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# Murray-Darling Basin Environmental Water Knowledge and Research Project

## Synthesis Report

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## Murray-Darling Basin Environmental Water Knowledge and Research Project Research Site Report

Report prepared for the Department of the Environment and Energy, Commonwealth Environmental Water Office by La Trobe University, Centre for Freshwater Ecosystems (formerly Murray-Darling Freshwater Research Centre).

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**Cover Image:** Floodplain inundation

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# Contents

<b>Executive Summary</b>	<b>1</b>
<b>1 Project Details</b>	<b>2</b>
1.1 Background .....	2
1.2 Summary information provided in this report .....	4
<b>2 Fish theme</b>	<b>5</b>
2.1 Fish theme research focus .....	5
2.2 Fish theme key findings.....	5
2.3 Fish theme synthesis .....	6
2.4 Fish theme information for managers .....	7
2.5 Fish theme knowledge status.....	8
<b>3 Food Webs Theme</b>	<b>9</b>
3.1 Food webs theme research focus .....	9
3.2 Food web theme key findings .....	9
3.3 Food web theme synthesis.....	10
3.4 Food web theme information for managers.....	10
3.5 Food web theme knowledge status .....	11
<b>4 Vegetation theme</b>	<b>12</b>
4.1 Vegetation theme research focus .....	12
4.2 Vegetation theme key findings .....	12
4.3 Vegetation theme synthesis.....	13
4.4 Vegetation theme information for managers .....	13
4.5 Vegetation theme knowledge status .....	14
<b>5 Waterbirds theme</b>	<b>15</b>
5.1 Waterbirds theme research focus .....	15
5.2 Waterbirds theme key findings.....	15
5.3 Waterbirds theme synthesis .....	16
5.4 Waterbird theme information for managers .....	17
5.5. Waterbird theme knowledge status .....	19
<b>6 Synthesis Between Themes</b>	<b>20</b>
6.1 The importance of floodplain inundation .....	20
6.2 Processes within rivers happen at many scales .....	20
6.3 Connectivity is a crucial component .....	21
6.4 Habitat can be improved through flow management.....	21
6.5 There is no one water management recipe for all species .....	21
6.6 There are significant opportunities created by projects such as EWKR.....	21
<b>7 References</b>	<b>23</b>
<b>Appendix 1: Research Site Report</b>	<b>25</b>

## Executive Summary

### *Project background*

- The Murray–Darling Basin Environmental Water Knowledge and Research Project (MDB EWKR) was a five-year project funded by the Commonwealth Environmental Water Office in the Department of the Environment and Energy
- Research focussed on four thematic areas, which were identified by water managers as high priority knowledge gaps. These were fish, waterbirds, vegetation and food webs
- Reviews, synthesis, models, experiments and field studies were undertaken to better understand processes in the Murray Darling Basin (Basin)
- The information is provided in this report for both scientists and managers as EWKR has conducted ground-breaking research that improves understanding of what we know and what remains to be discovered within each theme

### Key EWKR findings:

- Floodplain inundation is crucial to provide the highest quality resources for riverine foodwebs
- Processes within the Basin operate at a myriad of scales so managing a river for recruitment or dispersal, for example requires information at each scale (i.e. site, catchment, basin)
- Connectivity of rivers, habitats and catchments is needed to ensure the movement of organisms and resources across the Basin
- Improvements in habitat quality can be influenced by flow management and resource management e.g. by providing flows that promote fish movement or improve the structural complexity within rivers
- There is no one correct way to manage the Basin. The ‘boom and bust’ variability of unregulated Australian rivers needs to be mimicked to provide the maximum opportunity for all life history strategies
- Projects such as EWKR have value beyond the performance of research projects as they provide a unique opportunity for the formation of collaborations, networks and research directions between groups of scientists, and between scientists and water managers

# 1 Project Details

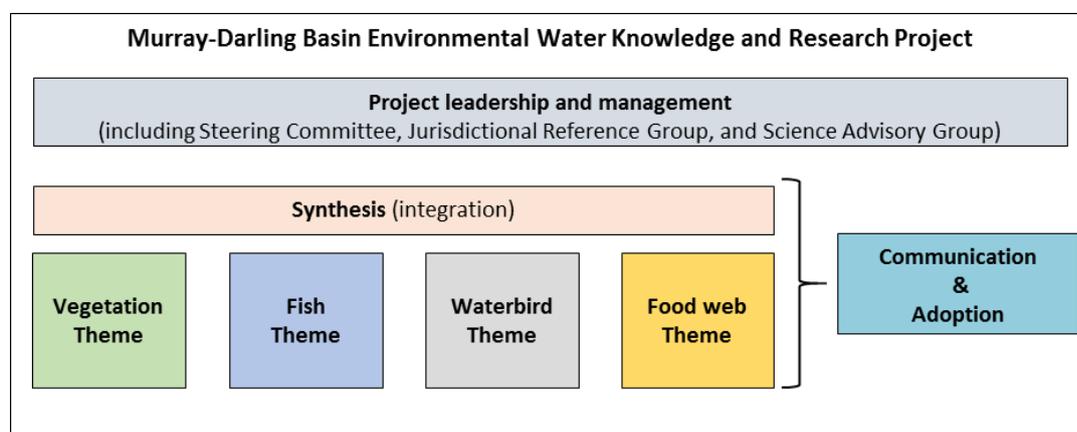
## 1.1 Background

The Murray–Darling Basin Environmental Water Knowledge and Research Project (MDB EWKR) was a five-year project funded by the Commonwealth Environmental Water Office in the Department of the Environment and Energy. The project was coordinated by the Centre for Freshwater Ecosystems at La Trobe University (formerly the Murray-Darling Freshwater Research Centre). The project was undertaken in collaboration with scientists from a range of research organisations. It commenced in June of 2014 and concluded in June of 2019. Phase 1 of the project included planning of the research during which stakeholders from the scientific community, managers and practitioners were engaged to identify potential research priorities and questions. Once these were chosen, research collaborators were selected, and the research planning process began.

Phase 2 of the project commenced in May 2015 when the first multi-year research plan, Annual Research Plan (for 2015/16) and site descriptions were drafted (MDFRC, 2015, MDFRC, 2016). Plans were finalised in 2016 and 2017 and subcontracts were executed. Research plans outlined what the research would be for each theme of the project, where it would occur, how and why. These documents were updated throughout the life of the project. As with any large, collaborative project, priorities and plans were changed as methods and processes were trialled and refined for greater efficiency and knowledge gain.

Originally it was intended that research would be conducted at four sites across the Murray-Darling Basin; Mid-Murray, Lower Murray, Macquarie Marshes and the Lower Balonne. However, as the project evolved it became clear that *not* limiting research to certain areas would provide better knowledge and coverage across the Basin. Expanding the areas also allowed projects to ‘piggy-back’ on other projects such as the Long-term Intervention Monitoring Project (LTIM) which increased the outputs of both projects and provided greater opportunities to demonstrate practical applications to water management. A summary of sites is provided in Appendix 1- Research Site Report.

Research focussed on four thematic areas, which were identified by water managers as high priority knowledge gaps. These were fish, waterbirds, vegetation and food webs (Figure 1). There was also a synthesis component (this report) that worked on drawing the information together. The outcomes of the research are captured in this document. For more detailed thematic and research project information please see the theme reports (Campbell et al., 2019, McInerney et al., 2019, McGinness et al., 2019, Price et al., 2019).



**Figure 1.** Structure of MDB EWKR showing themes and other major components.

The intent of MDB EWKR was to improve the science available to support the needs of environmental water managers in the Murray–Darling Basin. Research focused on:

- improved identification, assessment and understanding of the links between the ecological responses to watering regimes (e.g. natural and/or managed events) and incremental changes in ecological condition (the state of ecological systems including physical, chemical and biological characteristics and the processes and interactions that connect them (U.S. EPA, 2018)).
- medium and long-term changes in ecological condition, including the effects of threats (hydrological, aquatic and terrestrial) which may reduce or prevent the ecological improvement expected.
- how management or delivery of environmental flow influences environmental outcomes achieved over time.
- how complementary water management and natural resource management enhance outcomes of environmental water management.

The research also aimed to support the collaborative role of the Commonwealth in environmental watering within the Basin, in particular:

- Murray–Darling Basin Authority’s (MDBA) role in implementing the Basin Plan;
- Commonwealth Environmental Water Office’s (CEWO) role in managing environmental water;
- Basin States’ role in managing environmental water and aquatic assets.

The recommendations and information summarised in this report shows that these goals have been met to varying degrees. However, there remains much more to learn, and this report can help guide future investment into research that is needed to better understand the Murray Darling Basin.

Research promoted collaboration amongst research organisations which helped generate new knowledge about the complex responses of aquatic ecosystems to changes in flows across a range of spatial and temporal scales. It also uncovered important gaps in knowledge which future research programs can fill. The main contributing organisations are shown in Table 1.

La Trobe University/ Centre for Freshwater Ecosystems/Murray Darling Centre for Freshwater Research	University of New England
Charles Sturt University	University of Canberra
CSIRO	Deakin University
Charles Darwin University	NSW Department of Primary Industries
University of New South Wales	NSW Office of Environment and Heritage
Griffith University	Arthur Rylah Institute
South Australian Research and Development Institute	

**Table 1.** List of key contributing organisations to EWKR research

## 1.2 Summary information provided in this report

Each theme within MDB EWKR generated key knowledge about the Basin or supported theories about the ecology of the Basin. At the start of EWKR each theme chose key questions or knowledge gaps around which to base their research (presented as research focus). Each theme developed a number of individual research components (e.g. Fish projects 2.1 to 2.8) which took the form of models, experiments, field or laboratory studies or knowledge synthesis (presented as key findings); and related to the research questions. Each theme also synthesized their findings (presented as theme synthesis) and provided key considerations for water managers (presented as information for managers). Lastly themes provided information about the knowledge status of their area of study (presented as knowledge status) which highlights what remains to be learned to better understand flows and the environment within the research focus area. Reference is made to the relevant section of thematic reports at the end of paragraphs. For example, (Fish 3.5) refers to section 3.5 of the fish theme report.

This Synthesis Report integrates the information between all four themes and how they relate to one another.

Information from theme reports are briefly summarised in this report.

