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Assessment of environmental water requirements: Condamine–Balonne river system



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Postal Address: GPO Box 1801, Canberra ACT 2601
Telephone: (02) 6279 0100 international + 61 2 6279 0100
Facsimile: (02) 6248 8053 international + 61 2 6248 8053
Email: engagement@mdba.gov.au
Internet: www.mdba.gov.au

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Acknowledgement of the Traditional Owners of the Murray–Darling Basin

The Murray–Darling Basin Authority acknowledges and pays respect to the Traditional Owners, and their Nations, of the Murray–Darling Basin, who have a deep cultural, social, environmental, spiritual and economic connection to their lands and waters. The MDBA understands the need for recognition of Traditional Owner knowledge and cultural values in natural resource management associated with the Basin.

The approach of Traditional Owners to caring for the natural landscape, including water, can be expressed in the words of Darren Perry (Chair of the Murray Lower Darling Rivers Indigenous Nations) —

‘the environment that Aboriginal people know as Country has not been allowed to have a voice in contemporary Australia. Aboriginal First Nations have been listening to Country for many thousands of years and can speak for Country so that others can know what Country needs. Through the Murray Lower Darling Rivers Indigenous Nations and the Northern Basin Aboriginal Nations the voice of Country can be heard by all’.

This report may contain photographs or quotes by Aboriginal people who have passed away. The use of terms ‘Aboriginal’ and ‘Indigenous’ reflects usage in different communities within the Murray–Darling Basin.

Summary

This report describes the updated assessment of environmental water requirements for the Condamine–Balonne river system as a step in the process towards setting the Sustainable Diversion Limits for the system. This report describes a set of flow indicators that are subsequently used in hydrological modelling to identify likely environmental outcomes from different levels and patterns of water recovery. The information from the environmental water requirements and environmental outcomes reports will then be considered along with social, economic and hydrological analysis during the review of surface water Sustainable Diversion Limits for the northern basin (Northern Basin Review report).

The Basin Plan provides a framework for the management of water resources in the Murray-Darling Basin. The objectives of the Basin Plan include to protect and restore water-dependent ecosystems and functions, with the aim of achieving a healthy working Murray-Darling Basin.

Before making the Basin Plan in 2012, the environmental water requirements of 24 large environmental assets (known as umbrella environmental assets) across the Murray-Darling Basin were assessed. These assessments, along with information from other disciplines, were used to inform the setting of long-term average Sustainable Diversion Limits in the Basin Plan.

At the time of making the Basin Plan, it was decided that there would be a review into aspects of the Basin Plan relating to the northern basin. The Northern Basin Review includes research and investigations in social and economic analysis, hydrological modelling, and environmental science, supported by stakeholder engagement. The environmental science program within the Northern Basin Review focused on relationships between river flows and the ecological responses of key flora and fauna (particularly fish and waterbirds) as well as broader ecosystem functions. The environmental science program also included an analysis of the persistence of waterholes that act as drought refuges, and the mapping of floodplain inundation, in-channel habitat and floodplain vegetation.

The Northern Basin Review is re-applying the established and peer reviewed Environmentally Sustainable Level of Take method. The environmental science steps of the Environmentally Sustainable Level of Take method require selection of umbrella environmental assets (UEAs) within catchments; identification of the hydrological characteristics and ecological values and targets for those assets; and selection of flow indicators that represent important flow-ecology relationships. Each flow indicator is made up of a number of hydrologic metrics (magnitude, duration, timing, frequency) that have eco-hydrological relevance within the related UEA and, by inference, the catchment more broadly.

Two umbrella environmental assets were selected for the Condamine–Balonne river system: the Lower Balonne River Floodplain and Narran Lakes (Figure 1).



Figure 1: Stylised map of the Lower Balonne River Floodplain and Narran Lakes in the context of the broader catchment. The location of the Lower Balonne River Floodplain and Narran Lakes UEAs are indicated by the green shading and dotted lines.

The ecological values of these UEAs include species that are listed for protection under Commonwealth and NSW legislation, a large number of floodplain habitats that provide foraging habitat for migratory bird species listed under international agreements, and waterbird habitats in the Ramsar-listed Narran Lakes. In the Environmentally Sustainable Level of Take method, a number of ecological targets were specified to reflect these ecological values. The ecological targets from the original Basin Plan UEA assessments for the Lower Balonne River Floodplain and Narran Lakes have largely been retained. The targets focus on providing a flow regime which:

- maintains drought refuges, and supports recruitment opportunities, for a range of native aquatic species (e.g. fish, frogs, turtles, invertebrates)
- supports the habitat requirements of waterbirds and (for Narran Lakes) is conducive to successful breeding of waterbirds
- ensures the current extent of native vegetation of the riparian, floodplain and wetland communities is sustained in a healthy, dynamic and resilient condition
- supports hydrological connectivity between habitats, along the river (longitudinal) and between the river and its floodplain (lateral).

Four ecosystem functions have been used to inform the environmental water requirement assessments and link ecological targets and values to site-specific flow indicators. These ecosystem functions are:

- **vital habitat (drought refugia)** - provide a refuge for native water-dependent biota during dry periods and drought.
- **longitudinal connectivity** – provide hydrological connections along watercourses that: link a diversity of aquatic environments for feeding, breeding, dispersal, migration and re-colonisation by native aquatic species; and facilitate geomorphic processes, sediment movement and nutrient spiralling.
- **lateral connectivity** – provide hydrological connections between watercourses and adjacent floodplains and wetlands that: link a diversity of aquatic environments for feeding, breeding, migration and re-colonisation by native water-dependent species; support the vigour and condition of native vegetation; and facilitate off-stream primary production, and nutrient and organic matter exchange.
- **vital habitat and populations (waterbirds)** - provide for a diversity of important feeding, breeding and nursery sites for waterbirds including providing conditions conducive to large-scale breeding.

Site-specific flow indicators were selected to represent the water requirements of each of these ecosystem functions. Each site-specific flow indicator for the Lower Balonne River Floodplain and Narran Lakes is summarised in Table 1 and Table 2, respectively.

The site-specific flow indicators described in this report are used in a broad-scale assessment of likely environmental outcomes under different water recovery scenarios using hydrological models. Results of this assessment are available in the Northern Basin outcomes report. How effectively different water recovery scenarios reach flow indicator targets constitutes one line of evidence that is used in conjunction with economic and social evidence to understand the implications of different possible Sustainable Diversion Limits.

Table 1: Summary of site-specific flow indicators for the Lower Balonne River Floodplain UEA

Lower Balonne ecological targets	Ecosystem function	Flow indicator gauge	Magnitude: flow (ML/d)	Duration (days)	Timing	Frequency	Frequency
						Low uncertainty	High uncertainty
<p>Provide a flow regime which:</p> <ul style="list-style-type: none"> maintains drought refuges, and supports recruitment opportunities, for a range of native aquatic species (e.g. fish, frogs, turtles, invertebrates) supports the habitat requirements of waterbirds ensures the current extent of native vegetation of the riparian, floodplain and wetland communities is sustained in a healthy, dynamic and resilient condition supports hydrological connectivity between habitats, along the river (longitudinal) and between the river and its floodplain (lateral) 	Drought refugia (vital habitat)	Weilmoringle (Culgoa River)	Any flow	1	Any time of year	350 days (maximum period between events)	430 days (maximum period between events)
	Drought refugia (vital habitat)	Narran Park (Narran River)	Any flow	1	Any time of year	350 days (maximum period between events)	470 days (maximum period between events)
	Longitudinal connectivity	Brenda (Culgoa River)	1,000	7	Any time of year	90% of years (with at least 1 event)	80% of years (with at least 1 event)
	Longitudinal connectivity (small fresh)	Wilby Wilby (Narran River)	1,700	14	August - May	60% of years (with at least 1 event)	40% of years (with at least 1 event)
	Longitudinal connectivity (large fresh)	Brenda (Culgoa River)	3,500	14	August - May	60% of years (with at least 1 event)	40% of years (with at least 1 event)
	Lateral connectivity (riparian zone)	Brenda (Culgoa River)	9,200	12	Any time of year	2 years (average period between events)	3 years (average period between events)
	Lateral connectivity (inner floodplain)	Brenda (Culgoa River)	15,000	10	Any time of year	3 years (average period between events)	4 years (average period between events)
	Lateral connectivity (mid floodplain)	Brenda (Culgoa River)	24,500	7	Any time of year	6 years (average period between events)	8 years (average period between events)
	Lateral connectivity (outer floodplain)	Brenda (Culgoa River)	38,000	6	Any time of year	10 years (average period between events)	20 years (average period between events)

Table 2: Summary of site-specific flow indicators for the Narran Lakes UEA

Narran Lakes ecological targets	Ecosystem function	Flow indicator gauge	Magnitude: volume (ML)	Duration (days)	Timing	Frequency	Frequency
						Low uncertainty	High uncertainty
<p>Provide a flow regime which:</p> <ul style="list-style-type: none"> maintains drought refuges, and supports recruitment opportunities, for a range of native aquatic species (e.g. fish, frogs, turtles, invertebrates) supports the habitat requirements of waterbirds and is conducive to successful breeding of waterbirds ensures the current extent of native vegetation of the riparian, floodplain and wetland communities is sustained in a healthy, dynamic and resilient condition supports hydrological connectivity between habitats, along the river (longitudinal) and between the river and its floodplain (lateral) 	Vital habitat: bird breeding and nursery sites	Wilby Wilby (Narran River)	25,000	60	Any time of year	1 year (average period between events)	1.3 years (average period between events)
	Vital habitat: bird breeding and nursery sites - larger area than above	Wilby Wilby (Narran River)	50,000	90	Any time of year	1.3 years (average period between events)	1.7 years (average period between events)
	Trigger large-scale waterbird breeding	Wilby Wilby (Narran River)	154,000	90	Any time of year	Twice in 8 years	Twice in 10 years
	Lateral connectivity and vital habitat (waterbirds)	Wilby Wilby (Narran River)	250,000	180	Any time of year	8 years (average period between events)	10 years (average period between events)

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1 Introduction

The *Water Act 2007* (Cwlth) established the Murray–Darling Basin Authority (MDBA) and tasked it with preparing a Basin Plan to provide for the integrated management of the water resources of the Murray-Darling Basin. The objectives of the Basin Plan include to protect and restore water-dependent ecosystems and functions in the context of a healthy working Murray-Darling Basin. The characteristics of a healthy working river system are presented in Box 1, and reflect a balance between the water available to the environment and that used by communities and industries.

Box 1: Characteristics of a healthy working river system (from MDBA 2014)

A 'healthy working river' is one in which the natural ecosystem has been altered by the use of water for human benefit, but retains its ecological integrity while continuing to support strong communities and a productive economy in the long-term.

For the many rivers in the Basin, water is captured, extracted or diverted to support communities, agriculture and other industries. Communities also value healthy and functioning river and floodplain ecosystems, which provide many important services. These include clean water for drinking and agricultural use, nutrient cycling between the river and floodplain, fish stock for anglers, and an environment that supports tourism, recreation and cultural values. To achieve these multiple benefits, there needs to be a balance between the water available to the environment and the water that is used by communities and industries – hence the concept of a 'healthy working river'.

Typically, working rivers have dams, weirs and other infrastructure; and towns, agriculture and developments on adjacent floodplains. These will continue to exist, although how they are managed may evolve. A healthy working river also supports biological communities, habitats and ecological processes and is resilient to natural variability.

One of the key requirements of the Basin Plan is to establish environmentally sustainable limits on the amount of surface water that may be taken for consumptive use, termed Sustainable Diversion Limits (SDLs). SDLs are the maximum long-term annual average quantities of water that can be taken from the basin. SDLs reflect an Environmentally Sustainable Level of Take (ESLT). The method to determine an ESLT has been described in detail (MDBA 2011). The method was reviewed by a CSIRO-led group of scientists (Young et al. 2011). The ESLT method was applied across the Murray-Darling Basin prior to the making of the Basin Plan in 2012.

The Basin Plan provides a broad framework for the management of the water resources of the Murray-Darling Basin. Implementing the Basin Plan involves more detailed planning and management (examples are provided in Box 2).

Box 2: Examples of more detailed requirements under the Basin Plan

Since the making of the Basin Plan in 2012, a Basin-wide environmental watering strategy has been developed (MDBA 2014). The strategy is used to plan and manage environmental watering at a Basin scale over the long term, so as to meet the environmental objectives under the Basin Plan.

Consistent with this strategy, States are developing regional long term watering plans, which identify important environmental assets and ecosystem functions and their environmental watering requirements. States may use similar or different environmental assessment methods to those in the ESLT method, most likely at a greater level of detail, to inform more detailed planning decisions. For example, State planners may use data from more gauges and use a greater number of environmental indicators, so long as those methods are consistent with the Basin Plan.

With respect to short-term management of environmental water at a catchment or valley scale, and associated river operations, a flexible and adaptive process is used to respond to opportunities as they arise. That is, environmental managers decide how best to use the available environmental water to achieve environmental outcomes based on environmental opportunities, antecedent conditions and short-term water availability. Such environmental watering decisions are couched within longer term watering plans. The environmental water requirements described in this report do not represent a prescription of what environmental flows must or should be delivered in the short term. Environmental water managers may however draw on this information when deciding how much water to deliver in a particular watering event.

In finalising the Basin Plan in 2012, the MDBA recognised there was less knowledge available for the northern basin than the southern basin, and provided an opportunity in the Basin Plan for additional investigative work in multiple disciplines to see if there is a case for refining the initial Sustainable Diversion Limits (Hart 2015). This is referred to as the Northern Basin Review. In undertaking this work, it is recognised that estimating the water needs of aquatic ecosystems at a broad scale is a challenging task (see Box 3).

Box 3: Universal challenge in estimating the water needs of aquatic ecosystems (from Swirepik et al. 2015)

Imperfect knowledge of flow-ecology relationships is a universal challenge in determining the water needs of aquatic ecosystems (Poff and Zimmerman, 2010). We are not aware of any large river basin where high-quality science and hydrological modelling could comprehensively describe the flow regime required to protect and restore each part of the basin. It is generally not possible to explicitly know and understand the water requirements of all ecosystem components in a large basin. The disjunct between the timeframes for large-scale ecological investigations (decades) and the timeframes for policy development and implementation (years) creates the need to draw upon the existing and uneven knowledge base to inform the policy process. The Umbrella Environmental Asset approach (which the MDBA has used) enables the integration of existing information for key sites, which are then used to represent environmental water requirements across larger areas.

The ecology and hydrology of the northern basin is complex and any environmental assessment method inevitably has some uncertainties which are acknowledged (Appendix A). To improve our knowledge, the MDBA conducted and commissioned different research projects to improve our knowledge of the northern basin. The work included environmental science research projects and literature reviews, hydrological modelling and socio-economic projects. This report considers the environmental water requirements of the Condamine–Balonne river system based on the environmental science assessments. Other reports summarise the hydrological modelling and the socio-economic assessments.

The environmental science projects were selected using advice from basin governments, community groups, and findings from an independent scientific review (Sheldon et al. 2014). Other knowledge and advice, including that made available by basin jurisdictions through the Environmental Science Technical Advisory Group, was also considered. Organisations that provided input into the environmental science program are acknowledged in Appendix B.

New research since the making of the Basin Plan in 2012 in the Condamine–Balonne catchment and/or the Barwon-Darling catchment is indicated by italics throughout this report (e.g. *NSW DPI 2015*).

In this report we describe the rationale for the selection of different flow indicators (termed site-specific flow indicators) in the Lower Balonne River Floodplain and Narran Lakes that are used to represent the environmental water requirements of these systems. The flow indicators are used to assess environmental outcomes in subsequent hydrological modelling. Other statistics, such as maximum dry spells, are used to provide additional resolution of the expected environmental outcomes in the associated Northern Basin Review environmental outcomes report.

2 The Environmentally Sustainable Level of Take method

2.1 Overview

The Environmentally Sustainable Level of Take (ESLT) method was applied in the development of the Basin Plan (MDBA 2011) and has been re-applied in the Northern Basin Review. A summary of the main steps in the ESLT method is in Figure 2. The ESLT method includes decision making based on socio-economic, hydrological and environmental science knowledge.

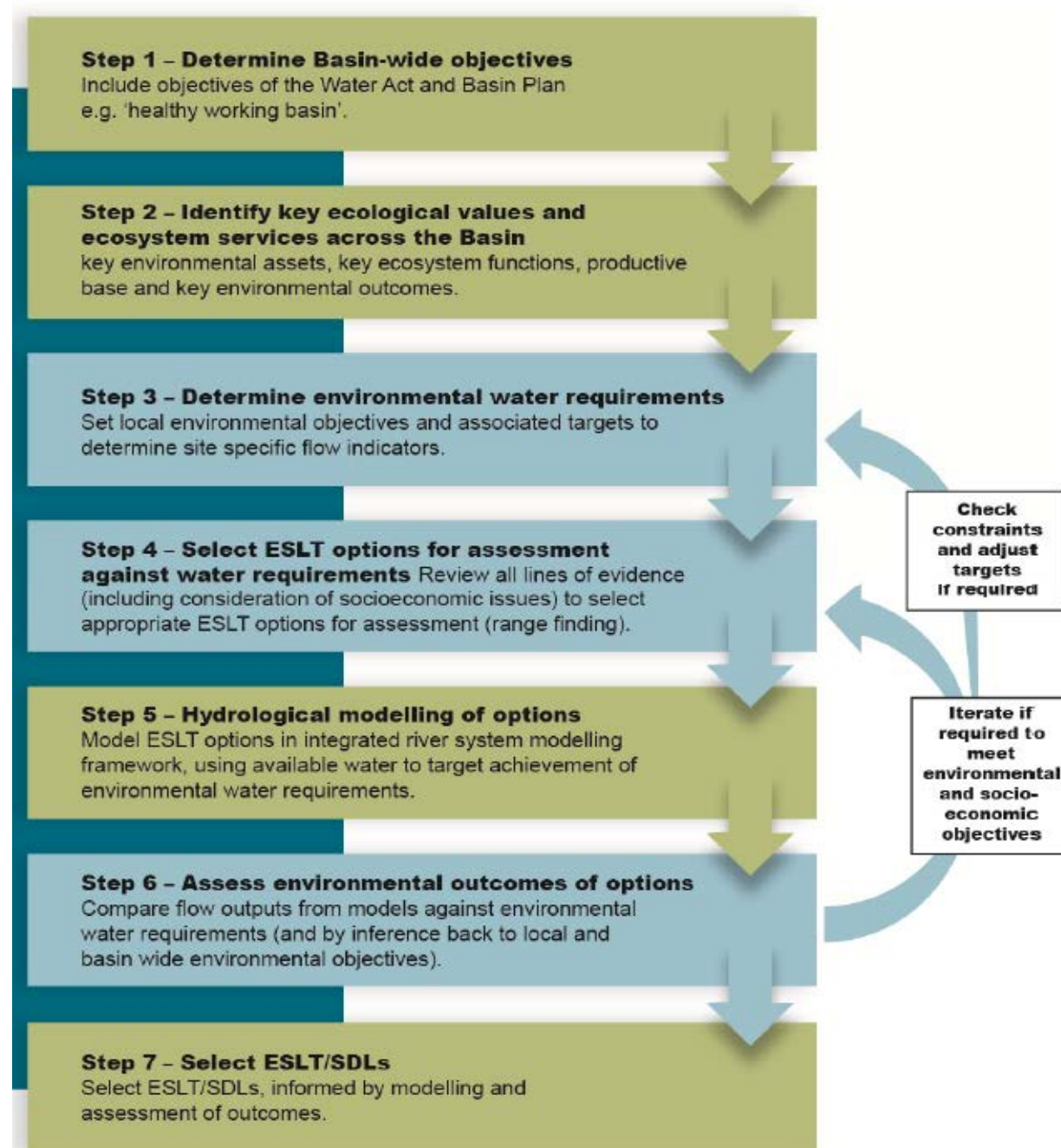


Figure 2: The Environmentally Sustainable Level of Take method (MDBA 2011). Steps 2 and 3 are the focus of this report.

This report documents the assessment of environmental water requirements (Steps 2 and 3 of the ESLT method in Figure 2. Importantly, this assessment does not determine the Sustainable Diversion Limits for the Condamine–Balonne river system in the Basin Plan. Rather it provides environmental indicators that are used in hydrological modelling to provide information into a subsequent review of Basin Plan settings.

The integration of all the ESLT steps, including the hydrological modelling¹ and socio-economic assessments², is described in the Northern Basin Review report.

While the ESLT method is the same as that used in the development of the Basin Plan, some of the terminology has changed here to be more consistent with international practice, as discussed in more detail in Swirepik et al. (2015). One particular change relates to the term for the spatial units used in the environmental water requirements assessments. The ESLT method report (MDBA 2011) refers to these as 'Hydrologic Indicator Sites', while the paper by Swirepik et al. (2015) uses the term 'Umbrella Environmental Assets' (UEA) to better reflect their role in the assessment approach. The latter aligns with the concept of umbrella species in conservation biology (Lambeck 1997; Roberge and Angelstam 2004).

The term ' Umbrella Environmental Asset ' refers to an area for which there is relatively rich knowledge with respect to flow-ecology relationships when compared to the broader region within which the area sits. The knowledge available for UEAs is used to develop flow-ecology relationships for a range of ecosystem functions (e.g. longitudinal connectivity, lateral connectivity) and the assumption of the approach is that the water needs of the UEAs will broadly reflect the water needs of a set of assets in the system. This approach directly addresses the issue of incomplete or developing knowledge, which is the typical situation in large-scale ecosystem management (see Box 3 above). There were 24 UEAs assessed across the Murray-Darling Basin to inform the Basin Plan³, two of which were UEAs in the Condamine–Balonne catchment: the Lower Balonne River Floodplain (MDBA 2012a) and the Narran Lakes (MDBA 2012b).

2.2 Approach to assess environmental water requirements

This section describes the approach for determining the environmental water requirements for the Condamine–Balonne river system. The steps in the approach are:

- selecting umbrella environmental assets (section 2.2.1)
- identifying ecological values and targets (section 2.2.2)
- identifying key flow components (section 2.2.3)
- considering evidence to inform selection of site-specific flow indicators (section 2.2.4)
- selecting site-specific flow indicators to represent important flow-ecology relationships (section 2.2.5)
- selecting flow indicator gauges (section 2.2.6)
- using site-specific flow indicators in hydrological modelling (section 2.2.7).

¹ Hydrological modelling is reflected in steps 1, and 4-7 of the ESLT method in particular

² Socio-economic assessments are reflected in steps 1, 4, 7 of the ESLT method in particular

³ ([click here to view these assessments or visit <http://www.mdba.gov.au/publications/mdba-reports/assessing-environmental-water-requirements-basins-rivers>](http://www.mdba.gov.au/publications/mdba-reports/assessing-environmental-water-requirements-basins-rivers))

2.2.1. Selecting umbrella environmental assets

Within each valley chosen for assessment, the following five principles were used to guide the selection of UEAs:

- **High ecological value.** The Basin Plan lists five criteria for identifying environmental assets, and four criteria for identifying ecosystem functions, which indicate a site has high ecological value. These criteria are listed in Box 4.
- **Representative of water requirements.** The water requirements of a UEA are assumed to represent the water needs of a broader reach of river or an entire river valley. This principle tends to focus the selection of UEAs on large, water-dependent ecosystems, typically at the downstream end of a river reach or valley. Flows at these downstream sites are associated with a broad extent of inundation, and are assumed to have provided flows, connectivity and benefits to the upstream riverine environment on the way through.
- **Spatially representative.** The hydrology and geomorphic character of UEAs is to be representative of river valleys or large reaches, rather than sites of unusual hydrology and geomorphic character.
- **Significant flow alteration.** UEAs experience significant departures from without development flows (i.e. simulated conditions without water resource development) in parts of the flow regime.
- **Availability of data.** The quality and quantity of hydrological and ecological information associated with a UEA needs to be sufficient to allow a detailed assessment of environmental water requirements.

Applying these selection principles to the Condamine–Balonne system has resulted in two UEAs being identified in the catchment: the Lower Balonne River Floodplain (Figure 3), and the Narran Lakes system (Figure 3 and Figure 4). The Lower Balonne River Floodplain extends from St. George in Queensland to the Barwon River in northern New South Wales. The Narran Lakes is connected to the Lower Balonne River Floodplain but is separated for assessment of environmental water requirements because of its particularly high ecological values (internationally recognised Ramsar wetland) and unique water requirements. The Narran River is considered in the Lower Balonne River Floodplain UEA, and flows into the Narran Lakes UEA.

Box 4: Relevant criteria from the Basin Plan

Criteria for identifying an environmental asset (from Basin Plan Schedule 8)

1. The water-dependent ecosystem is formally recognised in international agreements or, with environmental watering, is capable of supporting species listed in those agreements.
2. The water-dependent ecosystem is natural or near-natural, rare or unique.
3. The water-dependent ecosystem provides vital habitat.
4. Water-dependent ecosystems that support Commonwealth, State or Territory listed threatened species or communities.
5. The water-dependent ecosystem supports, or with environmental watering is capable of supporting significant biodiversity.

Criteria for identifying an ecosystem function (from Basin Plan Schedule 9)

1. The ecosystem function supports the creation and maintenance of vital habitats and populations.
2. The ecosystem function supports the transportation and dilution of nutrients, organic matter and sediment.
3. The ecosystem function provides connections along a watercourse (longitudinal connections).
4. The ecosystem function provides connections across floodplains, adjacent wetlands and billabongs (lateral connections).

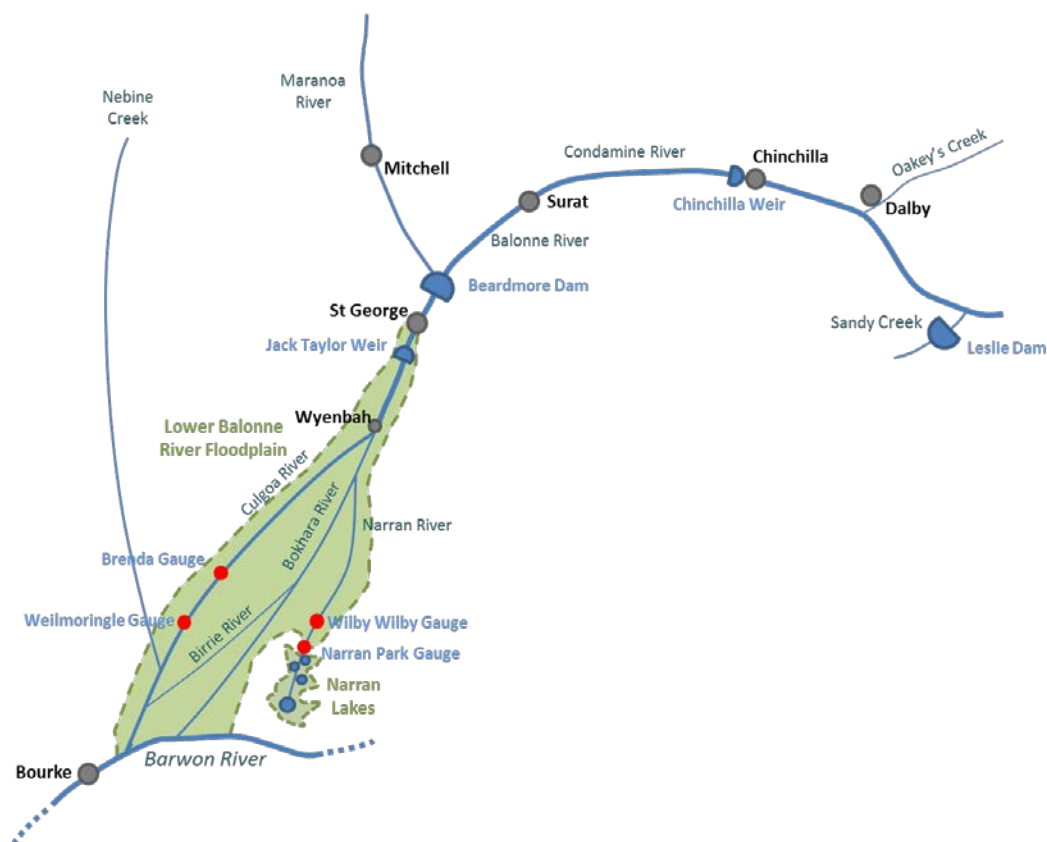


Figure 3: Stylised map of the Lower Balonne River Floodplain and Narran Lakes in the context of the broader catchment. The location of the Lower Balonne River Floodplain and Narran Lakes UEAs are indicated by the green shading and dotted perimeter.

