on the distribution of these species and any additional conservation actions that may be needed. These fauna groups should be considered for inclusion in future revision of the NSW LTWPs.

Within the MDB, platypus are most common in the headwaters or rivers and streams along the Great Dividing Range and become less common as you move further west (Scott and Grant 1997). Their ideal habitat is shallow rivers with a combination of riffles and pools with relatively steep banks with overhanging riparian vegetation (Scott and Grant 1997). Platypus numbers and foraging activity show a strong positive correlation with the number of trees, shrubs and low-growing plants growing on stream banks and overhanging the water (Serena and Williams 2010). An appropriate flow regime for platypus (Table C.9) would therefore need to support riparian vegetation to help stabilise the riverbanks they use for their burrows, while also avoiding sudden falls in water level to avoid bank collapse (Scott and Grant 1997).

Environmental watering requirements for platypus must also support suitable benthic habitat to ensure a good food supply of invertebrates. Appropriate flow velocities through riffle and pool areas are also required to provide calm water sections for resting and easy movement through riffle areas (Scott and Grant 1997). Platypus may avoid foraging in strong currents if habitats with slower-moving or still water are available (Serena and Williams 2010). Additionally, cold water pollution might have indirect effects on platypus by reducing the abundance of benthic invertebrates and hence the availability of food (Scott and Grant 1997).

[9] DPIE–BCD observations of successful breeding in private wetlands in Murray (DPIE–BCD unpublished data).

Sufficient permanent pools must be present in the system to sustain platypus populations through low or no flow periods (Serena and Williams 2010). CF periods must not be too long, and low flows must be supported to avoid harmful deterioration of water quality in pools. Larger water pulses (small fresh to bankfull) can help flush pools of sediment and improve water quality and productivity and are particularly important during periods of drought (Serena and Williams 2010). Large freshes can also improve the extent and productivity of foraging habitats for platypus before breeding (Serena and Grant 2017).

Small weirs with wall heights of 3 m or less do not appear to prevent the dispersal or movement of platypus (Scott and Grant 1997); however, they are unable to negotiate vertical concrete structures (such as dam or weir walls) and these are a significant barrier to movement (Serena and Williams 2010). Bankfull and overbank flows are therefore important in areas that are impacted by larger structures to support platypus movement across their habitat range. Ideal generic EWRs to support platypus can be found in Appendix 10.6.

Table C.9 Important flow regime characteristics required to deliver LTWP other species (platypus) objectives

Ecological objective	Important flow regime characteristics
OS4: Maintain water-dependent species richness	Low flows and riffle areas should be maintained between June and August to support foraging areas and movement between pools, which are platypus preferred habitat. They prefer to feed in water that is 1–3 m deep (Serena and Williams 2010).
	Large freshes and bankfull flows should ideally finish before the end of August to encourage female platypus to choose burrows higher on the riverbank. If these higher flows occur between September and February or for extended periods they can flood platypus burrows and reduce the availability of benthic invertebrates, therefore reducing breeding success (Scott and Grant 1997).

10.4. Determining environmental water requirements for each catchment integrating all species and functions

This step entailed defining a set of EWRs (or flows) that will meet the ecological requirements of multiple themes (waterbirds, native fish, etc.) in each catchment. This involved looking at overlap and alignment between the generic EWRs for each of the themes and then defining the full set of flows (EWRs) and their characteristics (magnitude, timing, frequency, etc.) that would achieve all environmental objectives in the catchment. Consequently, EWRs are generally linked with multiple objectives.

Taking the 'large fresh' flow category as an example, the generic EWRs for native fish indicated the need for 2 specific large freshes for flow pulse specialist native fish (e.g. golden perch):

- a large fresh for dispersal, productivity and pre-spawning condition in winter–early spring
- a large fresh for spawning between October and April.

Both were typically short duration events (at least 5 days or up to 15 days in some catchments). Consultation with experts, published information and the outcomes of previous environmental watering indicated that these EWRs would also likely support several ecosystem function objectives such as nutrient and carbon transport and dispersal of other biota. We considered the presence of flow pulse specialist fish in each catchment and if the functional group was present or had the potential for being established, the EWRs were included in the catchment-scale EWRs as large fresh 1 (LF1) and large fresh 2 (LF2).

These EWRs however, did not always meet the duration requirements of native non-woody vegetation occurring in river channels or low-lying wetlands connected by large freshes. In this case, a third large fresh EWR (large fresh 3, LF3) was defined for some catchments and had a longer duration than LF1 and LF2 to meet the requirements of native vegetation. The catchment EWRs are designed in such a way that if the longer duration LF3 occurs in the timing window of either LF1 or LF2, we would consider that LF1 and/or LF2 were also met in that year and would not need to be delivered in addition to LF3. Note for some catchments different large freshes were developed (e.g. a different LF3 specifically for Macquarie perch in the Murrumbidgee).

Similarly, for overbank flows, we considered alignment of the generic EWRs for native fish, native forest and woodland vegetation, non-woody wetland vegetation, waterbirds, frogs and ecosystem functions such as productivity. In the Gwydir catchment for example, there are 5 distinct overbank events (EWRs) recommended targeting different outcomes. As examples:

- Overbank 1 (OB1) is recommended 7–8 years in 10 from September–March for 2–8 months of habitat inundation, primarily targeting lignum regeneration and productivity but is also likely to benefit frogs, waterbirds and other vegetation communities.
- Overbank 2 (OB2) is set to occur less frequently (4–7 years in 10) and with slightly different timing (October–April), primarily targeting spawning of floodplain specialist fish species, river red gum, black box, coolabah and lignum maintenance, and productivity – but also delivering a range of other outcomes for waterbirds and other species.

The EWR characteristics were tailored to each catchment and in the case of large, complex catchments, to different areas of each catchment. So LF3 (in catchments that had this for vegetation objectives) may have a slightly different duration, timing or frequency in different catchments due to differences in hydrology, species composition, and characteristics of how rivers connect with low-lying wetlands and anabranches (filling and retention times), where such information was available.

Catchment-scale EWRs were developed in close consultation with environmental water managers, technical experts (e.g. fish and waterbird ecologists), asset managers and river operators. Analysis of observed and modelled flow time series, including the natural 'without development' flows was also used to inform the process (see Section 10.7).

10.5. Determining specific environmental water requirements for each planning unit

This step entailed applying and refining the catchment-scale EWRs to appropriately support each individual planning unit, and identifying specific magnitudes for each flow category. This involved:

- identifying the relevant catchment-scale EWRs for the planning unit by considering the identified environmental assets, objectives and targets for each planning unit (the process by which assets, objectives and targets were determined is described in more detail in Chapters 3–8 in Part B)

- for each planning unit, identifying the relevant flow rates for each of the flow categories. This was undertaken using multiple sources of information including floodplain inundation mapping, vegetation mapping, satellite imagery, channel survey data, aquatic habitat mapping, input from DPI Fisheries staff, river operations and environmental water managers, and analysis of flow data
- combining the catchment-scale EWRs with the flow rates to define the planning unit EWRs, taking into account any more accurate local knowledge on ecological needs and characteristics of the local flow regimes (e.g. typical duration of flow events)
- refining the specific EWRs using analysis of observed and modelled flows, repeating these steps as required.

10.6. Determining flow rates for environmental water requirements

Information available to assist in defining flow rates for EWRs is spatially variable across the NSW MDB. In each catchment the best available information has been used, in combination with the knowledge of environmental water managers, river operators, DPI Fisheries staff and other recognised experts. This process recognised the limitations of using single points, such as gauges, in a system to represent flow rates across an entire planning unit.

Specific flow rates were not developed for areas that are unregulated. Flows in these areas can only be protected through controls on extraction. The primary mode of water management is through rules in the WSPs that govern access to water for consumptive use. This means the water requirements of priority assets and functions are managed through the policy mechanisms that govern planned environmental water (PEW) in these areas. The process for developing recommendations for review of certain policy mechanisms to better support important environmental flows is described in Chapter 9.

A summary of the process and information sources used to develop flow rates for EWRs is provided below. For more detail refer to descriptions of the specific information sources used in each catchment.