Full theme research reports can be found on the Commonwealth Environmental Water Office website at: [www.environment.gov.au/water/cewo](http://www.environment.gov.au/water/cewo)

## 2 Fish theme

### 2.1 Fish theme research focus

The MDB EWKR Fish Theme focussed on fish recruitment in the Basin and sought to improve understanding of the key drivers, functional processes and limitations of successful recruitment of native fish. This was captured in three research focus areas:

1. What are the food and temperature requirements of the early-life stages of target species?
2. Where in the riverscape, and under what flow conditions, are these food and temperature requirements best met?
3. How do dispersal and retention influence recruitment?

### 2.2 Fish theme key findings

The fish theme created a conceptual model and conducted a literature review that summarised the influence of flow and non-flow related stressors on fish recruitment. This work found that 1) flow regulation impacts recruitment but how this happens is poorly understood; 2) temperature affects fish spawning, but it was not known how it influences growth and survival; 3) food quantity and quality are likely key drivers of recruitment and; 4) there is evidence for increased mortality of eggs and larvae associated with barriers and infrastructure (Fish 2.1). This information was used to design other research questions.

The fish theme identified knowledge gaps regarding the flow-related ecology of freshwater fish. This included a review of the contemporary scientific knowledge and the knowledge base and needs of water managers (review and workshop). The major objective was to provide an up-to-date synthesis of knowledge pertaining to the flow-related ecology of the Basin fishes, from both scientific and management perspectives. The main knowledge gap identified was a lack of understanding about the influence of flow on survival rates of all life-stages. The importance of close collaboration between scientists and managers was another key result of this work (Fish 2.2)

A riverscape recruitment model was developed by the fish theme which filled an important gap in understanding freshwater fish. This model allows the prediction of recruitment strength based on discharge, reach physical complexity, temperature and food availability, and the life history strategy of the fish (Fish 2.3).

A series of experiments examined the relationship between food density, temperature and fish growth and survival. These showed that larval fish growth and survival is influenced by food availability and water temperature, and the interaction between these factors with fish preferring species specific temperatures. For example, the survival of Murray Cod larvae was extremely low at cool temperatures. The results from this project have demonstrated the importance of the relationship of appropriate food densities with appropriate water temperatures for growth and survival of young Golden Perch and Murray Cod (Fish 2.4).

A field sampling study was undertaken to better understand the life history of fishes in the northern Basin, which differ from the southern Basin where flow is more permanent. The northern Basin rivers commonly retreat to unconnected waterholes, making the management of large waterholes crucial for maintaining fish population viability. This study was conducted during extreme drought and found that while small numbers of larval and adult fish were present, these had reduced by an order of magnitude from previous studies. This result highlights that certain large, deep and complex waterholes act as refugia for fish during drought and must be protected from extraction and flood

plain harvesting. Reconnection during high flow events will be needed to ensure recolonization and population mixing in previously dry areas (Fish 2.5)

Thermal and nutritional regimes were compared between the main channel and floodplain wetland and anabranch sites. This study found that floodplains are *not* warmer, more stable water temperature environments than the river channel, as has previously been published in the scientific literature. This may be due to insufficient temperature measurements being taken in other studies. The *density* of larval fish food (zooplankton) is higher in floodplain habitats (wetlands and anabranches) than the river channel, pointing to the need for connection of these habitats when water is available and larval fish are present. Anabranches are more readily connected than wetlands and so may be easier to manage (Fish 2.6).

A field study was designed to test the usefulness of the river recruitment model (Fish 2.3). The specific questions were: 1) what is the relationship between reach physical complexity and flow retentiveness and how does this change with discharge; and 2) what is the relationship between the density and composition of zooplankton in a lowland river and reach retentiveness, and how does this relationship change with discharge? This study found that as water discharge declines, reach retentiveness (the ability to retain nutrients, sediments and organisms) in specific parts of the river increases. However, this relationship was altered depending on the shape of the river channel and the complexity of the habitat (Fish 2.7).

A laboratory study aimed to improve the understanding of larval dispersal of three iconic Australian freshwater fish, Golden Perch (*Macquaria ambigua*), Murray Cod (*Maccullochella peelii*), and Trout Cod (*Maccullochella macquariensis*), by investigating swimming behaviour under a range of simulated flow conditions. This study found that larval fish are not drifting passively with river currents but are instead making choices about where they are in a river channel. This differs between species but is important to understand that larval fish are searching for optimal places within a river which supplies the correct food, structure and temperature for them to thrive. (Fish 2.8).

A field study quantified the relationship between flow and reach-scale retentiveness (ability to retain objects within the water due to slack-water, structure or other barrier) of larvae of species with different swimming abilities (Golden Perch and Murray Cod). In most cases, more larvae of both species were retained in reaches, regardless of reach retentiveness, than passive particles. This strongly suggests that Murray Cod and Golden Perch larvae are not passive in their movements through lowland river reaches but have some capacity to determine their location (Fish 2.9).

A Basin wide study investigated the spatial scale at which Murray Cod and Golden Perch populations operate. This study demonstrated that there is no one place which is the dominant source of recruitment for Murray Cod and Golden Perch in the Basin, for example, it is often said that the Menindee Lakes is the key source for Murray Cod <https://www.abc.net.au/news/2019-05-06/fish-hatchery-set-for-menindee/11082376>. For both Golden Perch and Murray Cod, connectivity between tributary and mainstem habitats can be a substantial driver of population structure. Where possible, maintaining the unique hydrologic and habitat characteristics of tributaries or mainstem rivers is paramount, as is facilitating connectivity between tributary and mainstem populations (Fish 2.10).

## 2.3 Fish theme synthesis

The success of fish recruitment in the Basin is complex and differs between species and spatial scales. Environmental water management that aims to promote population growth for any species needs to consider the scale at which the metapopulations of that species operate, and the need for hydrological and physical connectivity for all life stages (Fish 3.1).

At small scales within a river, the survival and growth of fish larvae is strongly influenced by the interaction between food density and temperature. Survival rates can vary substantially depending on food and temperature conditions. Different species can also tolerate different conditions, for example, Golden Perch larvae can tolerate much warmer temperatures than Murray Cod (Fish 3.2).

Food availability and temperature within a river channel vary depending on whether the river channel is connected to floodplain habitats such as wetlands and anabranches. Maximising survival of larval fish needs connection of these habitats through flow management, with flows closely tailored to spawning to allow larvae to access these good sources of food (Fish 3.3).

Spawning and/or recruitment was thought to be limited by both a lack of adults within the waterholes and limited flows in the northern Basin. Larvae were continually present in the permanent waterholes that were larger and deeper, peaks in larval abundances occurred with small flow rises. This is likely due to high habitat diversity in these larger waterholes, compared to smaller, less complex waterholes. Large waterholes are likely to confer resilience to resident fish during harsh conditions (Fish 3.4).

Where the structural complexity of the river channel is high e.g. benches, and hydraulic diversity of snags, macrophytes or slack-waters is maintained, zooplankton is retained in the system. Where these are low in the channel it will be more important to connect floodplain habitats to provide food. Retention of zooplankton provides improved conditions for larval fish (Fish 3.5).

At reach-scales, flow retention and discharge influence the dispersal and/or retention of fish larvae. Generally, more larvae of both species were retained in hydraulically, structurally and geomorphically complex reaches. Maintaining this diversity of complexity among river reaches will allow fish larvae to be retained if conditions are suitable or move through to avoid adverse conditions or to disperse to more favourable conditions (Fish 3.5).

Golden Perch and Murray Cod recruitment and population demographics are not homogenous across rivers of the Basin. Murray Cod population structure was influenced by *in situ* recruitment and emigration/immigration between adjacent river catchments, reaches or anabranches. For Golden Perch, recruitment was spatially and temporally variable among rivers (Fish 3.6).

## 2.4 Fish theme information for managers

Overall, physical complexity provides the basis for food production, retention of this food, and for fish larvae to either choose to remain or to move through. If retention is uniformly high throughout a reach, then a larva is likely to remain and survive. If retention is uniformly low, such reaches may not be very conducive for feeding, growth, survival and recruitment.

Golden Perch larvae are more tolerant of cooler water temperatures than Murray Cod however, growth is significantly reduced at temperatures below 19°C. Given that growth is strongly linked to survival, this has significant implications for recruitment in areas that are subject to cold water pollution. If managing for recruitment outcomes, consideration should be given to the timing of flows to provide larvae with appropriate temperatures for survival and growth.

Relatively high densities of zooplankton are required to maximise survival and growth. Zooplankton densities are naturally highly variable and watering decisions need to be based on knowledge of when and where high densities of zooplankton occur. For example, connecting an anabranch to a river channel immediately after fish have spawned would improve zooplankton nutrition, therefore improving fish retention, as anabranches have higher zooplankton density than the river channel. Anabranches often have the capacity to connect to the main channel at lower flows than floodplain wetlands so may be more frequently accessible for fish.

Key waterholes that help support adult fish persistence in the northern Basin need to be identified and protected. These are not only the biggest and deepest but also those with structural complexity. Small scale recruitment can occur in these waterholes with minor flows.

The capacity of water managers to maximise these conditions is dependent on the availability of water. Consequently, the scale at which management can occur, as well as the management outcomes that can be achieved, will vary depending on the amount of water available.

## **2.5 Fish theme knowledge status**

In this project we found that there was a strong relationship between food, temperature and retention of nutrients and larval fish, but only in lowland river systems. Future research could investigate these relationships in a range of river types (e.g. upland, ephemeral and dryland rivers) to determine whether they vary with river type.

To assist in water management, many of our studies have identified the importance of hydraulic and structural complexity. Areas that exhibit these characteristics should be protected to encourage native fish populations to persist and grow. Given that we found strong variability in all scales of rivers, it may be less expensive to explore the capacity to remotely measure physical complexity, thereby enabling water managers to make relatively rapid assessments. This would also be helpful in identifying critical fish refuges in the northern Basin which are crucial to support the persistence of fish in waterholes. Additionally, further experiments could identify the key characteristics of such waterholes that allow water, fish and nutrients to persist.

This work only looked at larval fish movement at a reach scale and only until fish had developed to the juvenile stage. Longer-term and larger-scale movement patterns where we follow larvae to recruitment into the adult population would provide more information to guide management actions.

The fish theme could only study some of the processes related to the persistence of fish populations in the Basin. Examination of the role of predation and competition with non-native species is also important as they represent a significant source of mortality for the early-life stages of native species and may impact on our ability to predictively manage flows for recruitment responses.