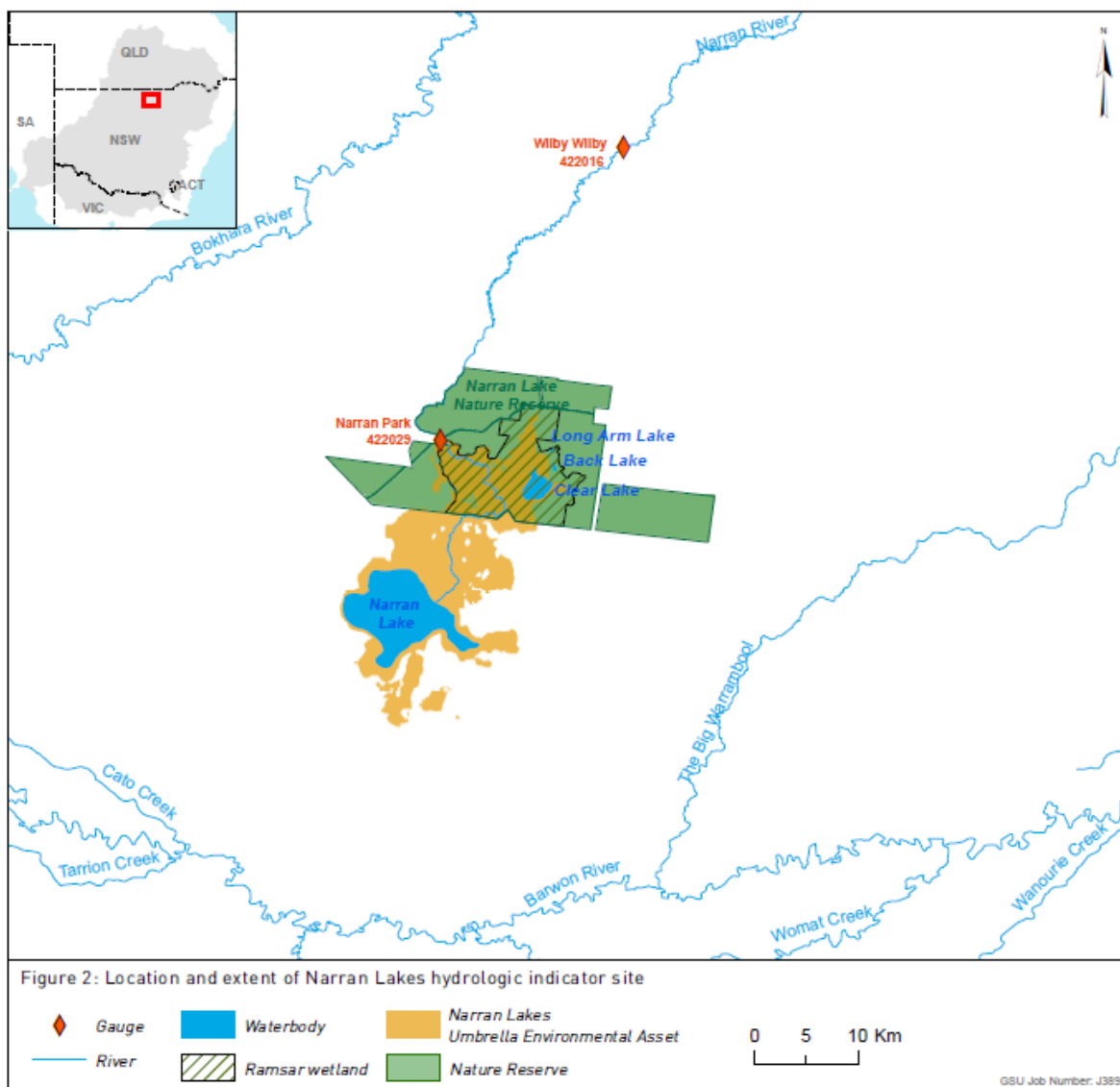


Figure 4: Location and extent of Narran Lakes UEA.

Consideration was also given to selecting an additional UEA to represent the Condamine River upstream of Beardmore Dam, particularly in the vicinity of Chinchilla (Figure 3), where there are a number of water diversions. While there may be sufficient flow alteration, the amount of scientific information available for the region is currently limited and the selection of an additional UEA at this time was not supported. The Queensland Government is undertaking a suite of science projects to improve the knowledge base for the mid-Condamine catchment. This new information can be used to inform future assessments of environmental water requirements for the Condamine–Balonne system.

2.2.2. Identifying ecological values and targets

Establishing environmental water requirements for UEAs requires an understanding of ecological values of the different ecosystem components in the area. The ecological values for the Lower Balonne River Floodplain and Narran Lakes UEAs are described in section 4.1.

The establishment of environmental water requirements for UEAs is guided by Basin-wide environmental objectives and ecological targets (*Water Act 2007*, Basin Plan 2012). Consistent

with these and drawing on site-specific ecological information, a series of qualitative ecological targets were selected for the two UEAs in the Condamine–Balonne system during the development of the Basin Plan. These are listed in section 4.2. The 2012 targets were reviewed in light of the new knowledge stemming from the Northern Basin Review and were found to be consistent with this new knowledge, so they were retained – and two new targets were added (see section 4.2). In addition, four ecosystem functions have been used to link the ecological targets to the site-specific flow indicators in chapters 5 and 6, as discussed in section 4.2.

2.2.3. Identifying key flow components

The flow regime is a primary determinant of the structure and function of ecosystems in streams and rivers (Poff et al. 2010). Alterations to flow regimes have been shown to result in ecological change in many systems (Poff and Zimmerman 2010). However, given the aim of a healthy working Basin, it is not intended to return river flows back to what naturally occurred. This assessment of environmental water requirements focuses on the different flow components required to meet the key known needs of ecosystem components (fish, waterbirds, vegetation) in the Lower Balonne River Floodplain UEA. The flow components are no-flows, in-channel freshes, bankfull flows and overbank flows; and their connections to known ecosystem functions and processes are shown in Figure 5.

For the Narran Lakes UEA, the flow component is a particular volume of water required to flow into the wetland system over a specified time period. This is consistent with the approach for other terminal wetland systems in the Basin, such as the Talyawalka - Teryaweynya system in the Barwon-Darling river system, the Macquarie Marshes, and the Gwydir Wetlands.

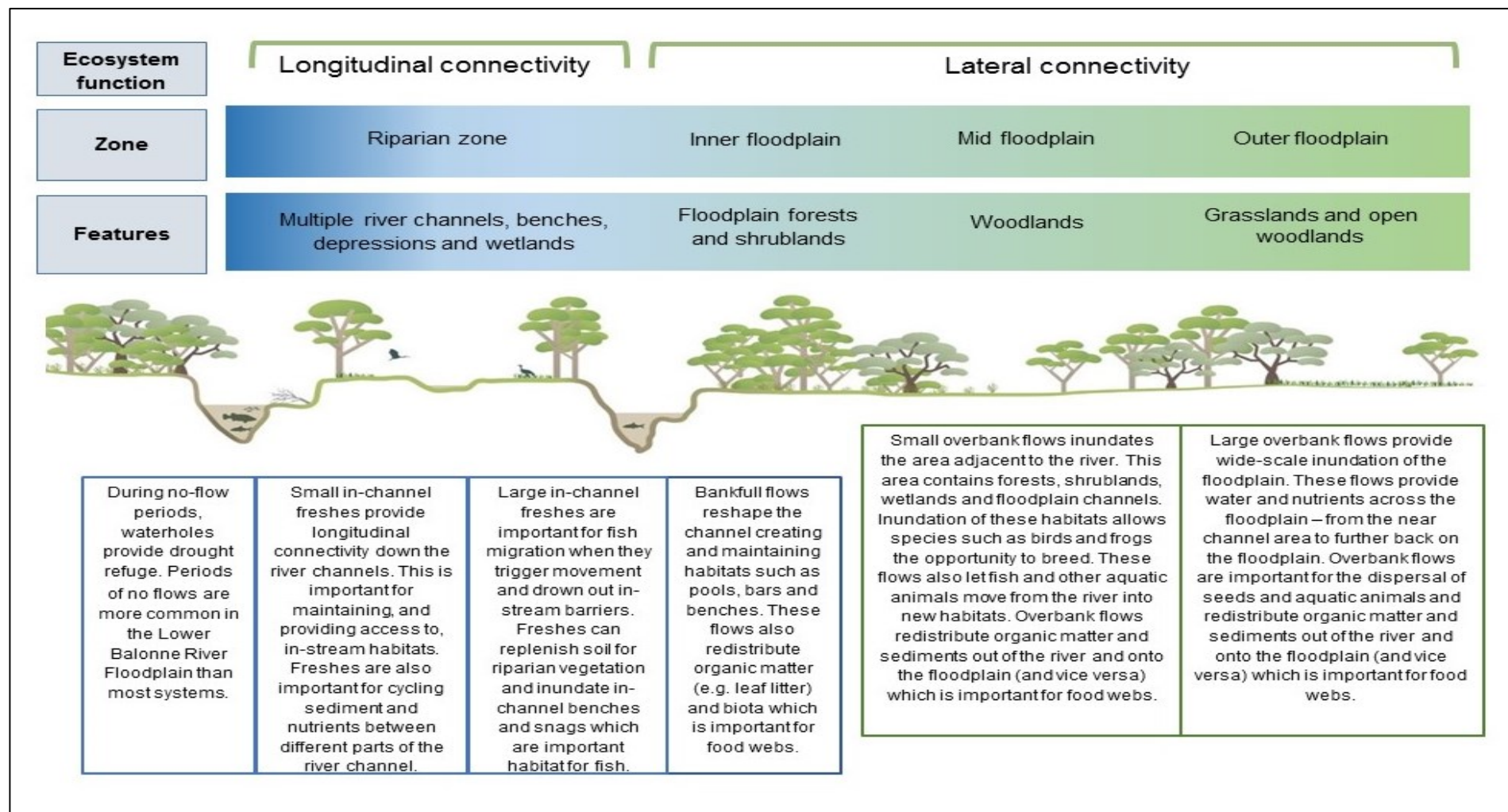


Figure 5: A stylised example of the zones, features and vegetation communities found in the Lower-Balonne River system, and some examples of their connection with ecosystem functions.

2.2.4. Considering evidence to inform the selection of site-specific flow indicators

Multiple lines of evidence were considered when selecting site-specific flow indicators to represent the environmental water requirements of the two UEAs in the Condamine–Balonne river system. The three components were: reviewing the evidence that was available prior to the making of the Basin Plan in 2012; generating new lines of evidence by commissioning science projects; and synthesising the resulting evidence. These components are discussed below.

The evidence available before the Basin Plan was made included some substantial research projects (e.g. ANU Enterprise 2011; Butcher et al. 2011; Brandis et al. 2011; DERM 2010; Sims 2004; Sims and Thoms 2003; Thoms et al. 2002; Thoms and Parsons 2003). This evidence was reflected in the original assessments of environmental water requirements for the UEAs in the Condamine–Balonne river system (MDBA 2012a; MDBA 2012b). This evidence was considered by the MDBA and jurisdictional scientists, independent scientists (*Sheldon et al. 2014*), and the community⁴, and knowledge gaps were identified.

In response to the most significant knowledge gaps, new lines of evidence were generated by undertaking new environmental science projects:

- reviews of literature and data on fish (*NSW DPI 2015*), waterbirds (*Brandis and Bino 2016*) and vegetation (*Casanova 2015*)
- with respect to the waterbird breeding indicator at Narran Lakes, an extension to the data underpinning ANU Enterprise (2011) and a review of the science leading to a recommendation of a site-specific flow indicator (*Merritt et al. 2016*)
- mapping the location and assess the persistence of waterhole refuges in the Culgoa and Narran systems (*DSITI 2015*)
- research to identify groups of fish species with similar flow needs (*NSW DPI 2015*)
- analysing satellite imagery to determine areas inundated at different flow rates (*MDBA 2016*)
- mapping of extensive areas of floodplain vegetation (*Eco Logical Australia 2016*) which can be related to the areas inundated.

Additionally, the Office of Environment and Heritage undertook an assessment of inundation of vegetation in the Narran Lakes (*Thomas et al. 2016*).

Three of these new projects involved extensive fieldwork (*DSITI 2015*; *NSW DPI 2015*; *Eco Logical Australia 2016*). Five of these projects included accessing and analysing existing unpublished data, such as data for additional waterbird breeding events at Narran Lakes, to update the best available eco-hydrology knowledge for the Condamine–Balonne (*NSW DPI 2015*; *MDBA 2016*; *Brandis and Bino 2016*; *Merritt et al. 2016*; *Thomas et al. 2016*). Three of these projects involved workshops of experts so that the project team could test whether the interpretation of eco-hydrology data was reasonable (*Brandis and Bino 2016*; *NSW DPI 2015*; *Casanova 2015*). Hydrological analysis of the Lower Balonne system was undertaken by the MDBA, with respect to the without development and baseline scenarios, to provide the system hydrology context (see Appendix G). Reports from each of the above projects are available on the MDBA website⁵. Other science that has become available since the Basin Plan was made

⁴ such as through meetings in the independent review process, and discussions with the Environmental Science Working Group of the Northern Basin Advisory Committee

⁵ <http://www.mdba.gov.au/publications>

was also considered (e.g. *Capon 2012; DSITIA 2013; Woods et al. 2012; Sternberg et al. 2012; Bond et al. 2015, Marshall et al. 2016*).

The MDBA synthesised the best available evidence by taking into account the quality, suitability, and relevance of knowledge from the pre-Basin Plan studies and the more recent studies. This involved consideration of the knowledge that was most relevant to the UEA, the study methodology, and the extent that the project provided information on both ecology and hydrology.

2.2.5. Selecting site-specific flow indicators to represent important flow-ecology relationships

For a UEA, each site-specific flow indicator consists of a set of four hydrologic metrics. These are:

- **magnitude:** either a specified minimum daily flow rate (ML/d); or a volume (ML), which is a specified minimum quantity of inflows over a period of time (and may or may not specify a minimum daily flow)
- **duration:** for flow, the number of days a flow remains at or above the specified magnitude (ML/d); for volume, the period of time flow contributes to meeting the specified quantity of water (ML)
- **timing:** the months of the year a flow of a specified magnitude and duration is sought
- **frequency:** frequency is expressed in several ways depending on the context of the flow indicator: the maximum number of days between flow events (e.g. 350 days); or the percentage of years in which there is at least one flow event of a specified magnitude, duration and timing (e.g. 60%); or the average period between events (e.g. 6 years); or a maximum return interval (e.g. once in every 10 years).

An example of a site-specific flow indicator (for the Narran Lakes UEA) is described in Box 5.

Box 5: Example of a site-specific flow indicator for the Narran Lakes

An inflow volume of 50,000 ML, measured at the gauge on the Narran River at Wilby Wilby, over a period of 90 days, at any time of year, with an average period between events of 1.3 years (low uncertainty, which means more confidence of achieving an ecological target and less risk) to 1.7 years (high uncertainty, which means less confidence and more risk).

The water needed to fulfil ecosystem functions was assessed based on identified ecological values and targets, known flow-ecology relationships, and hydrological analysis. The resulting site-specific flow indicators, and the associated lines of evidence, are in chapter 5 for the Lower Balonne River Floodplain UEA and in chapter 6 for the Narran Lakes UEA.

Of the hydrologic metrics considered, frequency was often the most challenging to select, as is discussed in Box 6.

Once draft site-specific flow indicators were selected, they were compared to the modelled without development flow patterns (conditions prior to significant human development) to ensure that the indicators selected were representative of the typical hydrology of the Condamine–Balonne system. This check was a practice retained from the original assessment (MDBA 2012a, MDBA 2012b). The frequency by which a site-specific flow indicator would be met for modelled SDL scenarios (i.e. scenarios that incorporate water recovery) would generally be expected to be

more often than under baseline conditions and less often than under without development conditions (no water resource development). This hydrological check gave confidence that the proposed site-specific flow indicators were reasonable (see Appendix G). Additionally, technical advice was sought from jurisdictional scientists and consultants, and a local context review was undertaken by community representatives on advisory groups⁶. Indicators were finalised after considering this advice and analysis.

Box 6 - Discussion of the frequency hydrologic metric

It is likely that there are thresholds for many plants and animals beyond which their resilience is diminished and their survival or ability to reproduce is lost. However, the precise details of those thresholds are mostly unknown. As a result of these uncertainties, the frequency metric in the ESLT method is usually given as a range from a low uncertainty of achieving an ecological target to a high uncertainty of achieving the target⁷. This range is referred to as the 'frequency range'. It was specified in this way in the original environmental water requirement reports used to develop the Basin Plan (e.g. MDBA 2012a; MDBA 2012b), and consistently used across the Basin. Where watering requirements are more certain, only one frequency target is specified.

For the low-uncertainty frequency, there is a high likelihood that the ecological targets will be achieved (MDBA 2011). Conversely, the high-uncertainty frequency is considered to represent a boundary beyond which there is a high likelihood that the ecological targets will not be achieved (MDBA 2011).

The condition of the water dependent ecosystems is expected to vary in response to climatic conditions, especially in the northern basin given the highly variable nature of rainfall. In particular, the frequency of flow events (and therefore ecological condition) will respond to weather patterns and decline during periods of prolonged drought, even under natural or without development conditions. For this reason, the frequency of events in site-specific flow indicators are usually long-term averages, with events occurring more often in wetter times and less often in drier times. Examples of these frequency metrics include the average number of years between environmental watering events (calculated using 114 years of modelled data), and the percentage of years within which a watering event occurs.

The site-specific flow indicators, particularly the frequency, were tested using hydrological modelling to check whether the indicators were reasonable in the context of the system's hydrology (section 2.2.5).

⁶ Environmental Science Working Group of the Northern Basin Advisory Committee, and the Lower Balonne Working Group

⁷ The convention adopted in this report is that the low uncertainty frequency is specified first, followed by the high uncertainty frequency

2.2.6. Selecting flow indicator gauges

The flow requirements of UEAs are expressed at one or more flow indicator gauges. These are river gauges within (or close to) the UEA which record flow on a daily basis. Four factors were taken into account when selecting the flow indicator gauges in the Condamine–Balonne river system. Firstly, the gauges selected can be used in the assessment of whether a site-specific flow indicator is met, by testing against a flow-ecology relationship that has been established for the gauge, or can be established through attenuation relationships between gauges. Secondly, there are relationships between flows in different distributary river channels where relevant. It is possible to relate flows at one flow indicator gauge (such as in the Culgoa River) to other sites (such as in the Narran and Bokhara Rivers). Thirdly, the gauges were located below the zone of major water diversion. Finally, the gauges are key reference points in hydrological models used in the hydrological modelling framework.

After considering these factors, flow indicator gauges on the Culgoa River at Brenda and on the Narran River at Wilby Wilby were selected for most site-specific flow indicators. In addition, more downstream gauges have been selected for the flow requirement assessments associated with waterhole refuges along the Culgoa (Weilmoringle gauge) and Narran Rivers (Narran Park gauge). Flows stipulated at these gauges will also provide water for environmental benefit down other channels in the lower Balonne such as the Balonne Minor, Ballandool, Bokhara and Birrie Rivers.

2.2.7. Using site-specific flow indicators in hydrological modelling

Once all the site-specific flow indicators were confirmed, they were incorporated into a linked Basin-wide hydrological modelling framework. This framework routes water through all rivers and UEAs in the Basin over a 114 year period of historical inflows (1895-2009) and represents the level of water resource development in 2009 (baseline). The framework is described in the accompanying hydrological modelling report.

The hydrological models are used to assess whether the site-specific flow indicators are met under different possible SDL scenarios (that is, scenarios of different environmental water recovery). A 'successful' flow event is recorded when the hydrologic metrics for a site-specific flow indicator are fully met by the flows in the model (as measured at the flow indicator gauge). The results of this analysis are provided in the environmental outcomes report and the hydrological modelling report.

In addition to analysis against site-specific flow indicators, the environmental outcomes report includes analysis of complementary modelling statistics, including the extent of partially met flow indicators and changes in dry spells (i.e. the number of consecutive years without a specified flow event), as these periods may put biota at risk. These complementary assessments provide another layer of analysis to the frequency metrics and give a fuller picture of likely outcomes.

3 Overview of the Condamine–Balonne river system

3.1 Physical attributes

The Condamine–Balonne catchment covers 143,900 square kilometres. The catchment extends from the high country in the upper Condamine in the east near Warwick to the western plains which are south-west of St George that extend into northern NSW. The catchment of the Lower Balonne River Floodplain covers an area of approximately 19,880 square kilometres (Sims and Thoms 2002), or about 14% of the Condamine–Balonne catchment. Approximately 30% of the Lower Balonne River Floodplain system is in Queensland, and approximately 70% is in New South Wales (McCosker 1996).

The geomorphology of the river channels of the Condamine–Balonne system has been classified into five distinct types: constrained upland, armoured, mobile, meandering and anabranching (Thoms and Parsons 2003). The river channels in both of the UEAs are of the anabranching type. The hydraulics resemble that of a flat delta, with smaller flows dispersing into distributary flow channels, and larger flows spreading across the floodplain. While the river channels of the Lower Balonne are laterally stable (Kernich et al. 2009), within the channels small changes to the flow can result in significant changes to in-channel morphology (Smith et al. 2006), maintaining a diversity of geomorphic features such as benches, bars, and waterholes (O'Brien et al. 2002; DSITI 2015).

The combined length of the Condamine, Balonne and Culgoa Rivers is 1,195 km. The Culgoa and Narran Rivers are the main-channels of the Lower Balonne floodplain (Thoms et al. 2002). The catchment also includes tributaries such as the Maranoa River and Nebine Creek, and distributaries such as the Bokhara and Birrie river system (Figure 3). The Culgoa River flows into the Barwon River forming the Darling River, and the Narran River flows into the Narran Lakes, which is a terminal wetland system (Figure 6).

The Condamine–Balonne system has public water management structures, most of which were constructed in the 1960s and 1970s. Whilst there are several public structures along the Condamine–Balonne river system, of particular note are Beardmore Dam and a series of weirs including Jack Taylor Weir near St George (Figure 3). These relatively small-scale public storages provide some flow regulation and assist with diversions, particularly through the Lower Balonne River Floodplain (CSIRO 2008). The major public storages and weirs have a combined capacity of 234 GL, which is small when compared to average surface water availability (1,305 GL/year). Therefore, the ability of these public storages to regulate flows is relatively low compared to other parts of the Basin (CSIRO 2008).

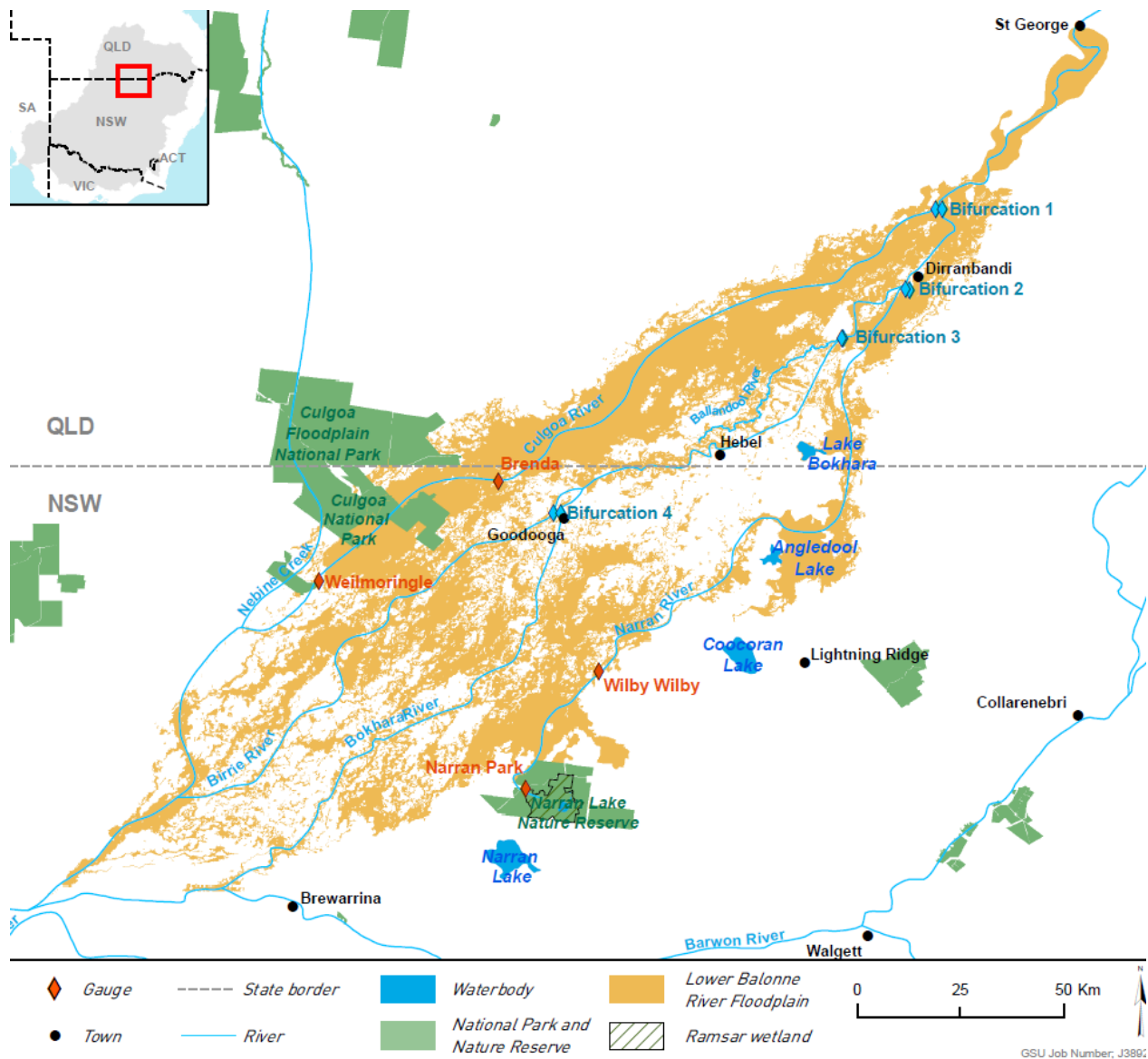


Figure 6: Location and extent of Lower Balonne River Floodplain UEA. Insert map shows location context within the Murray-Darling Basin.

Downstream of Jack Taylor Weir near St George, rivers divide into a number of distributary channels, like a delta. The system includes four major bifurcations, with lower flows down each of the distributary channels typically controlled by a series of weirs. For example, bifurcation 1 is located where the Balonne River divides into the Culgoa and Balonne Minor Rivers (Figure 7). The weir on the Culgoa River just downstream of bifurcation 1 is shown in Figure 8. The Balonne Minor River subsequently divides into the Narran River and Bokhara system, as shown in Figure 6.