10.6.1. Bankfull and in-channel flows

Bankfull flow rates were typically the first to be determined as they are important in determining flow rates for other flows. Bankfull flow rates were informed by a number of information sources and analyses including:

- river cross-sections including from gauge sites
- documented CTF levels for anabranches, wetlands and floodplain areas
- floodplain inundation models (where available)
- remote sensing imagery collected during observed high flow events (where available)
- knowledge of river operators and environmental water managers
- flow percentiles, as described in Alluvium (2010)
- NSW State Emergency Service flood warning levels
- other projects that have sought to define bankfull flow rates (e.g. Page et al. (2005) for the Murrumbidgee or Stewardson and Guarino (2017) for LTIM).

Once bankfull flow rates were identified, flow rates for in-channel flows were determined using the following information sources:

- guidelines provided by DPI Fisheries on the hydraulic requirements for in-channel flows to achieve fish outcomes, in combination with river cross-section data, rating curves and flow velocity recordings:
    - very low flows (or baseflows in some catchments) – ideally velocity 0.03–0.05 m/s to maintain water quality by preventing stratification in refuge pools (Mitrovic et al. 2003)
    - baseflows – ideally depth >0.3 m above CTF to enable small and moderate-bodied fish movement (Gippel 2013; O'Connor et al. 2015)
    - small freshes – ideally depth >0.5 m above CTF to enable large-bodied fish movement (Fairfull and Witheridge 2003; Gippel 2013; O'Connor et al. 2015)
    - large freshes – ideally depth >2 m above CTF and velocity ≥0.3–0.4 m/s to support flow specialist fish spawning and movement (Bice et al. 2017; Mallen-Cooper and Zampatti 2015; Marshall et al. 2016)
- analysis of channel form using the approach developed by Stewardson and Guarino (2017)
- local hydraulic habitat mapping describing flows required to inundate in-channel benches and woody habitats
- CTF thresholds for low-lying wetlands and anabranches that connect at below bankfull flow levels where this was available from grey literature, river operators, or environmental water managers
- flow analysis to identify the frequency of occurrence for flows of different magnitudes
- documented ecological outcomes from previous environmental watering actions
- local knowledge of river operators and environmental asset and water managers
- hydraulic models (only available in a very limited number of locations).

10.6.2. Overbank and wetland inundating flows

Overbank flows are typically for wetland and floodplain vegetation objectives, together with waterbird and broader riverine productivity objectives. Where floodplain inundation mapping was available, this was overlaid with vegetation mapping to identify the flow rates or volumes required to inundate specific vegetation communities.

Where inundation mapping was not available, flow rates or volumes were determined based on documented CTF levels, observed outcomes from past flow events (including assessment of satellite imagery), assessment of average recurrence intervals (ARI) of different flow rates, and using knowledge of river operators and environmental water managers.

10.7. Flow analysis to inform refinement of environmental water requirements

The EWRs developed though the processes described above were informed by and refined using analysis of observed and modelled flow time series. Within each planning unit, flow time series were collated for gauges considered to be representative of flows across the planning unit (Table C.10).

Table C.10 Flow data used to inform and refine EWRs

Flow data	Description of flow data
Observed flow data	Actual flows recorded at the gauge site. Length of record varies. Some gauges have long records (occasionally >100 years), including periods representing near 'natural' or 'pre-regulation' conditions, and more recent periods representing 'current' or 'post regulation' conditions. Gaps (short and long) are typically present in the record. Data typically obtained from the WaterNSW 'Latest Water Data' website or through DPE–Water's Hydstra database.
Modelled current conditions	A modelled representation of flow conditions at the site with current water infrastructure, extractions, water sharing policies and river operation practices in place. Inflows/water availability typically based on rainfall-runoff modelling for observed climate conditions, calibrated to match observed inflows to major rivers. Length of record typically 110–120 years, from about 1890–1895 to 2009–2016 depending on the river catchment. Continuous data with no gaps. Data typically obtained from DPE–Water or MDBA (Murray and Lower Darling).
Modelled without-development conditions	A modelled representation of flow conditions at the site with all water extractions and infrastructure removed. Best estimate of 'natural' or 'pre-development' conditions, whilst noting that rainfall-runoff modelling reflects developed catchment conditions (i.e. vegetation clearance, forestry, farm dams, etc.) Inflows/water availability typically based on rainfall-runoff modelling for observed climate conditions, calibrated to match observed inflows to major rivers. Length of record typically 110–120 years, from about 1890–1895 to 2009–2016 depending on the river catchment. Continuous data with no gaps. Data typically obtained from DPE–Water or MDBA (Murray and Lower Darling).

At most gauges all 3 types of flow time series were available. At a small number of gauge sites only one or 2 data types were available.

All available time series were used to inform and refine EWRs. This approach recognises that each of the data types have their strengths and weaknesses. For example, river system models, given their long record period, provide a useful basis for assessing EWRs against a range of climate conditions; however, can give a poor representation of low flow conditions (e.g. for the Barwon–Darling system see CSIRO (2008), Vertessy et al. (2019)). Observed flows on the other hand can have a limited length of record, gaps in the data, and uncertainties (e.g. some gauges do not effectively capture floodplain flows). EWR development was undertaken with an awareness of such limitations and used multiple sources of information to reduce such uncertainty.

Analytical tools were developed to characterise flow regimes at the selected gauges to inform EWRs (e.g. identify the typical timing/seasonality and duration of flow events), and also to assess the extent to which the proposed EWRs were met under modelled and observed conditions. In assessing EWRs, the tools identify events that either exceed the minimum flow (exceedance events) or are between the minimum and maximum flows (in-band events), for the required duration, within the timing window (if specified). Events may commence prior to the timing window, or cease after the timing window, so long as the required duration is met within the timing window. Similarly, if no timing window is specified, events may commence in the previous year, or end in the following year, so long as the required duration is achieved within the given year.

In assessing and refining the EWRs the following principles were applied:

1. **EWRs must be consistent with the local hydrology and achieved historically**
    - Hydrology varies significantly across the MDB. To ensure EWRs are realistic and achievable they must be consistent with the local hydrology; for example, the typical timing and duration of flows at a site.
    - EWRs seek to reinstate aspects of the historical flow regime that are critical to achieving the environmental objectives, or retain aspects of the current (or recent past) flow regime that are important.
    - Those EWRs that seek to reinstate aspects of the historical flow regime must either be assessed to have occurred under modelled without-development conditions or assessed to have occurred under observed flow conditions prior to major river regulation and extraction[10].
    - Those EWRs that seek to retain aspects of the current (or recent past) flow regime must either be consistent with modelled current conditions, and/or assessed to have occurred under observed flow conditions during a recent, relevant time period[10].
2. **EWRs may enhance current flows in modified systems, where appropriate**
    - In some situations, it may be appropriate to enhance the current flow regime to support existing environmental assets or values; for example, providing low flows in some regulated streams to provide drought refuge habitat for fish populations that have established in the regulated conditions. In these instances, the criteria under principle 1 may not be met, but the EWR should be achievable with management of environment water.
3. **Within a catchment, EWRs should follow a logic across and between planning units**
    - Within a catchment, EWRs across planning units will typically be achieved by the same flow events, taking into account tributary inflows, attenuation and losses through floodplain storage, evaporation and infiltration. Accordingly, there should be a logic or level of consistency in EWRs between planning units, whilst also recognising that geomorphology and ecosystems are spatially variable. This consistency and logic should also apply across and between connected catchments, especially at their junctions.

EWRs were assessed against these principles and refined where required in an iterative process.

10.8. Protection of ecologically important flow categories in unregulated planning units

Specific EWRs were not able to be set for all priority water-dependent environmental assets. In unregulated river systems, hydrological models do not typically exist with the same level of accuracy as regulated systems and there are often fewer (if any) gauges

[10] Except where there are recognised issues with the model data and insufficient observed data are available to effectively refine the EWRs.

in these areas. This makes setting EWRs challenging. In addition, water cannot be delivered through a regulating structure in these areas, so the most effective means of protecting environmentally important flows is through the rules in the catchment's unregulated WSP. In these instances, potential changes to the unregulated WSP were investigated to reduce extraction pressure on instream flows in planning units with moderate to high levels of impact and high ecological values within the next 5 years. These recommendations are outlined in Part B of the 9 NSW LTWPs.