The fish theme of the EWKR project focused largely on Golden Perch and Murray Cod. Research on a greater diversity of species is needed to protect the biodiversity of the Basin. Understanding recruitment drivers and the influence of flow, particularly for small-bodied floodplain species, is crucial. Many of which small-bodied species are critically endangered but knowledge about them is limited.

## 3 Food Webs Theme

### 3.1 Food webs theme research focus

The Basin Plan seeks to protect and restore biodiversity in the Basin's aquatic ecosystems. Food webs are one of several critical ecosystem functions believed to be important for sustaining patterns of diversity along with connectivity and nutrient cycling. Improved understanding of the influence of flow on food webs will complement our understanding of the influence of flow on habitat and connectivity and that in combination, this knowledge will enable better management of environmental flows within the Basin.

The food web theme identified a knowledge gap around the role of flow in generating the required resources for key life-history events, which result in recruitment of plants and animals into breeding populations. For example, even where fish breeding is initiated by a flow event, we have limited evidence that the resulting fish larvae have access to the resources needed to allow them to grow to sexual maturity and therefore recruit into the population. The food web theme therefore aims to understand the relationship between flows and the provision of resources at critical stages.

### 3.2 Food web theme key findings

There was an initial review of available literature as well as a conceptualisation at the initial phase of the food webs theme. This supported the initial assumption that there is a knowledge gap relating flow to food web dynamics (Food webs 2.1).

A field program was conducted in collaboration with the fish theme to identify where in a river system the nutritional needs of larval fish are most likely to be met. This was done by analysing stable isotopes and fatty acids in different parts of the food web. This work found a higher *quality* of food for larval fish in floodplain habitats (wetlands and anabranches) than the river channel, with floodplain habitat characterised by high concentration of fatty acids. Floodplain inundation and reconnection to the main river channel are crucial for the establishment of healthy energy pathways in riverine systems (Food webs 2.2).

Another field program looked at the primary diets of Royal Spoonbills and Straw-necked Ibis. Royal Spoonbills rely primarily on aquatic prey and Straw-necked Ibis are sourcing energy from terrestrial prey. In particular Spoonbills are relying largely on fish while Ibis rely on beetles. These results suggest that consideration of specific waterbird species trophic requirements is important when tailoring management of environmental watering to maximise food availability to support waterbird recruitment for different species (Food webs 2.3).

Mesocosm experiments were conducted to understand how resources are taken up into food webs and how efficiently nutrients are transferred through the food webs. The food resources for larvae of two fish species (Murray Cod and Carp Gudgeon) were examined. This showed that green (photosynthetic) algae are the basis of the food web that supports the diets of invertebrates that are eaten by larval fish (Food webs 2.4).

Trophic niche is a fundamental dimension of food web structure and it is determined by energy availability, energy transfer and the diversity of carbon and nutrients in ecosystems. Animals like fish occupy a niche that places them at a point within a food web e.g. species like Murray Cod and Golden Carp are top predators. A tool, the Basin scale trophic niche indicator, was developed to trace where species fit into the food web, depending on what foods were consumed. Where changes are observed in the trophic niche it is reflected by a change in food resources in the system (Food webs 2.5).

A model that linked environmental flows to ecological outcomes was also developed. This model produced a quantitative food web that ranked watering events based on fish biomass produced. Overall this study found that fish biomass was proportional to the area and duration of inundation, however, the biomass was also strongly influenced by diet quality and composition. By targeting shifts in diet composition and producer quality, watering events can be designed to benefit fish. Green algae have the potential for high production rates and can contribute a large proportion of the energy used by the invertebrates eaten by fish (Food webs 2.6).

### **3.3 Food web theme synthesis**

Floodplain inundation is crucial for river productivity, as anabranches and wetlands provide abundant, high-quality food sources that are the basis of the food web for fish and waterbirds. Floodplain inundation needs to occur as frequently as possible to mobilise food resources and allow consumers to access valuable feeding areas.

These results suggest that consideration of specific waterbird species requirements is important when tailoring management of environmental watering to maximise food availability to support waterbird recruitment.

Work undertaken in mesocosm experiments reinforced patterns observed in field experiments. Green algae are a key basal resource for consumers, providing a high-quality food. Essential fatty acids from green algae were traced through food webs from invertebrates to fish. Dissolved organic carbon-based food webs provide the lowest invertebrate density, richness and lowest fish growth and survival.

The methods developed in the trophic niche activity provide a monitoring tool for managers to evaluate changes in the trophic position of fish communities in the Basin. The trophic niche indicator provides a cost-effective annual monitoring tool relevant to CEWO watering objective 'ecosystem function'.

The modelling work was informed by empirical data from mesocosm, site and basin scale experimental work, and builds on our current understanding of trophic responses to environmental watering. By targeting shifts in diet composition and producer quality, watering events can be designed to disproportionately benefit fish. Green algae have the potential for high production rates and can contribute a large proportion of the energy used by fish (Food webs 3).

### **3.4 Food web theme information for managers**

Where possible, water managers should link the river channel to anabranches and wetlands to allow consumers to access the highest quality food resources. More frequent links also reduce the likelihood of blackwater events, as resources are regularly washed into the river channel.

Habitat heterogeneity is needed to maximise high quality biofilms and green algae which support the basis of riverine foodwebs. This can be done through maintenance of hydraulic and structural diversity.

Given multi-year datasets, the trophic niche indicator could be further developed to evaluate the direct effects of flow metrics and therefore environmental flows, on the trophic niche of fishes and other consumers including waterbirds. The trophic niche indicator can tell us whether the delivery of flows is providing the food resources needed for recruitment and for maximising the production of adult fish populations (Food webs 4).

### 3.5 Food web theme knowledge status

Conceptual, mesocosm, reach and basin scale research conducted by the EWKR food web theme has improved the current understanding of two primary aspects of how environmental water can be used to enhance productivity and consumer responses. This work has emphasised the critical importance of:

- 1) Managing for high quality resources spatially and temporally
- 2) Targeting flows to support basal resources

While the EWKR food web theme has gone a long way in improving our understanding the relationship between environmental flows and food webs that transfer energy to support recruitment of native fish and water birds, the work has also identified several knowledge gaps that require further investigation.

Areas that require further attention include:

- Consideration of hydrology in studies of trophic dynamics in river and floodplain systems. This would improve the ability to predict how flows will influence food webs.
- An understanding of the importance of prior events and the nature of trophic dynamic responses to different flow events would allow us to provide more robust models and tools and increase the applicability of results to more rivers.
- Identification of the spatial scales at which trophic dynamics operate in response to hydrology would allow greater generalisation of results.
- Improved understanding of how to optimise the nutritional quality of basal resources (synthesis of essential fatty acids) including timing, frequency and duration of watering to best support biodiversity in rivers would allow specific recommendations to be made around specific management scenarios.

## 4 Vegetation theme

### 4.1 Vegetation theme research focus

The value of wetland and floodplain vegetation is reflected in the Basin-wide Environmental Watering Strategy which lists maintaining the extent and improving the condition of forests and woodlands, shrublands and non-woody vegetation as expected outcomes. The diversity of plants, vegetation communities and mosaics of communities in Murray-Darling Basin wetlands and floodplains is tremendous and take many forms, from floating ferns to ancient trees. Environmental water managers may seek to achieve a range of vegetation outcomes that reflect the diversity of functions and values supported by wetland and floodplain vegetation.

The overarching research question for the Vegetation Theme was: What are the drivers of sustainable populations and diverse communities of water-dependent vegetation?

This high-level aim was applied to two priority research topics:

- 1 **Diversity** of non-woody (understory and wetland) plants
- 2 **Recruitment** of long-lived woody vegetation [river red gum (*Eucalyptus camaldulensis* Dehnh.), black box (*Eucalyptus largiflorens* F.Muell.), coolibah (*Eucalyptus coolabah* Blakely & Jacobs) and lignum (*Duma florulenta* Meissner)]

### 4.2 Vegetation theme key findings

The vegetation theme asked the question ‘How do we define vegetation response objectives to consider multiple trait responses, ecological levels of organisation, functions and values and spatio-temporal scales?’ This was answered by providing a framework to support water managers to identify i) more explicit vegetation management objectives that are linked to values; ii) relevant response attributes / traits to inform the selection of appropriate indicators to monitor; iii) expected time frames for measurable responses of relevant attributes / traits to inform target setting; and iv) appropriate spatial scale for measuring response. Clearly defining the objective helps guide the design of flow regimes to meet these objectives, developing monitoring / research programs to detect relevant responses and in evaluating the outcomes of the delivery of environmental water. (Vegetation theme 2.1).

Synthesis and data integration exercises were undertaken to ask 1) What drives vegetation responses to watering actions (focussing on non-woody vegetation, flow regimes and climate). 2) How can we learn more from existing data? A wetland response model was created that considered how several hydrological indicators (e.g. water depth, time since last flooding, proportion of time wet) influence vegetation richness and abundance. Variability in vegetation responses to the same watering actions were predicted to arise as a result of differences in location, recent flow conditions (e.g. water depth, time-since-last inundation, proportion time wet), vegetation structure, and medium to long term flow regimes (Vegetation 2.2).

Field assessments and germination trials asked, ‘What drives vegetation responses to watering actions?’ This study assessed the influence of regional location, flood-return-frequency and woody vegetation structure on existing and soil seed bank vegetation assemblages, lignum structure and woody seedling recruitment. This component found that there is a huge diversity in vegetation outcomes in space and time and this diversity comes from differences in location, recent flow conditions, vegetation structure and medium to long term flow regimes. In addition, this study found that watering lignum annually, or 1 in every 1.5 – 3 years assists in greatest clump size (Vegetation 2.3).

A seedling mesocosm experiment helped improve knowledge about seedling establishment. Specifically, this research sought to improve the understanding of flow requirements for seedling establishment, including an understanding of whether responses varied with seedling age. This component found that Eucalypt tree seedlings have a range of strategies to respond to watering actions: constant inundation suppresses seedling growth but not mortality; dry periods are important to allow seedling roots to establish and; some species are sensitive to floods relative to their age (Vegetation 2.4).