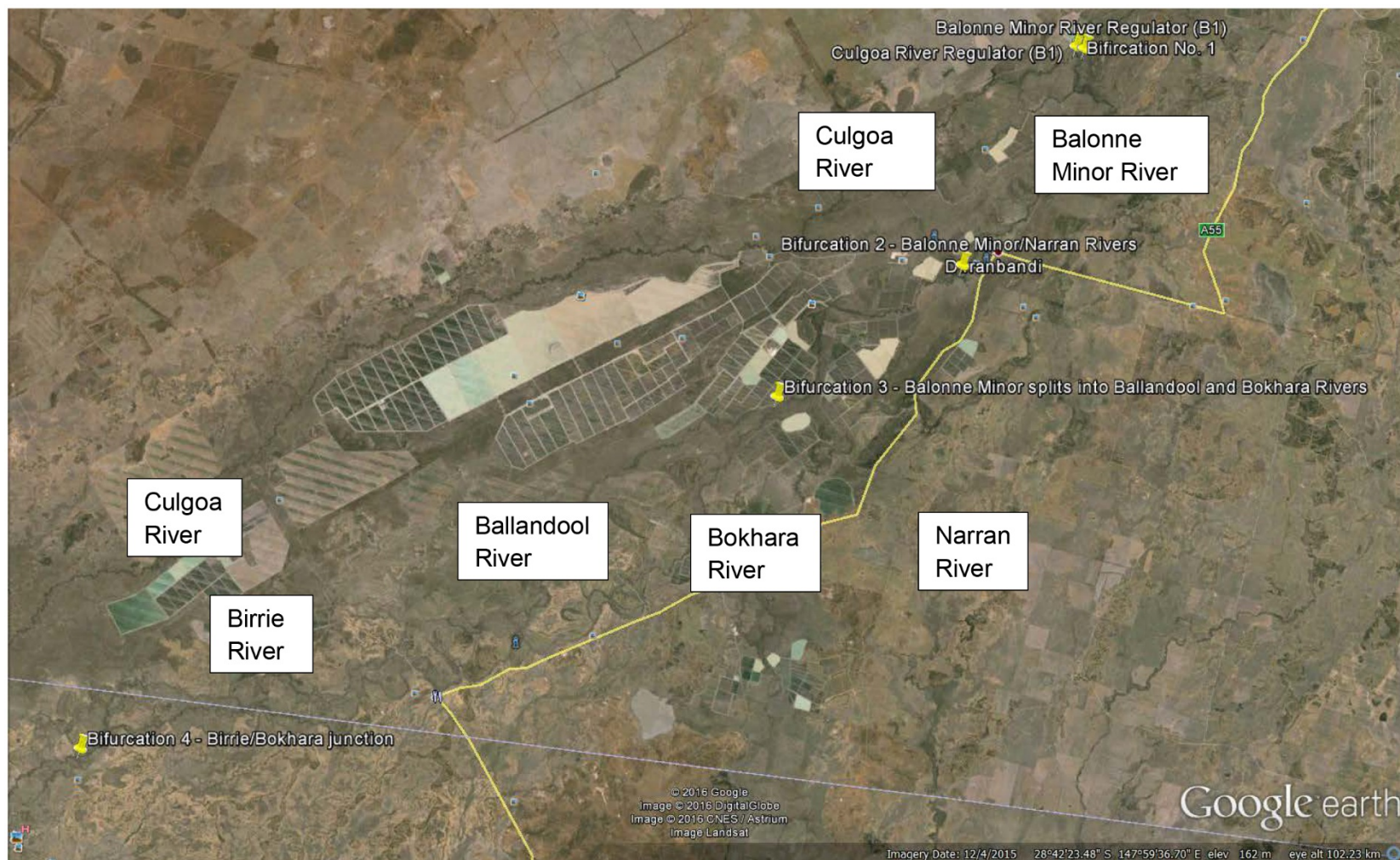


Figure 7: Part of the Lower Balonne River Floodplain, showing four bifurcations (Source: Google Earth. Imagery date: 12/4/2015)



Figure 8: Weir below bifurcation 1 on the Culgoa River at Whyenbah (photo: DNRM Queensland)

There has been significant development on the Lower Balonne River Floodplain for agricultural purposes, particularly in the 1980s and 1990s. Some agricultural development can be seen on Figure 7. Most irrigation water is retained in private on-farm storages within the Lower Balonne River Floodplain. These private storages hold approximately seven times the total volume of public storages (MDBA 2012a). There is a range of different types of water entitlements in the relevant State water resource plans under which irrigators divert water in both Queensland and NSW. For example, in Queensland, these entitlements include diversions from entitlements for which the water is supplemented from storages, particularly Beardmore Dam; stock and domestic entitlements that allow small volumes of water to be diverted often; un-supplemented entitlements with a range of commence-to-pump thresholds; and overland flow licences that allow large volumes of water to be diverted when floodplain flows occur. There are a number of weirs between the bifurcations to aid in the management of these diversions.

An environmental asset of particular significance in the Lower Balonne River Floodplain is the Narran Lakes, located at the bottom of the Narran River. The Narran Lakes is a wetland system consisting of four lakes: Clear Lake, Back Lake, Long Arm (which form the northern lakes), and the main Narran Lake; as well as a complex network of river channels that dissect the floodplain (ANU Enterprise 2011; Thapa et al. 2016). The complex geomorphic nature of the Narran Lakes ecosystem means that the pattern of inundation is also complex, and may differ over time (Thoms et al. 2007; Thomas et al. 2016). This is a result of different areas of the ecosystem holding water for different lengths of time. Therefore, the total area inundated is not just a result

of the amount of water in a single flow event, but of the volume of flows entering within the past several years (Sims and Thoms 2003), as well as antecedent conditions including any recent local rainfall.

3.2 Hydrology

3.2.1. Hydrology prior to the development of water resources

The northern basin is characterised by extremely variable rainfall, even by international standards. Catchment 'losses' are also extremely variable, due to evaporation and infiltration into the soil. Resulting annual river flow may range from 1% to over 1,000% of the annual mean, and periods of no-flow can extend from months to years (Saintilan and Overton 2010). Modelled flows in the Culgoa and Narran Rivers for the without development scenario reflects this variability (Figure 9). Flood frequency was also highly variable.

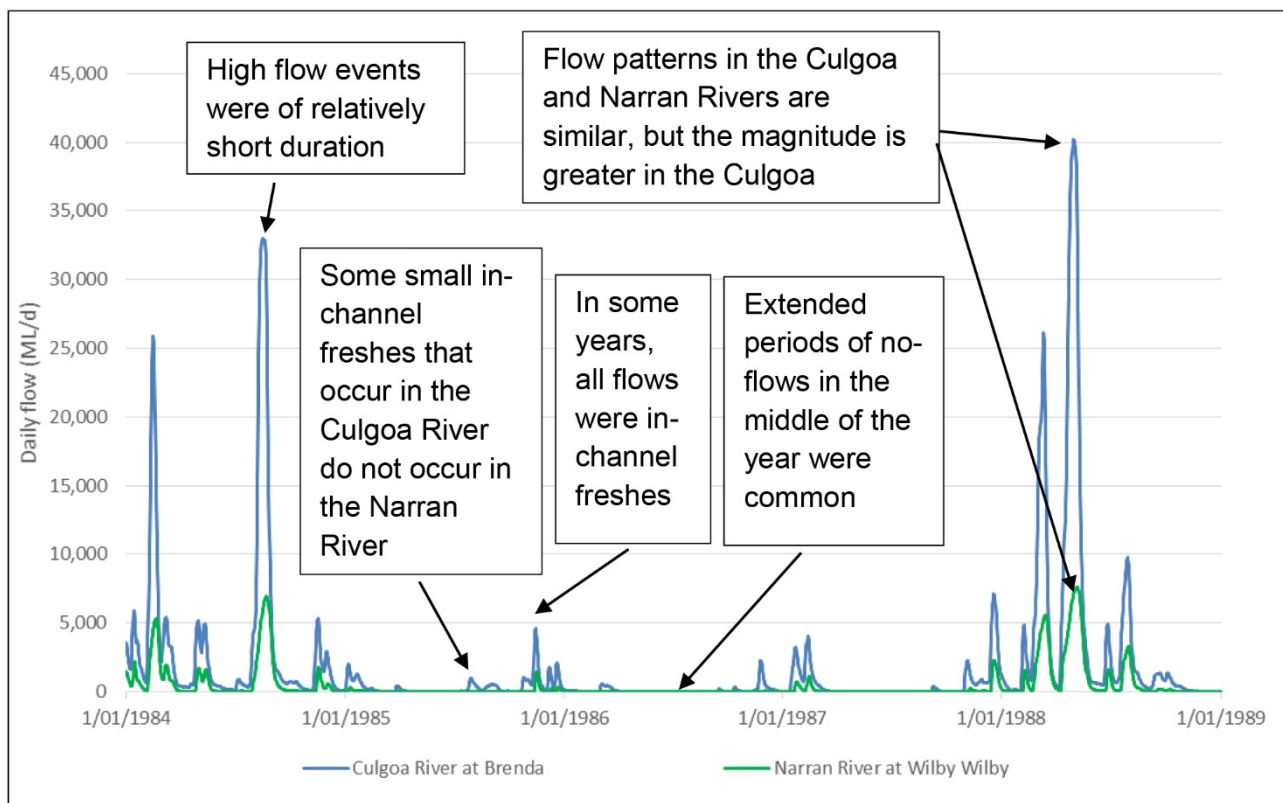


Figure 9: Daily flows of the Culgoa River at Brenda and Narran River at Wilby Wilby over a five year period from 1984 to 1989 (modelled without development conditions).

Modelled flows in the Culgoa and Narran Rivers in the five year period from 1984 to 1989 are shown in Figure 9. This period of five years was selected because it includes typical events: short events with flows of a high magnitude, in-channel freshes with a range of durations, and extended periods of no-flows. Figure 9 shows that under without development conditions, there were usually some flows in the summer wet season, but flows occurred at any time of the year. The flows in the Culgoa River always exceeded those in the Narran River under without development conditions. There are some events where there is a flow in the Culgoa River but not in the Narran River, possibly due to the influence of the bifurcations. No flow periods in Narran River tend to be longer than those in the Culgoa River.

3.2.2. Hydrology following the development of water resources

A comparison of modelled daily flows under without development and baseline (pre Basin Plan conditions) are shown in Figure 10 for the Culgoa River at Brenda and in Figure 11 for the Narran River at Wilby Wilby.

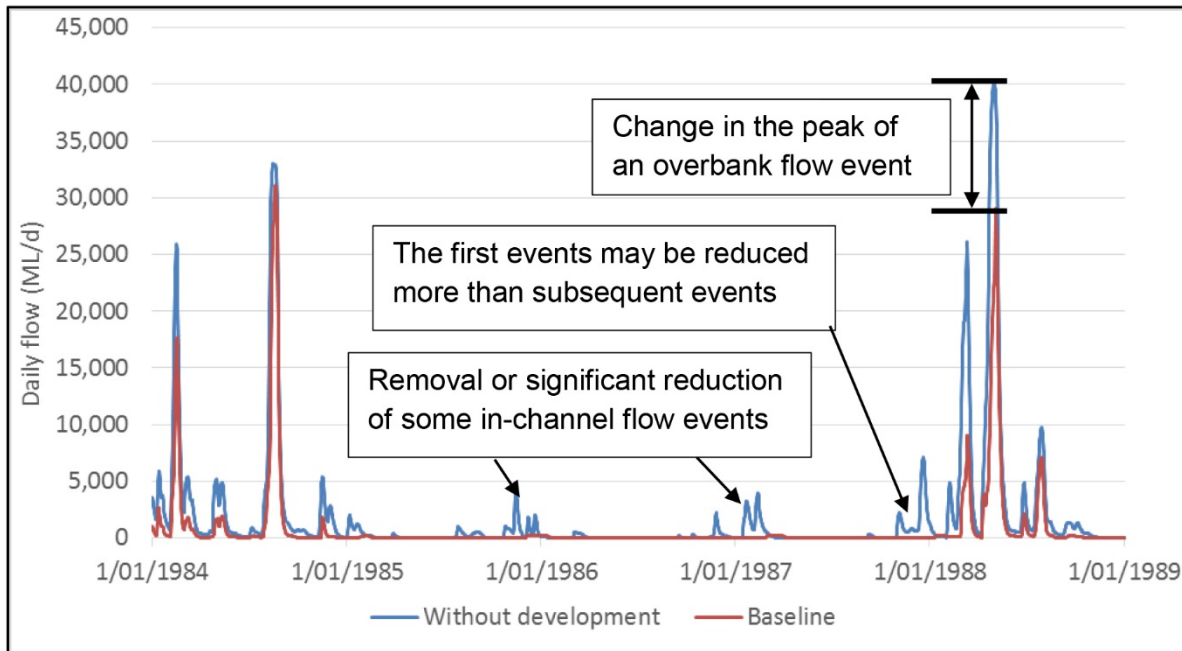


Figure 10: Daily flows of the Culgoa River at Brenda over a five year period from 1984 to 1989 (modelled without development conditions and baseline conditions)

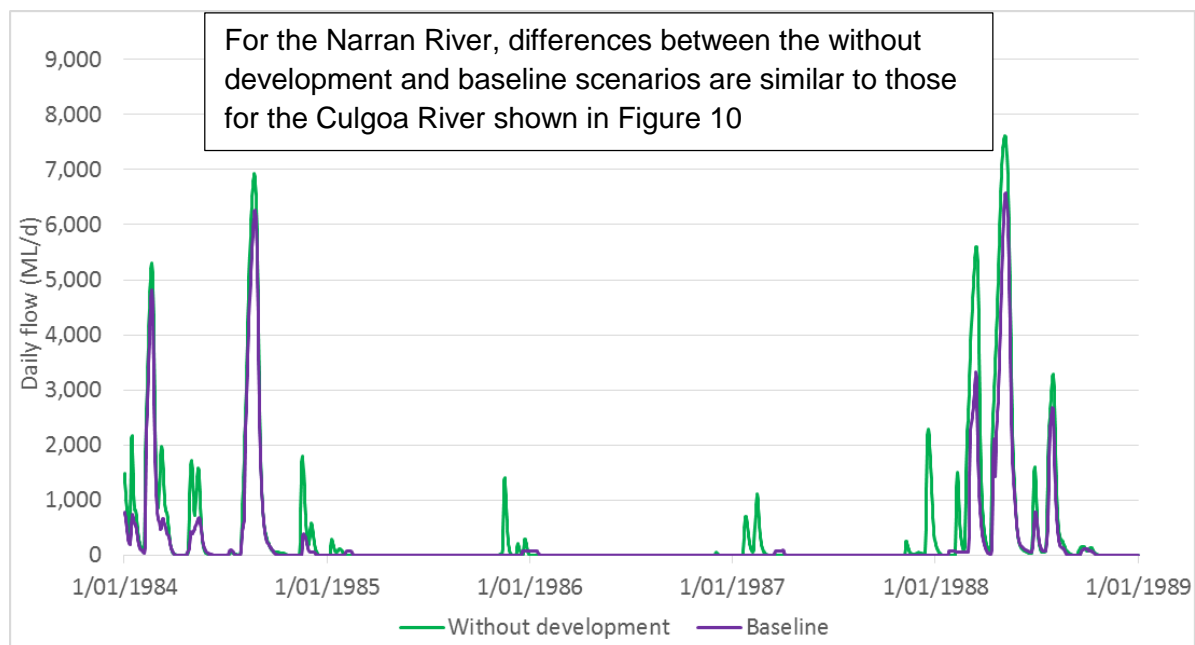


Figure 11: Daily flows of the Narran River at Wilby Wilby over a five year period from 1984 to 1989 (modelled without development conditions and baseline conditions). Note that the vertical scale is different to that on Figure 10.

As the Culgoa and Narran Rivers are part of the same distributary system on the Lower Balonne River Floodplain UEA both hydrographs show similar patterns. These figures show that flows under baseline conditions are now significantly lower than under without development conditions.

Modelling suggests that most in-channel freshes between January 1985 and January 1988 would have been removed by water diversions as a result of development as shown in Figure 10 and Figure 11. In general, flow events are usually reduced in magnitude and sometimes duration as a result of water resource development (Thoms and Sheldon 2000).

Management of water resources in the Condamine–Balonne system has modified flow components, increasing the frequency of no-flow events, and reducing the frequency of in-channel freshes and overbank flows in the Lower Balonne River Floodplain UEA and into the Narran Lakes UEA. Some of the key ecological consequences of these hydrological changes are discussed in the following section.

3.3 Eco-hydrology

Similarly to other semi-arid rivers in Australia, the Lower Balonne was thought to have a 'boom and bust' ecology as a result of its highly variable flow regime (Sheldon et al. 2000; Bunn et al. 2006). That is, in response to occasional large scale flooding, species with flexible and opportunistic life-cycles would respond quickly to the increased availability of resources (food), water (for floodplain species), and access to off-channel habitats for feeding and breeding. For some river systems in the northern Basin, including the Lower Balonne River Floodplain UEA, recent research suggests that the 'boom and bust' may be more subtle than expected (*Woods et al. 2012*) and may be different for different species. Material returning to the river following flooding did create 'booms' in the biomass of some aquatic invertebrates in the Moonie River (*Sternberg et al. 2012*). For fish species such as golden perch (*Macquaria ambigua*), this boom appeared to be much less pronounced (*Woods et al. 2012*), but still important for sustaining these species during dry periods (*Sternberg et al. 2012*).

During prolonged dry spells ('busts') some aquatic species are confined to isolated waterholes which act as refugia (*DSITI 2015*). These waterholes allow populations to persist prior to the re-establishment of longitudinal and lateral connectivity during flow events. Infrequent large floods connect vast areas of the floodplain with the river, providing for processes such as nutrient spiralling; sediment transport and biotic dispersal (Thoms 2003); the maintenance of various habitats through erosion and depositional processes (Foster et al. 2002) and the stimulation of floodplain productivity (e.g. invertebrates hatching from soil egg banks (Kingsford 2000)); and vegetation recruitment (*Capon 2012*). Increased food availability as a result of floodplain connection during periods of lateral connectivity helps sustain animals such as fish and waterbirds during dry periods (Kingsford and Porter 1999, *Sternberg et al. 2012*). Therefore, in systems such as the Lower Balonne River Floodplain UEA, the provision of flows at a range of magnitudes supports a wide range of important underlying ecosystem functions (Figure 5) and ensures habitat heterogeneity and connectivity is maintained, thereby contributing to biodiversity (Yarnell et al. 2015).

Knowledge of flow-hydrology relationships suggests that changes away from a without-development flow regime would result in negative environmental impacts (e.g. Poff et al. 2010). As shown in section 3.2, with development of water resources, no-flow periods have increased, and in-channel freshes and overbank flows have been reduced, reducing the number of 'booms',

increasing the number of 'busts', and increasing stresses on ecosystems that may have reduced resilience through time. There has been less re-filling of drought refuges, diminished longitudinal and lateral connectivity, and fewer opportunities for the Narran Lakes and other wetlands to receive large inflows as a result of water resource development.

The rivers of the Condamine–Balonne system were recently assessed as having poor ecosystem health (MDBA 2012c), due to a combination of flow-related and non-flow related factors.

4 Ecological values, targets, and functions

4.1 Ecological values

Step 2 of the ESLT method (Figure) includes an assessment of the ecological values of each UEA. The assessment is guided by the criteria for identifying environmental assets and ecosystem functions from the Basin Plan (Box 4).

Based on the ecological values identified for the Lower Balonne River Floodplain UEA and Narran Lakes UEA, the various elements of the system meet all environmental asset criteria in Box 4 - that is linkages to international agreements or threatened species legislation, naturalness, vital habitat, and significant biodiversity.

The Lower Balonne system supports a diversity of native fish. The Culgoa River, between St George and the junction of the Culgoa and Barwon-Darling Rivers, has been identified as a site of high fish biodiversity with threatened species (MDBA 2014). Four of the 14 native fish species recorded are listed under threatened species legislation. The Murray-Darling Basin population of freshwater catfish (*Tandanus tandanus*) and the western population of olive perchlet (*Ambassis agassizii*) are listed as endangered under the *Fisheries Management Act 1994* (NSW). Murray cod (*Maccullochella peelii*) is listed as vulnerable under the *Environment Protection and Biodiversity Conservation Act 1999* (Cwlth) (EPBC Act). Silver perch (*Bidyanus bidyanus*) is listed as critically endangered under the EPBC Act 1999, and vulnerable under the *Fisheries Management Act 1994* (NSW DPI 2015). Silver perch has been recorded in the Narran Lakes (Thoms et al. 2007). Olive perchlet have been found to prefer wetland habitats like Narran Lakes (Hutchison et al. 2008).

The Lower Balonne river system is an important site for waterbird habitat. The Narran Lakes is of international significance as it supports species listed in the Japan–Australia Migratory Bird Agreement, the China–Australia Migratory Bird Agreement or the Republic of Korea–Australia Migratory Bird Agreement (Appendix F). The Narran Lakes UEA includes the Ramsar-listed Narran Lake Nature Reserve (Figure 4).

The Narran Lakes system has recorded some of the highest densities and greatest abundances of waterbirds in Australia (Kingsford et al. 2010). Sixty five species of waterbirds have been recorded there (Thoms et al. 2007). The Narran Lakes system has supported the largest and most diverse waterbird breeding events in the Condamine–Balonne and Barwon–Darling catchments (Brandis and Bino 2016). Of the 65 species recorded at Narran Lakes, 54 are known to breed in the system (Brandis and Bino 2016), five are listed under the NSW *Threatened Species Conservation Act 1995* including the brolga (*Grus rubicundus*), freckled duck (*Stictonetta naevosa*) and magpie goose (*Anseranas semipalmata*). Waterfowl considered to have a

restricted breeding distribution in western New South Wales that breed in the Narran Lake Nature Reserve include the great cormorant (*Phalacrocorax carbo*), the pied cormorant (*P. varius*), the darter (*Anhinga melanogaster*), the rufous night heron (*Nycticorax caledonicus*), the little egret (*Ardea gazetta*), the intermediate egret (*A. intermedia*), the great crested grebe (*Podiceps cristatus*) and the gull-billed tern (*Sterna nilotica*) (Smith 1993).

In addition to the Narran Lakes, there are two nationally important wetlands in the Lower Balonne system; the Balonne River Floodplain (downstream of St George to the first bifurcation in Qld), and the Culgoa River Floodplain (in NSW on the Culgoa River). More than 3,400 wetlands have been identified within the Lower Balonne River Floodplain (Thoms et al. 2002), which is the largest number of wetlands in the Murray-Darling Basin (CSIRO 2008). These wetlands provide foraging habitat for birds, including migratory species (Brandis and Bino 2016).

The Lower Balonne River Floodplain supports large areas of native vegetation which is periodically inundated. The floodplain is dominated by coolibah (*Eucalyptus coolabah*) woodlands. The largest and least disturbed contiguous area of this vegetation type remaining in NSW is found on the floodplains of the Culgoa River at the Culgoa National Park (Hunter 2005). The floodplain coolibah–black box woodland community of the northern riverine plains (Darling Riverine Plains and the Brigalow Belt South bioregions) is listed as an endangered ecological community under the *Threatened Species Conservation Act 1995* (NSW).

The Narran Lakes UEA also supports a number of different flood dependent vegetation types, which are important habitats for a range of biota. The Narran Lakes UEA contains some of the largest expanses of lignum (*Duma florulenta*) in NSW and is vital habitat for colonial waterbird breeding. The geomorphology of the Narran Lakes is significant as an excellent example of a terminal (or closed) lake system in NSW (Thoms et al. 2002; NPWS 2000).

4.2 Ecological targets and functions

Step 3 of the ESLT method (Figure 2) includes developing ecological targets based on the ecological values of a UEA. These ecological targets are then used to guide the assessment of environmental water requirements. The ecological targets from the original Basin Plan UEA assessments for the Lower Balonne River Floodplain (MDBA 2012a) and Narran Lakes (MDBA 2012b) were reviewed with respect to new evidence, including the new science undertaken in the Northern Basin Review. Two changes were made: a new target aimed at supporting drought refuges for a range of native species and the Narran Lakes waterbird breeding target is no longer limited to colonial-nesting species. The ecological targets are to provide a flow regime which:

- maintains drought refuges, and supports recruitment opportunities, for a range of native aquatic species (e.g. fish, frogs, turtles, invertebrates)
- supports the habitat requirements of waterbirds and (for Narran Lakes) is conducive to successful breeding of waterbirds
- ensures the current extent of native vegetation of the riparian, floodplain and wetland communities is sustained in a healthy, dynamic and resilient condition
- supports hydrological connectivity between habitats, along the river (longitudinal) and between the river and its floodplain (lateral).

Since the original UEA assessments (MDBA 2012a, MDBA 2012b), further work has been done to understand the relationships between ecosystem functions and environmental watering. For example, the Basin-wide environmental watering strategy emphasises the functional aspects of longitudinal and lateral connectivity (MDBA 2014). With relevant wording from the Basin Plan in mind (Box 4), and considering the ecological and hydrological evidence available for the Lower Balonne River Floodplain and Narran Lakes UEAs, four ecosystem functions have been considered:

- **vital habitat** (drought refugia) - provide a refuge for native water-dependent biota during dry periods and drought⁸
- **longitudinal connectivity** – provide hydrological connections along watercourses that: link a diversity of aquatic environments for feeding, breeding, dispersal, migration and re-colonisation by native aquatic species; and facilitate geomorphic processes, sediment movement and nutrient spiralling.⁹
- **lateral connectivity** – provide hydrological connections between watercourses and adjacent floodplains and wetlands that: link a diversity of aquatic environments for feeding, breeding, migration and re-colonisation by native water-dependent species; support the vigour and condition of native vegetation; and facilitate off-stream primary production, and nutrient and organic matter exchange.¹⁰
- **vital habitat and populations** (waterbirds) - provide for a diversity of important feeding, breeding and nursery sites for waterbirds including providing conditions conducive to large-scale breeding.¹¹

Longitudinal and lateral connectivity are illustrated conceptually in Figure 12.

⁸ This ecosystem function is consistent with Basin Plan, schedule 9, criterion 1

⁹ consistent with Basin Plan, schedule 9, criteria 2 and 3

¹⁰ consistent with Basin Plan, schedule 9, criteria 2 and 4

¹¹ consistent with Basin Plan, schedule 9, criterion 1



Figure 12: Conceptual diagram of the longitudinal and lateral connectivity of flows in a river system

The ecosystem functions are expressed in a way that reflects different parts of the flow regime (e.g. drought refuges are vital habitats that relate to low- and no-flows, longitudinal connectivity is important for fish migration during fresh flows, lateral connectivity and vital waterbird habitat are important for breeding during overbank flows). For this reason, they provide a convenient set of sub-headings in which to describe environmental water requirements. In the following two chapters, the ecological targets and ecosystem functions described above are linked to the specification of site-specific flow indicators for the Lower Balonne River Floodplain UEA (chapter 5) and Narran Lakes UEA (chapter 6).

5 Selecting site-specific flow indicators for the Lower Balonne River Floodplain UEA

5.1 Drought refugia (vital habitat)

The watercourses of the Lower Balonne River Floodplain UEA become a series of waterholes during no-flow periods (*DSITI 2015*). These waterholes allow aquatic biota to survive through periods of no-flow by acting as refuges. When subsequent flow events occur, biota in these waterholes re-colonise the broader river system (Puckridge et al. 1998; Humphries and Baldwin 2003; Magoulick and Kobza 2003; Balcombe et al. 2007; DERM 2010). It is therefore important that a network of waterholes persist through extended no-flow periods (Sheldon et al. 2010; *DSITI 2015*).

The ability of a waterhole to act as a refuge for aquatic biota depends on the persistence time of water in the waterhole, the habitat and water quality of the waterhole and the degree of connectivity of waterholes during flow events (Puckridge et al. 1998; Humphries et al. 1999;

Thoms and Sheldon 2000; Balcombe et al. 2007; Woods et al. 2012; Marshall et al. 2016). The flow indicators have been set based on the persistence time of waterholes (including an assumed minimum depth).

For aquatic biota to be healthy, waterholes must contain sufficient food, have suitable water quality, and be comprised of diverse habitats (Woods et al. 2012). These attributes change as waterholes evaporate and become shallower. For example, a reduction in dissolved oxygen arising from an algal bloom can result in local extinction events (Boulton and Brock 1999).

Water resource development has increased the length of no-flow events in both the Culgoa and Narran Rivers (section 3.2) The longer the no-flow periods are, the greater the chance of waterholes drying up causing local extinction of aquatic biota. Dams (such as Beardmore Dam) and large weirs (such as Jack Taylor Weir) can act as a refuge for some aquatic biota and may play an important role for aquatic biota to re-colonise parts of the river system, but they also act as barriers limiting movement throughout the system.