Work completed as part of the NSW risk assessments[11] was used to help identify unregulated planning units whose flows are currently impacted by extraction pressure from existing water entitlements (DPIE–Water 2019).

For each planning unit that is unregulated or has significant unregulated sections, information is presented on the hydrology and the degree of alteration, by comparing flows under modelled near natural conditions (with no dams or water extractions) and flows under modelled current (post-development) conditions. Table C.11 describes how the hydrology changes are presented for each planning unit. In addition, flow estimates for the 80th percentile, 50th percentile, 20th percentile, 1.5 ARI, 2.5 ARI and 5 ARI are presented in the LTWPs for most of the unregulated planning units.

Table C.11 Key to hydrological alteration used in the NSW LTWPs

Key from DPIE–Water 2019		
L = Low: <20% difference (+/–) from modelled without development for the hydrologic metric		
M = Medium: 20–50% difference (+/–) from modelled without development for the hydrologic metric		
H = High: >50% difference (+/–) from modelled without development for the hydrologic metric		
N/A = no risk outcome or no hydrological modelling data available		
$^{+}$ increase from near-natural condition	$^{-}$ decrease from near-natural condition	^{0} no change from near-natural condition

Occasionally there was no gauge present in the planning unit. In these cases, a nearby gauge in another planning unit was used if the flows in the 2 systems were similar and they had similar levels of extraction. In areas where there are a number of tributaries that exist in a planning unit, but no main channel, the largest stream or the stream with the most entitlements on it will be used to estimate flows and extraction pressure for the entire planning unit. In other cases, planning units were not modelled at all as they either had few water entitlements in them (and therefore negligible extraction pressure) or their flows were associated with the regulated river.

To focus attention, areas that will most benefit from reviewing rules in the unregulated WSP to better protect environmentally important flows were considered before any recommendations were proposed. Table C.12 outlines all potential management strategies considered and how the relevant planning units were identified.

This approach is consistent with the NSW macro planning method for pools (NSW Office of Water 2011), which recommends that water access rules for in-river and off-river (wetland) pools be reviewed and alternative rules considered where moderate or high risks to instream environmental values are identified.

[11] NSW risk assessments were completed for each catchment as part of the NSW Water Resource Packages (DPIE–Water 2019a-i)

Table C.12 Potential management strategies to protect environmentally important flows in unregulated planning units and criteria for identifying key areas for them to be implemented in relevant unregulated WSPs

Potential management strategy	Purpose and description	When to consider a management strategy in a planning unit	Additional elements to consider
1. Investigate opportunities to reduce extraction pressure on in-channel flows in the planning unit within 5 years	To identify planning units that are impacted by extraction and are ecologically important. Relevant to CFs, low flows or baseflows, freshes.	• Medium (M) or High (H) degree of hydrological alteration to in-channel flows AND • M or greater consequence score OR • supports endangered native fish species OR • supports native fish objectives NF7, NF8 or NF9	
1A. Consider reviewing existing rules to ensure visible flow is maintained downstream of extraction points	To help relieve CF periods across the water source. Currently, in many cases, extraction can occur until there is no visible flow (i.e. until the stream stops flowing). For licences that have cease-to-pump (CtP) rules, these rules are sometimes referenced to a gauge that is distant from the pump site, so flow may cease at the pump site even when the reference gauge has flow.	• Criteria for management strategy (1) are met AND • M^+ OR H^+ degree of hydrological change to CF OR • M^- OR H^- degree of hydrological change to low flows or baseflows	This change should be considered both for licences with CtP rules and those that only have the 'no visible flow' CtP rules

Potential management strategy	Purpose and description	When to consider a management strategy in a planning unit	Additional elements to consider
1B. Where a CtP rule currently exists, consider reviewing the threshold	To help relive unnatural or detrimental CF periods and support more ecologically relevant low flows and baseflows.	• Criteria for (1) are met AND • CtP rule exists AND • M^+ OR H^+ degree of hydrological change to CF OR • M^- OR H^- degree of hydrological change to low flows or baseflows	
1C. Where no CtP rule currently exists, consider introducing a CtP rule (relating to a flow or water level gauge)	To help relive unnatural or detrimental CF periods and support more ecologically relevant low flows and baseflows.	• Criteria for (1) are met AND • CtP rule does not exist AND • M^+ OR H^+ degree of hydrological change to CF OR • M^- OR H^- degree of hydrological change to low flows or baseflows	

Potential management strategy	Purpose and description	When to consider a management strategy in a planning unit	Additional elements to consider
1D. Consider implementing a commence-to-pump threshold that is higher than the CtP threshold	This protects the initial flow to allow water quality to improve and provide movement and breeding opportunities for native fish and other aquatic biota.	• Criteria for (1) are met AND • M⁻ OR H⁻ degree of hydrological change to freshes	How many water access licences (WALs) exist in the planning unit, what volumes and where are they located across the water source? The hydrology of the water source (is it a high or a low flow system?) Events should be of sufficient magnitude to avoid adverse water quality incidents. This will require identification of refuge pools, work to estimate the flow requirements that are sufficient to replenish these pools and ensure there is sufficient dilution, and water quality monitoring to help establish and confirm these estimates
1E. Consider installing water level gauges at or near extraction sites	This would improve monitoring, compliance and effectiveness of rules in the unregulated WSP. May also improve equity of water sharing provisions across all WAL holders.	• Criteria for (1) are met AND • no gauge in the planning unit or limited flow data[12] OR • gauge is in an inappropriate location	

[12] Limited or no flow data exists when there is no gauge in the planning unit and it has an area factor >0.2 difference from 1, or the percentage of estimated data in the sequence is >5%

Potential management strategy	Purpose and description	When to consider a management strategy in a planning unit	Additional elements to consider
1F. Consider installing a river flow gauge or improving the gauging network	Enables flows to be set with a rule other than just the 'visible flow' rule.	• Criteria for (1) are met AND • no gauge in the planning unit or limited flow data[12] AND • H degree of hydrological change to in-channel flows	Median flows should be >10 ML/d to ensure there is enough flow in the river to be picked up by a river flow gauge Be selective based on known ecological information to support need for improved flow data
1G. Consider rostering landholder water access	Rostering take could involve an 'odds and evens' arrangement where half of licence holders are able to access water on one day and the other half on the next. This is to reduce the daily extraction pressure on smaller flows where a significant proportion of the daily flow could be pumped if all pumps were activated simultaneously. Rostering could be triggered at certain times, such as low flow months or ecologically significant months to support native fish populations.	• Criteria for (1) are met AND • low flow / baseflow / freshes = M^- OR H^- degree of hydro change AND • moderate / high/ very high consequence OR • NF7, NF8 or NF9 is relevant in the planning unit	Include a description of the low flow months (without development) How many WALs exist in the planning unit, what volumes and where are they located across the water source? The hydrology of the water source (is it a high or a low flow system?) Not relevant where WALs are distributed across different creeks in the planning unit

Potential management strategy	Purpose and description	When to consider a management strategy in a planning unit	Additional elements to consider
1H. Consider implementing total and/or individual daily extraction limits	Individual daily extraction limits (IDELs) would limit the amount of water a licence holder could take on any one day. Total daily extraction limits (TDELs) would limit the daily take for the zone. These limits could be set at different levels for different flow sizes, so the proportion of any flow taken is able to be better managed and highly impacted and important flow types could be preserved.	• Criteria for (1) are met AND • M^- OR H^- degree of hydrological change to low flows, baseflows, freshes, or overbanks AND • moderate / high/ very high consequence OR • NF7, NF8 or NF9 is relevant in the planning unit	How many WALs exist in the planning unit, what volumes and where are they located across the water source? The hydrology of the water source (is it a high or a low flow system?) Consider specifically what needs to be protected (i.e. objectives and EWRs) Size of overbanks and number and size of WALs could mean that pump capacity may provide sufficient limit of daily take Not relevant where WALs are distributed across different creeks in the planning unit
2. Consider targeted WAL purchases from willing sellers or the negotiation of enduring agreements with licence holders	For lagoon licences that are the target of environmental water, could provide more effective and efficient use of environmental water in lagoons.	• Criteria for (1) are met AND • H^- degree of hydrological change in any flow category AND • EF3 and/or EF7	Consider recommending if it helps achieve Basin Plan site-specific flow indicators (SFIs), even indirectly (e.g. for flows into the Barwon River)