### **4.3 Vegetation theme synthesis**

The framework created for water managers provides information to support the development of objectives and expected outcomes and to evaluate success. The framework aids managers by guiding them to consider a range of potential influences on their desired outcome (e.g. richness, seed viability). This work has shown there is incredible variation in local plant communities and seed banks in space and time even though many wetland and floodplain species have wide distributions and are rarely considered endemic.

Location is overwhelmingly the most important predictor of local community composition, followed by recent flow conditions (e.g. preceding three months) in terms of determining community responses. After location and recent flow, the story becomes more complicated and interactions between factors play a role. For example, if a wetland has been dry over the medium term, around 3-10 years, then vegetation structure appears to be a key predictor of wetland community. In contrast, if a wetland has been wet over the medium term, around 3-10 years, then the medium to long term flow regime becomes a key predictor of wetland community.

Seedling establishment is a vulnerable stage for floodplain trees and understanding their specific watering requirements is important for the long-term survival of the species. The three eucalypt species studied displayed different growth strategies in response to the watering treatments. Understanding the likely mechanisms behind these strategies enables better predictions of outcomes and more targeted watering regimes.

Data was collected around the structural condition of lignum. There is a strong association between lignum clump size and flood inundation category, with lignum clump size (volume) greatest in the most frequently inundated categories.

### **4.4 Vegetation theme information for managers**

The water management framework developed by the vegetation theme guides how environmental watering events might be undertaken for vegetation outcomes. Using this framework helps predict responses to environmental watering events and can be used to help plan or prioritise watering actions (Vegetation 2.1.2).

Analysis of existing data identified that the abundance of non-woody vegetation was maximised when areas were dry for approximately 50% of the time; supporting the idea that regimes of wetting and drying are needed to support semi-arid wetland ecosystems (Vegetation 2.2.2).

Maintaining lignum with structural qualities to support processes such as waterbird breeding and fledging is likely to require flow regime characteristics, including flood-return-frequency in the range of 1 flow in every 1 – 3 years (Vegetation 2.3.2).

While constant flooding suppressed seedling growth the seedlings of black box and coolibah are flood tolerant. If managing for seedling recruitment it is important to allow for a dry period of approximately 6 months after germination. This allows roots to establish which are necessary for seedling establishment (Vegetation 2.4.2).

## 4.5 Vegetation theme knowledge status

The water management framework developed by the vegetation theme provides a framework and guiding principles to aid the development of objectives, indicators and management of water for vegetation outcomes. To improve the usefulness of this framework it would be useful to workshop this framework between scientists and managers, expand the framework to include different spatial and temporal scales and the development of decision support tools.

The vegetation theme also developed a vegetation response model to assess the main drivers of plant species richness and abundance. This model has been developed in semi-arid systems and would benefit from testing in different environments to improve its applicability across the Basin. Including additional environmental metrics such as soil type, soil moisture and canopy condition would also improve understanding of wetland dynamics.

Field and laboratory components highlighted the overwhelming influence of location on vegetation community composition. However, the inclusion of additional metrics in analysis (especially tree data) would allow structural characteristics to be explored. This would improve understanding of the drivers of community composition beyond where things occur.

The seedling mesocosm component investigated the trait and strategy responses of river red gum, black box and coolibah to different watering treatments. Valuable extensions to this work would include assessing the influence of non-flow drivers such as salinity (soil and groundwater), soil type, soil compaction and grazing.

The vegetation theme found that lignum benefitted from watering regimes of yearly, to every three years. Further analysis of lignum structural responses with better hydrology metrics, such as depth and duration, will aid refinement of the characteristics required to improve lignum condition.

The vegetation theme focussed primarily on non-woody vegetation and seedlings. Tree recruitment and population dynamics remain poorly understood. Similar projects addressing flow impacts on tree ecology would be a fruitful area for research (Vegetation 5).

## 5 Waterbirds theme

### 5.1 Waterbirds theme research focus

Environmental watering events in the Basin are frequently targeted at supporting completion of waterbird breeding. While knowledge exists regarding key breeding locations and the flows required to trigger and complete nesting events, there is relatively limited knowledge about nest success, bird movements, demographics (including juvenile and adult mortality rates) and associated drivers – particularly in terms of the relative influence of flow variables, habitat variables, pressures and threats. These knowledge gaps exist even for common and conspicuous taxa such as colonially-nesting waterbirds that are often thought to be relatively well-understood. Knowledge gaps are particularly severe for cryptic and uncommon species.

The two main research activities relate to these gaps and focus on colonial-breeding waterbirds.

*Critical Knowledge Gap 1: Where and what are the critical foraging habitats during and after breeding events for recruitment? How might these be affected by environmental flows and threats such as habitat change?*

*Critical Knowledge Gap 2: What are the critical nesting habitat characteristics we need to maintain and how do these affect recruitment? How might environmental flows, vegetation management and pressures and threats, such as predation, interact with nesting habitat characteristics to affect recruitment?*

### 5.2 Waterbirds theme key findings

A review of existing literature was conducted in order to inform development of other research questions within the waterbird theme. Firstly, there was a review of known and unknown waterbird responses to flows and flooding in Australia. Secondly a review of international literature looked at how waterbirds respond to other stressors such as predation and disease. This process uncovered that flow regimes affect waterbirds (location, frequency, volume, timing, duration) and that flooding regimes were also important (location, frequency, extent, duration, timing, depth, rate of change in depth, dry period). These interact with stressors such as habitat loss, fragmentation and degradation, predation, competition, diseases and parasites, pollution, human disturbance and climate change (Waterbird 2.1).

One of the largest knowledge gaps identified was waterbird movements and their drivers, including: timing; distances travelled; differences between juveniles and adults; key foraging habitat locations and characteristics; effects of habitat availability; quality and productivity on site choice, bird condition and survival; site fidelity; mechanisms, cues or drivers inducing movements and choices and how these interact. Satellite tracking of 42 Straw-necked Ibis (*Threskiornis spinicollis*), 15 Royal Spoonbill (*Platalea regia*), and seven Australian White Ibis (*Threskiornis molucca*) revealed that there is a common long-distance route for different individuals and species of waterbirds. Foraging habitat during nesting is within 1-4 km of nests for Royal Spoonbills and from 6-44km for Straw-necked Ibis. The main causes of mortality of tracked birds was exposure to weather extremes and predation by native and introduced predators (Waterbirds 2.2).

Non-breeding Straw-necked Ibis forage in agricultural lands while White Ibis forage in aquatic habitats. There was a consistent difference between movements of non-breeding Straw-necked Ibis and Australian White Ibis. Straw-necked Ibis dispersed further on average from the capture site, and in all directions post-release, while Australian White Ibis primarily dispersed north and south. The movement of Ibis to foraging sites can assist in our understanding of what habitats, other than wetlands, are important for Ibis in the landscape (Waterbirds 2.3).

Ibis and Spoonbill eggs and chicks were monitored using cameras. Rapid reductions in flooding and water depth triggered nest abandonment and reduced the proportion of successful nests. The greatest source of mortality was egg predation, primarily by raptors. When water levels were low mammalian predators also had access to nests (Waterbirds 2.4).

A field study asked: what is the variability in annual breeding responses and success by colonial waterbirds at Reed Beds in relation to water depths? Analysis found that relationships between water depths and reproductive success were strongest for Straw-necked Ibis. Offspring success of Straw-necked Ibis was significantly lower than that of Australian White Ibis, with greatest loss occurring at young chick and egg stages. Straw-necked Ibis responded later to flow thresholds triggering breeding, nesting later than Australian White Ibis (Waterbirds 2.5).

A field study explored the relationship between river flow volumes and the breeding responses of Ibis in the Barmah-Millewa forest. This study found that flow requirements for colonial waterbird breeding has a positive linear relationship between the two flow thresholds for breeding, total volume July-December >2,300,000 ML and >30 consecutive days >15,000 ML day. Australian White Ibis and Straw-necked Ibis bred on average 7 out of 10 years, coinciding with periods of high flow in the River Murray (Waterbirds 2.6).

Drone imagery was used to map Ibis and Spoonbill nests and colonies. This allowed for accurate counting of nests that are not accessible during ground-based measurements. It also provided very accurate vegetation maps to be created for the area studied. Visual analysis of nest distribution shows that nests are frequently located near areas of open water (Waterbirds 2.7).

Another study examined waterbird chick diet to explore differences between the two Ibis species and the age of chicks. The composition of chick scats suggested a preference of terrestrial invertebrates as prey by Straw-necked Ibis, and aquatic invertebrates by Australian White Ibis. There were no significant patterns in chick age (stage) and prey items consumed (Waterbirds 2.8).

Ibis and Spoonbill regurgitates from adults were examined in a field-based study. Royal Spoonbills fed predominately on fish and yabbys (71% and 15% of total diet respectively). In contrast straw-necked Ibis fed primarily on beetles (49%), centipedes (11%) and other indeterminate insects (11%) (Waterbirds 2.9).

Ibis and Spoonbill chick energy requirements were analysed in a literature review and new measurements and analysis from samples taken in the field. Using prey energy values from the literature, extrapolations indicate that for either species, a nesting event of 1000 nests producing three chicks per nest would require an estimated ten tonnes of freshwater crayfish (*Cherax destructor*) or eight tonnes of small fish to support chicks from hatching to independence (Waterbirds 2.10)

### 5.3 Waterbirds theme synthesis

Ibis juveniles leave nesting areas over summer while Royal Spoonbills remain at nesting sites into autumn. Tracking showed that Spoonbills forage for extended periods of weeks to months in and around the nesting site – particularly juveniles who have just left the nest. In contrast, Straw-necked Ibis and Australian White Ibis typically left the nest site not long after starting to fly. Movement of adults and juveniles of all species tracked is highly variable with some individuals moving 100's of kilometres and others staying in one or two areas (Waterbird 3.1).

Nesting takes place in reeds (*Phragmites australis*), and lignum (*Duma florulenta*) for Ibis species. Royal Spoonbills nest in giant rush (*Juncus ingens*) but may also use lignum or trees. Common features of nesting sites include surface water surrounding or under nesting vegetation, structures that can support the weight of multiple birds and nests and patchy water and vegetation mosaic around nesting sites (Waterbirds 3.2).