5.1.1 Summary of available evidence

To improve the knowledge of waterhole refuge persistence in the Culgoa and Narran Rivers, a research project was commissioned as part of the Northern Basin Review (DSITI 2015). The project used satellite imagery between 1988 and 2015 to detect water during periods of no-flow to locate waterholes and estimate their persistence time. Field measurements were also taken (bathymetry, depth, rate of drawdown) to permit modelling of persistence times of waterholes in the Culgoa and Narran Rivers (Figure 13). An example of a waterhole is shown in Figure 14. The project considered both natural waterholes and those that have been created or augmented with a weir. The method to estimate the persistence of waterholes was based on a similar project undertaken in the adjacent Moonie system (DERM 2010).

The models estimated how long it takes for each waterhole to dry out, and how long water is retained to a depth of 0.5 metres. When water levels drop below 0.5 metres, the risk of poor water quality and biological limitations (such as insufficient food resources) are greater (DSITI 2015). Therefore a threshold of 0.5 metres was adopted by DSITI (2015) as an estimate of the minimum amount of water required to maintain a healthy aquatic biota in waterholes.

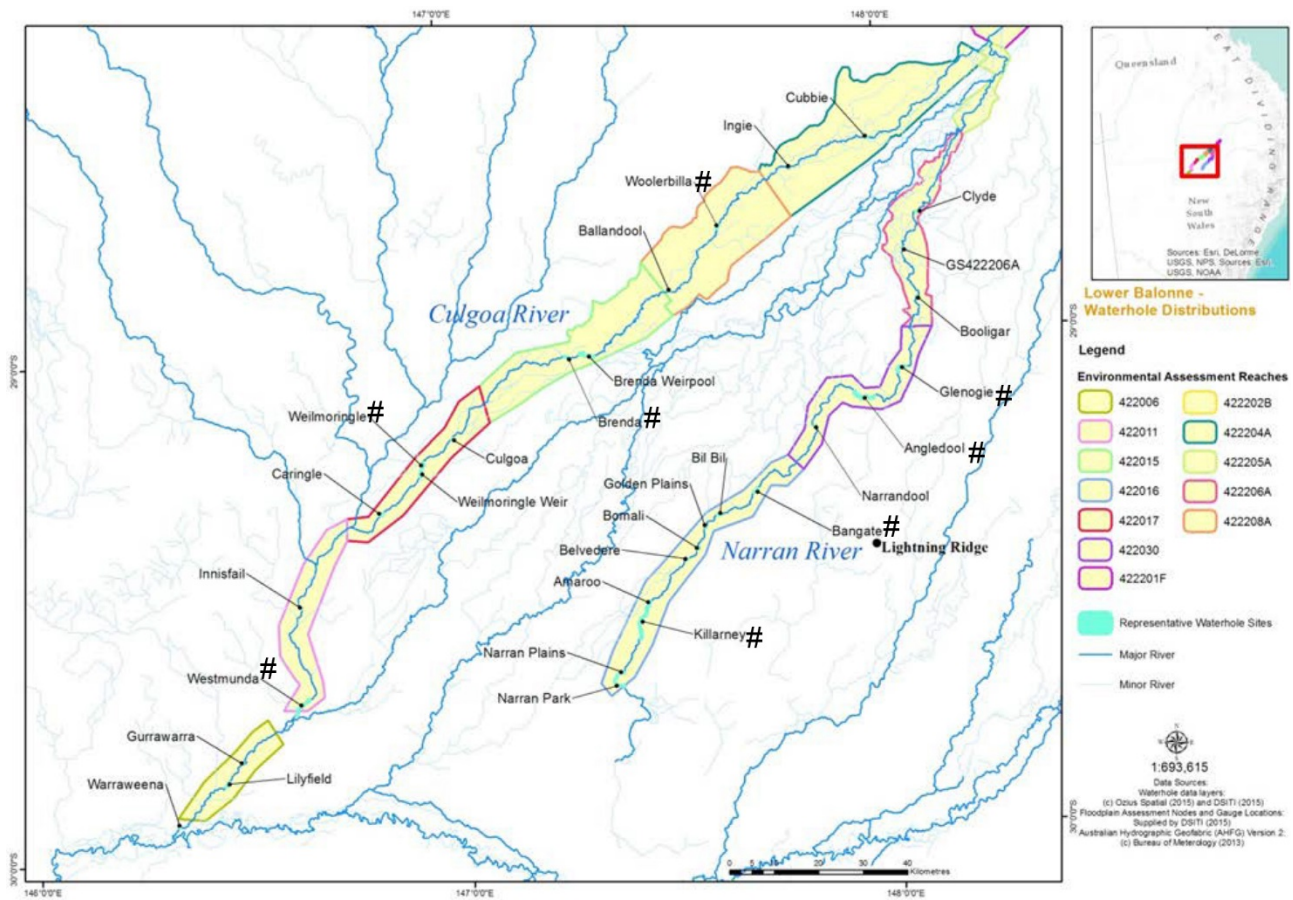


Figure 13: The 30 representative waterholes selected for modelling on the Culgoa and Narran Rivers (DSIT 2015). The eight waterholes that persist for longer than 350 days to a depth greater than 0.5 m are shown by #



Figure 14: Waterhole on the Lower Balonne River Floodplain (photo: Will Lucardie, MDBA)

The assessments of *DSITI (2015)* focused on the Culgoa and Narran as these rivers are larger and have deeper channels compared to the Bokhara, Ballandool and Birrie Rivers (Webb 2009). A key element of the project was to identify waterholes that could persist with a minimum depth of 0.5 metres through an extended no-flow period of 350 days. This duration was chosen as it was identified as a threshold of concern for waterholes under stress at a reach scale (*DSITI 2015*). Of the 27 waterholes assessed as a part of the project, eight were identified as being suitable refuge waterholes - four each in the Culgoa and Narran systems. Table 3 shows the results of the assessment of modelled waterhole persistence for waterholes in the Culgoa and Narran Rivers.

Table 3: Waterholes modelled in the Culgoa and Narran Rivers

Waterhole	Natural or Weir pool	Maximum depth (m)	Persistence threshold to 0.5 m depth (days)	Persistence threshold to empty (days)
Culgoa at Cubbie	Natural	2.66	335	405
Culgoa at Ingie	Natural	2.19	245	301
Culgoa at Woolerbilla GS	Natural	2.58	358#	437
Culgoa at Ballandool	Natural	2.70	320	384
Culgoa at Brenda	Natural	2.82	430#	514
Culgoa at Brenda Weir Pool	Weir pool	2.25-2.50	N/A	N/A
Culgoa at Culgoa NP (NSW)	Natural	1.91	225	295
Culgoa at Weilmoringle GS	Natural*	2.79	495#	587
Culgoa at Weilmoringle Weir Pool	Weir pool	>3.00	N/A	N/A
Culgoa at Caringle	Natural	1.68	180	247
Culgoa at Innisfail	Natural	1.45	155	236
Culgoa at Westmunda	Natural	2.37	389#	486
Culgoa at Gurrawarra	Natural	1.68	170	236
Culgoa at Lilyfield	Natural	2.08	310	396
Culgoa at Warraweena	Natural	1.50-1.75	N/A	N/A
Narran at Clyde	Natural	1.87	198	253
Narran at GS422206A	Natural	2.04	206	261
Narran at Booligar	Natural	2.57	284	342
Narran at Glenogie	Natural*	2.90	402#	478
Narran at Angledool	Natural*	3.05	538#	637
Narran at Narrandool	Natural	1.29	130	202
Narran at Bangate	Natural	3.00	473#	563
Narran at Bil Bil	Weir pool	1.68	190	263
Narran at Golden Plains	Natural	1.31	100	165
Narran at Bomali	Natural	2.06	270	347
Narran at Belvedere	Natural	1.32	140	214
Narran at Amaroo	Natural*	1.30	210	327
Narran at Killarney	Weir pool	2.43	360#	448
Narran at Narran Plains	Natural	2.74	345	419
Narran at Narran Park	Natural*	2.41	310	388

* natural waterhole that has been augmented with a weir; # considered a refuge waterhole as persistence threshold to 0.5 m water depth is longer than 350 days (i.e. suitable); N/A insufficient data

The *DSITI (2015)* project also looked at different durations of no-flow periods in the Culgoa and Narran Rivers and their impacts on waterholes. They identified no-flow periods of 470 days at Narran Park on the Narran River and 430 days at Weilmoringle on the Culgoa River as those maximum no-flow periods expected to maintain at least two refuge waterholes to at least 0.5 metres depth on the two respective rivers. *DSITI (2015)* found a no-flow period of 550 days as the threshold where the system is approaching complete failure. At 550 days, approximately 10% of waterholes modelled would retain any water (i.e. Culgoa River at Weilmoringle gauging station, Narran River at Angledool gauge as shown in Figure 15, Narran River at Bangate gauge) and all have water depths less than 0.5 metres, and hence refuge habitat is considered to be at significant risk.



Figure 15: Weir on the Narran River at Angledool, which is associated with the most persistent refuge waterhole in the Lower Balonne River Floodplain (photo: Adam Sluggett, MDBA)

5.1.2 Site-specific flow indicators

Two site-specific flow indicators have been specified to reflect a flow regime that maintains refuge waterholes for aquatic biota along the Culgoa and Narran Rivers.

Both the remote sensing and modelling of waterhole persistence supported the importance of maintaining refuge waterholes in the mid reach of the Culgoa River and the mid to lower reaches of the Narran River. To ensure flows are sufficient to replenish the refuge waterholes, they have been specified towards the downstream end of each river, at the Weilmoringle gauge on the Culgoa River and Narran Park gauge on the Narran River. This is because any flow detected by these gauges will have passed through and topped-up the refuge waterholes on the way through. Weilmoringle gauge was selected as the most appropriate downstream gauge for refuge waterholes on the Culgoa River. Nebine Creek flows into the Culgoa River downstream of the Weilmoringle gauge, significantly reducing the periods without flow. The Narran Park gauge is downstream of the major refuge waterholes along the Narran River.

Indicator: Any flow (a minimum of 2 ML/d for at least 1 day) in the Culgoa River at Weilmoringle, any time of the year, with a maximum period between flow events of between 350 (low uncertainty) and 430 days (high uncertainty).

Magnitude: Any flow in the mid reach of the Culgoa River would top up refuge waterholes. The Weilmoringle gauge is downstream of the refuge waterholes, therefore any flow that is detected by this gauge has already filled upstream waterholes.

2 ML/d flow has been adopted as the minimum flow at the Weilmoringle gauge for the purposes of analysing modelled flows, and recognising the limitations in simulating low flows within existing hydrological modelling.

Duration: As any flow detected at the gauge would have filled the upstream waterholes, a minimum duration of 1 day is required.

Timing: Waterhole replenishment flows can occur at any time of year as the primary aim is to ensure the maximum persistence of the waterholes is not exceeded.

Frequency: No-flow periods are a significant natural feature of the flow regime in the rivers of the Lower Balonne River Floodplain UEA. These periods have become longer as a result of the development of water resources (such as the period between January 1985 and January 1988 shown in Figure 10 and Figure 11).

The low uncertainty frequency provides for at least four refuge waterholes in the Culgoa River to persist to a water depth of at least 0.5 metres. The maximum no-flow period of 350 days was selected based on the research findings of *DSITI (2015)* which is supported by the persistence thresholds presented in Table 3. The provision of these four waterholes corresponds to about thirty percent of waterholes.

The high uncertainty frequency was set so that at least two refuge waterholes in the Culgoa River retain a water depth of at least 0.5 metres. From Table 3, the high uncertainty frequency was set at a maximum no-flow period of 430 days at Weilmoringle on the Culgoa River to maintain the waterholes at Brenda and Weilmoringle Gauging Stations. The provision of these two waterholes corresponds to about fifteen percent of waterholes.

Indicator: Any flow (minimum of 2 ML/d for at least 1 day) in the Narran River at Narran Park, any time of the year, with a maximum period between flow events of between 350 (low uncertainty) and 470 days (high uncertainty).

Magnitude: Any flow in the mid to lower reaches of the Narran River would top up refuge waterholes. The Narran Park gauge is downstream of the refuge waterholes, therefore any flow that is detected by this gauge has already filled upstream waterholes.

2 ML/d flow has been adopted as the minimum flow at the Narran Park gauge for the purposes of analysing modelled flows, and recognising the limitations in simulating low flows within existing hydrological modelling.

Duration: As any flow detected at the gauge would have filled the upstream waterholes, a minimum duration of 1 day is required.

Timing: Waterhole replenishment flows can occur at any time of year as the primary aim is to ensure the maximum persistence of the waterholes is not exceeded.

Frequency: No-flow periods are a significant natural feature of the flow regime in the rivers of the Lower Balonne River Floodplain UEA. These periods have become longer as a result of the development of water resources (such as the period between January 1985 and January 1988 shown in Figure 10 and Figure 11).

The low uncertainty frequency provides for at least four refuge waterholes in the Narran River to persist to a water depth of at least 0.5 metres. The maximum no-flow period of 350 days was selected based on the research findings of *DSITI (2015)* which is supported by the persistence thresholds presented in Table 3. The provision of these four waterholes corresponds to about thirty percent of waterholes.

The high uncertainty frequency was set so that at least two refuge waterholes in the Narran River retain a water depth of at least 0.5 metres. From Table 3, the high uncertainty frequency was set at a maximum no-flow period of 470 days at Narran Park on the Narran River to maintain the waterholes at Angledool and Bangate. The provision of these two waterholes corresponds to about fifteen percent of waterholes.

A summary of the basis of the site-specific flow indicators for drought refugia in the Lower Balonne River Floodplain is presented in Table 4.

Table 4: Lower Balonne River Floodplain UEA site-specific flow indicators related to drought refuges. In this table, frequency is the maximum number of days between events. The frequency range is shown from low uncertainty to high uncertainty

Magnitude: minimum flow (ML/d)	Basis of magnitude	Duration (consecutive days)	Basis of duration	Timing	Basis of timing	Frequency range	Basis of frequency
Any flow (min. 2 ML/d) for Culgoa River at Weilmoringle	Any flow will top up waterholes	1	Minimum time in the model for a flow to be observed	Any time of year	The primary aim is to break up long dry spells: timing is not important	350 - 430 days (maximum period between flow events)	Based on modelled persistence time to a depth of 0.5 m in four waterholes (350 days), or two waterholes (430 days) in the Culgoa River
Any flow (min. 2 ML/d) for Narran River at Narran Park	Any flow will top up waterholes	1	Minimum time in the model for a flow to be observed	Any time of year	The primary aim is to break up long dry spells: timing is not important	350 - 470 days (maximum period between flow events)	Based on modelled persistence time to a depth of 0.5 m in four waterholes (350 days), or two waterholes (470 days) in the Narran River

5.2. Longitudinal connectivity (along watercourses)

The range of aquatic habitats in the Lower Balonne River Floodplain UEA support a diverse assemblage of aquatic species. During no-flow periods, each waterhole contains localised and confined populations of biota, which mix during periods of flow (Puckridge et al. 1998; Thoms and Sheldon 2000; Balcombe et al. 2007; Bond et al. 2015). These local populations may die out during extended dry periods, with species then relying on subsequent re-colonisation from more persistent waterholes when flows recommence and longitudinal connectivity is restored (Balcombe et al. 2006, Bunn et al. 2006).

5.2.1 Summary of available evidence

Site-specific flow indicators for longitudinal connectivity were developed after considering a range of information sources, including a mixture of existing research and recently commissioned studies in the Northern Basin Review.

A primary line of evidence considered was commissioned research on the relationship between fish and flows in the northern Basin (*NSW DPI 2015*). This project brought together over 20 fish ecology experts and water managers, who considered more than 150 items of research. This project used the most up-to-date research on flows and the relationship to fish spawning, recruitment, movement, migration and condition. The project classified fish into northern Basin-specific functional groups based on fish with similar life-cycle requirements for flows (Box 7). For some functional groups, such as the flow dependent specialists and in-channel specialists, there is a particularly strong dependency on flows at some stages of their life-cycles.

A variety of flows is integral to the structure and diversity of the aquatic communities, including fish, in the Murray–Darling Basin (Baumgartner et al. 2013; Rolls et al. 2013). Variable flows allow aquatic animals to access a diversity of aquatic environments. For example, research in the nearby Barwon–Darling River shows variable flows are needed to inundate snags that are important for fish as they can provide habitat, protection from predation and have been demonstrated to be an important breeding location for many species such as Murray cod (Boys et al. 2005; Boys et al. 2013).

The provision of opportunities for dispersal of aquatic species is important for maintaining healthy populations. For example, the dispersal of larvae of fish species such as golden perch and silver perch has been shown to be facilitated by flowing water (*NSW DPI 2015*). The provision of opportunities for movement and migration of some fish species supports healthy populations. Reynolds (1983) observed upstream migration patterns of tagged golden perch and silver perch in the Murray River, and observed some large-scale movements by golden perch over 1,000 km in response to rises in water level. Research in the Cooper Creek catchment and northern Basin shows that some fish use connecting flows between waterholes to move over large spatial scales (Puckridge et al. 1998; Balcombe et al. 2007; Marshall et al. 2016). Species such as Murray cod, golden perch and silver perch commonly migrate to flowing water habitats as juveniles and also during the spawning season (Saddler et al. 2008; Koehn et al. 2009; Mallen-Cooper and Zampatti 2015).

Box 7: Native fish functional groups (adapted from NSW DPI 2015)

Group 1: Flow dependent specialists. (golden perch, silver perch, spangled perch (*Leiopotherapon unicolor*), and Hyrtl's tandan (*Neosilurus hyrtl*)).

Group 2a: In-channel specialists - flow dependent (Murray cod).

Group 2b: In-channel specialists - flow independent (freshwater catfish, purple spotted gudgeon).

Group 3: Floodplain specialists (Darling River hardyhead (*Craterocephalus amniculus*), olive perchlet and Rendahl's tandan (*Porochilus rendahli*)).

Group 4: Generalists (bony bream (*Nematalosa erebi*), carp gudgeon (*Hypseleotris klunzingeri*), flat-headed gudgeon (*Philypnodon grandiceps*), Australian smelt (*Retropinna semoni*) and unspotted hardyhead (*Craterocephalus fulvus*).

Group 5: Generalists - alien species (e.g. carp - *Cyprinus carpio*).

The flow attributes that benefit each functional group are detailed in *NSW DPI (2015)*.

Some functional groups have a particularly strong association with parts of the flow regime. For example:

- Flow dependent specialists need flow freshes for a number of life-cycle requirements including to generate spawning responses, aid in larvae drift, and to undertake moderate to large-scale migrations (e.g. hundreds of km).
- Some in-channel specialists such as Murray cod also have important flow related requirements, such as requiring stable flows to allow for nest development and spawning.

Recent research on fish movements in the nearby Moonie River has demonstrated that water level, temperature and the first post-winter flow are important cues for the movement of golden perch and freshwater catfish (*Marshall et al. 2016*). The research found that fish responded to changes in river height of over 2 metres from commence to flow, and moved when water temperature was greater than 15 degrees Celsius (*Marshall et al. 2016*). Subsequent unpublished analysis by the Queensland Government has assessed the flow rates at multiple gauges across the Lower Balonne River Floodplain UEA where water velocity is greater than 0.3 metres per second. This velocity is thought to be a useful threshold for biota that need flowing water for lifecycle responses, such as golden perch (Ramírez and Pringle 1998; Passy 2001; Mallen-Cooper and Zampatti 2015).

Recent initial results from a fish acoustic tagging study undertaken in the Lower Balonne River Floodplain UEA by Queensland Government suggest that fish movement can be an almost immediate response to river rise (or increased velocity) for some species such as Hyrtl's tandan (R. Woods, pers. comm., April 2016). Other species, such as golden perch, may require more significant events to elicit a response. The fish movements were observed around the Brenda gauge on the Culgoa River, with the event having a peak of 2,500 ML/d (equivalent to a river height just greater than 2 metres above commence to flow) at Brenda on 19 February 2016. The distance moved by the fish was considered to be primarily constrained by instream barriers

(weirs or naturally as flow receded and waterholes became disconnected). This study is ongoing and is expected to provide a technical report in 2017.

More generally, sufficient maintenance of longitudinal connectivity for fish and other aquatic species to move through the river system to access habitat, food resources and to provide spawning opportunities is important in overcoming potential genetic bottlenecks in dryland river systems (Huey et al. 2011).

There are physical barriers between waterholes in the Lower Balonne system, including many low-level weirs, which may restrict fish movement. The Queensland Government has a current research project to identify the location and characteristics of barriers to fish movement in the Queensland section of the Murray-Darling Basin. This project is also trialling a method to estimate the "drown-out" of a number of barriers in the Lower Balonne River Floodplain. This information is primarily being collected for another Queensland Government project to model the movement of migratory fish species but once completed, will also be useful to help assess the scale of fish movement opportunities.

5.2.2 Site-specific flow indicators

Three site-specific flow indicators have been specified to provide a flow regime that supports longitudinal connectivity for dispersal of biota such as fish larvae, movement (including migrations for spawning), re-colonisation opportunities and access to habitat. The indicators are also anticipated to support habitat requirements for a range of other native aquatic species. The indicators are a small in-channel fresh and two larger in-channel freshes.

Small in-channel freshes

Indicator: Minimum of 1 flow event of 1,000 ML/d in the Culgoa River at Brenda for 7 consecutive days any time of year for 90% (low uncertainty) to 80% (high uncertainty) of years.

Magnitude and duration: MDBA analysis of flow data from the NSW Water Information website showed events above 1,000 ML/d for 7 days generally correspond to a water level rise above 1 metre along the Culgoa River (such as a 1.3 m rise at Brenda).

A flow of 1,000 ML/d for 7 days at Brenda inundates lower sections of the river banks over hundreds of kilometres of river length across several channels providing access to habitat and inundation of riparian vegetation. It would provide opportunities for small-scale fish movement, including for species with short lifespans, such as spangled perch which lives for less than five years (NSW DPI 2015). It is anticipated that longitudinal movement opportunities would be relatively small, perhaps to neighbouring pools, depending on barriers.

The maximum water level rise would be subject to the peak flow of the event, with events resulting in a peak greater than 2,500 ML/d at Brenda corresponding to a 2 m rise above commence to flow. This level of flow has been observed to be associated with movement of some fish species (R. Woods, pers. comm., April 2016). This flow is also highly likely to result in a small in-channel fresh in the Narran River, with the response in the Bokhara River more variable. The actual size of the fresh is dependent on antecedent conditions (e.g. how dry or wet the catchment is), the influence of the bifurcation weirs and other regulating infrastructure, and the level of diversions.

A duration of 7 days is considered to provide opportunities for the drift of biota, including fish larvae and macroinvertebrates over significant distances.

Timing: While summer flows are most likely given the summer dominated flow regime, longitudinal connectivity at any time of year would be beneficial for maintenance of fish populations.

Frequency: The flow event is required to occur in most years, with a low uncertainty frequency of 90% of years and high uncertainty frequency of 80% of years specified. This frequency range is consistent with the findings of *NSW DPI (2015)* for the neighbouring Barwon-Darling River system, where small in-channel freshes generally occurred annually.

Large in-channel freshes

Indicator: Minimum of 1 flow event of 1,700 ML/d in the Narran River at Wilby Wilby for 14 consecutive days from August to May for 60% (low uncertainty) to 40% (high uncertainty) of years.

Magnitude: MDBA analysis of flow data from the NSW Water Information website showed flows of 1,700 ML/d at Wilby Wilby correspond to a 2 m rise above commence-to-flow and 0.3 metres per second velocity along much of the Narran River.

Research in the Moonie River found that a threshold of 2 m above commence-to-flow river height resulted in the movement of golden perch and freshwater catfish if the water temperature was above 15 degrees Celsius (*Marshall et al. 2016*). Subsequent unpublished analysis by the Queensland Government identified an average velocity of 0.3 metres per second as a threshold cue for fish movement, and specified flows at which this velocity occurs at each gauge. This velocity to trigger fish migration is supported by other research in the Murray-Darling Basin (Mallen-Cooper and Zampatti 2015).

Duration: The minimum duration of 14 days has been informed by both ecologic and hydrologic considerations. This duration meets the hatch time for Murray cod eggs, considered appropriate as this is the longest hatch time for native fishes in the Lower Balonne River Floodplain. This duration also corresponds with the median duration of flows above these thresholds under without development conditions.

Timing: The timing is August to May to exclude the two coldest months of the year when fish responses are expected to be subdued (Reynolds 1983; Mallen-Cooper et al. 1995; Lyon et al. 2008). This is supported by observed average water temperatures at Brenda on the Culgoa River, which showed average monthly water temperature above 15 degrees Celsius in the months of August to May - a temperature known to be a threshold for fish movement responses (*Marshall et al. 2016*).

The timing has not been limited to the months when spawning occurs, but rather it has been limited to the period when water temperatures are generally above 15 degrees Celsius, which is the temperature threshold that fish have been observed moving on in the nearby Moonie River (*Marshall et al. 2016*).

Frequency: The frequency of large in-channel freshes needed in highly intermittent systems for fish lifecycle requirements is around 50 percent of years (*NSW DPI 2015*). The frequency range selected is 60% (low uncertainty) and 40% (high uncertainty) of years to reflect this requirement.

Indicator: Minimum of 1 flow event of 3,500 ML/d in the Culgoa River at Brenda for 14 consecutive days from August to May for 60% (low uncertainty) to 40% (high uncertainty) of years.

Magnitude: MDBA analysis of flow data from the NSW Water Information website showed flows of 3,500 ML/d at Brenda correspond to a 2 m rise above commence-to-flow and 0.3 metres per second velocity along the Culgoa River.

Research in the Moonie River found that a threshold of 2 m above commence-to-flow river height resulted in the movement of golden perch and freshwater catfish if the water temperature was above 15 degrees Celsius (*Marshall et al. 2016*). Subsequent unpublished analysis by the Queensland Government identified an average velocity of 0.3 metres per second as a threshold cue for fish movement, and specified flows at which this velocity occurs at each gauge. This velocity to trigger fish migration is supported by other research in the Murray-Darling Basin (*Mallen-Cooper and Zampatti 2015*).

Duration: The minimum duration of 14 days has been informed by both ecologic and hydrologic considerations. This duration meets the hatch time for Murray cod eggs, considered appropriate as this is the longest hatch time for native fishes in the Lower Balonne River Floodplain. This duration also corresponds with the median duration of flows above these thresholds under without development conditions.

Timing: The timing is August to May to exclude the two coldest months of the year when fish responses are expected to be subdued (Reynolds 1983; Mallen-Cooper et al. 1995; Lyon et al. 2008). This is supported by observed average water temperatures at Brenda on the Culgoa River, which showed average monthly water temperature above 15 degrees Celsius in the months of August to May - a temperature known to be a threshold for fish movement responses (*Marshall et al. 2016*).

The timing has not been limited to the months when spawning occurs, but rather it has been limited to the period when water temperatures are above the point ¹² where fish have been observed moving in the nearby Moonie River (*Marshall et al. 2016*). Fish movement can be important for fish conditioning, dispersal, and habitat access, as well as spawning and recruitment (*NSW DPI 2015*).

Frequency: The frequency of large in-channel freshes needed in highly intermittent systems for fish lifecycle requirements is around 50 percent of years (*NSW DPI 2015*). The frequency range selected is 60% (low uncertainty) and 40% (high uncertainty) to reflect this requirement.

A summary of the basis of the site-specific flow indicators for longitudinal connectivity in the Lower Balonne River Floodplain is presented in Table 5.

¹² generally greater than 15 degrees Celsius

Table 5: Site-specific flow indicators for in-channel freshes for the Lower Balonne River Floodplain UEA. In this table, frequency is the percentage of years in which there is at least one flow event. The frequency range is shown from low uncertainty to high uncertainty.