Potential management strategy	Purpose and description	When to consider a management strategy in a planning unit	Additional elements to consider
	Less complex monitoring and compliance requirements.	• Off-channel pools are filled with environmental flows AND • off-channel pool is considered of high value AND • compliance and monitoring requirements are highly complicated AND • the licence holder is willing to sell or negotiate	
3. Use increased trade restrictions to protect sensitive water sources from greater impact		In rare occasions when: • there is currently allowance to trade in AND • the ecological value of the planning unit is high AND • the ecological value of the planning unit being traded out of is not higher	

Potential management strategy	Purpose and description	When to consider a management strategy in a planning unit	Additional elements to consider
4. Review conditions on larger instream storages	To help prevent low level weirs or dams impacting on threatened fish populations.	• There is a storage of 1,000 ML or greater AND • M OR H degree of hydrological change to CF, low flows, baseflows, freshes, or small overbanks AND • M or greater consequence score OR • NF7, NF8 or NF9 is relevant in the planning unit	This should include consideration of the need for environmental releases.
5. Consider introducing rules and/or amendments to WAL conditions that protect water for the environment that originates from held water entitlements and the environmental water allocation (EWA) as it enters unregulated streams and off-channel pools (wetlands)[13]	To protect all flow sizes and provide connectivity downstream of watered areas. Environmental water releases may trigger responses such as fish spawning and productivity increases, which makes the protection of this water downstream more valuable.	• All planning units that receive held environmental water and water from the EWAs.	The Matthews reports (2017a,b) noted that the protection of environmental flows is 'a precondition if the anticipated environmental benefits of the [Basin] plan are to be delivered'.
6. Consider restrictions on water extraction in planning units bordering the Barwon River when embargoes on take exist in the Barwon River	All flow categories	• All planning units that connect to the Barwon River	

[13] This is in line with the Basin Plan (Section 7.15(2)) requirement to protect delivered environmental water. It is also recommended by the Matthews reports (2017a,b).

Potential management strategy	Purpose and description	When to consider a management strategy in a planning unit	Additional elements to consider
7. Ensure compliance with WAL conditions	To ensure all flows are protected from unauthorised extraction for the environment and other users.	• All planning units	
8. As a minimum, maintain existing rules in the unregulated WSP to protect priority environmental assets and values	These rules include trade rules and extraction rules. This strategy is to ensure no reduction in protection. Changes may be made where recommended to increase protection.	• All planning units	
9. Monitor for changes in water demand and review access rules if usage increases or if the pattern of use changes	Patterns of usage and demand may change with changing crop choices and practices. This may alter the seasonality and volume of take and have differing impacts on different flows.	• All planning units	

Shortened forms

ARI	average recurrence interval
Basin Plan	Murray–Darling Basin Plan 2012
BF	baseflow
BK	bankfull
BWS	Basin-wide environmental watering strategy
CAMBA	China–Australia Migratory Bird Agreement
CF	cease-to-flow
CPOM	coarse particulate organic matter
CTF	commence-to-flow
CtP	cease-to-pump
DO	dissolved oxygen
DOC	dissolved organic carbon
the department	NSW Department of Planning and Environment
DPE	NSW Department of Planning and Environment
DPE–EHG	NSW Department of Planning and Environment – Environment and Heritage Group
DPIE–BCD	Biodiversity and Conservation Division of the former NSW Department of Planning, Industry and Environment
DPIE–Water	former NSW Department of Planning, Industry and Environment – Water
DPI Fisheries	NSW Department of Primary Industries Fisheries
EWA	environmental water allocation
EWR	environmental water requirement
GDE	groundwater-dependent ecosystem
JAMBA	Japan–Australia Migratory Bird Agreement
LF	large fresh
LTIM	Long Term Intervention Monitoring project
LTWP	NSW Long Term Water Plan
MDB	Murray–Darling Basin
MDBA	Murray–Darling Basin Authority
NSW	New South Wales
OB	overbank
PCT	plant community type
PEF	priority ecosystem function
PEW	planned environmental water
RoKAMBA	Republic of Korea–Australia Migratory Bird Agreement
SF	small fresh
VF	very low flow
WAL	water access licence
WL	wetland inundating flow
WRP	water resource plan
WRPA	water resource plan area
WSP	water sharing plan

Glossary

Bankfull flow (BK)	River flows at maximum channel capacity with little overflow to adjacent floodplains. These flows engage the riparian zone, anabranches, flood runners and wetlands located within the meander train. They inundate all in-channel habitats including benches, snags and backwaters.
Baseflow (BF)	Reliable background flow levels within a river channel that are generally maintained by seepage from groundwater storage, but also by surface inflows. They typically inundate geomorphic units such as pools and riffle areas.
Cease-to-flow (CF)	The absence of flowing water in a river channel that leads to partial or total drying of the river channel. Streams contract to a series of isolated pools.
Colonial-nesting waterbird	Colonial-nesting waterbird species can nest in very large numbers in single or multi- species colonies. This group usually obtain most of their food from aquatic sources such as fish, invertebrates and amphibians. In the MDB colonial-nesting species include members of 6 waterbird families: Ardeidae (egrets and herons), Threskiornithidae (ibises and spoonbills), Phalacrocoracidae (cormorants), Anhingidae (darter) and Pelecanidae (pelican).
Dissolved organic carbon (DOC)	A measurement of the amount of carbon from organic matter that is soluble in water. DOC is transported by water from floodplains to river systems and is a basic building block available to bacteria and algae that are food for microscopic animals that are in turn consumed by fish larvae, small-bodied fish species, yabbies and shrimp. DOC is essential for building the primary food webs in rivers and ultimately generates a food source for large-bodied fish like Murray cod and golden perch, and predators such as waterbirds.
Duration	The minimum duration of river flows required to achieve the stated environmental objective (sometimes written more fully as minimum duration). Longer flow durations are generally desirable and will typically deliver better outcomes (except where explicitly stated). For volume-based events the duration may represent the duration that standing water should persist in the wetlands, recognising that gauged inflows may occur for a shorter time.
Ecological objective	Objective for the protection and/or restoration of an environmental asset or ecosystem function. Objectives are set for all priority environmental assets and PEFs, and have regard to the outcomes described in the BWS.
Ecological processes	The biological, geochemical and physical actions and interactions that operate within an ecosystem and contribute to ecosystem functions.
Ecological target	Level of measured performance that must be met to achieve the defined objective. The targets in the LTWPs are SMART (specific, measurable, achievable, realistic, time-bound) and are able to demonstrate progress towards the objectives and the outcomes described in the BWS.
Ecosystem function	The processes and interactions occurring within and between ecosystems that sustain plant and animal communities and contribute to the state, integrity and regulation of an ecosystem.
Environmental asset	The physical places that make up an ecosystem.

Environmental water	Water for the environment. It serves a multitude of benefits not only to the environment, but to communities, industry and society. It includes water held in reservoirs (held environmental water) or protected from extraction from waterways (planned environmental water) for the purpose of meeting the water requirements of water-dependent ecosystems.
Environmental water requirement (EWR)	An environmental water requirement describes the characteristics of a flow event (e.g. magnitude, duration, timing, frequency, and maximum dry period) within a particular flow category (e.g. small fresh), that are required for that event to achieve a specified ecological objective or set of objectives (e.g. to support fish spawning and in-channel vegetation). For each flow category (e.g. baseflows or small freshes), there may be multiple EWRs (small fresh 1, 2, etc.), each aimed at meeting specific objectives, differing in duration, timing, frequency, etc. and described at a specific gauge. Achievement of each of the EWRs will be required to achieve the full set of ecological objectives for a planning unit.
Flow category	The type of flow in a river defined by its magnitude (e.g. bankfull). See Section 10.2.2 and Table C.1 above for definitions of flow categories.
Flow category code	Each EWR is given a specific code that abbreviates the flow category name (e.g. SF1 – small fresh 1). This code is used to link environmental objectives and EWRs.
Flow rate	The daily discharge at a specified gauge (usually measure in megalitres per day).
Flow regime	The pattern of flows in a waterway over time that will influence the response and persistence of plants, animals and their ecosystems.
Flow volume	The cumulative volume of daily discharge over a specified time required to achieve the relevant environmental objectives, measured at a specified gauge. Flow volumes are typically used in large wetland systems or terminal wetlands.
Frequency	The frequency at which the flow event (threshold, timing and duration) should re-occur within a 10-year period to achieve the specified environmental objectives, recognising that more frequent flows will likely deliver better outcomes. Where a range of frequencies is indicated (e.g. 3–5 years in 10), the lower number refers to the minimum frequency required to achieve the target ecological objectives, while the higher number indicates the preferred frequency, including supporting the recovery of degraded fish or waterbird populations or vegetation communities. The range may also reflect uncertainty in the knowledge base. Note that clustering of events in multiple successive years in line with natural flow cues is often ecologically desirable and should be considered in water-use planning. Clustering of events is important for the recovery and recruitment of native fish, vegetation and waterbird populations. Frequency should be considered together with the maximum inter-event period when assessing the demand/urgency of each EWR in annual water delivery planning.
Gauge	The gauging station that best represents inflows and flows through the planning unit, for the purpose of the respective EWR. For the purpose of assessing EWRs, flow recorded at this gauge should be used.