Exposure to extreme weather and predation are the primary drivers of mortality in juvenile and adult waterbirds. Nests that are well protected by vegetation exhibited reduced mortality. Declines in populations suggest that there is poor recruitment of juveniles into the adult population. Preliminary analyses indicate that associations between weather extremes and mortality or missing status are strongest where there is a shift from heat to cold and windy conditions within two days. Such conditions are likely to affect bird thermoregulation and can result in immune system depression and increased susceptibility to diseases, toxins and parasites. Juveniles are more susceptible than adults to these pressures, at least in part because they are naïve, are still learning to feed themselves and find shelter, use a lot of energy on first leaving the nesting area, and require high-quality food (Waterbirds 3.3).

An enormous amount of energy is required to support waterbird chicks from hatching to the juvenile stage, therefore the nesting habitat needs to be managed to encourage the growth of food resources. Using Ibis and Spoonbill chick biometrics, growth curves and energy models, the total energy estimated to raise a single Royal Spoonbill chick from hatching to independence was 71,290 kJ and for an Australian White Ibis chick was 67,160 kJ (Waterbirds 3.4).

## **5.4 Waterbird theme information for managers**

Satellite tracking of waterbird movements has emphasised the need for Basin scale thinking and coordination in planning environmental watering and in managing expectations regarding responses. There is clearly population connectivity between the northern Basin and the southern Basin – and birds can move very quickly from north to south and vice versa. Planning and response predictions may need to account for varying population movement strategies such as nomadism, residency and possibly migration – and also for differences between species.

The discovery of a common movement route between the northern and southern Basin suggests that for maximum impact, water and site management for foraging and stopover (refuelling) could be embedded within this route. However individual sites differ in importance among years and species and we don't yet fully understand this variation. Additional tracking of species dependent on surface water to feed will provide further information about key sites and movement routes that can be managed with environmental water.

Foraging habitat availability needs management both during and between breeding events. For example, tracking suggests that Ibis and Spoonbills target watered foraging sites within 1-3 km of appropriate roosting or nesting habitat. Environmental water could be used to increase the number or area of foraging sites within 10 km of nest sites after breeding, potentially extending watering for foraging into autumn and winter and possibly staggering inundation of foraging sites to maximise food productivity over a period of months to support juvenile survival.

At nesting sites used by Royal Spoonbills, satellite tracking has revealed the importance of extended duration of water availability for foraging by juveniles. Use of environmental water to extend nest and adjacent site flood duration during and after nesting beyond just the 'fledging' time threshold may facilitate increased juvenile survival. It is important to recognise that species such as Spoonbills feeding in surface waters require different foraging-habitat provision and management to species with mixed terrestrial and aquatic diets such as Ibis.

Management of over-wintering sites and foraging habitats may also be important for juvenile survival. Tracking indicates that over winter, even small habitat areas may be important, and there may be some site fidelity for such sites. Overwintering occurs in both the north and south of the Basin, yielding a range of opportunities for supporting juveniles and sub-adults using environmental water to create or sustain foraging habitats and food sources. This may be particularly important in areas where water sources effectively 'dry up' over winter. This highlights the need for real time data on genuine habitat condition and availability (Vegetation 2.2.3).

The movement of Ibis to foraging sites can assist in our understanding of what habitats are important for Ibis in the landscape. For example, Straw-necked Ibis utilised agricultural lands as a foraging sites, while the more aquatic habitats were used by Australian White Ibis. This knowledge has implications for water and wetland managers. For Straw-necked Ibis, which forage in agricultural lands, which are frequently beyond the management scope for water and wetland managers, it highlights the life history stage for which water management is most important in supporting Straw-necked Ibis. Due to the specific water requirements that Straw-necked Ibis need for successful breeding, it is during this life history stage that water management is most critical. For Australian White Ibis, the water requirements for breeding appear to be less stringent than those for Straw-necked Ibis, however the provision of aquatic habitat for foraging is also important in supporting breeding events (Waterbird 2.3.3).

Water management actions to support survival of eggs and chicks include provision and maintenance of water within breeding habitats. It is well known that rapid or early declines in water levels can trigger nest abandonment. Abandonment is more likely during the egg stage than the chick stage, however it is still important to maintain water levels late in the breeding season, for two primary reasons: 1) Maintaining food and foraging habitat availability; and 2) Preventing feral predator access. In addition to provision of environmental water for breeding sites, provision of water to support nearby foraging sites and food before, during and after a breeding event is likely to affect the size and success of the event (Waterbird 2.4.3).

The dietary differences between Straw-necked Ibis (terrestrial feeders) and Australian White Ibis (more aquatic feeders) illustrate niche partitioning between two closely related species to avoid interspecific competition. The implications for water management include:

- Recognising that waterbird species differ in their dietary requirements,
- Different diets are sourced from different foraging habitats,
- Ensuring that a mosaic of habitats is available for foraging,
- Not all waterbirds forage in wetland areas, managing these terrestrial foraging sites is often beyond the remit of the water manager (Waterbirds 2.8.3).

Management can be tailored to support the specific dietary requirements of different waterbird species. For example, if Royal Spoonbills are known to breed in a particular location, watering should be targeted to maximise the abundance of aquatic food resources, such as small fish, yabbies and prawns. If, however, a location is known to support primarily Straw-necked Ibis colonial breeding, environmental water might be better used to promote diverse floodplain, riparian and terrestrial foraging habitats that support a diverse array of vertebrate and invertebrate prey (Waterbird 2.9.3).

Both nesting and foraging habitats must be carefully managed during and after breeding to optimise energy source availability and quality. However, at present we have limited knowledge regarding the biomass or availability of appropriate food sources for waterbirds, spatially or temporally, or how these are affected by environmental flows and other pressures. The primary food sources for which this information is needed include: small fish (including juvenile large fish) such as smelt, gudgeons, carp, goldfish, gambusia, redfin; frogs and tadpoles; crustaceans such as yabbies, crayfish, crabs, shrimp, prawns, amphipods, isopods; molluscs such as shellfish, bivalves and snails; aquatic invertebrates such as dragonfly nymphs, bugs, beetles; and terrestrial invertebrates such as spiders, locusts, crickets, beetles, caterpillars, grubs, centipedes and earthworms).

If we can quantify prey energy value and availability, this information could be used together with chick energy requirements and food web information to develop landscape scale management targets to ensure that food requirements are met to support chicks until they attain independence (Waterbirds 2.10.3).

## 5.5. Waterbird theme knowledge status

The waterbirds theme uncovered knowledge about the drivers of mortality for chicks and eggs, however there is still limited knowledge about these drivers for juveniles and adults. Given ongoing population reductions in colonial waterbird populations, in spite of flows targeted to improve breeding outcomes, it is important to address all sources of mortality and this needs further study.

These studies have identified important information about waterbird diet and energy needs however we are still unsure how much food is available in a wetland, and which flows best support the provision of these resources. The current study could also be expanded to other waterbird species and populations that are declining to improve understanding.

This research has showed that there is a consistent north-south route being used by colonial waterbirds. Future research should focus on identifying critical foraging, roosting and stopover sites. In addition, more information about what stimulates movement and the relationship to other factors such as flooding, weather and food availability will allow identification of critical habitats for protection (Waterbirds 5).

## 6 Synthesis Between Themes

This report has pulled together information from all four themes with learnings that can be applied across the Basin. This section brings together information that is highlighted by the theme reports and is consistent across themes. The six ideas below are a synthesis of the main findings of EWKR.

### 6.1 The importance of floodplain inundation

There is overwhelming support for the importance of regular floodplain inundation. In-channel flows do not provide the breadth of energy that can be generated from more productive habitats such as anabranches and wetlands. Green algae that grow in floodplain wetlands are crucial in providing essential fatty acids that are transferred through the food web to invertebrates, fish and waterbirds. It is these highly productive regions that support larval fish and juvenile waterbird recruitment. Floodplain inundation needs to happen multiple times, connecting and reconnecting habitats to allow consumers to take advantage of resources and to move important energy stocks from the floodplain into the river channel.

The timing, duration and frequency of floodplain inundation is also important in maintaining floodplain vegetation health and diversity. Inundation provides an important trigger for germination for many species, while dry periods are needed for seedling establishment. The frequency and duration of such flooding will also change the types of vegetation in a community, for example frequent flooding will promote the growth of lignum, while less frequent flooding promotes the establishment of woody vegetation.

The frequency and duration of floodplain inundation needs to be carefully considered from a management perspective. Retaining water on the floodplain for relatively long periods (weeks to months) may be needed to support waterbird and fish recruitment but may come at a cost in terms of seedling establishment. Longer-inundation cycles must also be managed while considering the risks of blackwater events. For example, ponding of water on floodplains, with no additional mixing may in some cases be risky. Currently there are local projects quantifying floodplain leaf litter loads to better understand these risks and how they vary spatially and from year to year.

### 6.2 Processes within rivers happen at many scales

Rivers can be divided into multiple scales: patch, site, reach, segment, catchment and Basin (see Figure 2 in the Fish Theme report for more detail). Processes that affect the biodiversity in the river happen at each of those scales and interact to influence where and when organisms will be found. Management across these scales is complex. From patch to reach the retention of nutrients in regions with higher hydraulic complexity and water residence time can make those regions more likely to have higher production of algae, zooplankton and hence fish and birds. Vegetation may help provide retentive zones on the floodplain and high concentrations of waterbirds in the vegetation may focus even more nutrients in small areas. However, the movement of adult fish, waterbirds and vegetation propagules (e.g. seeds) is more likely to be operating at a catchment scale (e.g. Murray Cod) or a Basin scale (e.g. Golden Perch and waterbirds). The consequence of this is that processes such as recruitment and movement need to be managed at multiple scales. Colonial waterbirds that nest together in high densities at sometimes, may, outside of breeding times, move 1000's of kilometres to forage and disperse widely to different habitats. Therefore, breeding and non-breeding management operates at different scales. Importantly, both may impact on long-term population dynamics of such species.

### **6.3 Connectivity is a crucial component**

We know the importance of connecting the main river channel to the floodplain, wetlands and anabranches. However, connectivity has other important implications throughout the Basin. In the Northern Basin, waterways often shrink to a series of disconnected waterholes and only re-join when there is sufficient flow. Providing enough water to allow this connectivity is crucial in ensuring the movement of nutrients, larvae, seeds, adults and juveniles of a range of species. In one waterhole a species may go seasonally extinct and without connection to other populations will not recover. Disjunct populations can also experience low genetic diversity, and so in general maintaining dispersal patterns, which may be linked to flow, is critical.