Magnitude: minimum flow (ML/d)	Basis of magnitude	Duration (consecutive days)	Basis of duration	Timing	Basis of timing	Freq. range	Basis of frequency
1,000 (Culgoa River at Brenda)	Provide small-scale movement opportunities, perhaps to neighbouring pools and some short term connection between distributaries (subject to barriers).	7	Duration to achieve connectivity along the main distributary channels and potential for drift of biota such as fish larvae.	Any time of the year	At any time of year would provide benefits of connection and improved habitat condition.	90% – 80% of years (with at least 1 event)	To provide regular freshes (close to annual) for maintenance and conditioning of fish populations and other aquatic biota.
1,700 (Narran River at Wilby Wilby)	Provide small-scale movement opportunities (subject to barriers). Trigger fish movement of flow dependent specialists, for dispersal and spawning. Provides both a 2 m rise and an average velocity (0.3 metres per second).	14	The typical duration of this size event and meets the required hatch time for native fish eggs.	Aug - May	Fish response expected when the water temperature exceeds the critical temperature threshold (15 degrees).	60% - 40% of years (with at least 1 event)	Based on fish lifecycle requirements.
3,500 (Culgoa River at Brenda)	Provide small-scale movement opportunities (subject to barriers). Trigger fish movement of flow dependent specialists, for dispersal and spawning. Provides both a 2 m rise and an average velocity (0.3 metres per second).	14	The typical duration of this size event and meets the required hatch time for native fish eggs.	Aug - May	Fish response expected when the water temperature exceeds the critical temperature threshold (15 degrees).	60% - 40% of years (with at least 1 event)	Re-colonisation of aquatic species. Provide regular opportunities for mixing of populations.

5.3 Lateral connectivity (with the floodplain)

Floodplains are an important component of river systems. Many, if not all, of the species that live in rivers depend in some way on the river connecting with its' floodplain (Mussared 1997). Flooding flows that punctuate dry spells and inundate floodplains are an essential component of dryland river systems. When rivers overflow and floodwaters extend across the floodplain there is an exchange of nutrients which replenishes the floodplain and river, and a dispersal of seeds and organisms (Thorp et al. 2008). This process is important for the lifecycle needs of fauna including fish, waterbirds, and other aquatic organisms (Balcombe et al. 2007; Leigh et al. 2010; Sternberg et al. 2012).

Periodic inundation is important for the health of the river system and the floodplain (Thorp et al. 2008). Floodwaters inundate a diverse suite of environments, including wetlands and floodplain vegetation communities such as forests, woodlands and grasslands (Figure 5). Wetlands, creeks and anabranches provide foraging habitat for bird species. Fish move into the anabranches and wetlands that are inundated with floodwaters to feed in these nutrient-rich areas, and many small bodied fish use these habitats to breed (*Nichols et al. 2012, NSW DPI 2015*). Other animals including amphibians and reptiles also depend on areas of the river banks and floodplain (*DSITIA 2013*). Floodwaters are also important for triggering events that are important for river-floodplain food webs (e.g. Jenkins and Boulton, 2007).

A diversity of out-of-channel flows (lateral connectivity) is needed to connect different parts of the floodplain system and have a range of environmental benefits. These are described below.

5.3.1 Summary of available evidence

New evidence gathered through the Northern Basin Review includes: hydrological analysis undertaken by the MDBA; inundation mapping; vegetation mapping in NSW (*Eco Logical Australia 2016*); and reviews of knowledge on waterbirds (*Brandis and Bino 2016*) and vegetation (*Casanova 2015*). Also, the interaction between floodplain flows and ecology was recently analysed following observations during the summer floods of 2010/11 (*Woods et al. 2012; Capon 2012*). Other recent studies from the northern basin relevant to the assessment of environmental water requirements of the floodplain includes *DSITIA (2013)*, *Marshall et al. (2016)*, *Sternberg et al. (2012)*, and *Senior et al. (2016)*.

Additionally, Whittington et al. (2002), and Sims (2004) undertook work to assess the flow rates required to inundate the floodplain in the Lower Balonne. They used satellite images (captured between September 1989 and April 1999) to analyse floodplain inundation patterns and identified flow rates at the St George gauge that inundate different areas of the Lower Balonne floodplain.

The St George gauge is the gauge immediately upstream of the Lower Balonne River Floodplain UEA (Figure 3). Flows described at this gauge therefore take account of the total flow entering the Lower Balonne River Floodplain UEA. However, a large proportion of the water extracted for irrigation occurs downstream of St. George. The gauge located at Brenda on the Culgoa River provides a better reflection of the impact of diversions and flows into the mid and lower reaches of the Lower Balonne River Floodplain UEA. For this reason, the Brenda gauge has been selected as a better location to specify and assess environmental water requirements of the Lower Balonne River Floodplain UEA.

As part of the original assessment of environmental water requirements for the Lower Balonne, the relationship between flows at the St George gauge on the Balonne River and flows at the Brenda gauge on the Culgoa was determined (MDBA 2012a). This relationship was updated as part of the Northern Basin Review. This was done by developing flow attenuation relationships between pairs of gauges from St George successively downstream to the Brenda gauge on the Culgoa River (MDBA 2016). This approach took into account travel times when comparing flows between gauges such as those at Whyenbah, Woollerbilla, and Brenda. This recent work (Table 6) is considered to provide a more accurate estimate of the corresponding flows at Brenda than the original assessment in 2012.

Table 6: Examples of the relationship between flows on the Balonne River at St George and the corresponding flows expressed at Brenda on the Culgoa River (MDBA 2016).

Flow measured in the Balonne River at St George (ML/d)	Estimated flow at the Culgoa River at Brenda (ML/d)
26,000	7,800
30,000	9,200
45,000	15,000
70,000	24,500
120,000	38,000

The relationship in Table 6 provides an indication of how flow magnitude changes down the river channel and downstream of bifurcation 1. Broadly, the flow at Brenda in the Culgoa River is usually about a third of the flow in the Balonne River at St George within this range of flows. However, this relationship is general and the attenuation of individual flow events may differ due to factors such as the size of the event, impact of diversions, and antecedent conditions.

MDBA (2016) describes the method used to assess which flow rates breach the river banks and the approximate proportion of floodplain inundated. An example of areas inundated by flows at the Brenda gauge on the Culgoa on particular days is given in Figure 16 (MDBA 2016).

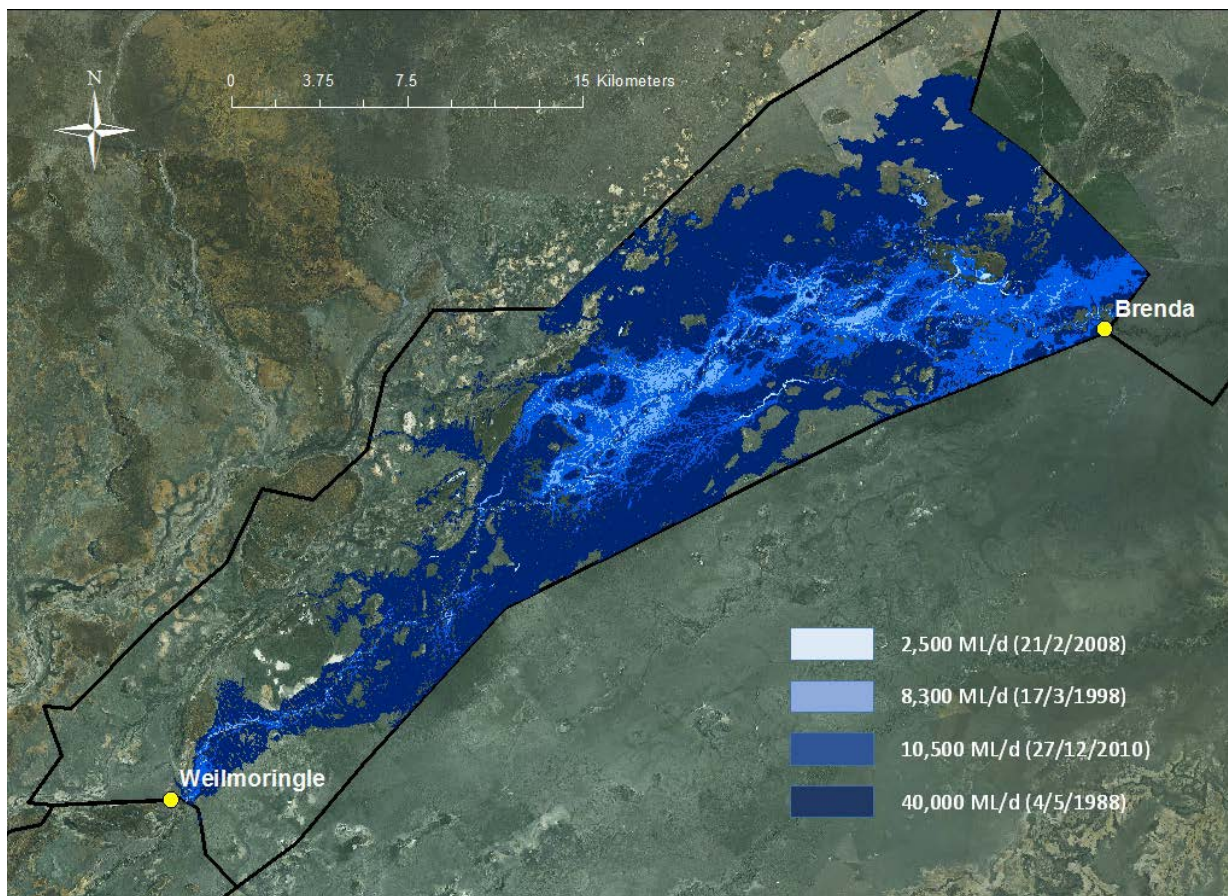


Figure 16: Example of floodplain areas inundated downstream of Brenda associated with flows measured at Brenda. The black lines corresponds to borders between zones used in the recent floodplain inundation analysis (MDBA 2016)

Figure 16 shows that flows of 8,300 ML/d or less measured at Brenda inundate small areas of the floodplain just downstream of Brenda, whereas flows between 10,500 ML/d and 40,000 ML/d inundate substantial areas of the floodplain.

Vegetation communities vary across the Lower Balonne floodplain according to flood frequency and position (Sims and Thoms 2002). This change in vegetation communities across different parts of the floodplain is shown conceptually in Figure 5. The vegetation communities include riparian trees such as river red gum (*Eucalyptus camaldulensis*), wetland species such as lignum, floodplain woodland species such as coolibah, and floodplain grassland species such as Mitchell grass (*Astrebla lappacea*, *Astrebla pectinata*) (Eco Logical Australia 2016). New vegetation community mapping was undertaken in the Lower Balonne as a part of the Northern Basin Review (Eco Logical Australia 2016). This mapping has helped identify the extent and location of floodplain vegetation communities in the region.

Water requirements (in the form of overbank flows) for four of the dominant floodplain vegetation species found in these vegetation communities were summarised from Roberts and Marston (2011). These were reviewed by a group of vegetation ecologists for the northern basin (Casanova 2015), and the results are provided in Table 7. The table summarises the average overbank flow requirements of a plant in average condition for vigorous growth and regeneration, and the critical interval between overbank flow events to maintain vigour.

Table 7: Water requirements (frequency, timing, depth) for the four most common flood-dependent species summarised from Roberts and Marston (2011). This data represents the best available general knowledge from across the Murray-Darling Basin and was reviewed in Casanova (2015). The table summarises the overbank flow requirements of a plant in average condition for vigorous growth and regeneration, and the critical interval between overland flow events to maintain vigour.

Species	Water regime requirements
River red gum	<p>For vigorous growth: Flooding about every one to three years for forests, about every two to four years for woodlands, depth not critical, variability is preferable, timing best in spring-summer</p> <p>For regeneration: Flood recession in spring or later, follow-up flood for establishment, depth 20-30 cm, but longer is tolerated</p> <p>Critical interval: Flooding after about three years for forests, five to seven years for woodlands, longer intervals lead to loss in condition</p>
Lignum	<p>For vigorous growth: Frequency about every one to three years for vigorous growth, three to five years to sustain, seven to ten years for persistence, depth not critical (< 1m), timing not critical (natural flow patterns should be followed if possible).</p> <p>For regeneration: Depth not critical, timing in autumn-winter, follow-up flooding nine to 12 months after germination likely to assist establishment. Flooding once every 12 to 18 months during first three years desirable, depth to 15 cm, before or during summer.</p> <p>Critical interval Flood every five to seven years, although rootstock can survive up to 10 years.</p>
Black box	<p>For vigorous growth: Frequency every three to seven years, depth not critical, timing probably not important (natural flow patterns should be followed if possible)</p> <p>For regeneration: Following flood recession or in run-off areas after rainfall, timing in spring-summer, additional moisture in first or second year likely to be beneficial</p> <p>Critical interval: Trees may survive 12 to 16 years, but in poor condition with diminished capacity to recover</p>
Coolibah	<p>For vigorous growth: About every 10 to 20 years, but could be as little as seven years, depth not critical, timing not expected to be important</p> <p>For regeneration: Likely to be on flood recession or in run-off areas after rainfall, timing not critical, additional moisture in the first summer likely to improve establishment</p> <p>Critical interval: Not known, possibly 10 to 20 years</p>

The requirements presented in Table 7 are a general guide and do not prescribe exact watering required for every individual tree of the species listed. Individual trees vary in age, condition and position in the landscape and they may have access to water of different quality and quantity. All of this can influence the ability of an individual tree to survive dry times. For example local advice is that a large proportion of coolibah trees of a variety of ages (e.g. saplings to mature trees)

have died on the Narran floodplain around Angledool and Narrandool in recent years (R. Treweek, pers. comm., April 2016) despite large-scale flooding in 2011 and 2012. It is not clear why there seems to be a large disparity in the ability of individual coolibah trees to survive drought. It is known that water can re-charge the soil profile and shallow groundwater systems and can be stored in wetlands or depressions, and this enables water to be utilised by plants well beyond the duration of the flow event (*Senior et al. 2016*). This observation reiterates the complexity of water movement in the region (Appendix A), the differences that may occur between individual trees and the need for ongoing research.

The health of floodplain vegetation is important for the ecosystem of the river. For example, the floodplain vegetation on the Lower Balonne River Floodplain is eaten by terrestrial insects which in turn are blown into the river (*Woods et al. 2012*). This has been demonstrated to be one of the most important sources of food for some native fish species including golden perch (*Woods et al. 2012*).

Wetlands are an important feature of the Lower Balonne River Floodplain UEA. Thoms et al. (2002) identified more than 3,400 wetlands within the Lower Balonne River Floodplain. This is the largest number of wetlands in a discrete area in the Murray-Darling Basin (CSIRO 2008). The wetlands are diverse in form, and include large wetlands and temporary billabongs. They are found within low-lying areas adjacent to the rivers and ephemeral channels of the system. Wetlands closer to the river hold water more often and may be dominated by aquatic vegetation such as reeds and sedges. As these wetlands dry out, species composition changes depending on the tolerance of the species to dry conditions. Soil seed-banks are important for the regeneration of wetland species upon re-wetting (Webb et al. 2006).

Wetlands provide habitat for many different animals. Fish move into the anabranches and wetlands that are inundated with floodwaters to feed in these nutrient-rich areas and many small bodied fish use these habitats to breed (*NSW DPI 2015*). Some small native fish species are wetland generalists (Box 7). Other animals such as amphibians and reptiles also depend on areas of the floodplain and river banks (*DSITIA 2013*). The numerous wetlands of the Lower Balonne River Floodplain provide foraging habitat for migratory bird species that are listed under international agreements (*Brandis and Bino 2016*). Ensuring these areas are periodically inundated is important for the health of the entire river system (Thorp et al. 2008).

5.3.2 Site-specific flow indicators

Four site-specific flow indicators associated with lateral connectivity between the river and the floodplain have been selected. These are connectivity with the riparian zone (near channel floodplain and some wetland areas); the inner floodplain (low lying areas of floodplain, wetlands and creeks adjacent to river channels); the mid floodplain (areas of floodplain and wetlands that are higher up on the elevation gradient); and outer floodplain (the area of floodplain furthest from the channel or at the highest elevation).

For each of the flow indicators, timing is not constrained as floodplain flows historically occur at any time of year and water on floodplains and in wetlands is generally retained beyond the flow event. The flow indicator gauge for the four flow indicators is Brenda on the Culgoa River, downstream of major diversions, and relates to the whole Lower Balonne River Floodplain (including the Narran and Bokhara river systems).

Lateral connectivity with the riparian zone (including near channel floodplain and some wetland areas)

A riparian zone along the Narran River at Angeldool is shown in Figure 17. River red gum and lignum can be seen.



Figure 17: Riparian zone in the Lower Balonne River Floodplain: Narran River at Angeldool (photo: Andrea Prior, DNRM Queensland)

Indicator: A minimum of 1 flow event of 9,200 ML/d in the Culgoa River at Brenda for 12 consecutive days any time, with an average period between events of 2 (low uncertainty) to 3 years (high uncertainty) on average.

Magnitude: Thoms et al. (2002) reported that a flow rate at St George corresponding to a flow of 7,800 ML/d on the Culgoa River at Brenda disperses water into the many small flood channels on the Lower Balonne River Floodplain. Additionally, Sims (2004) and Sims and Thoms (2002), reported that floodplain inundation commences at a flow corresponding to 9,200 ML/d on the Culgoa River at Brenda, inundating about 12,000 hectares of the floodplain upstream of the Queensland border. This magnitude of flow at Brenda is consistent with more recent inundation analysis (MDBA 2016). For comparison, the bankfull discharge at Brenda has been estimated by the Queensland Government to be 8,500 ML/d.

Based on the above evidence, a flow of 9,200 ML/d at Brenda was selected to reflect inundation of riparian zone and the near channel zone, including some wetlands.

At this flow, there would be inundation of river red gum, ephemeral wetlands and lignum communities with about 3% of the floodplain connected to the river (MDBA 2016). In addition to

providing for riparian plant communities, the flow would facilitate a range of other floodplain and in-channel functions.

Duration: Consistent with past practice (e.g. MDBA 2012a), the duration selected was the median duration for a flow of 9,200 ML/d from the without development flow scenario. The median rather than the average was chosen so that it is not overly biased by very long overbank events which occur occasionally in the Lower Balonne River System UEA.

For a flow of 9,200 ML/d the median duration is 12 days. It is expected that water would be retained in wetlands and depressions for longer than the 12 days and be likely to meet the needs of wetland vegetation.

Frequency: The frequency is 2 years (low uncertainty) to 3 years (high uncertainty) on average between events. This frequency is consistent with the flooding requirements of river red gum forest and lignum (Table 7).

Lateral connectivity with the inner floodplain

A typical wetland on the inner floodplain is shown in Figure 18.



Figure 18: Wetland on the Lower Balonne River Floodplain (photo: Eco Logical Australia)

Indicator: A flow event of 15,000 ML/d in the Culgoa River at Brenda for 10 consecutive days any time of year, with an average period between events of 3 (low uncertainty) to 4 years (high uncertainty) on average.

Magnitude: Whittington et al. (2002) concluded that a flow corresponding to 15,000 ML/d in the Culgoa River at Brenda (Table 6) would inundate riparian forest, lignum and some coolibah open woodlands in the Queensland section of the floodplain. This is consistent with MDBA inundation analysis (MDBA 2016) that indicates this flow inundates riparian and wetland communities, as well as around 15% of the floodplain. The analysis showed a third of coolibah and lignum communities along the channels of the Culgoa and Narran Rivers would be inundated. This flow is high enough to allow anabranches to carry water out onto the floodplain, particularly in the northern floodplain sections (Sims 2004).

Duration: Consistent with past practice (e.g. MDBA 2012a) and the logic for the duration of the other flow indicators for lateral connectivity, the median duration of the without development scenario was used. For a flow magnitude of 15,000 ML/d measured at Brenda, the median event duration was 10 days.

Frequency: The frequency is 3 years (low uncertainty) to 4 years (high uncertainty) on average between events. This is consistent with the watering requirements for vigorous growth in river red gum woodlands and black box woodlands and to sustain lignum shrublands (Table 7).

Lateral connectivity with the mid floodplain

A typical coolibah woodland on the Lower Balonne River mid-floodplain is shown in Figure 19.



Figure 19: Coolibah woodland on the Lower Balonne River Floodplain: near Whyenbah Road (photo: Andrea Prior, DNRM Queensland)

Indicator: A minimum of 1 flow event of 24,500 ML/d in the Culgoa River at Brenda 7 consecutive days any time of year, with an average period between events of 6 (low uncertainty) to 8 years (high uncertainty) on average.

Magnitude: Sims (2004) identified a flow corresponding to 24,500 ML/d at Brenda as a flow that provided an important transition in floodplain inundation whereby floodwater emerged from the Culgoa River in the vicinity of bifurcation 1, travelled across the floodplain and re-entered the Culgoa River downstream near the Woolerbilla gauge. Such a flow would inundate at least 40% of the floodplain (MDBA 2016). This flow would result in significant exchange of nutrients, sediment and biota between the river and floodplain (Whittington et al. 2002; Thoms 2003; Sims 2004). Flows of this magnitude inundate areas of floodplain woodlands (containing a mixture of river red gum, coolibah, river cooba and black box) and significant areas of lignum shrublands.

Duration: Consistent with past practice (e.g. MDBA 2012a) and the logic for the duration of the other flow indicators for lateral connectivity, the median duration of the without development scenario was used. The median event duration under without development conditions for a flow of 24,500 ML/d at Brenda is 7 days.

Frequency: The frequency is 6 years (low uncertainty) to 8 years (high uncertainty) on average between events. This is expected to support the watering requirements of lignum shrublands and woodlands species (e.g. river red gum, coolibah, river cooba and black box) (Table 7).

Lateral connectivity with the outer floodplain

A typical Mitchell grass floodplain grassland shown in Figure 20.



Figure 20: Mitchell grass floodplain grassland (photo: Eco Logical Australia)

Indicator: A minimum of 1 flow event of 38,000 ML/d in the Culgoa River at Brenda for 6 consecutive days any time of year, with an average period between events of 10 (low uncertainty) to 20 years (high uncertainty) on average.

Magnitude: Based on Whittington et al. (2002), the flow indicator selected for lateral connectivity with the outer floodplain is 38,000 ML/d in the Culgoa River at Brenda. This provides large-scale inundation (e.g. 70% of floodplain area in Queensland) across the Lower Balonne floodplain.

Inundation at this level, although infrequent, has been shown to be vital for maintaining the productivity of grasslands on the outer floodplain (Capon 2003; *Parsons and Thoms 2012*), which make up nearly 40% of the total flood dependent vegetation (*Eco Logical Australia 2016*). Maintaining these grassland communities is important for providing terrestrial animal habitat and energy sources for aquatic animals (*Parsons and Thoms 2012; Woods et al. 2012*). Flooding has been shown to produce a greater growth response in floodplain vegetation than rainfall alone on the Lower Balonne River Floodplain (*Parsons and Thoms 2012*). In addition, large floods have been shown to promote the recruitment of floodplain plant species on the Lower Balonne Floodplain - but this response varied between species and locations, thought to be a result of local scale factors (*Woods et al. 2012, Capon 2012*).

Duration: Consistent with past practice (e.g. MDBA 2012a) and the logic for the duration of the other flow indicators for lateral connectivity, the median duration of the without development scenario was used. The median event duration under without development conditions for a flow of 38,000 ML/d at Brenda is 6 days.

Frequency: The frequency is 10 years (low uncertainty) to 20 years (high uncertainty) on average between events. This is consistent similar grassland communities to the Balonne, which are inundated between every 10 - 20 years (NSW DEWCC 2011).

A summary of the Lower Balonne lateral connectivity site-specific flow indicators is shown below at Table 8.

Table 8: Lower Balonne Floodplain site-specific flow indicators developed to support lateral connectivity. Flows are measured at the Brenda gauge on the Culgoa River. Frequency is the average number of years between watering events. The frequency range is shown from low uncertainty to high uncertainty

Magnitude: minimum flow (ML/d)	Basis of magnitude	Duration (consecutive days)	Basis of duration	Timing	Basis of timing	Freq. range (years)	Basis of frequency
9,200 (Culgoa River at Brenda)	Near channel floodplain inundated. Flow rate overtops river channels and inundates adjacent riparian forests, wetlands and low lying areas. This flow is around bankfull, which is important in river channel forming processes.	12	The median duration of flows above this flow rate under the without development scenario	Any time of year, preferably summer	Summer dominated system, most high flows tend to occur in summer	2-3 years (average period between events)	Flow requirements of river red gum and lignum communities in riparian forests.
15,000 (Culgoa River at Brenda)	About 15% of floodplain inundated. Flow rate at which anabranches begin to flow in the northern section of the floodplain and most of riparian forests and lignum are wetted.	10	The median duration of flows above this flow rate under the without development scenario	Any time of year, preferably summer	Summer dominated system, most high flows tend to occur in summer	3-4 years (average period between events)	Flow requirements of river red gum and lignum communities inner floodplain and wetlands.
24,500 (Culgoa River at Brenda)	About 40% of floodplain inundated. Extensive lateral connectivity from flows leaving the river and returning. This enables a substantial exchange of material between the floodplain and the river.	7	The median duration of flows above this flow rate under the without development scenario	Any time of year, preferably summer	Summer dominated system, most high flows tend to occur in summer	6-8 years (average period between events)	Flow requirements of woodland species.
38,000 (Culgoa River at Brenda)	Inundates significant area of floodplain including native grasslands on the outer floodplain.	6	The median duration of flows above this flow rate under the without development scenario	Any time of year, preferably summer	Summer dominated system, most high flows tend to occur in summer	10-20 years (average period between events)	Flow requirements of grassland species.

6 Selecting the site-specific flow indicators for Narran Lakes UEA

6.1 Summary of available evidence

The Narran Lakes UEA includes a highly diverse mosaic of wetland habitats, creeks, channels and floodplain environments (Figure 21). Different parts of the landscape are inundated at different volumes and form distinct hydrological zones. The hydrology zones are shown in Figure 22. The method for classifying these hydrological zones is described in *Thomas et al. (2016)*.

Whilst the northern lakes are relatively small in area, they are particularly important for waterbird breeding, and are part of the Narran Lake Nature Reserve. The northern lakes are included in the Ramsar-listed area and contribute substantially to the values that support the listing.