Groundwater	Water located below the earth's surface in soil pore spaces and in the fractures of rock formations. Groundwater is recharged from, and eventually flows to the surface naturally.
Hydro-ecological functional group	A set of species, or collection of organisms, that respond to flow conditions in a similar way.
Hydrograph	A graph showing the rate of flow and/or water level over time past a specific point in a river. Typically expressed in megalitres per day (ML/d).
Hydrological connectivity	The linking of natural aquatic environments.
Hypoxic blackwater	Occurs when dissolved oxygen (DO) levels fall below the level needed to sustain native fish and other water-dependent species. Bacteria that feed on DOC use oxygen in the water. When they multiply rapidly their rate of oxygen consumption can exceed the rate at which oxygen can be dissolved in the water. As a result, oxygen levels fall and a hypoxic (low oxygen) condition occurs. DO is measured in milligrams per litre (mg/L). Generally native fish begin to stress when DO levels fall below 4 mg/L. Fish mortality occurs when DO levels are <2 mg/L.
Large fresh (LF)	High-magnitude flow pulse that remains in-channel. These flows may engage flood runners with the main channel and inundate low-lying wetlands. They connect most in-channel habitats and provide partial longitudinal connectivity, as some low-level weirs and other in-channel barriers may be drowned out.
Lateral connectivity	The flow linking river channels and the floodplain.
Long Term Water Plan (LTWP)	A component of the Murray–Darling Basin Plan, Long Term Water Plans give effect to the BWS (MDBA 2014) relevant for each river system and guide the management of water over the longer term. These plans identify the environmental assets that are dependent on water for their persistence, and match that need to the water available to be managed for or delivered to them. The plans set objectives, targets and watering requirements for key plants, waterbirds, fish and ecosystem functions. DPE–EHG developed 9 plans for river catchments across NSW, with objectives for 5, 10 and 20-year timeframes.
Longitudinal connectivity	The consistent downstream flow along the length of a river.
Maximum inter-flow or inter-event period	The maximum time between successive events before a significant decline in condition, survival or viability is likely to occur. Wherever possible, this period should not be exceeded. Annual planning of environmental water should consider placing priority on EWRs that are approaching (or have exceeded) the maximum inter-event period.
Overbank (OB) flow	Flows that spill over the riverbank or extend to floodplain surface flows.
Planning unit	A division of a WRPA based on water requirements (in catchment areas in which water is actively managed), or a sub-catchment boundary (all other areas).
Priority ecosystem function (PEF)	An ecological function defined by the Basin Plan (Schedule 9) that can be affected by held environmental water.

Priority environmental asset	A place meeting the criteria set by the Basin Plan (Schedule 8) that is water-dependent and can be affected by held environmental water.
Recruitment	Successful development and growth of offspring; such that they have the ability to contribute to the next generation.
Refuge pool	Sections of river channel or waterholes that are deep relative to the rest of the channel that retain water for longer periods can provide refuge for aquatic biota during periods of no flow. Refugial waterholes and lakes can also be present in floodplain areas. Not only do these features provide refugial habitat and nursery sites for aquatic life, they are important sinks for nutrients and DOC cycling within the riverine environment.
Refugium	An area in which a population of plants or animals can survive through a period of decreased water availability. Plural is refugia.
Regulated river	A river gazetted under the *NSW Water Management Act 2000.* Flow is largely controlled by major dams, water storages and weirs. River regulation brings more reliability to water supplies but has interrupted the natural flow characteristics and regimes required by native fish and other plants and animals to breed, feed and grow.
Riffle	A rocky or shallow part of a river where river flow is rapid and broken.
Riparian	The part of the landscape adjoining rivers and streams that has a direct influence on the water and aquatic ecosystems within them.
River cross-section	The profile, taken sideways, of a river's channel at points in the river's course.
Small fresh (SF)	Low-magnitude in-channel flow pulse. Unlikely to drown out any significant barriers but can provide limited connectivity and a biological trigger for animal movement.
Substrate	A habitat surface such as a stream bed.
Surface water	Water that exists above the ground in rivers, streams, creeks, lakes and reservoirs. Although separate from groundwater, they are interrelated and over extraction of either will impact on the other.
Timing	The required timing (or season, typically expressed as a range of months within the year) for a flow event to achieve the specified ecological objective(s) of the EWR. In some cases, a preferred timing is provided, along with a note that the event may occur at 'anytime'. This indicates that ecological objectives may be achieved outside the preferred timing window, but perhaps with sub-optimal outcomes. In these instances, for the purposes of managing and delivering environmental water, the preferred timing should be used to give greater confidence in achieving ecological objectives. Natural events may occur at other times and still achieve ecological objectives.
Unregulated river	A waterway where flow is mostly uncontrolled by dams, weirs or other structures.
Very low flow (VF)	Small flow in the very low flow class that joins river pools, thus providing partial or complete connectivity in a reach. These flows can improve DO saturation and reduce stratification in pools.
Water access licence (WAL)	In water sharing plan areas, water access licences permit the licence holder to take water from a specified water source in accordance with the licence.

Water-dependent	An ecosystem or species that depends on periodic or sustained inundation, waterlogging or significant inputs of water for natural functioning and survival.
Wetland inundating flow (WL)	Flows that fill wetlands at flow rates below bankfull or via regulating structures over weeks or sometimes months (i.e. longer than a typical fresh/pulse), or flows that are required to inundate wetlands in areas where there are very shallow channels or no discernible channels exist (e.g. terminal wetlands).

References

Adams SB and Warren M (2005) ‘Recolonization by warmwater fishes and crayfishes after severe drought in upper Coastal Plain hill streams’, *Transactions of the American Fisheries Society*, 134:1173–1192.

Alluvium (2010) *Key ecosystem functions and their environmental water requirements*, report by Alluvium for Murray–Darling Basin Authority, Canberra.

Amoros C and Bornette G (2002) ‘Connectivity and biocomplexity in waterbodies of riverine floodplains’, *Freshwater Biology*, 47:761–776.

Amos C (2017) ‘Response of frogs to environmental factors at multiple scales in the Lachlan Catchment of New South Wales’, PhD thesis, Charles Sturt University.

Amtstaetter F, O’Connor J and Pickworth A (2016) ‘Environmental flow releases trigger spawning migrations by Australian grayling *Prototroctes maraena*, a threatened, diadromous fish’, *Aquatic Conservation: Marine and Freshwater Ecosystems*, 26:35–43.

Anstis M (2017) *Tadpoles and frogs of Australia*, New Holland Publishers Pty Limited.

Arthington AH, Balcombe SR, Wilson GA, Thoms MC and Marshall JC (2005) ‘Spatial and temporal variation in fish assemblage structure in isolated waterholes during the 2001 dry season of an arid-zone river, Cooper Creek, Australia’, *Marine and Freshwater Research*, 56:25–35.

Baldwin DS, Colloff MJ, Mitrovic SM, Bond NR and Wolfenden B (2016) ‘Restoring dissolved organic carbon subsidies from floodplains to lowland river food webs: a role for environmental flows?’ *Marine and Freshwater Research*, 67:1387–1399.