How often connections need to be made remains a critical knowledge gap and will vary through time as a result of antecedent events. For example, following disturbance events such as fish kills (e.g. those associated with extreme events such as heatwaves and blackwater events), it may be more important to provide connection events to allow animals (and sometimes plants) to recolonise. Conversely, the ability to move between habitats during extreme events, to avoid adverse conditions is an important component of connectivity that has in some instances been lost from the Basin.

### **6.4 Habitat can be improved through flow management**

Retentiveness, or the ability to trap particles (including seeds, eggs and larvae) being transported in the water column, is an important property of rivers. Maintaining structural complexity within a river channel (e.g. by maintaining channel meanders, or with the addition of snags, benches, and other in-channel features) increases retention. Managers can add or remove such structures or influence their formation by varying flow.

Retentiveness also varies considerably between river reaches and with flow. The relationship between flow and retention is complex, and more work is required to provide guiding principles regarding managing flows to increase retention.

Cold water pollution can significantly reduce the growth of algae, zooplankton and larval fish. This could also reduce the prey availability for juvenile waterbirds. Care needs to be taken that large cold-water releases happen outside of peak breeding periods to ensure the health of species.

### **6.5 There is no one water management recipe for all species**

Across all themes there were species specific responses to changes in flow regimes, temperature, timing of events, scales and a host of other factors. In unregulated rivers, natural cycles of 'boom and bust' would ensure that conditions are right for recruitment, movement etc. at some point in time. Australia's biota has evolved to ensure that different species are ready to take advantage of different events. In regulated systems we need to recreate this diversity of conditions. We need fast and slow water velocity, large floods and dry periods, connections at multiple scales and a range of wetting and drying regimes to ensure that we recreate all the niches that species have evolved to exploit. Regularly doing the same thing, be it low or high flow, single flood events or regular connections will homogenise a system so that it becomes reflective of those specific actions. Diversity is maintained and enhanced when we change management regularly.

### **6.6 There are significant opportunities created by projects such as EWKR**

There are few projects that provide opportunities for collaboration and knowledge exchange such as EWKR. Scientists working in specific knowledge domains such as vegetation science are rarely part of teams that provide access to complimentary knowledge practitioners such as hydrologists. Bringing multi-disciplinary groups together often sparks innovation that provides insights that transcend any

one domain. Additionally, bringing together scientists and water managers creates a new dialogue where each group better understands the messages and needs of the other.

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# Appendix 1: Research Site Report

## 1. Sites

The Research Site report brings together an overview of the research that was conducted at broad scale sites within the Environmental Water Knowledge and Research (EWKR) program and provides a platform for future Murray-Darling Basin research to build on rather than duplicate.

### 1.1. Site Choice Rationales

The EWKR project sought to identify four broad scale sites that were to be the focus of field-based research activities, the research sites needed to span the Basin. Ideally, with at least one northern, one central and one southern. The broad scale sites were the basis for field-based studies, but the project did also undertake laboratory experiments and data analysis activities that were not defined by the boundaries of the four sites.

The selection criteria outlined below was used to support the evaluation of potential research sites for EWKR. Broad scale sites were evaluated qualitatively but ultimately the choice of these sites required subjective judgement to weigh up the relative significance of the criteria.

### 1.2. Identification of candidate sites

The process of identifying research sites began with the identification of candidate sites. These are sites of a sufficient size and with some available baseline and inventory knowledge that would support research, and that are likely to receive environmental flows under the Basin Plan. It should be noted that the site names are used in a general sense, that each of the sites would include the full spectrum of adjacent riverine, wetland and floodplain components (e.g. Barmah–Millewa Forest would include the associated reaches of the River Murray and Edward River system), and that the exact boundary of the sites will be determined based on requirements to facilitate research.

#### Potential candidate sites for EWKR

1. Barmah–Millewa Forest
2. Booligal Wetlands
3. Lower Campaspe River
4. Edward–Wakool River system
5. Great Cumbung Swamp
6. Gunbower–Koondrook–Perricoota Forest
7. Gwydir wetlands
8. Hattah Lakes
9. Lachlan Swamp
10. Lindsay, Mulcra and Wallpolla islands
11. Lower Loddon River
12. Lower Balonne floodplain
13. Lower Darling River
14. Lower Goulburn River
15. Lower Murray (including Riverland Ramsar site and Chowilla)
16. Lower Murrumbidgee River and associated wetlands
17. Macquarie Marshes
18. Mid Murrumbidgee wetlands
19. Narran Lakes
20. Nimmie–Caira system
21. Warrego–Darling junction
22. Wimmera terminal wetlands

The following sites were also considered but not included as potential candidate sites for the reasons identified:

- Banrock Station wetland — Ramsar listed but small in size and therefore does not cover the full spectrum of riverine and floodplain components. Potential for inclusion as an extension to the Lower Murray site (if selected), but not considered a potential site in its own right.
- Ginini Flats — Ramsar listed, but as a sub-alpine bog it is not representative of priority environmental assets to receive water under the Basin Plan.
- Lower Ovens River — recognised for its high conservation values, but unlikely to receive significant environmental water under the Basin Plan. Potential for inclusion as an extension to the Barmah–Millewa Forest, but not considered a potential site in its own right.
- Paroo River and associated wetlands — Ramsar listed, but unlikely to receive environmental water under the Basin Plan.

### 1.3. Site selection criteria

The following criteria were used as the basis for evaluating the candidate sites and informing the selection of research sites for EWKR.

#### **Criterion 1: Recognised environmental significance, including in relation to the priority questions**

This criterion was to ensure that the selected research sites were recognised as having the environmental characteristics and values associated with the proposed research themes, and questions and that the research focusses on sites that are of significance to Basin governments and communities.

##### Indicators

1. Recognised values at the Basin scale
  - a. Vegetation — contains large areas (greater than approximately 5000 ha) of multiple vegetation types including wetland, lignum and tree communities
  - b. Fish — identified as an important Basin environmental asset for fish
  - c. Waterbirds — identified as an important Basin environmental asset for waterbirds (particularly, recruitment of colonial nesting waterbirds)
2. Formal recognition of significance
  - a. Ramsar listing
  - b. The Living Murray icon site
3. Other indicators
  - a. Likely achievement of criteria for identifying environmental assets (Schedule 8 of the Basin Plan) — using the assessments undertaken by the MDBA in developing the Basin Plan as a guide (noting this assessment and outcomes have no formal significance)

#### **Criterion 2: Existing data and knowledge to support the proposed research questions and activities**

This criterion recognised that EWKR project would achieve the best outcomes where there was a high level of existing data and knowledge available to support the proposed research questions and activities, rather than a 'greenfield' site where resources will need to be directed to collecting baseline knowledge and information. Historical monitoring data and baseline data will be useful in identifying current and historical characteristics of the site (e.g. does the site support a target species of plant, fish or bird).

##### Indicators

1. Inundation modelling and mapping — categorised according to the type of modelling or mapping available

2. Past monitoring and research activities — summary descriptions of available information under the themes of vegetation, fish and waterbirds
3. Sustainable Rivers Audit — fish sites
4. State monitoring program sites — Victorian Environmental Flows Monitoring and Assessment Program (VEFMAP), Index of Stream Condition (ISC), NSW Integrated Monitoring and Environmental Flows (IMEF)
5. Number of references identified in Google Scholar and Web of Science search engines — as general indicators of past research activities
6. Basin Plan hydrologic indicator sites

### **Criterion 3: Alignment with current and future monitoring programs**

Recognising that the EWKR project was likely to achieve better research outcomes where it was aligned to other relevant monitoring and research programs. There may also be efficiencies in the coordination of activities, reducing costs for one or multiple programs.

#### Indicators

1. Commonwealth Environmental Water Office (CEWO) Long Term Intervention Monitoring (LTIM) sites
2. MDBA Basin Plan fish and bird monitoring sites
3. Other — including state Basin Plan monitoring sites, where these are known

### **Criterion 4: Geographic spread of sites**

The objective of EWKR to provide knowledge that is transferable across the Basin (noting that there will be some limitations on the extent to which knowledge will be transferable from site to site) required a spread of sites across the Basin within different regions and bioregions. The objective for this was to identify if responses/drivers differ across the Basin, and the extent to which outcomes are representative and transferable.

#### Indicators

1. Basin region — south (Murray and southern tributaries), central (Murrumbidgee, Lachlan, Macquarie) or north (Darling and northern tributaries)

## **1.4. Selected sites**

The sites that were selected are listed below and shown in Figure 1, the exact boundaries of the research sites were fluid to the consideration of how best able to support the research and provide effective alignment with past and future monitoring and research activities. This means the scale of the sites are not truly defined – as the option to reduce or expand from the identified boundaries listed below was given to enhance research opportunities within the EWKR project.

### **Southern basin**

The Living Murray icon sites and adjacent river reaches evaluated strongly against the criteria used due to the size, recognised environmental significance and scale of past investment in data collection, monitoring and research.

The two sites selected in the southern basin were:

- the Mid Murray centred around Barmah–Millewa Forest and potentially including lower reaches of adjacent tributaries (Goulburn, Campaspe and Ovens) and parts of the Edward–Wakool system.
- the Lower Murray centred around the Chowilla–Lindsay–Wallpolla floodplain and potentially including the Riverland Ramsar site and adjacent floodplain systems and river reaches.

## Central basin

Within the central basin, the Macquarie Marshes evaluated most favourably against the stated criteria. The marshes are recognised as being internationally important under the Ramsar Convention because of their size, diversity of wetland types, extent of wetland communities and large-scale colonial waterbird breeding events.

The selected site for the central basin was:

- the Macquarie Marshes that is one of the largest semi-permanent freshwater wetlands in south-east Australia.

The Lower Murrumbidgee, including the Nimmie–Caira system, also evaluated highly. However, the Lower Murrumbidgee at the time did not have the same depth of historical research activity as the Macquarie Marshes. The more northern location of the Macquarie Marshes also provided a better geographic spread across the Basin.

## Northern basin

The Lower Balonne floodplain is identified as a research site for EWKR in the project funding agreement to facilitate delivery of the Queensland Floodplain Vegetation Water Requirements Project. Incorporating Narran Lakes given its recognised values in supporting waterbird breeding and recruitment, and available monitoring data and monitoring infrastructure.