Figure 21: Diversity of wetland habitats in the Narran Lakes (photo by Peter Terrill, 2012)

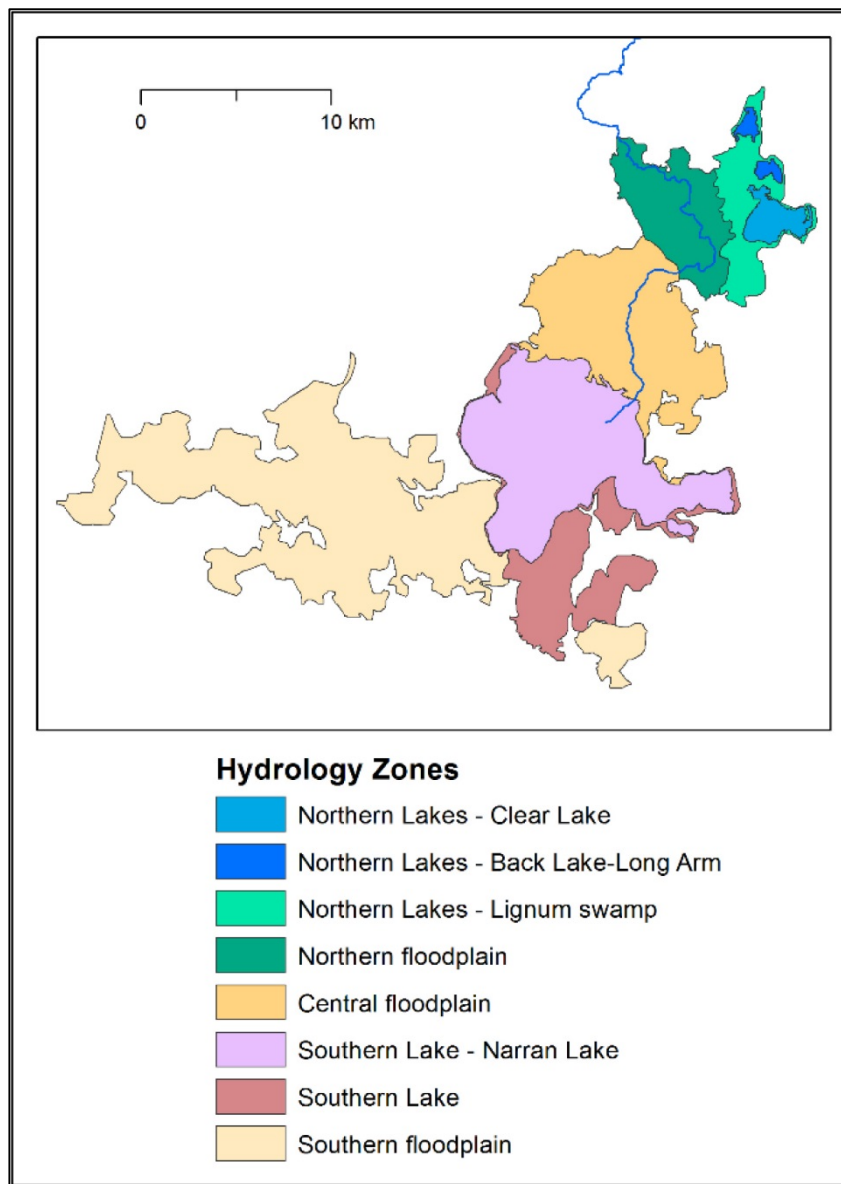


Figure 22: Hydrological zones for the Narran Lakes system (Thomas *et. al* 2016)

Thomas *et al.* (2016) used inundation maps derived from satellite imagery between 1988 and 2013 to predict the likely inundated area, and its distribution, through the Narran Lakes system associated with a range of inundation frequencies (Figure 23). By investigating the observed flow regime entering the Narran Lakes system during the same period of observation (1988-2013), a relationship between event volume and inundation duration was generated (Table 9). In general, the system tends to fill from north to south given sufficient inflow volumes, with the exception that Narran Lake in the south progressively receives some water at even relatively low inflows. With respect to the northern lakes, flows generally fill Clear Lake first, and when the lake is at a sufficient level, flow connections are activated to fill Back Lake and Long Arm (Thomas *et al.* 2016). This inundation pattern has been noted in other work (e.g. Sims and Thoms 2003). The complex geomorphic nature of the Narran Lakes system means that the pattern of inundation is also complex, and may differ over time (Thoms *et al.* 2007).

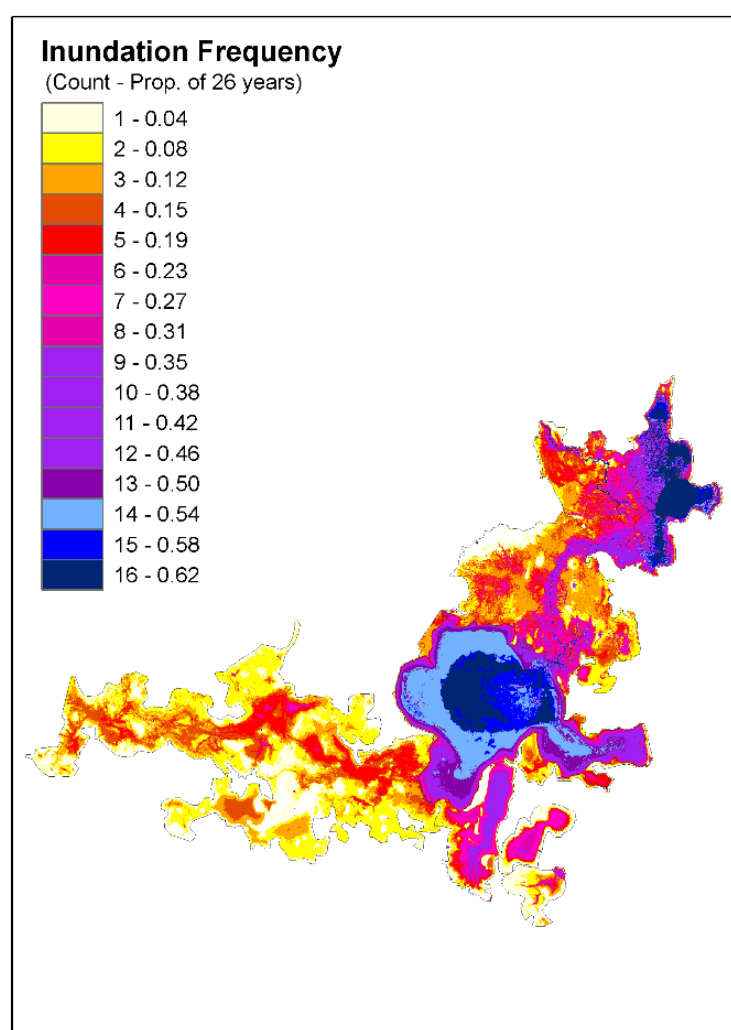


Figure 23: Inundation frequencies (as a proportion of 26 years) across the different areas of the Narran Lakes system (Thomas et al. 2016).

Table 9: Number of events observed for the Narran Lakes flow indicators during the period 1988-2013

Flow Volume (ML)	Period of inundation (days)	Number of events observed (1988-2013)
25,000	60	18
50,000	90	15
154,000	90	8
250,000	180	5

The vegetation of the Narran system is diverse. The distribution of broad vegetation community types is shown in Figure 24 (Thomas et al. 2016). Lignum shrublands are widely distributed across the floodplains of the Narran Lakes (Thoms et al. 2007). However, the form of lignum varies considerably in relation to the flooding history and its position in the landscape (Thoms et al. 2007). Lignum shrubs of different forms can provide different functions in the ecosystem, for example healthy, tall stands of lignum provide the structure necessary for waterbirds to build nests, whereas smaller stands are used as foraging habitat (Thomas et al. 2016). Figure 25

depicts some examples of these different lignum shrubs. The Narran Lakes UEA also includes relatively small areas of riparian open forest and floodplain woodlands dominated by coolibah, river red gum, and river cooba. Ephemeral herb fields establish on beds of wetlands as flood waters recede (Scott 1997).

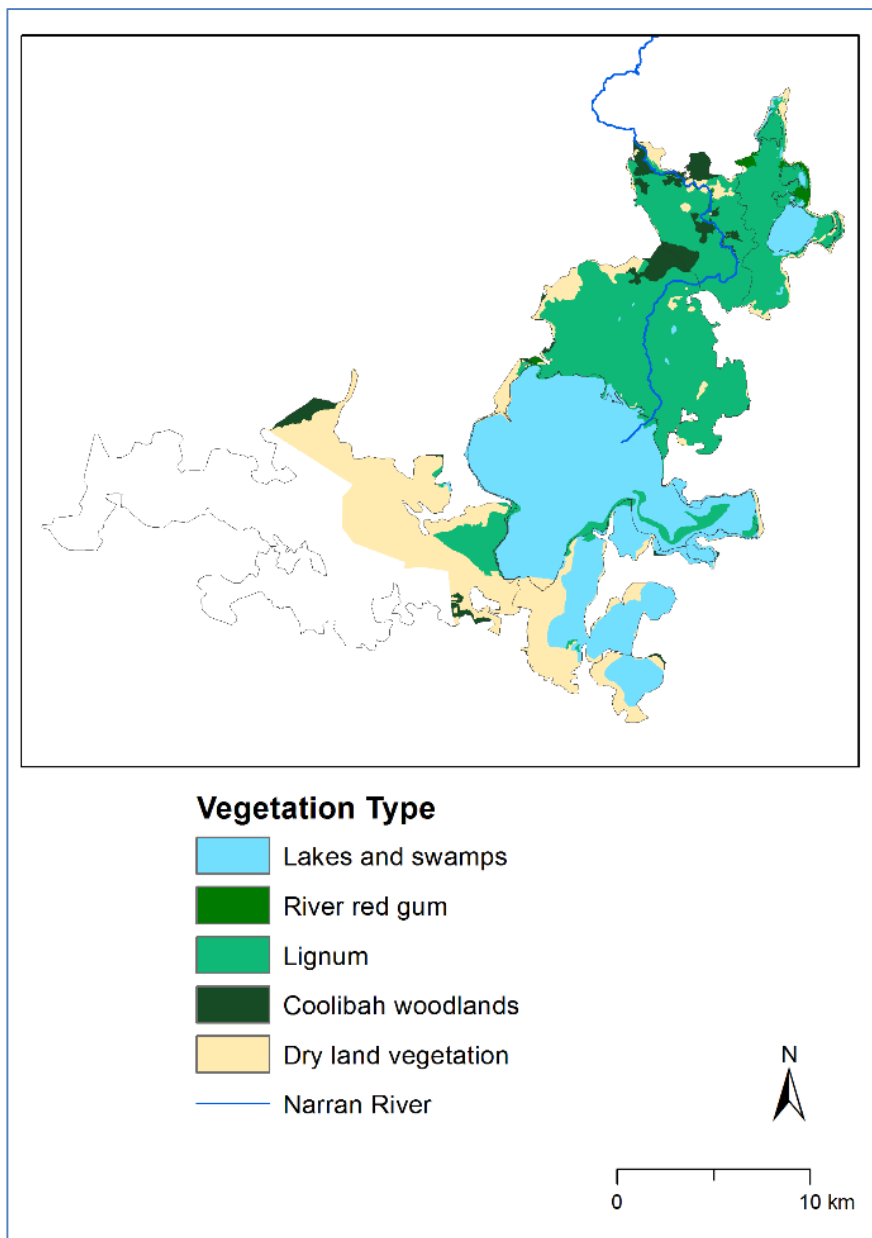


Figure 24: The different categories of vegetation communities in the Narran Lakes (Thomas et al. 2016)

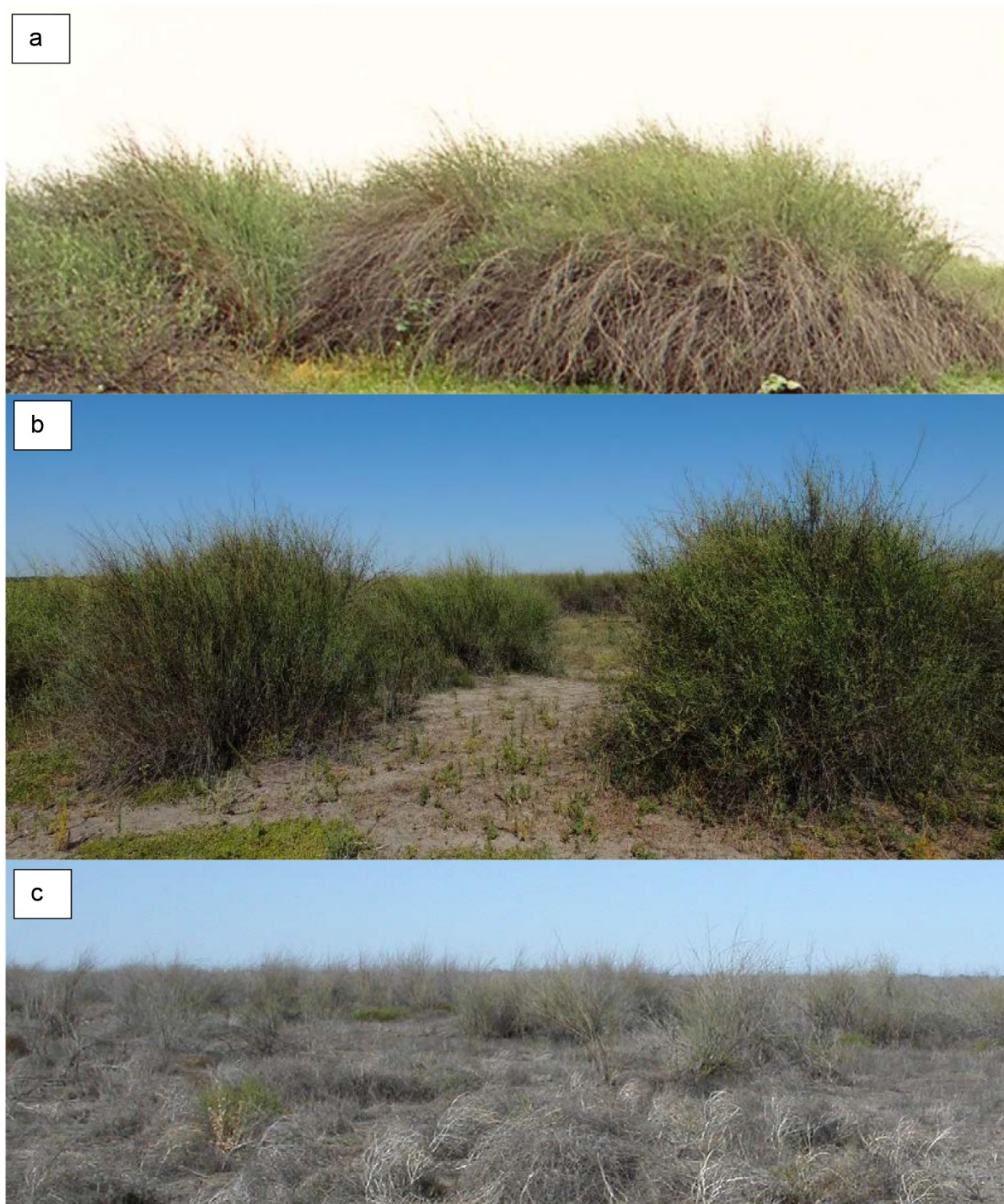


Figure 25: Lignum in the Narran Lakes. a - large clumps, high % cover; b - less % cover, small clumps; c - sparse plants on sections of the floodplain that are inundated less often. (photos taken during fieldwork within Thoms et al. 2007)

The relationship between inundation and vegetation at the Narran Lakes was explored during the development of a decision support system (ANU Enterprise 2011). This work provides details about the relationship between inundation frequency and the form of lignum observed in the Narran Lakes, particularly with respect to the percent cover of lignum and size of shrubs.

The Narran Lakes provides internationally significant habitats and breeding sites for waterbirds. The 33rd annual waterbird survey of eastern Australia in 2015 surveyed all major wetland sites in

the Murray-Darling Basin for waterbirds and reported that total wetland area was the smallest seen in all the years of the survey, and that the number of breeding waterbirds was the lowest on record.

Waterbird data for Narran Lakes was extended and re-analysed in the Northern Basin Review (Merritt *et al.* 2016; Brandis and Bino 2016). Successful waterbird breeding requires particular hydrological characteristics (related to volume, depth, timing and frequency) and habitat conditions (e.g. presence of suitable nesting vegetation such as vigorous lignum shrublands) (Brandis and Bino 2016). Vigorous lignum thickets provide important nesting habitat for waterbird breeding (Brandis and Bino 2016). For many waterbird species, nests also need to be surrounded by water in order to avoid predation (Burger 1981).

Straw-necked-ibis have specific flow and habitat condition requirements for breeding and these needs are generally within the range of other species (Brandis and Bino 2016). Therefore, straw-necked ibis were selected to represent a flow-ecology relationship that would meet the breeding requirements for this and many other waterbird species (ANU Enterprise 2011). Partially inundated lignum provides nesting structure for many waterbirds in Narran Lakes (Figure 26). When conditions are suitable, straw-necked ibis congregate in large numbers to breed in the Narran Lakes (Merritt *et al.* 2016). The small areas of forest and woodland communities in the Narran Lakes area are significant for nesting and roosting by egrets, herons, cormorants and darters (NPWS 2000).



Figure 26: Partially inundated lignum providing nesting structure for waterbirds in Narran Lakes (photos: Kate Brandis, 2008)

Any inflow event into the Narran Lakes may result in some waterbird breeding, possibly including some colonial nesting species. Larger volume events are expected to result in greater numbers of individual waterbirds and species attempting to breed, along with a higher chance of successful fledging and recruitment (Merritt *et al.* 2016; Brandis and Bino 2016).

6.2 Site-specific flow indicators

Four site-specific flow indicators have been selected for the Narran Lakes UEA to reflect a flow regime that would support the vital habitat and foraging requirements of migratory birds and waterbirds. These indicators are associated with:

- the key rookery habitat of the northern lakes (Clear Lake, Back Lake, Long Arm and the adjacent lignum swamp) (two indicators)
- supporting large-scale waterbird breeding events and the habitat of the northern lakes and northern floodplains (one indicator)
- the habitat of all of the Narran Lakes and much of the northern and central floodplain (one indicator).

The volume (magnitude) for each flow indicator is measured at the flow indicator gauge on the Narran River at Wilby Wilby. This has been used in past studies (such as Rayburg and Thoms 2009, ANU Enterprise 2011) and is suitable for the current purpose because it is upstream of the Narran Lakes (see Figure 4). Flow indicators for larger volume events tend to have a greater duration to allow time for water to flow through the complex landforms.

The site-specific flow indicators are not constrained in terms of timing. High flows are dependent on the occurrence of heavy rainfall in the catchment and will be largely unregulated events, and water can be retained in key habitat areas for several months.

Whilst the emphasis is on the habitat required for waterbirds and waterbird breeding, ephemeral wetland systems such as the Narran Lakes also provide broader ecosystem functions (Scott 1997). When these wetlands dry up, the dead aquatic vegetation, invertebrates and fish form a rich organic substrate. This provides an abundance of food for foraging migratory birds and breeding waterbirds. Inundation also provides important breeding and nursery habitats for native fish (Beesley et al. 2012; Górski et al. 2013). For example, the critically endangered¹³ silver perch has been recorded in the Narran Lakes (Thoms et al. 2007) and the endangered¹⁴ olive perchlet is strongly associated with habitats like Narran Lakes, particularly for recruitment (Hutchison et al. 2008). The Narran Lakes also provides habitat for amphibians, water-dependent invertebrates, and reptiles (NPWS 2000). These lakes also provide drought refuge as the Narran Lakes will retain water for up to two years following inundation (*Thomas et al. 2016*). These refuges may provide source populations to re-colonise the Narran River system, and potentially other tributary rivers, during subsequent watering events, subject to the effect of any instream barriers in the Narran River.

Key rookery habitat of the northern lakes

Indicator: A volume of 25,000 ML delivered over 60 days, any time of year, with an average period between events of 1 (low uncertainty) to 1.3 years (high uncertainty).

Magnitude: A volume of around 25,000 ML delivered over at least 60 days would substantially inundate Clear Lakes (80%: 545 ha) and Back Lake-Long Arm (96%: 250 ha), inundate some of

¹³ Appendix E, silver perch is listed under the Environment Protection and Biodiversity Conservation Act 1999 (Cwlth)

¹⁴ Appendix E, olive perchlet is listed under the Fisheries Management Act 2004 (NSW)

the lignum swamp (38%: 774 ha) and Narran Lake (18%: 1,496 ha), and inundate the flow paths in between (*Thomas et al. 2016*).

Duration: Lignum needs to be inundated for a duration of at least 90 days to maintain vigorous shrubs (ANU Enterprise 2011; Roberts and Marston 2011). An event of 60 days duration would be sufficient to meet this requirement as water would be retained in the core wetland areas following the 60 days, and hence lignum would remain inundated for a sufficient duration.

Frequency: Inundation frequency influences lignum shrub size. ANU Enterprise (2011) found that when inundation is more frequent than once every 1.33 years at Narran Lakes, the cover, height and perimeter of lignum of each clump is significantly increased. A dense cover of tall, vigorous shrubs provides suitable rookery habitat for nesting waterbirds (ANU Enterprise 2011). The ANU Enterprise report (2011) noted that areas that are inundated more frequently than 1.33 years had an average of 60% lignum cover but less clumps, whereas areas that were inundated less frequently had a 20% lignum cover but more clumps. The report also noted that while the more frequently inundated sites had less clumps of lignum, the height and perimeter of clump was significantly larger. The 1.33 year flood frequency identified in ANU Enterprise (2011) is within the frequency range of 1 to 3 years which has been suggested to provide for the vigorous growth of lignum (see Table 7). The vigour and cover of lignum is important in providing key rookery habitat and for this reason, a frequency range of 1 to 1.3 years was selected.

Indicator: A volume of 50,000 ML delivered over 90 days, any time of year, with an average period between events of 1.3 (low uncertainty) to 1.7 years (high uncertainty).

Magnitude: A volume of around 50,000 ML delivered over at least 90 days would fill Clear Lake and Back Lake-Long Arm (941 ha in total), inundate some of the lignum swamp (69%: 1,410 ha) and Narran Lake (18%: 1496 ha), and reach into the northern floodplain (*Thomas et al. 2016*).

A volume of 50,000 ML may also result in a waterbird breeding response. Such a breeding event would typically be of a small-scale (see Table 10). One large-scale breeding event of 74,000 nests did occur at an inflow of 55,000 ML in 2008, which is believed to be a drought response that was supported by environmental water delivery (*Merritt et al. 2016*, *Butcher et al. 2011*).

Duration: The duration of this flow indicator meets the requirements of lignum, which needs to be inundated for at least 90 days to maintain vigorous shrubs (ANU Enterprise 2011; Roberts and Marston 2011). The 90 day duration and the retention of water in the core wetland areas beyond this period would provide conditions to support small-scale bird breeding.

Frequency: The 50,000 ML indicator is aimed at maintaining a broader area of breeding habitat within the northern lakes than the 25,000 ML indicator. A frequency range of 1.3 to 1.7 years was selected based on the findings from the ANU Enterprise (2011) study and *Thomas et al. (2016)*. At an inundation frequency of 1.3 years, the form of lignum changes with cover decreasing but the number of clumps increasing (ANU Enterprise 2011) - thus offering complementary habitat to that provided by the 25,000 ML indicator. *Thomas et al (2016)* reported that an inundation frequency of between 1.7 and 2.6 years generally resulted in lignum shrublands remaining in good condition. Given the importance of lignum at Narran Lakes in providing vital habitats, a high uncertainty frequency of 1.7 years was selected based on these local observations.

Large-scale waterbird breeding events and habitat of the northern lakes and northern floodplains

Indicator: A volume of 154,000 ML for a duration of at least 90 days, any time of year, with a frequency of 2 events in any 8 year period (low uncertainty) to 2 events in any 10 year period (high uncertainty).

Magnitude and duration: Analysis of straw-necked ibis breeding data from 1971 to 2014 (33 flow events¹⁵, 18 breeding events in total) indicated that there was a 100% probability of breeding when total cumulative flows exceeded 154,000 ML at Wilby Wilby in the first 90 days of the flow event (11 flow events, 11 breeding events) (*Merritt et al. 2016*). This volume would inundate around 12,300 ha of the Narran Lakes ecosystem (*Thomas et al. 2016*). A flow event of this magnitude would be beneficial for vegetation on a third of the northern floodplain and about 20% of the central floodplain (*Thomas et al. 2016*). This includes the majority of lignum shrublands where colonial nesting waterbirds establish their nests. Additionally, a flow duration of 90 days or more at the Wilby Wilby gauge meets the breeding duration requirements (from incubation, chick rearing to fledging) of at least 14 more waterbird species, including non-colonial waterbird species that breed in the Narran Lakes system (*Brandis and Bino 2016*).

Over the period of analysis (1971 to 2014) 18 known breeding events occurred over 16 defined flow events, with two flow events (5/1983 – 1/1985; 2/1988 – 11/1988) supporting two separate breeding events within the same flow event (*Merritt et al. 2016*). Of these 18 events, only 11 have estimates of the size of straw-necked ibis colonies (nest numbers) in the Narran Lakes Nature Reserve.

Table 10 shows the 11 flow events between 1970 and 2014 where nest number estimates were available. Of these events, six resulted in large-scale breeding (>50,000 nests). The other five resulted in nest numbers ranging from approximately 9,000 to 25,000.

¹⁵ A watering event was defined as commencing at 100 ML/day flow at Wilby Wilby, as recommended in *Merritt et al. 2016*.

Table 10: Estimated total nest numbers against cumulative flows for the whole flow event (from Wilby Wilby gauge) based on observed successful straw-necked Ibis breeding events from 1971–2014 in the Narran Lakes Nature Reserve (modified from Merritt et al. 2016).

Flow Event	Approximate nest numbers	Event volume (ML)	90 day volume (ML)
12/1970 - 6/1971	10,000	489,738	446,713
5/1983 - 1/1985	200,000	1,073,279	532,612
2/1988 - 11/1988	25,000	414,866	314,812
4/1989 - 10/1989	9,000	177,331	170,892
4/1990 - 10/1990	50,000	317,668	311,495
12/1995 - 4/1996	102,000	229,107	229,065
5/1998 - 12/1998*	50,000	190,185	20,093*
12/2007 - 4/2008*	74,000	55,159	55,159*
2/2010 - 7/2010	13,303	172,847	172,642
10/2010 - 9/2011	21,018	625,134	166,331
11/2011 - 9/2012	131,442	323,653	181,384

Note: large breeding events are in bold with the * representing large breeding events with a 90 day volume less than 154,000 ML. There were other events, for which the number of nests was not estimated or the event was probable based on records from outside the reserve - these have been excluded from this table.

Of the six events associated with large-scale breeding, four were associated with flow events of greater than 154,000 ML over the first 90 days. The two large scale waterbird breeding events that occurred with less than 154,000 ML in the first 90 days occurred in 1998 and 2007–08. The 1998 flow event started in May 1998, following successive flow events over 1996 and 1997 and a large flow peak which occurred over September–October 1998. This resulted in a delayed straw-necked ibis breeding response with nesting commencing in mid-September after the first 90 days of the defined flow event and a total cumulative flow of 190,185 ML (*Merritt et al. 2016*). The large breeding event in 2007–08 (90 day volume of 55,159 ML) was unusual in that it occurred during an extended period of drought across the Murray-Darling Basin when breeding opportunities for straw-necked ibis would have been limited and there was evidence of chick mortality because flows were insufficient to sustain water depth and inundation in the colony site during chick rearing (*Brandis et al. 2011*).

Flow events of at least 154,000 ML in 90 days often commence with a large fresh at the start of the flow event (e.g. 20–30 GL in the first 10 days). This priming flow event could provide an important trigger to guide management actions in order to provide suitable breeding habitat for waterbirds in the Narran Lakes, but this was not included as an additional condition in the flow indicator.

Timing: Records for straw-necked ibis in the Narran Lakes Nature Reserve show that 59% of breeding events were initiated in January (14%), February (18%) or March (27%), with 73% of all breeding events beginning in the six months between October and March (Figure 27) (*Merritt et al. 2016*). However, there are records of straw-necked ibis continuing breeding events across winter (see Table 10) though some of these nests were unsuccessful with eggs abandoned (*Magrath 1991*). This pattern may reflect the vulnerability of chicks to exposure during winter months and limited food availability (*Merritt et al. 2016*).

Based on the above evidence, the site-specific flow indicator is not constrained in terms of timing. High flows are dependent on the occurrence of heavy rainfall in the catchment and will be largely unregulated events, and water can be retained in key habitat areas for several months. However, the higher likelihood of fledging success outside the winter months should be noted, and may form a key consideration in any management actions for the provision of suitable waterbird breeding habitat.