Baldwin DS, Rees GN, Wilson JS, Colloff MJ, Whitworth KL, Pitman TL and Wallace TA (2013) ‘Provisioning of bioavailable carbon between the wet and dry phases in a semi-arid floodplain’, *Oecologia*, 172:539–550.

Ballinger AA and Lake PS (2006) ‘Energy and nutrient fluxes from rivers and streams into terrestrial food webs’, *Marine and Freshwater Research*, 57:15–28.

Ballinger AA and Mac Nally RC (2006) ‘The landscape context of flooding in the Murray–Darling Basin’, *Advances in Ecological Research*, 39:85–105.

Barrett R, Nielsen DL and Croome R (2010) ‘Associations between the plant communities of floodplain wetlands, water regime and wetland type’, *River Research and Applications*, 26(7):866–876.

Baumgartner L (2011) *Establishment of a long term environmental watering and monitoring regime to improve ecological condition in the Wakool-Yallakool River system*, special project proposal prepared by NSW Department of Primary Industries and Murray–Daring Catchment Management Authority, NSW Department of Primary Industries, Narrandera.

Baumgartner LJ, Conallin J, Wooden I, Campbell B, Gee R, Robinson WA and Mallen-Cooper M (2014) ‘Using flow guilds of freshwater fish in an adaptive management framework to simplify environmental flow delivery for semi-arid riverine systems’, *Fish and Fisheries*, 15(3):410–427, https://doi.org/10.1111/faf.12023.

Bice CM, Zampatti BP and Mallen-Cooper M (2017) ‘Paired hydraulically distinct vertical-slot fishways provide complementary fish passage at an estuarine barrier’, *Ecological Engineering*, 98:246–256.

Bino G, Kingsford RT, Brandis K and Porter J (2014) *Setting waterbird objectives and priorities for the Basin-wide environmental watering strategy*, report to the Murray–Darling Basin Authority, Centre for Ecosystem Science, University of New South Wales.

Bino G, Sisson SA, Kingsford RT, Thomas RF and Bowen S (2015) 'Developing state and transition models of floodplain vegetation dynamics as a tool for conservation decision-making: a case study of the Macquarie Marshes Ramsar wetland', *Journal of Applied Ecology*, 52:654–664.

Blanch SJ, Walker KF and Ganf G (2000) 'Water regimes and littoral plants in four weir pools of the River Murray, Australia', *Regulated Rivers: Research and Management*, 16(5):445–456.

Boulton AJ (2003) 'Parallels and contrasts in the effects of drought on stream macroinvertebrate assemblages', *Freshwater Biology*, 48(5):1173–1185.

Bowen S and Simpson S (2010a) *Changes in extent and condition of floodplain wetland vegetation communities in the Gwydir Wetlands and floodplain 1996–2009*, NSW Department of Environment and Climate Change, Sydney.

Bowen S and Simpson SL (2010b) *Changes in extent and condition of the vegetation communities of the Macquarie Marshes floodplain 1991–2008*, final report for NSW Wetland Recovery Program, Department of Environment, Climate Change and Water, Sydney.

Brandis KJ, Spencer J, Wolfenden B and Palmer D (2020) 'Avian-botulism risk in waterbird breeding colonies and implications for environmental water management', *Marine and Freshwater Research*, 71:179–190.

Brandis K and Bino G (2016) *A review of the relationships between flow and waterbird ecology in the Condamine–Balonne and Barwon–Darling River Systems*, report prepared for the Murray–Darling Basin Authority by Centre for Ecosystem Science, University of New South Wales, Sydney.

Brandis K (2010) 'Colonial waterbird breeding in Australia: wetlands, water requirements and environmental flows', PhD thesis, Australian Wetlands and Rivers Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney.

Brandis K (2017) *High resolution monitoring of waterbird colonies in the Macquarie Marshes*, final report to the Commonwealth Environmental Water Office 2017, Centre for Ecosystem Science, University of New South Wales, Sydney.

Brandis K, Roshier D and Kingsford RT (2009) *Environmental Watering for Waterbirds in The Living Murray Icon Sites — A literature review and identification of research priorities relevant to the environmental watering actions of flow enhancement and retaining floodwater on floodplains*, report to the Murray–Darling Basin Authority, Canberra.

Brandis K, Kingsford RT, Ren S and Ramp D (2011) 'Crisis Water Management and Ibis Breeding at Narran Lakes in Arid Australia', *Environmental Management*, 48(3):489–498.

Brierley GJ and Fryirs KA (2005) *Geomorphology and River Management: Applications of the River Styles Framework*, Blackwell Publishing, Carlton, VIC.

Bunn SE and Arthington AH (2002) 'Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity', *Environmental Management*, 30:492–507.

Burns A and Walker KF (2000) 'Effects of water level regulation on algal biofilms in the River Murray, South Australia', *Regulated Rivers: Research and Management*, 16:433–444.

Carrick R (1962, 'Breeding, movement and conservation of ibises (Threskiornithidae) in Australia', *CSIRO Wildlife Research*, 7:71–90.

Casanova MT (2015) *Review of Water Requirements for Key Floodplain Vegetation for the Northern Basin: Literature review and expert knowledge assessment*, report to the Murray–Darling Basin Authority, Charophyte Services, Lake Bolac.

Catford JA, Downes BJ, Gippel CJ and Vesk PA (2011) 'Flow regulation reduces native plant cover and facilitates exotic invasion in riparian wetlands', *Journal of Applied Ecology*, 48:432–442.

Catterall CP, Lynch RJ and Jansen A (2006) 'Riparian wildlife and habitats', in Lovett S and Price P (eds), *Principles for Riparian lands Management*, Land and Water Australia, Canberra, pp.141–158.

CSIRO (2008) *Water availability in the Barwon–Darling*, report to the Australian Government from the CSIRO Murray–Darling Basin Sustainable Yields Project, CSIRO, Australia.

Cunningham SC, Read J, Baker PJ and Mac Nally R (2007) 'Quantitative assessment of stand condition and its relationship to physiological stress in stands of *Eucalyptus camaldulensis* (Myrtaceae) in southeastern Australia', *Australian Journal of Botany*, 55:692–699.

Davie AW and Mitrovic SM (2014) 'Benthic algal biomass and assemblage changes following environmental flow releases and unregulated tributary flows downstream of a major storage', *Marine and Freshwater Research*, 65:1059–1071.

Doody TM, Barron OV, Dowsley K, Emelyanova I, Fawcett J, Overton IC and Warren G (2017) 'Continental mapping of groundwater dependent ecosystems: A methodological framework to integrate diverse data and expert opinion', *Journal of Hydrology: Regional Studies*, 10:61–81

DPI (NSW Department of Primary Industries) (2013) 'Flows for fish recruitment in the Barwon-Darling River', unpublished final report prepared for the Murray–Darling Basin Authority, NSW Department of Primary Industries, Armidale.

DPI (2015) *Fish and flows in the Northern Basin: responses of fish to changes in flows in the Northern Murray–Darling Basin*, report prepared for the Murray–Darling Basin Authority by the NSW Department of Primary Industries, Tamworth

DPIE–EES (NSW Department of Planning, Industry and Environment – Environment, Energy and Science) (2020) 'Chapter 2: Defining water-dependent assets and values', *NSW Long Term Water Plans: Background information, A description of the development of the nine LTWPs in NSW,* NSW Department of Planning, Industry and Environment.

DPIE–Water (NSW Department of Planning, Industry and Environment – Water) (2019) documents a – i.

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

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

Gippel CJ (2013) *Assessment of the hydraulics of the Little Murray River Weir Pool under alternative operating scenarios*, Fluvial Systems Pty Ltd, Stockton, Goulburn-Murray Water, Shepparton, January.

Górski K, Buijse AD, Winter HV, De Leeuw JJ, Compton TJ, Vekhov DA, Zolotarev DV, Verreth JAJ and Nagelkerke LAJ (2013) 'Geomorphology and flooding shape fish distribution in a large-scale temperate floodplain', *River Research and Applications*, 29(10):1226–1236.

Growns I (2004) 'A numerical classification of reproductive guilds of the freshwater fishes of southeastern Australia and their application to river management', *Fisheries Management and Ecology*, 11:369–377.

Hancock PJ and Boulton AJ (2008) 'Stygofauna biodiversity and endemism in four alluvial aquifers in eastern Australia', *Invertebrate Systematics*, 22:117–126.