The selected site for the northern basin was:

- the Lower Balonne floodplain including Narran Lakes.

## EWKR Research Site locations

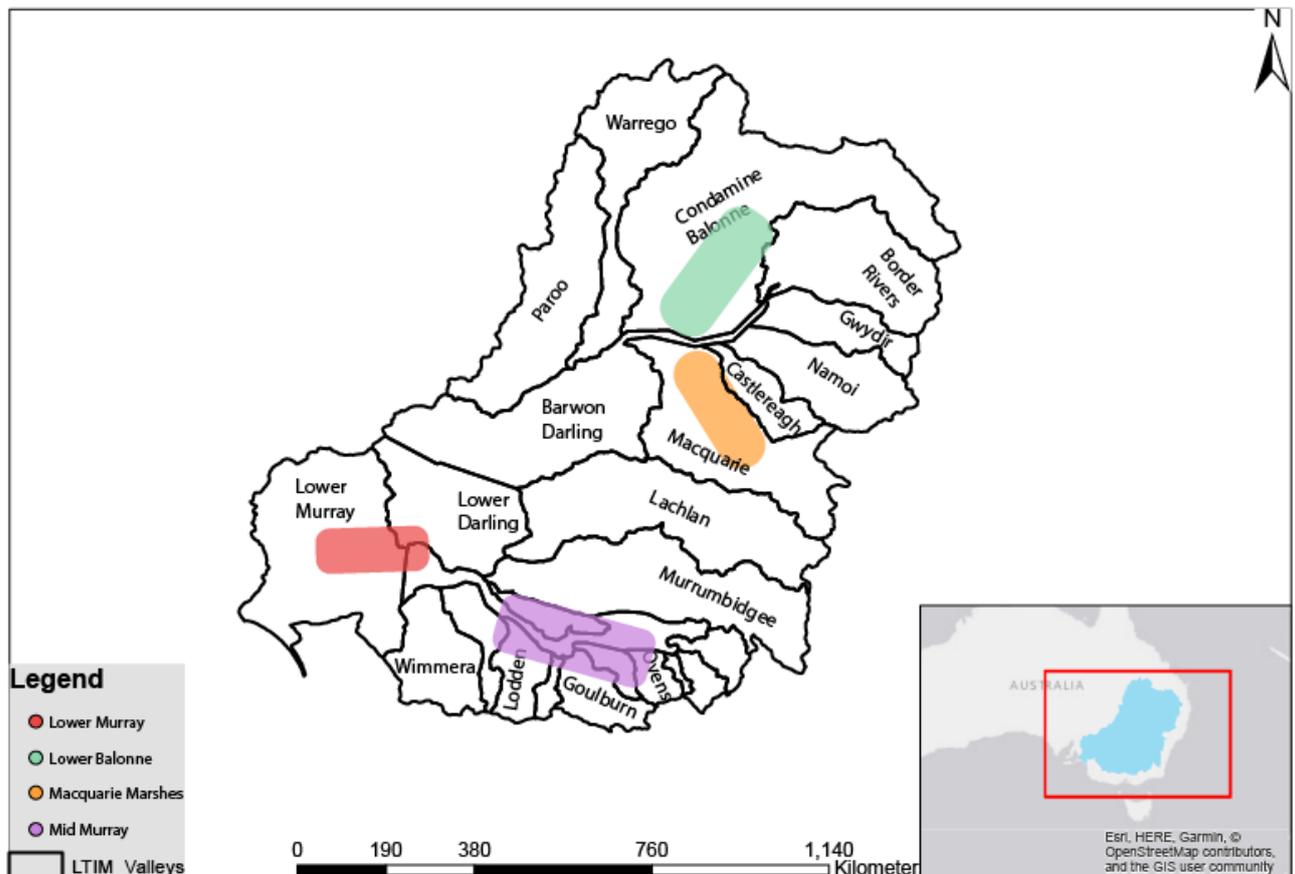


Figure 1. Overview of selected research site locations within the Murray–Darling Basin.

## 2. Site Descriptions

### 2.1. Mid-Murray Site

This site centred around the Barmah–Millewa Forest and included the lower reaches of the adjacent tributaries of the Goulburn, Campaspe and parts of the Edward–Wakool river systems. The research undertaken on the Ovens River is also included in this section as had been indicated as an option when candidate sites were identified.

The Barmah–Millewa Forest Icon Site supports the largest river red gum forest in Australia and is the largest and most intact freshwater floodplain system along the River Murray. The Victorian component of the Icon Site also supports the most extensive area of moira grass plains in the state, despite recent declines (MDBA 2012b).

Ecological communities within the Barmah–Millewa Icon Site have evolved to use a variable flooding regime, dictated by the combination of natural seasonal flows and the effect of the Barmah Choke.

The Barmah–Millewa Forest supports important species and habitats that are listed in international agreements such as Ramsar that includes vulnerable and endangered species (MDBA 2012a). At least 381 indigenous flora species and 221 indigenous vertebrate fauna species have been recorded in Barmah Forest including birds, fish and reptile (MDBA 2012b).

When flooded, Barmah–Millewa Forest provides important feeding and breeding habitat for thousands of waterbirds. About 54 species have been recorded breeding in the forest, including 25 colonial nesting species. Barmah Forest regularly supports 1% of the population of Australian white ibis (*Threskiornis molucca*) and straw-necked ibis (*T. spinicollis*) (MDBA 2012b).

The site also supports large numbers of migratory bird species, including 13 listed under international migratory bird treaties (China–Australia Migratory Bird Agreement, Japan–Australia Migratory Bird Agreement, and the Republic of Korea – Australia Migratory Bird Agreement) and 23 listed under the Bonn Convention on Migratory Species (MDBA 2012b).

### 2.2. Lower Murray site

The Lower Murray site is centred around the Chowilla–Lindsay–Wallpolla floodplain and includes the Riverland Ramsar site and adjacent floodplain systems and river reaches, such as Hattah Lakes.

The Lower River Murray extends from the junction of the Murray and Darling Rivers in Victoria downstream to the Lower Lakes in South Australia. The site comprises of four floodplain areas: the Chowilla Floodplain and Lindsay–Mulcra–Wallpolla Islands.

The Lower River Murray channel and the island anabranch environments support significant populations of native fish. In particular, these areas provide valuable habitat for Murray cod (*Maccullochella peelii peelii*), providing important habitat for a wide range of size-classes (Zampatti et al. 2008; Newall et al. 2009; Zampatti et al. 2011). This attribute is considered to be somewhat rare since regulation of the River Murray and is largely restricted to the Lower River Murray and other Ramsar sites.

The Chowilla Floodplain and Lindsay–Mulcra–Wallpolla Islands are dominated by river red gum woodland, lignum shrublands, black box woodlands and grasslands. A total of 28 threatened wetland plant species have been reported on Lindsay Island (SKM 2003; MDBA 2012d).

The Chowilla Floodplain and Lindsay–Mulcra–Wallpolla Islands provide critical habitat for both nomadic and migratory waterbirds during times of drought in central and eastern Australia. This includes ‘stop-over’ habitat for a number of migratory bird species listed under the Japan–Australia, China–Australia and Republic of Korea–Australia migratory bird agreements (Newall et al. 2009; Chowilla EWR 2012). Forty-nine species of birds, dependent upon water habitats, are known to use the Lindsay–Mulcra–Wallpolla floodplains for breeding, feeding and roosting. Of these, 40 are considered threatened in Victoria; 24 are listed under the *Flora and Fauna Guarantee Act 1988* (Vic.) and three are listed under the *Environment Protection and Biodiversity Conservation Act 1999* (Cwlth) (Ecological Associates 2007; MDBA 2012c).

## 2.3. Macquarie Marshes site

The Macquarie Marshes are a representative example of an inland floodplain wetland relying on water from a higher rainfall upper catchment and having extensive and changeable wetlands in the semi-arid lowland reaches. They are unique in terms of both their size (approximately 200,000 ha) and their diversity of wetland types. The Macquarie Marshes contain a variety of habitats including aquatic, riparian, floodplain and woodland, including Ramsar-listed wetlands and a diversity of ecologically valuable species. Any change to the process of water distribution to the Marshes will inevitably mean changes for the wetlands receiving that flow.

The Macquarie Marshes is located in the area covered by the endangered ecological community listed under the NSW *Fisheries Management Act 1994* as the 'aquatic ecological community in the natural drainage system of the lowland catchment of the Darling River'. This community covers all native fish and aquatic invertebrates and the natural rivers, creeks, lagoons, billabongs, wetlands, lakes, tributaries, anabranches and effluents in which they live. Densities of microinvertebrates in recently inundated floodplain habitats are amongst the highest recorded in the world (Jenkins and Wolfenden 2006).

Vegetation includes extensive areas of common reed, water couch, stands of cumbungi, river red gum forests and woodlands, lignum and river cooba shrubland that all provide critical habitat for waterbirds and other wetland animals in the Marshes (NSW Department of Environment, Climate Change and Water 2010).

The Macquarie Marshes are one of the more important wetlands in Australia for breeding of colonial nesting waterbirds (Kingsford and Auld 2005). Seventy-six waterbird species have been recorded in the Marshes, 42 of which have been recorded breeding. This includes species that are listed as threatened in New South Wales and nationally, as well as the only recorded pied heron (*Ardea picata*) breeding in New South Wales (NSW Department of Environment, Climate Change and Water 2010).

The Macquarie Marshes have long been regarded as an important refuge for waterbirds during dry times, as well as supporting some of Australia's largest recorded waterbird breeding colonies (Macquarie Marshes Investigation Committee 1951; Marchant and Higgins 1990; Kingsford and Johnson 1998; Kingsford and Auld 2005).

## 2.4. Lower Balonne floodplain including Narran Lakes site

The Lower Balonne Floodplain forms the most southerly portion of the Condamine Balonne catchment ranging from St George to the Queensland Border. It is essentially a large floodplain wetland complex (Thoms et al. 2002). It supports the largest number of wetlands greater than five hectares in size within the Murray Darling Basin.

Narran Lake Nature Reserve forms part of the Condamine Balonne catchment in the central north of NSW, between Brewarrina and Walgett. It is comprised of Narran Lake and the Northern Lakes: Clear Lake, Back Lake, Long Arm and the interconnecting channels and lignum floodplains (Merret et al. 2009). Significantly it provides waterbird habitat and refuge for species of conservation concern. The lakes are surrounded by extensive expanses of channelised wetlands. Surrounding the wetlands are extensive and dense stands of lignum and less extensive stands of river red gum.