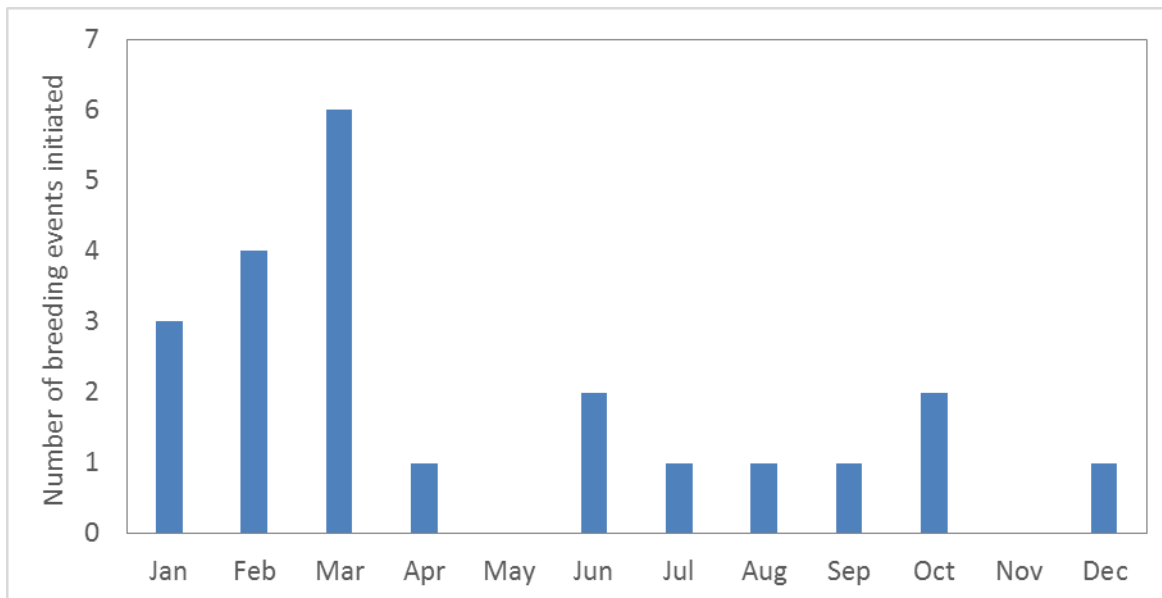


Figure 27: The timing of initiation of all known straw-necked ibis breeding events (n=22) that started in each month in the Narran Nature Reserve between 1971 and 2014 (Merritt et al. 2016).

Frequency: The lifecycles of many of these waterbird species are episodic, responding to intermittent large flows with large-scale breeding. These 'booms' are important for maintaining populations that can survive the often longer-duration 'busts' when breeding does not occur or is minimal. To support these episodic breeding events, *Brandis and Bino (2016)* recommend a frequency of 2 events in any 8 year period (low uncertainty) and 2 events in any 10 year period (high uncertainty). The high uncertainty frequency is considered to represent a boundary beyond which there is a risk of significant declines of waterbird populations at the Narran Lakes (*Brandis and Bino 2016*).

The recommendations from *Brandis and Bino (2016)* are based upon life-history traits of the straw-necked ibis, and the assumption that opportunities for breeding are also provided elsewhere in the Murray-Darling Basin. Life history information for straw-necked ibis is limited with only a small number of birds being seen again after banding when they are juveniles (15 live birds resighted out of 56,909 birds banded and 375 bands recovered) (ABBBS 2016). Based on this banding data and on information for other ibis species (Clapp et al. 1982) the straw-necked ibis is likely to have a lifespan of 10 to 16 years, reaching sexual maturity at around three to four years (based on age at which adult plumage is achieved) (Marchant and Higgins 1990). The recommended frequencies for this flow indicator provide at least two breeding opportunities during the life-cycle of a straw-necked ibis.

The frequency of breeding opportunities are particularly critical if waterbird species only breed where they were hatched, or exhibit natal site fidelity. It is unknown whether straw-necked ibis exhibit natal site fidelity to the Narran Lakes but site fidelity has been shown in other waterbird

species (Hazlitt and Butler, 2001; Atwood and Massey 1988; Gratto 1988). The MDBA has commissioned further research into how waterbirds make use of habitat areas for breeding purposes across a larger regional area including other northern Basin and outside-basin breeding sites.

Where suitable flows occur (at least 154,000 ML over 90 days) that are providing 2 opportunities for breeding in any 8 year period, this would support both the maintenance of populations (through replacement of adult birds) and restoration of populations (by increasing total straw-necked ibis abundance) (*Brandis and Bino 2016*). Achieving this ecological outcome becomes more uncertain once the frequency is lengthened to 2 opportunities in a 10 year period (*Brandis and Bino 2016*).

Hydrological analysis shows that these frequencies do not occur under the modelled without development scenario (Appendix G), due to some very dry sequences (e.g. five decades at the start of the modelled record). This means that there were some sequences of years in which the indicator was not met twice in ten years.

Habitat of all of the Narran Lakes, and much of the northern and central floodplain

Indicator: A volume of 250,000 ML delivered over 180 days, any time of year, with the average period between events of 8 (low uncertainty) to 10 years (high uncertainty).

Magnitude: A volume of 250,000 ML delivered over 180 days would inundate about two thirds (17,900 ha) of the Narran Lakes ecosystem. **Error! Reference source not found.** (*Thomas et al. 2016*). This volume would fill Narran Lake to about 84% capacity (*Thomas et al. 2016*), depending on prevailing water levels before the event. Water may then stay in Narran Lake for up to 18 months, providing potential drought refuge (Thoms et al. 2007).

This flow would inundate 80% of the lignum shrublands throughout the broader floodplain, inundating all of the lignum in the northern lakes zone, 90% in the northern floodplain and 80% of the lignum within the central floodplain zone (*Thomas et al. 2016*). Fieldwork suggests that lignum further out onto the floodplain, such as in the central floodplain zone, is likely to be dominated by small lignum shrubs (*Eco Logical Australia 2016*). At this volume, large-scale waterbird breeding would be likely, particularly in the key rookery area.

Duration: The duration is over 180 days, as this is indicative of the period required to largely fill the lakes and for water to spread more broadly through the Narran Lakes system.

Frequency: This flow indicator would inundate lignum shrublands throughout the broader floodplain. The broader floodplain areas are likely to be dominated by sparsely arranged small lignum shrubs (*Eco Logical Australia 2016*). Drawing upon Roberts and Marston (2011), an average inundation frequency of at least once every 10 years is required to maintain these lignum shrublands. A frequency range of 8-10 years was selected with the 10 year period representing high uncertainty.

The site-specific flow indicators for the Narran Lakes UEA are summarised in Table 11.

Table 11: Site-specific flow indicators for the Narran Lakes UEA. All volumes are measured at the Wilby Wilby gauge on the Narran River. The frequency, unless otherwise indicated, is the average number of years between events. The frequency range is shown from low uncertainty to high uncertainty.

Magnitude: minimum volume (ML)	Basis of magnitude	Duration (consecutive days)	Basis of duration	Timing	Basis of timing	Frequency (years)	Basis of frequency
25,000	Habitat vigour of lignum in northern lakes zone, core rookery habitat	60	Required duration to fill the lakes of northern lakes zone	Any time of year, preferably summer	Summer dominated system, most flows tend to occur in summer	1 - 1.3 (average period between events)	Frequency of inundation for vigour of large clumps of lignum in key rookery habitats.
50,000	Habitat vigour of lignum surrounding core habitat, some of northern floodplain.	90	Retention of water on northern lakes zone and part of the northern floodplain	Any time of year, preferably summer	Summer dominated system, most flows tend to occur in summer	1.3 - 1.7 (average period between events)	Frequency of inundation for form and vigour of lignum in key rookery habitats.
154,000	Volume associated with large-scale waterbird breeding	90	Time that it takes many waterbird species to fledge	Any time of year, preferably summer	Summer dominated system, but waterbirds may continue breeding events across winter	Twice in 8 years - twice in 10 years	To provide at least two breeding opportunities during the life-cycle of a straw-necked ibis to protect and restore waterbird populations.
250,000	Habitat in all of open water lakes and much of the northern and central floodplains.	180	Required duration for water to move onto large areas of northern and central floodplain	Any time of year, preferably summer	Summer dominated system, most flows tend to occur in summer	8 - 10 (average period between events)	Critical period for survival of lignum in Narran Lakes (in small form and sparse) and other key vegetation species on northern and central floodplains

7 Knowledge Gaps

Imperfect knowledge of flow-ecology relationships is a universal challenge in determining the water needs of aquatic ecosystems (Swirepik et al. 2015). As a result of a science review undertaken for the Northern Basin Review (*Sheldon et al. 2014*) and a number of subsequently commissioned projects (*Brandis and Bino 2016, Casanova 2015, DSITI 2015, Merritt et al. 2016, NSW DPI 2015*), the scientific evidence underpinning the application of the ESLT method has been improved in the Condamine–Balonne catchment. However, gaps remain in our understanding. This section draws on the recommendations of the various projects and reviews to describe avenues for further research and investigation that would improve the specification of environmental water requirements in the northern basin.

An assumption of the UEA approach is that the provision of adequate flow regimes at individual assets will support the environmental water requirements of the broader set of water-dependent ecosystems (Swirepik et al. 2015). The authors noted that it is not feasible to test this assumption until the environmental water requirements of the broad suite of water-dependent ecosystems were better understood. The key sources of knowledge that will allow this to be tested are identification of floodplain ecosystem types, assessment the ecological values and water requirements of those ecosystem types, and mapping of floodplain inundation extents at different flows. While some work has commenced (e.g. Brooks et al. 2014 - Australian National Aquatic Ecosystem Interim Classification; Fielder et al. 2011 - Queensland Aquatic Conservation Assessments; Chen et al. 2012 - Murray-Darling Basin Floodplain Inundation Model; MDBA 2016 - Inundation mapping in the Northern Basin Review), the outputs are not consistent in terms of scale or coverage to undertake a northern Basin-wide assessment. The MDBA is continuing to invest in these areas of work and the new information is expected to inform future assessments of environmental water requirements across the Murray-Darling Basin.

In the absence of being able to comprehensively determine that UEAs fully represent broader ecosystem needs, one solution is to select a number of UEAs within a river system for eco-hydrological assessment. In this regard, consideration was given to selecting a third UEA in the Condamine–Balonne system, to represent the Condamine River upstream of Beardmore Dam. While there is sufficient flow alteration as a result of water management to warrant selection of a UEA, the scientific information to adequately understand the eco-hydrological relationships is currently lacking. The Queensland Government is undertaking some projects to improve the knowledge base for the mid Condamine catchment, which may warrant selection of this area as a UEA in future environmental water requirements assessments.

The determination of environmental water requirements has focused on the relationship between flows and the needs of fish, waterbirds and vegetation - reflecting both the underlying knowledge base and the focus of the new science projects. Rogers and Ralph (2011) and others have identified other species that have particular water requirements - for example, amphibians (e.g. southern bell frog), mammals (e.g. platypus), reptiles (e.g. turtles), macroinvertebrates, and molluscs and crustaceans. The addition of faunal surrogates improves the representation of species inundation requirements (Rogers et al. 2012) and in doing so reduces the risk that some species will not have their water requirements met. Further work is required to develop knowledge of these other species' water needs before this understanding could be integrated into the specification of site-specific flow indicators.

A review of the ESLT method (Young et al 2011) identified the inclusion of key ecosystem functions (KEF) in the method as a challenge as the relevant knowledge base was more limited than for environmental assets. They recommended including a regionalisation of KEFs, mapping their importance across the Basin, and doing further work to understand the relationships between flow and ecosystem functions. While the conceptual basis for considering ecosystem functions and the role of connectivity have received greater attention in this assessment compared to the original Condamine–Balonne environmental water requirement assessments (MDBA 2012a, MDBA 2012b), there is still work to be done to be able to implement the more systematic approach proposed by Young et al. (2011).

In addition to the broader knowledge gaps identified above, there are more specific gaps that have been catalogued in the commissioned science projects. A summary of these is provided below.

Brandis and Bino 2016 (Waterbirds)

- Role of poorly studied wetlands in Narran Lakes waterbird breeding
- Food resource requirements of waterbirds during breeding events
- Pre-breeding habitat requirements of waterbirds
- Quality of nesting habitat for waterbirds
- Movement of waterbirds between wetland sites
- Effect of environmental flows on lignum channel infilling and expansion
- Role of floodplain vegetation in providing food resources for herbivorous waterbird species

Casanova 2015 (Vegetation)

- Information on the basic ecology of *Eucalyptus camaldulensis* (subspecies *acuta*) and all subspecies of *E. coolabah*
- Uncertainty regarding required duration of flooding for most tree species
- Requirement for consistent vegetation mapping across States' border
- Spatial variation in character and condition of vegetation communities both historically and currently
- Information on vegetation community response to flow, especially understory species
- Whether plant species response to flow differs from the same species occurring in the southern Basin
- Role of non-flow related factors (e.g. grazing, fire, weeds) in structuring plant communities
- Development of Water Plant Functional Groups to identify water requirements of groups of species
- Identification of ecological thresholds for key plant species
- Identification of stress and recovery pathways of key plant species in response to inundation

DSITI 2015 (Waterholes)

- Additional data on waterhole depths at cease to flow to give a better understanding of waterhole persistence throughout the region
- Review the impact of sedimentation on waterholes

- The depths at which habitat and water quality decline in persistent waterholes across the Lower Balonne
- How the spatial distribution of waterholes across the Lower Balonne maintains populations of aquatic organisms, which could be informed by the movement behaviour of important species of biota.

Merritt et al. 2016 (Straw-necked Ibis breeding)

- Ongoing collection of flow data and Straw-necked Ibis breeding data to further develop the Narran DSS
- Further refinement of hydrological, Straw-necked Ibis breeding and wetland vegetation models that underpin the Narran DSS

NSW DPI 2015 (Fish)

- Undertaking further habitat mapping in systems other than the Barwon-Darling
- Analysis and modelling of flow hydrodynamics in the Barwon-Darling and other northern basin valleys

Glossary

Antecedent conditions – refers to the moisture conditions in a catchment prior to a flow event.

Bankfull flows – The maximum amount of water a stream channel can carry without overflowing—a key factor in determining the shape of a river.

Baseline – a modelled scenario reflecting the consumptive use, rules, sharing arrangements and levels of infrastructure as at June 2009.

Basin Plan – A plan for the management of water resources of the Murray-Darling Basin under the Water Act 2007.

Hydrological modelling framework – A modelling framework that routes water through all rivers in the Basin over a 114 year period of historical inflows (1895-2009) and represents the level of water resource development in 2009.

Basin-wide environmental watering strategy – A strategy developed under the Basin Plan for the management of environmental water.

Connectivity – the hydrological connections between natural habitats, such as a river channel, adjacent wetland areas and along the length of rivers, including connections above ground (surface water) or below ground (groundwater).

Dry spell – the number of consecutive years without a ‘site-specific flow indicator’ flow event.

Duration – for flow, the number of days a flow remains at or above the specified magnitude (ML/d); for volume, the period of time flow contributes to meeting the specified quantity of water (one of the hydrologic metrics used to define a site-specific flow indicator).

Ecological targets – the ecosystem components, such as fish, waterbirds, and vegetation at an Umbrella Environmental Asset (UEA) that are targeted by site-specific flow indicators.

Ecological values – is the perceived importance of an ecosystem, which is underpinned by the biotic and/or abiotic components and processes that characterise that ecosystem.

Ecosystem components – parts of an ecosystem at a UEA such as fish, waterbirds, vegetation.

Ecosystem functions – The processes that arise from the interaction of biota with the physical environment and with each other, that maintain the integrity and health of an ecosystem.

Environmental objectives – statements of desired longer term environmental objectives set out in Chapters 5 and 8 of the Basin Plan.

Environmental Science Technical Advisory Group – representatives from State and Federal Government agencies that advised on development of the Northern Basin Review environmental science program.

Environmentally Sustainable Level of Take – the level at which water can be taken from a water resource which, if exceeded, would compromise:

- key environmental assets of the water resource; or
- key ecosystem functions of the water resource; or
- productive base of the water resource; or
- key environmental outcomes for the water resource.

Functional groups – a classification of fish into northern MDB-specific functional groups based on fish with similar life-cycle requirements for flows: flow dependent specialists, in-channel specialists, floodplain specialists, generalists, generalist alien species.

Flow components – The different parts of river flow that make up a flow regime. They typically include cease-to-flow periods, low flows, freshes, bank-full flows and over-bank flows.

Flow-ecology relationships (short for flow alteration-ecological response relationships) – relationships that correlate measures of ecological condition, which can be difficult to manage directly, to streamflow conditions, which can be managed through water-use strategies and policies.

Flow event – a river flow with particular magnitude, duration and timing characteristics (see hydrologic metrics). The flow defined by a site-specific flow indicator is a flow event.

Flow indicator gauge – These are river gauges within (or close to) a UEA which record flow on a daily basis. Flow requirements of UEAs are expressed at one or more flow indicator gauges.

Flow regime – The description of the characteristic pattern of a river's flow including the quantity, timing and variability.

Frequency – the maximum number of days between flow events; or the percentage of years in which there is at least one flow event of a specified magnitude, duration and timing; or the average period between events; or a maximum return interval (one of the hydrologic metrics used to define a site-specific flow indicator).

Frequency range – the range in frequency from low uncertainty of achieving an ecological target to a high uncertainty of achieving the target.

Freshes – A pulse of water in a river channel, usually caused by heavy rainfall upstream.

High uncertainty – the frequency considered to represent a boundary beyond which there is a high likelihood that the ecological targets associated with a site-specific flow indicator will not be achieved.

Hydrology – The study of the occurrence, distribution and movement of water on, in and above the earth.

Hydrologic metrics – the four metrics that make up a site-specific flow indicator; magnitude, duration, timing and frequency.

Inundation – the movement of water over the land surface, most notably on floodplains but also in river channels with fluctuating flows.

Lateral connectivity – the hydrological connections between watercourses and adjacent floodplains and wetlands that: link a diversity of aquatic environments for feeding, breeding, migration and re-colonisation by native water-dependent species; support the vigour and condition of native vegetation; and facilitate off-stream primary production, and nutrient and organic matter exchange.

Low uncertainty – the frequency considered to represent a high likelihood that the ecological targets associated with a site-specific flow indicator will be achieved.

Longitudinal connectivity – the hydrological connections along watercourses that: link a diversity of aquatic environments for feeding, breeding, dispersal, migration and re-colonisation by native aquatic species; and facilitate geomorphic processes, sediment movement and nutrient spiralling.

Magnitude – either a specified minimum daily flow rate (ML/d); or a volume (ML), which is a specified minimum quantity of inflows over a period of time (and may or may not specify a minimum daily flow) (one of the hydrologic metrics used to define a site-specific flow indicator).

Northern Basin Review – the environmental, social and economic research and investigations being undertaken to review the basis of Sustainable Diversion Limits in the northern Murray-Darling Basin.

Nutrient spiralling - the process whereby nutrients in the water column are assimilated into living organisms, and are subsequently released back into the water via excretion or decomposition — in a repeating process as water flows downstream.

Overbank flows – Flows that spill over the riverbank and onto floodplains.

Ramsar-listed – An area listed under the Ramsar Convention, an international treaty to maintain the ecological character of key wetlands.

Refugia (refuges) – places in the landscape that provide habitat for biota to persist during periods of environmental stress – for example, waterholes along a river that provide habitat for native fish and other species to ‘ride out’ dry periods and drought before flows re-connect the system.

Resilience – the capacity of an ecosystem to recover from disturbance or withstand ongoing pressures. It is a measure of how well an ecosystem can tolerate disturbance without collapsing into a different state that is controlled by a different set of processes.

Riparian – the part of the landscape adjoining rivers and streams that has a direct influence on the water and aquatic ecosystems within them.

Site-specific flow indicator – the hydrology indicator used to express a water requirement of one or more ecosystem components (e.g. fish, waterbirds, vegetation) at a UEA.

Sustainable Diversion Limit – the maximum long-term annual average quantities of water that can be taken on a sustainable basis from the Basin water resources.

Umbrella Environmental Asset – an area for which there is relatively rich knowledge with respect to flow-ecology relationships when compared to the broader region within which it sits,

and which is used to establish environmental water requirements for a river reach or river system.

Vital habitat – places that provide refugia for native water-dependent biota during dry periods and drought; and places that provide for a diversity of important feeding, breeding and nursery sites for waterbirds including providing conditions conducive to large-scale bird breeding.

Water-dependent ecosystem – An ecosystem that depends on periodic or sustained inundation, waterlogging or significant inputs of water for natural functioning and survival.

Waterholes – places along the channel of a river that retain water during periods of no flow.

Water Act 2007 – Commonwealth legislation to make provision for the management of the water resources of the Murray-Darling Basin.

Water recovery – the program by governments to obtain water for the environment to meet Sustainable Diversion Limits – either through the purchase of water entitlements by willing sellers or by infrastructure investments that improve the operation of off-farm delivery systems and help irrigators improve on-farm water use efficiency.

Without development – A modelled scenario approximating river flows without any dams, weirs or consumptive use – it is a representation of the Basin at conditions which approximate its natural state.

Abbreviations

ESLT	Environmentally Sustainable Level of Take
MDBA	Murray–Darling Basin Authority
ML/d	Megalitres per day
SDL	Sustainable Diversion Limit
UEA	Umbrella Environmental Asset

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Appendix A - Acknowledgement of system complexity and uncertainty regarding method

There are uncertainties with the Environmentally Sustainable Level of Take method that influence the accuracy of assessments of environmental water requirements. These are discussed in MDBA (2011), and a summary is provided in Box A1.

Box A1 - Examples of complexity

- Regarding the identification of key environmental assets and ecosystem functions - limitations in data, data inconsistencies, and criteria definition.
- Limitations in extrapolating flows from flow indicator gauges to a larger UEA.
- Regarding overbank environmental watering and lateral connectivity, limitations of knowledge on: the nature, extent and condition of wetlands; inundation patterns of various geomorphic features; the water requirements of some biota and vegetation communities, particularly with respect to frequency and duration of flooding.
- The adequacy of the existing knowledge base.
- Assumptions in hydrological models, how well models can reflect the variability of conditions and whether they incorporate policy change, and the potential impact of climate change.

This assessment of environmental water requirements includes consideration of eco-hydrology, which results in the selection of site-specific flow indicators. As a set, the site-specific flow indicators reflect a broad range of flow events and are a practical compromise between understanding the complexity of large eco-hydrological systems, and the need to focus on key flow-ecology characteristics when planning and setting Sustainable Diversion Limits.

In the Environmentally Sustainable Level of Take method, the focus is on linking ecological outcomes associated with the restoration of different flow components. These relationships in reality are impacted by a range of complex and interacting features including antecedent conditions, time lags and other factors that affect ecosystem response over the longer term. Figure 18 below depicts some of the factors at play that influence the health of the riverine environment at different time scales.

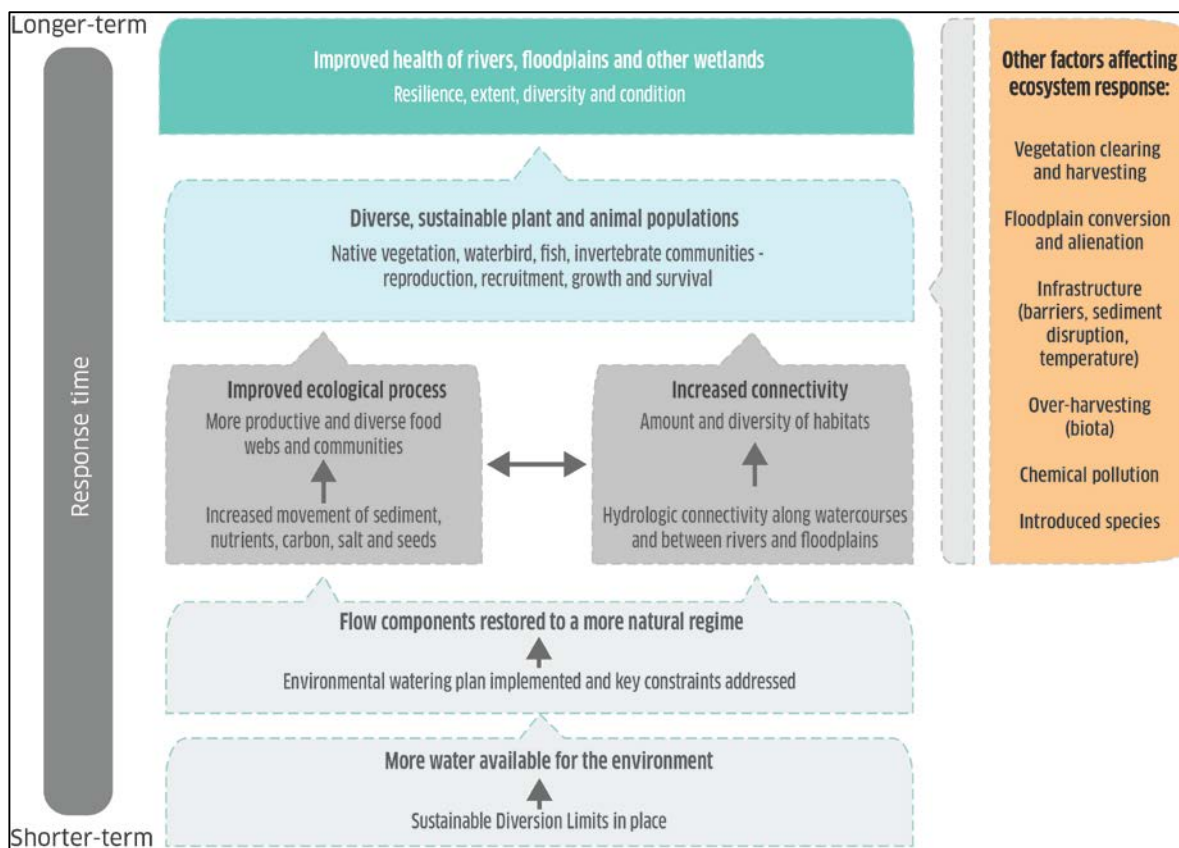


Figure 28 A conceptual diagram showing the various factors influencing the health of rivers, floodplains and wetlands the short and long term.

The following tables show the main logic, key assumptions, and confidence assessments for the flow volumes, duration, timing and frequency for each flow indicator. Confidence is assessed as either 'high' or 'pragmatic'.

- **High confidence** - the decision is based on relevant, recent and specific research and/or work; or multiple lines of evidence support the assumption
- **Pragmatic** - where there aren't specific studies or pieces of evidence; and hence the decision is based on expert opinion/advice; is consistent with previous work; is consistent with relevant analysis based on modelled baseline and without development flows; and/or is supported by general and relevant scientific understanding.

As a result of further scientific investigations in the future, a more complete picture will emerge of the relative importance of the above complexity and uncertainties at the broad scale of the basin. This, combined with continued monitoring and evaluation will provide information to help adaptively refine the Basin Plan and water resource plans established by the states in the future, through specified review mechanisms in the Basin Plan.