Hancock PJ, Boulton AJ and Humphreys WF (2005) 'Aquifers and hyporheic zones: Towards an ecological understanding of groundwater', *Hydrogeology Journal*, 13:98–111.

Higgins PJ and Davies SJJF (eds) (1996) *Handbook of Australian, New Zealand and Antarctic Birds, Volume 3: Snipe to Pigeons*, Oxford University Press, Melbourne.

Hose GC, Sreekanth J, Barron O and Pollino C (2015) *Stygofauna in Australian Groundwater Systems: Extent of knowledge*, report to the Australian Coal Association Research Program (ACARP), Canberra: CSIRO.

Humphreys WF (2006) 'Aquifers: the ultimate groundwater-dependent ecosystems', *Australian Journal of Botany*, 54:115–132.

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

Humphries P, King AJ and Koehn JD (1999) 'Fish, flows and floodplains: links between freshwater fish and their environment in the Murray–Darling River system, Australia', *Environmental Biology of Fishes*, 56:129–151.

Jenkins K and Boulton A (2003) 'Connectivity in a dryland river: short-term aquatic microinvertebrate recruitment following floodplain inundation', *Ecology*, 84:2708–2723.

Johnson M, Reich P and Mac Nally R (2007) 'Bird assemblages of a fragmented agricultural landscape and the relative importance of vegetation structure and landscape pattern', *Wildlife Research*, 34:185–193.

Keith DA, Orschega C, Simpson CC, Clarke PJ, Hughes L, Kennelly S, Majora RE, Soderquista TR, Wilson AL and Bedward M (2009) 'A new approach and case study for estimating extent and rates of habitat loss for ecological communities', *Biological Conservation,* 142(7):1469–1479.

Kingsford RT and Auld KM (2005) 'Waterbird breeding and environmental flow management in the Macquarie Marshes, arid Australia', *River Research and Applications*, 21:187–200.

Kingsford RT and Thomas RF (2004) 'Destruction of wetlands and waterbird populations by dams and irrigation on the Murrumbidgee River in arid Australia', *Environmental Management*, 34:383–396.

Kingsford RT (2000) 'Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia', *Austral Ecology*, 25:109–127.

Langhans S and Tockner K (2006) 'The role of timing, duration, and frequency of inundation in controlling leaf litter decomposition in a river-floodplain ecosystem (Tagliamento, northeastern Italy)', *Oecologia*, 147(3):501–509.

Lloyd LN, Puckridge JT and Walker KF (1991) 'The significance of fish populations in the Murray–Darling system and their requirements for survival', in *Conservation in*

Management of the River Murray System, Dendy T and M Coombe (eds), Department of Environment and Planning, Adelaide, S.A.

Lytle DA and Poff NL (2004) 'Adaptation to natural flow regimes', *Trends in Ecology and Evolution*, 19:97–100.

Mac Nally R, Cunningham SC, Baker PJ, Horner GJ and Thomson JR (2011) 'Dynamics of Murray–Darling floodplain forests under multiple stressors: The past, present, and future of an Australian icon', *Water Resources Research*, 47:W00G05.

Magrath MJL (1991) *Waterbird Breeding in the Narran Wetlands*, Department of Water Resources, November 1991.

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

Mallen-Cooper M and Zampatti B (2015) *Rethinking the Natural Flow Paradigm in the Murray–Darling Basin*, Fishway Consulting Services.

Marchant S and Higgins PJ (eds) (1990) *Handbook of Australian, New Zealand and Antarctic birds, Volume 1: Ratites to Ducks*, Oxford University Press, Melbourne.

Marchant S and Higgins PJ (eds) (1993) *Handbook of Australian, New Zealand and Antarctic Birds, Volume 2: Raptors to Lapwings*, Oxford University Press, Melbourne.

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

McGinness HM, Arthur AD and Reid JRW (2010) 'Woodland bird declines in the Murray–Darling Basin: are there links with floodplain change?', *The Rangeland Journal*, 32:315–327.

McGinness H, Brandis KJ, Robinson F, Piper M, O'Brien L, Langston A, Hodgson J, Wenger L, Martin J, Bellio M, Callaghan D, Webster E, Francis F, McCann J and Lyons M (2019) *Murray–Darling Basin Environmental Water Knowledge and Research Project – Waterbird Theme Research Report*, report prepared for the Department of the Environment and Energy, Commonwealth Environmental Water Office by CSIRO and La Trobe University, Centre for Freshwater Ecosystems, CFE, https://doi.org/10.26181/5d2eb0ed77159.

MDBA (Murray–Darling Basin Authority) (2014) *Basin-wide environmental watering strategy*, MDBA Publication No 20/14, Murray–Darling Basin Authority for and on behalf of the Commonwealth of Australia, 2014.

MDBA (2019) *Basin-wide environmental watering strategy*, second edition, Murray–Darling Basin Authority, Canberra.

MDBA (2012a) *Assessment of environmental water requirements for the proposed Basin Plan*, series of 24 reports, Murray–Darling Basin Authority, Canberra, www.mdba.gov.au/what-we-do/basin-plan/development/bp-science/assessing-environmental-water-requirements.

MDBA (2012b) *Hydrologic modelling to inform the proposed Basin Plan: methods and results*, MDBA publication no: 17/12, Murray–Darling Basin Authority, Canberra, www.mdba.gov.au/what-we-do/basin-plan/development/bp-science/assessing-environmental-water-requirements.

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

Mitrovic SM, Hardwick L and Dorani F (2010) 'Use of flow management to mitigate cyanobacterial blooms in the Lower Darling River, Australia', *Journal of Plankton Research*, 33(2):229–241.

Mora-Gomez J, Elosegi A, Mas-Marti E and Romani AM (2015) 'Factors controlling seasonality in leaf-litter breakdown in a Mediterranean stream', *Freshwater Science,* 34(4):1245–1258.

Naiman RJ, Decamps H and McClain ME (2010) *Riparia: Ecology, Conservation, and Management of Streamside Communities*, Elsevier Academic Press.

NOW (NSW Office of Water) (2011, *Macro water sharing plans – the approach for unregulated rivers, Access and trading rules for pools*, NSW Office of Water, August 2011.

NSW BioNet (2016) *NSW BioNet*, data downloaded 2–3 May 2016, www.bionet.nsw.gov.au.

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

Ocock JF (2013) *Linking frogs with flow: Amphibian community response to flow and rainfall on a dryland floodplain wetland*, University of New South Wales.

Ocock JF, Kingsford RT, Penman TD and Rowley JJ (2014) 'Frogs during the flood: differential behaviours of two amphibian species in a dryland floodplain wetland', *Austral Ecology*, 39(8):929–940.

Ocock JF, Kingsford RT, Penman TD and Rowley JJ (2016) 'Amphibian abundance and detection trends during a large flood in a semi-arid floodplain wetland', *Herpetological Conservation and Biology*, 11:408–425.

Ocock J, Spencer J, Amos C and Walcott A (2018) *Monitoring manual OEH environmental water program Standard methods – frogs*, NSW Office of Environment and Heritage.

Odum EP (1953) *Fundamentals of Ecology* (first ed.), WB Saunders Co, Philadelphia, USA.

OEH (Office of Environment and Heritage) (2014) *Native Vegetation Information Strategy 2014–2018*, NSW Office of Environment and Heritage, July 2014, www.environment.nsw.gov.au/resources/vegetation/Information%20Strategy/140560-NV-info-strategy.pdf (PDF 595KB).

OEH (2017) *Vegetation Information System: Classification*, NSW Office of Environment and Heritage, www.environment.nsw.gov.au/research/Visclassification.htm

Overton IC, Colloff MJ, Doody TM, Henderson B and Cuddy SM (2009) *Ecological Outcomes of Flow Regimes in the Murray–Darling Basin*, report prepared for the National Water Commission by CSIRO Water for a Healthy Country Flagship, 422 pp., CSIRO, Canberra.

Page K, Read A, Frazier P and Mount N (2005) 'The effect of altered flow regime on the frequency and duration of bankfull discharge: Murrumbidgee River, Australia', *River Research and Applications*, 21(5):567–578.