Flow indicator	Ecological objective(s)	Flow threshold/volume assumptions and evidence	Duration assumptions and evidence	Timing assumptions and evidence	Frequency (target range) assumptions and evidence
<p>2 ML/d for 1 day, any time of the year at Weilmoringle.</p> <p>Frequency: 350-430 days</p> <p>AND</p> <p>2 ML/d for 1 day, any time of the year at Narran Park.</p> <p>Frequency: 350-470 days</p>	<p>A network of waterholes in the lower part of the system with at least 0.5 m water depth is needed to maintain resilient aquatic communities during dry spells</p>	<p>High</p> <p>Flow magnitude based on critical lower threshold for flow to be observed downstream of refuge waterholes (<i>DSITI 2015</i>).</p> <p>The 0.5 m water depth is an appropriate estimate for the threshold to maintain suitable habitat, particularly with regards to water quality (<i>DSITI 2015</i>).</p> <p>The logic behind gauge selection is that is that any flow recorded downstream of the refuge waterholes will have wetted the river channel and topped-up the upstream waterholes on the way through.</p>	<p>Pragmatic</p> <p>One day is the minimum time step to observe flow in the model</p>	<p>High</p> <p>The timing is not relevant as the aim is to reduce the longer no-flow spells whenever possible.</p>	<p>High</p> <p>Based on waterhole persistence research (<i>DSITI 2015</i>) and analysis of observed and modelled no-flow periods in the Lower Balonne.</p> <p>The 350 day target is to maintain at least seven waterholes along the Culgoa River, with at least four of these to a depth of more than 0.5 m. The 430 days target provides at least two refuge waterholes to at least 0.5 m (informed by <i>DSITI 2015</i>).</p> <p>The 350 day target is to maintain at least six waterholes along the Narran River, with at least four of these to a depth of more than 0.5 m. The 470 days target provides at least two refuge waterholes to at least 0.5 m.</p>
<p>1,000 ML/d for 7 days, any time of the year at Brenda.</p> <p>Frequency: 80% to 90% of years</p>	<p>The flow indicator describes a small in-channel fresh that would flow through the Culgoa and Narran Rivers and at least part of the Bokhara River.</p> <p>This type of flow connects the system longitudinally and aims to provide</p>	<p>High</p> <p>An event above 1,000 ML/d for 7 days generally corresponds to a water level rise above 1 metre along the Culgoa River (such as a 1.3 m rise at Brenda).</p> <p>This flow magnitude is sufficient to provide small scale fish movement to neighbouring pools.</p> <p>This flow is also highly likely to result in a small in-channel fresh in the Narran River, with the response in the Bokhara River more variable.</p>	<p>High</p> <p>A duration of 7 days is considered to provide opportunities for the drift of biota, including fish larvae and macroinvertebrates over significant distances.</p>	<p>Pragmatic</p> <p>The high flow season is generally summer to autumn, and research from the nearby Moonie River shows fish move any time of the year (linked to water level rise,</p>	<p>Pragmatic</p> <p>Regular flows are important for the ecological functioning of the river system to ensure fish and other animals are healthy and resilient.</p> <p>Frequency target is based on expert advice for flows that provide connectivity in dryland rivers of the northern basin. It is not based on site-specific information (other than this small fresh occurred in 98% of years under WOD).</p>

Flow indicator	Ecological objective(s)	Flow threshold/volume assumptions and evidence	Duration assumptions and evidence	Timing assumptions and evidence	Frequency (target range) assumptions and evidence
	small-scale fish movement opportunities.			temp above 15 degrees and the first post winter flow). Average temp at Brenda is above this threshold between August and May, but it is assumed this flow provides benefit to the ecosystem any time of the year.	
1,700 ML/d for 14 days, between Aug and May at Wilby Wilby. Frequency: 40% to 60% of years	This large in-channel pulse (around bankfull) is expected to provide a range of outcomes with the main one being improved movement and breeding opportunities for flow dependent fish. Large freshes are important to maintain	High Fish in the Lower Balonne will respond to the same types of flow that fish responded to in other catchments (no site-specific fish movement data). MDBA analysed site-specific hydrological data to describe a flow that provides a river rise of at least 2 m and an average velocity of 0.3 m/s.	Pragmatic Based on ecological and hydrological information. The hatch time of Murray cod eggs represents the longest breeding requirement for native fish in the area. The duration is consistent with the typical hydrology (median under WOD of 15 days).	High The timing is August to May to exclude the two coldest months of the year when fish responses are expected to be subdued (Reynolds 1983; Mallen-Cooper et al. 1995; Lyon et al. 2008). Average temp at Brenda is above this threshold	Pragmatic The frequency of large in-channel freshes needed in highly intermittent systems for fish lifecycle requirements is around 50 percent of years (NSW DPI 2015).

Flow indicator	Ecological objective(s)	Flow threshold/volume assumptions and evidence	Duration assumptions and evidence	Timing assumptions and evidence	Frequency (target range) assumptions and evidence
	populations of flow dependent fish; and provide a range of other benefits for the river system including channel forming processes.			between Aug and May.	
3,500 ML/d for 14 days, between Aug and May at Brenda. Frequency: 40% to 60% of years	<p>This large in-channel pulse (around bankfull) is expected to provide a range of outcomes.</p> <p>The flow will provide opportunities for fish to move large distances and past in-channel barriers.</p> <p>Large freshes are important to maintain populations of flow dependent fish; and provide a range of other benefits for the river system</p>	<p>High</p> <p>Fish in the Lower Balonne will respond to the same types of flow that fish responded to in other catchments (no site-specific fish movement data).</p> <p>MDBA analysed site-specific hydrological data to describe a flow that provides a river rise of at least 2 m and an average velocity of 0.3 m/s. These flow attributes have been linked to fish movement responses in other nearby catchments.</p>	<p>Pragmatic</p> <p>Based on ecological and hydrological information. The hatch time of Murray cod eggs represents the longest breeding requirement for native fish in the area.</p> <p>The duration is consistent with the typical hydrology (median under WOD is 17 days).</p>	<p>Pragmatic</p> <p>Linked to research about the water temperature for golden perch to move large distances (15-16 degrees). Golden perch is the main flow dependent fish in the region.</p> <p>Average temp at Brenda is above this threshold between Aug and May.</p>	<p>Pragmatic</p> <p>Based on general advice from experts that 50% of years would generally have a large in-channel pulse in the dryland rivers of the northern basin.</p> <p>The frequency target is between the baseline frequency (30%) and WOD frequency (68%), and is expected to provide conditions to improve native fish populations over time.</p>

Flow indicator	Ecological objective(s)	Flow threshold/volume assumptions and evidence	Duration assumptions and evidence	Timing assumptions and evidence	Frequency (target range) assumptions and evidence
	including channel forming processes.				
9,200 ML/d for 12 days, any time of the year at Brenda. Frequency: average period between events of 2 to 3 years.	This event is expected to inundate riparian and near channel areas across the Lower Balonne, particularly river red gum, ephemeral wetlands and lignum communities.	High Flows at Brenda represent floodplain connectivity for the Lower Balonne. Changes in the spatial distribution of water recovery (between channels) can be represented by flows at Brenda Thoms et al. (2002) reported that a flow rate at St George corresponding to a flow of 7,800 ML/d on the Culgoa River at Brenda disperses water into the many small flood channels on the Lower Balonne River Floodplain. Additionally, Sims (2004) and Sims and Thoms (2002), reported that floodplain inundation commences at a flow corresponding to 9,200 ML/d on the Culgoa River at Brenda, inundating about 12,000 hectares of the floodplain upstream of the Queensland border. This magnitude of flow at Brenda is consistent with more recent inundation analysis (MDBA 2016).	Pragmatic Consistent with past practice (e.g. MDBA 2012a), the duration selected was the median duration for a flow of 9,200 ML/d from the without development flow scenario (12 days). It is expected that water would be retained in wetlands and depressions for longer than the 12 days and be likely to meet the needs of wetland vegetation.	High Timing has not been constrained to reflect that the flows are unregulated and occur in response to natural rainfall events within the catchment.	Pragmatic The average flooding frequency requirements of vegetation adopted are an adequate surrogate for maintaining vegetation communities in this zone. Between flooding, vegetation will use a variety of water sources including groundwater. Consistent with the scientific literature describing the watering requirements of river red gum forests and lignum (as per Marston and Roberts 2015). Tested against the baseline and WOD frequency to ensure consistency with the hydrology of the Lower Balonne.
15,000 ML/d for 10 days, any time of the year at Brenda. Frequency: average	This event is expected to inundate riparian and wetland areas as well as around	High Whittington et al. (2002) concluded that a flow corresponding to 15,000 ML/d in the Culgoa River at Brenda would inundate riparian forest, lignum and	Pragmatic Consistent with past practice and the logic for the duration of the other flow indicators for	Pragmatic Timing has not been constrained to reflect that the	Pragmatic The average flooding frequency requirements of vegetation adopted are an adequate surrogate for maintaining vegetation communities in this zone.

Flow indicator	Ecological objective(s)	Flow threshold/volume assumptions and evidence	Duration assumptions and evidence	Timing assumptions and evidence	Frequency (target range) assumptions and evidence
period between events of 3 to 4 years.	15% of the floodplain.	some coolibah open woodlands in the Queensland section of the floodplain. This is consistent with MDBA inundation analysis (<i>MDBA 2016</i>)	lateral connectivity, the median duration of the without development scenario was used. For a flow magnitude of 15,000 ML/d measured at Brenda, the median event duration was 10 days.	flows are unregulated and occur in response to natural rainfall events in the catchment.	Between flooding, vegetation will use a variety of water sources including groundwater. Consistent with the scientific literature describing the watering requirements of river red gum and black box woodlands and to sustain lignum (as per <i>Marston and Roberts 2015</i>).
24,500 ML/d for 7 days, any time of the year at Brenda. Frequency: average period between events of 6 to 8 years.	This event is expected to inundate mid floodplain areas (around 40% of the floodplain). This flow would result in significant exchange of nutrients, sediment and biota between the river and floodplain (Whittington et al. 2002; Thoms 2003; Sims 2004).	High Sims (2004) identified a flow corresponding to 24,500 ML/d at Brenda as a flow that provided an important transition in floodplain inundation whereby floodwater emerged from the Culgoa River in the vicinity of bifurcation 1, travelled across the floodplain and re-entered the Culgoa River downstream near the Woolerbilla gauge.	Pragmatic Consistent with past practice and the logic for the duration of other flow indicators for lateral connectivity, the median duration of the WOD was used. The median event duration under without development conditions for a flow of 24,500 ML/d at Brenda is 7 days.	Pragmatic Timing has not been constrained to reflect that the flows are unregulated and occur in response to natural rainfall events in the catchment.	Pragmatic The average flooding frequency requirements of vegetation adopted are an adequate surrogate for maintaining vegetation communities in this zone. Between flooding, vegetation will use a variety of water sources including groundwater. Consistent with the scientific literature describing the watering requirements black box woodlands and to support coolibah in this zone (as per <i>Marston and Roberts 2015</i>).
38,000 ML/d for 6 days, any time of the year at Brenda. Frequency: average period between	This event is expected to inundate outer floodplain areas	High Based on Whittington et al. (2002), the flow indicator selected for lateral connectivity with the outer floodplain is	Pragmatic Consistent with past practice (e.g. MDBA 2012a), the duration	Pragmatic Timing has not been constrained to	Pragmatic Consistent with the scientific literature describing the watering requirements of similar grasslands in

Flow indicator	Ecological objective(s)	Flow threshold/volume assumptions and evidence	Duration assumptions and evidence	Timing assumptions and evidence	Frequency (target range) assumptions and evidence
events of 10 to 20 years.	(around 70% of the floodplain). This infrequent event plays an important role in the overall productivity of the outer floodplain grasslands and the facilitating mass exchanges of, nutrients, sediment and biota between the river and floodplain.	38,000 ML/d in the Culgoa River at Brenda. This provides large-scale inundation (e.g. 70% of floodplain area in Queensland) across the Lower Balonne floodplain. Inundation at this level, although infrequent, has been shown to be vital for maintaining the productivity of grasslands on the outer floodplain (<i>Parsons and Thoms 2012</i> , Capon 2003), which make up nearly 40% of the total flood dependent vegetation (<i>Eco Logical Australia 2016</i>).	selected was the median duration from the without development flow scenario. The median duration is 6 days.	reflect that the flows are unregulated and occur in response to natural rainfall events in the catchment.	parts of the Gwydir Wetlands and to support coolibah woodlands (NSW DEWCC 2011).
Narran Lakes: A volume of 25,000 ML delivered over 60 days at any time of year, with the average period between events of 1 to 1.3 years	This event aims to maintain healthy vigour and cover of lignum shrubs in the key waterbird rookery habitat It is assumed that colonial waterbirds have access to other sites for breeding opportunities.	High The flow volume will maintain a sufficient area of habitat in suitable quality to support colonial waterbird breeding events. A volume of around 25,000 ML delivered over at least 60 days would inundate Clear and Back Lakes in the northern lakes, some parts of the lignum swamp and Narran Lake, and some of the flow paths in between (<i>Thomas et al. 2016</i>).	High Lignum needs to be inundated for a duration of at least 90 days to maintain vigorous shrubs (ANU Enterprise 2011; Roberts and Marston 2011). An event of 60 days duration would be sufficient to meet this requirement as water would be retained in the core wetland areas	High Timing has not been constrained to reflect that the flows are unregulated and occur in response to natural rainfall events in the catchment.	Pragmatic The average flooding frequency requirements of vegetation adopted are an adequate surrogate for maintaining vegetation communities in this zone. ANU Enterprise (2011) found that when inundation is more frequent than once every 1.33 years in the Narran Lakes, the cover, height and perimeter of lignum clumps is significantly increased. The 1.33 year flood frequency identified in ANU Enterprise (2011) is within the frequency range of 1 to 3 years which has been suggested in the literature to provide for the vigorous growth of lignum.

Flow indicator	Ecological objective(s)	Flow threshold/volume assumptions and evidence	Duration assumptions and evidence	Timing assumptions and evidence	Frequency (target range) assumptions and evidence
			following inflows for over a month, and hence lignum would remain inundated for a sufficient duration.		
Narran Lakes: A volume of 50,000 ML delivered over 90 days at any time of year, with the average period between events of 1.3 to 1.7 years	This event is aimed at maintaining a larger area of waterbird breeding habitat within the northern lakes It is assumed that colonial waterbirds have access to other sites for breeding opportunities.	High A volume of around 50,000 ML delivered over at least 90 days would inundate about 50% or 2,350 ha of the northern lakes (<i>Thomas et al. 2016</i>). Clear Lake and Back Lake-Long Arm would fill, substantial parts of the lignum swamp would be inundated and some water would flow into Narran Lake (<i>Thomas et al. 2016</i>).	High Lignum needs to be inundated for a duration of at least 90 days to maintain vigorous shrubs (ANU Enterprise 2011; Roberts and Marston 2011). An event of 90 days duration meets this requirement.	High Timing has not been constrained to reflect that the flows are unregulated and occur in response to natural rainfall events in the catchment.	Pragmatic The average flooding frequency requirements of vegetation adopted are an adequate surrogate for maintaining vegetation communities in this zone. The frequency range of 1.3 to 1.7 years was selected based on the effect of inundation on the form of lignum and the local observations that this inundation frequency has maintained these communities in good condition (<i>Thomas et al. 2016</i>).
Narran Lakes: A volume of 154,000 ML for a duration of 90 days any time of year with a frequency 2 events in any 8 year to 10 year period.	This event aims to facilitate large-scale waterbird breeding events and habitat of the northern lakes and northern floodplains. It is assumed that colonial waterbirds have access to	High Merritt et al. (2016) analysed breeding events of straw-necked ibis breeding from 1971 to 2014 (33 flow event and 18 breeding events in total) to set this indicator. Breeding occurred during this time period when flows exceeded 154,000 ML at Wilby Wilby in the first 90 days of the flow event (11 flow	High Meets the breeding requirements (from incubation, chick rearing to fledging) of at least 15 waterbird species, including colonial and non-colonial waterbird species that breed in the Narran Lakes	High Timing has not been constrained to reflect that the flows are unregulated and occur in response to natural rainfall	Pragmatic The lifecycles of many of waterbird species are episodic, responding to intermittent large flows with large-scale breeding. These 'booms' are important for maintaining populations that can survive the often longer-duration 'busts' when breeding does not occur or is minimal. To support these episodic breeding events, <i>Brandis and Bino (2016)</i> recommend a frequency of 2 events in any 8 year period (low uncertainty)

Flow indicator	Ecological objective(s)	Flow threshold/volume assumptions and evidence	Duration assumptions and evidence	Timing assumptions and evidence	Frequency (target range) assumptions and evidence
	other sites for breeding opportunities.	events resulted in 11 breeding events) (<i>Merritt et al. 2016</i>). Inundates a third of the northern floodplain and about 20% of the central floodplain, including the majority of lignum shrublands (<i>Thomas et al. 2016</i>).	system (<i>Merritt et al 2016</i>).	events in the catchment. Waterbirds have been recorded breeding throughout the year (<i>Brandis and Bino 2016</i>)	and 2 events in any 10 year period (high uncertainty). The high uncertainty frequency is considered to represent a boundary beyond which there is a risk of significant declines of waterbird populations at the Narran Lakes (<i>Brandis and Bino 2016</i>).
Narran Lakes: A volume of 250,000 ML delivered over 180 days at any time of year, with the average period between events of 8 to 10 years	This event aims to improve habitat including lignum shrublands, in the wider Narran Lakes system including much of the northern and central floodplain. It is assumed that colonial waterbirds have access to other sites for breeding opportunities.	High This volume delivered over 180 days would inundate about two thirds of the Narran Lakes ecosystem and would fill Narran Lake to about 85% capacity (<i>Thomas et al. 2016</i>). Water may then stay in Narran Lake for up to 18 months, providing potential drought refuge. At this volume, large-scale waterbird breeding would be expected (<i>Brandis and Bino 2016</i>).	High The period required to largely fill the lakes and for water to spread more broadly through the Narran Lakes system (<i>Thomas et al. 2016, ANU Enterprise, 2011</i>).	High Timing has not been constrained to reflect that the flows are unregulated and occur in response to natural rainfall events in the catchment.	Pragmatic The average flooding frequency requirements of vegetation adopted are an adequate surrogate for maintaining vegetation communities across the Narran Lakes. The broader floodplain areas are likely to be dominated by sparsely arranged small lignum shrubs. Drawing upon Roberts & Marston (2011), an average inundation frequency of at least once every 10 years is required to maintain these lignum shrublands.

Appendix B - Contributors

The MDBA took account of the advice and input from the contributors listed below in preparing this document.

Environmental Science Technical Advisory Group members

Name	Department/ Organisation
Anthony Townsend	NSW Department of Primary Industries - Fisheries
Neal Foster	NSW Department of Primary Industries - Water
Debbie Love, Sharon Bowen, Rachael Thomas	NSW Office of Environment & Heritage
Jonathan Marshall, Jaye Lobegeiger	QLD Department of Science, Information Technology & Innovation
Rosemary Coburn, Andrea Prior, Simon Hausler	QLD Department of Natural Resources & Mines
Lucy Vincent, Kathryn Anthonisz, Amy Fox	Department of Agriculture and Water Resources
Christine Mercer, Andrew Warden	Commonwealth Environmental Water Office
Lindsay White, Adam Sluggett, Gavin Pryde, Michael Peat, Kelly Marsland, Nadeem Samnakay, Chris Pulkkinen, Janet Pritchard, Rebecca Thornberry, Beatrix Spencer, Kyra Evanochko	Murray-Darling Basin Authority

Environmental scientists directly involved in the development, implementation and analysis of the elements of the environmental science program were from the following organisations.

Organisation	Organisation
Queensland Department of Science, Information Technology and Innovation	Monash University
Queensland Department of Science, Information Technology and Innovation	University of New South Wales
Queensland Department of Natural Resources and Mines	Queensland Department of Agriculture, Fisheries and Forestry
NSW Department of Primary Industries - Water	Griffith University
NSW Office of Environment and Heritage	Murray-Darling Freshwater Research Centre/Charles Sturt University
Australian National University	Murray-Darling Freshwater Research Centre/Charles Sturt University
NSW Department of Primary Industries - Fisheries	Victorian Department of Environment, Land, Water and Planning
CSIRO	Eco Logical Australia (Dr. Mark Southwell)

Appendix C: Lower Balonne 2012 flow indicators

Lower Balonne ecological targets	Flow indicator gauge	Magnitude: flow (ML/d)	Duration (days)	Timing	Frequency	Frequency
					Low uncertainty	High uncertainty
Provide a flow regime which: <ul style="list-style-type: none"> ensures the current extent of native vegetation of the riparian, floodplain and wetland communities is sustained in a healthy, dynamic and resilient condition supports the habitat requirements of waterbirds supports a range of native aquatic species (e.g. fish, frogs, turtles, invertebrates) supports key ecosystem functions, particularly those related to connectivity between the river and floodplain 	Brenda	1,200	7	Any time of year	1.8 years (maximum period between events)	2.3 years (maximum period between events)
	Brenda	12,000	11	Any time of year	3 years (average period between events)	4 years (average period between events)
	Brenda	18,500	9	Any time of year	4 years (average period between events)	5 years (average period between events)
	Brenda	26,500	7	Any time of year	7 years (average period between events)	10 years (average period between events)
	Brenda	38,500	6	Any time of year	20 years (average period between events)	20 years (average period between events)

Appendix D: Narran Lakes 2012 flow indicators

Narran Lakes ecological targets	Flow indicator gauge	Magnitude: volume (ML)	Duration (months)	Timing	Frequency	Frequency
					Low uncertainty	High uncertainty
Provide a flow regime which: <ul style="list-style-type: none"> ensures the current extent of native vegetation of the riparian, floodplain and wetland communities is sustained in a healthy, dynamic and resilient condition supports the habitat requirements of waterbirds and is conducive to successful breeding of colonial nesting waterbirds supports recruitment opportunities for a range of native aquatic species (e.g. fish, frogs, turtles, invertebrates) supports key ecosystem functions, particularly those related to connectivity between the river and floodplain 	Wilby Wilby	25,000	2	Any time of year	1 year (average period between events)	1.1 years (average period between events)
	Wilby Wilby	50,000	3	Any time of year	1 year (average period between events)	1.33 years (average period between events)
	Wilby Wilby	250,000	6	Any time of year	8 years (average period between events)	10 years (average period between events)
	Wilby Wilby	100,000	12	N/A	6 years (maximum period between events)	8 years (maximum period between events)
	Wilby Wilby	50,000	3	Any time of year	7 years (maximum period between events)	10 years (maximum period between events)

Appendix E - Listed species, Lower Balonne River Floodplain

Species	Environment Protection & Biodiversity Conservation Act 1999 (Cwlth)	Fisheries Management Act 2004 (NSW)	Threatened Species Conservation Act 1995 (NSW)
Birds			
Australasian bittern (<i>Botaurus poiciloptilus</i>)	E		E
Blue-billed duck (<i>Oxyura australis</i>)			V
Brolga (<i>Grus rubicundus</i>)			V
Freckled duck (<i>Stictonetta naevosa</i>)			V
Australian painted snipe (<i>Rostratula australis</i> or <i>R. benghalensis</i>)	E		E
Fish			
Silver perch (<i>Bidyanus bidyanus</i>)	CE	V	
Olive perchlet (<i>Ambassis agassizii</i>)		E	
Murray cod (<i>Maccullochella peelii peelii</i>)	V		
Freshwater catfish (<i>Tandanus tandanus</i>)		E	
Plants			
Narrow-leafed bumbe (<i>Capparis loranthifolia</i> var. <i>loranthifolia</i>)			E

Species	Environment Protection & Biodiversity Conservation Act 1999 (Cwlth)	Fisheries Management Act 2004 (NSW)	Threatened Species Conservation Act 1995 (NSW)
Desert cow-vine (<i>Ipomoea diamantinensis</i>)			E
Winged pepper-cress (<i>Lepidium monoplacoides</i>)	E		E
Communities			
Lowland Darling River aquatic ecological community		E	
Coolibah–black box woodland of the northern Riverine Plains in the Darling Riverine Plains and Brigalow Belt South bioregions			E
Brigalow–gidgee woodland/shrubland in the Mulga lands and Darling Riverine Plains bioregion			E

E = endangered V = vulnerable CE = critically endangered

Apart from the Australian painted snipe (vulnerable), there are no relevant listings under Queensland legislation (Queensland Nature Conservation Act 1992).

Appendix F - Listed species, Narran Lakes

Species	Recognised in international agreement(s) (1)	Environment Protection & Biodiversity Conservation Act 1999 (Cwlth)	Fisheries Management Act 2004 (NSW)	Threatened Species Conservation Act 1995 (NSW)
Birds				
Australasian bittern (<i>Botaurus poiciloptilus</i>)		E		E
Bar-tailed godwit (<i>Limosa lapponica</i>)	Yes			
Black-necked stork (<i>Ephippiorhynchus asiaticus</i>)				E
Black-tailed godwit (<i>Limosa limosa</i>)	Yes			V
Blue-billed duck (<i>Oxyura australis</i>)				V
Brolga (<i>Grus rubicundus</i>)				V
Caspian tern (<i>Sterna caspia</i>) ³	Yes			
Cattle egret (<i>Ardea ibis</i>)	Yes			
Curlew sandpiper (<i>Calidris ferruginea</i>) ²	Yes	CE		E
Eastern great egret (<i>Ardea modesta</i> var. <i>Ardea alba</i> , <i>Egretta alba</i>)	Yes			
Freckled duck (<i>Stictonetta naevosa</i>)				V
Greenshank (<i>Tringa nebularia</i>)	Yes			
Latham's snipe (<i>Gallinago hardwickii</i>)	Yes			

Species	Recognised in international agreement(s) (1)	Environment Protection & Biodiversity Conservation Act 1999 (Cwlth)	Fisheries Management Act 2004 (NSW)	Threatened Species Conservation Act 1995 (NSW)
Magpie goose (<i>Anseranas semipalmata</i>)				V
Marsh sandpiper (<i>Tringa stagnatilis</i>)	Yes			
Sharp-tailed sandpiper (<i>Calidris acuminata</i>)	Yes			
Fish				
Silver perch (<i>Bidyanus bidyanus</i>)		CE	V	
Olive perchlet (<i>Ambassis agassizii</i>)			E (MDB population)	

E = endangered V = vulnerable CE = critically endangered,
of Korea – Australia Migratory Bird Agreement

1 Japan–Australia Migratory Bird Agreement, China–Australia Migratory Bird Agreement, or Republic

Appendix G - Comparison of frequencies for site-specific flow indicators

The site-specific flow indicators for the Lower Balonne River Floodplain UEA are in the table below. Unless otherwise indicated, the flow indicator gauge is at Brenda on the Culgoa River.

Site-specific flow indicator	Without development frequency	SFI low uncertainty frequency	SFI high uncertainty frequency	Baseline frequency	Maximum spell under without development	Maximum spell under baseline
Any flow, taken as 2 ML/d for one day any time of the year - (Culgoa R. at Weilmoringle)	397 days b/w events (maximum)	350 days b/w events (maximum)	430 days b/w events (maximum)	712 days b/w events (maximum)	397 days	712 days
Any flow (taken as 2 ML/d for one day any time of the year) - (Narran R. at Narran Park)	624 days b/w events (maximum)	350 days b/w events (maximum)	470 days b/w events (maximum)	866 days b/w events (maximum)	624 days	866 days
1,000 ML/d for 7 days any time of the year	98% of years	90% of years	80% of years	74% of years	1.7 years	3.5 years
1,700 ML/d for 14 days between Aug and May (Narran R. at Wilby Wilby)	61% of years	60% of years	40% of years	25% of years	5.7 years	13 years
3,500 ML/d for 14 days between Aug and May	68% of years	60% of years	40% of years	30% of years	4.4 years	11 years
9,200 ML/d for 12 days any time of the year	1.3 years b/w events (average)	2 years b/w events (average)	3 years b/w events (average)	5.3 years b/w events (average)	5.3 years	29 years
15,000 ML/d for 10 days any time of the year	1.9 years b/w events (average)	3 years b/w events (average)	4 years b/w events (average)	6.7 years b/w events (average)	8.9 years	55 years
24,500 ML/d for 7 days any time of the year	3.3 years b/w events (average)	6 years b/w events (average)	8 years b/w events (average)	8.4 years b/w events (average)	11 years	55 years
38,000 ML/d for 6 days any time of the year	9.1 years b/w events (average)	10 years b/w events (average)	20 years b/w events (average)	34 years b/w events (average)	55 years	55 years

The site-specific flow indicators for the Narran Lakes UEA are in the table below. For each indicator, the flow indicator gauge is at Wilby Wilby on the Narran River.

Site-specific flow indicator (SFI)	Without development frequency	SFI low uncertainty frequency	SFI high uncertainty frequency	Baseline frequency	Maximum spell under without development	Maximum spell under baseline
25,000 ML inflow volume over 60 days	0.7 years between an event (average)	1 year between an event (average)	1.3 years between an event (average)	1.3 years between an event (average)	3.2 years	7.5 years
50,000 ML inflow volume over 90 days	0.9 years between an event (average)	1.3 years between an event (average)	1.7 years between an event (average)	1.9 years between an event (average)	3.3 years	7.9 years
154,000 ML inflow volume over the first 90 days of the event	2 events in 79% of all 8 year periods; 2 events in 90% of all 10 year periods	Twice in 8 years	Twice in 10 years	2 events in 20% of all 8 year periods; 2 events in 27% of all 10 year periods	N/A	N/A
250,000 ML inflow volume over 180 days	6.5 years between an event (average)	8 years between an event (average)	10 years between an event (average)	16 years between an event (average)	30 years	55 years