Platteeuw M, Kiss JB, Zhmud MY and Sadoul N (2004) *Colonial waterbirds and their habitat use in the Danube Delta: as an example of a large-scale natural wetland*, RIZA report 2004,002, Lelystad, the Netherlands, Institute for Inland Water Management and Waste Water Treatment (RIZA).

Poff NL and Zimmerman JKH (2010) 'Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows', *Freshwater Biology*, 55(1):194–205.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE and Stromberg JC (1997) 'The natural flow regime: a paradigm for river conservation and restoration', *Bioscience*, 47(11):769–784.

Reid MA and Capon S (2011) 'Role of the soil seed bank in vegetation responses to environmental flows on a drought-affected floodplain', *River Systems,* 19(3):249–259.

Ren S, Kingsford RT and Thomas RF (2010) 'Modelling flow to and inundation of the Macquarie Marshes in arid Australia', *Environmetrics*, 21:549–561.

Roberts J and Marston F (2011) *Water regime for wetland and floodplain plants: a source book for the Murray–Darling Basin*, National Water Commission, Canberra.

Roberts J, Colloff M and Doody T (2016) 'Riverine vegetation of inland south-eastern Australia', in: *Vegetation of Australian Riverine Landscapes, Biology, ecology and management*, Capon S, James C and Reid M (eds), CSIRO Publishing, Clayton South, VIC.

Robertson AI, Bacon P and Heagney G (2001) 'The response of floodplain primary production to flood frequency and timing', *Journal of Applied Ecology*, 38:126–136.

Rogers K (2011) 'Vegetation', in *Floodplain Wetland Biota in the Murray–Darling Basin: Water and Habitat Requirements*, Rogers K and TJ Ralph (eds), CSIRO Publishing, Collingwood, pp.17–82.

Rolls RJ, Growns IO, Khan TA, Wilson GG, Ellison TL, Prior A and Waring CC (2013) 'Fish recruitment in rivers with modified discharge depends on the interacting effects of flow and thermal regimes', *Freshwater Biology*, 58(9):1804–1819.

Ryder DS (2004) 'Response of epi xylic biofilm metabolism to water level variability in a regulated floodplain river', *Journal of the North American Benthological Society*, 23:214–223.

Schmutz S and Moog O (2018) 'Dams: Ecological Impacts and Management', in *Riverine Ecosystem Management, Aquatic Ecology Series*, vol 8, Schmutz S and Sendzimir J (eds), Springer, Cham.

Scott A (1997) *Relationship between waterbird ecology and environmental flows in the Murray–Darling Basin*, CSIRO Land and Water technical report 5–97, Canberra.

Scott A and Grant T (1997) *Impacts of water management in the Murray–Darling Basin on the platypus (Ornithorhynchus anatinus) and the water rat (Hydromys chrysogaster),* Technical Report 23/97, CSIRO Land and Water, Canberra, Australia.

Serena M and Grant TR (2017) 'Effect of flow on platypus (*Ornithorhynchus anatinus*) reproduction and related population processes in the upper Shoalhaven River', *Australian Journal of Zoology*, 65(2):130–139.

Serena M and Williams GA (2010) *Conserving platypus and water-rats: Information and guidelines*, Australian Platypus Conservancy, Wiseleigh, Australia.

Sheldon F and Thoms MC (2006) 'In-channel geomorphic complexity: The key to the dynamics of organic matter in large dryland rivers?', *Geomorphology*, 77:270–285.

Southwell MR and Thoms MC (2011) 'Patterns of nutrient concentrations across multiple floodplain surfaces on a large dryland river system', *Geographical Research*, doi: 10.11111/j.1745-5871.2011.00699.x.

Spencer J (2017) *Evaluation of colonial waterbird breeding in NSW Murray–Darling Basin: 2006–16*, NSW Office of Environment and Heritage.

Spencer JA (2010) *Historical records of waterbirds and fish populations in the Gwydir wetlands*, final report for the NSW Wetland Recovery Program, Rivers and Wetlands Unit, NSW Department of Environment and Climate Change, Sydney.

Stanford JA and Ward JV (1993) 'An Ecosystem Perspective of Alluvial Rivers: Connectivity and the Hyporheic Corridor', *Journal of the North American Benthological Society*, 12:48–60.

Stewardson MJ and Guarino F (2017) *2015–16 Basin scale evaluation of Commonwealth environmental water — Hydrology*, final report prepared for the Commonwealth Environmental Water Office by The Murray–Darling Freshwater Research Centre, MDFRC Publication 142/2017, October 2017, 45 pp. plus annex.

Tabacchi E, Lambs L, Guilloy H, Planty-Tabacchi A-M, Muller E and Décamps H (2000) 'Impacts of riparian vegetation on hydrological processes', *Hydrological Processes*, 14(16–17):2959–2976.

Taft OW, Colwell MA, Isola CR and Safran RJ (2002) 'Waterbird responses to experimental drawdown: implications for the multispecies management of wetland mosaics', *Journal of Applied Ecology*, 39:987–1001.

Thapa R, Thoms M and Parsons M (2016) 'An adaptive cycle hypothesis of semi-arid floodplain vegetation productivity in dry and wet resource states', *Ecohydrology*, 9(1):39–51.

Thomas R, Bowen S, Simpson S, Cox S, Sims N, Hunter S and Lu Y (2010) Inundation response of vegetation communities of the Macquarie Marshes in semi-arid Australia', in *Ecosystem Response Modelling in the Murray–Darling Basin*, N Saintilan and I Overton (eds), CSIRO Publishing, Melbourne, pp.137–150.

Thomas R, Kingsford R, Lu Y and Hunter S (2011) 'Landsat mapping of annual inundation (1979–2006) of the Macquarie Marshes in semi-arid Australia', *International Journal of Remote Sensing*, 32:4545–4569.

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

Tzaros C, Davidson I, Robinson D and Herrod A (2014) *Grey-crowned Babblers on Victoria's lower Loddon River floodplain, Bird Life Australia Conservation Statement No. 16*, May 2014, pp.34–35.

Vertessy R, Barma D, Baumgartner L, Mitrovic S, Sheldon F and Bond N (2019) *Independent assessment of the 2018–19 fish deaths in the lower Darling*, final report, March 2019.

Walker KF and Thoms MC (1993) 'Environmental effects of flow regulation on the lower River Murray, Australia', *Regulated Rivers: Research and Management*, 8:103–119

Warburg M (1965) 'Studies on the water economy of some Australian frogs', *Australian Journal of Zoology*, 13:317–330.

Wassens S (2010) 'Frogs', in *Floodplain Wetland Biota in the Murray–Darling Basin: Water and Habitat Requirements*, 5th ed., pp.253–272, CSIRO Publishing.

Wassens S and Maher M (2011) 'River regulation influences the composition and distribution of inland frog communities', *River Res Appl*, 27:238–246.

Wassens S, Spencer J, Wolfenden B, Thiem J, Thomas R, Jenkins K, Hall A, Ocock J, Kobayashi T, Bino G, Davis T, Heath J, Kuo W, Amos C and Michael D (2019)

Commonwealth Environmental Water Office Long-Term Intervention Monitoring project Murrumbidgee River System Selected Area evaluation, Technical Report, 2014–18, report prepared for the Commonwealth Environmental Water Office.

Waudby HP, Amos C, Healy S, Dyer J, McGrath N, Maguire J, Conallin A and Childs P (2020) *Saving the southern bell frog (*Litoria raniformis*), 2018–19 monitoring report*, NSW Department of Planning, Industry and Environment, Albury, NSW.

Westhorpe DP, Mitrovic SM and Kobayashi Y (2010) 'Limitations of lowland riverine bacterioplankton by dissolved organic carbon and inorganic nutrients', *Hydrobiologia*, 320:292–298.

Wolfenden B, Mika S, Boulton A and Ryder D (2004) 'Assessing change in riverine organic matter dynamics in the Hunter River, NSW, over the last 200 years: implications for stream restoration', paper presented at the *Proceedings of the 4th Australian Stream Management Conference: Linking Rivers to Landscapes, 19–22 October 2004, Launceston, Tasmania*, pp.697–703.

Young JE, Christian KA, Donnellan S, Tracy CR and Parry D (2005) 'Comparative analysis of cutaneous evaporative water loss in frogs demonstrates correlation with ecological habits', *Physiological and Biochemical Zoology*, 78:847–856.

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