Flooding frequency defines and structures ecosystem types in the Lower Balonne Floodplain with types ranging from river red gum, coolabah and lignum communities in the high flood frequency regions to open grasslands in the less flooded regions (Sims and Thoms 2002; Sims 2004).

# 3. Relationship between sites and questions

Not all priority research questions and topics were to be explored at the four sites. For some topics, the proposed research approach is one of laboratory experiments and/or data analysis activities that are not defined by the boundaries of the four sites. For the other topics, some sites may not contain the necessary environmental characteristics to support the research and/or may not have the necessary existing

information to enable the proposed research. In addition, there is the issue of getting value for money and the potential value of focussing on a number of sites, rather than spreading resources thinly across all four sites.

Table 1 shows the sites and priority research topics where fieldwork was undertaken during the EWKR project.

All fieldwork sites conducted as part of the EWKR project, irrespective of whether they occurred in the four broad-scale sites, are shown in the following Basin-scale maps (Figure 1 and Figure 2). A list of sites corresponding to these maps is provided in Appendix 1.

Table 1. Sites and priority topics for fieldwork undertaken during the EWKR project.

		EWKR fieldwork sites			
		Mid Murray	Lower Murray	Macquarie Marshes	Lower Balonne, including Narran Lakes
Vegetation	Diversity (understorey)	✓	✓	✓	✓
	Survival/condition (trees, lignum) <sup>1</sup>	✓	✓	✓	✓
	Reproduction (trees, lignum)	✓	✓	✓	✓
	Recruitment <sup>1</sup> (trees, lignum)	✓	✓	✓	✓
Native fish	Survival/condition				✓
	Reproduction				✓
	Recruitment	✓	✓	✓	✓
Waterbirds	Survival/condition	✓		✓	
	Reproduction	✓			
	Recruitment	✓		✓	
Food webs	Basal resources	✓			
	Trophic niche	✓	✓		
	Modelling	✓	✓	✓	✓

<sup>1</sup>Lower Balonne on trees and lignum; Lower Murray, Macquarie Marshes & Narran Lakes had lignum assessed; lignum communities not relevant to the Mid Murray

## EWKR Field sampling sites

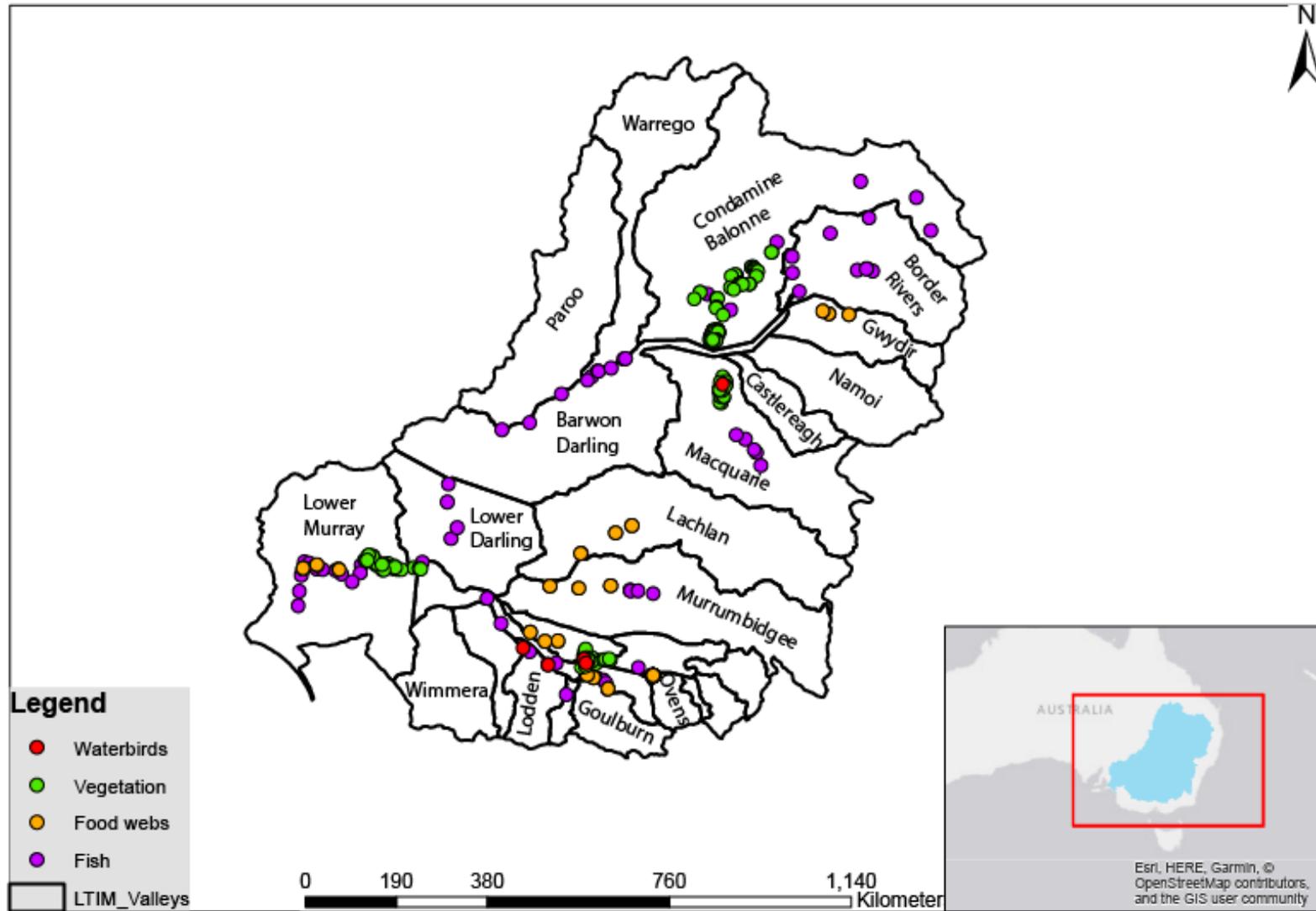


Figure 2. Field sampling sites undertaken from across the EWKR project defined by LTIM valleys.

# 4. Summary of Research Activities

## 4.1. Mid-Murray Site research activity

Fieldwork undertaken in the Mid-Murray was predominantly in the Barmah–Millewa Forest but also included Kerang Lakes, Kow Swamp, Goulburn River, Campaspe River, Loddon River, Edward-Wakool Rivers and the Ovens River. All four themes undertook fieldwork at this site, as shown in Table 2. Sites by theme are shown in Figure 3.

**Mid Murray Field sampling sites**

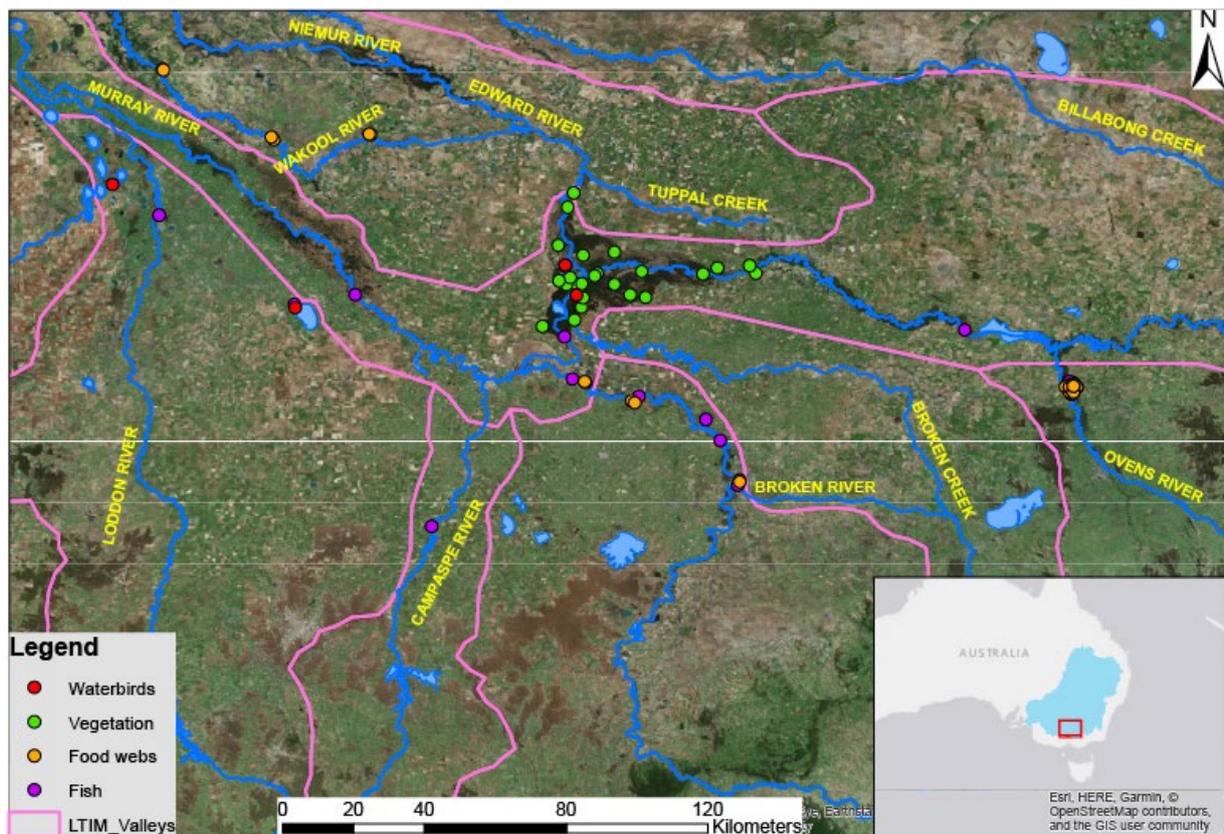


Figure 3. Field sampling sites undertaken during the EWKR project in the Mid Murray.

Table 2. Research activities undertaken by themes in the Mid Murray with the activity and question listed for reference to EWKR reports.

Theme	Component – Activity	Research question	Location
Vegetation	V3 — Field site assessments and germination trials	Are species unique to locations and are the relatively assemblages of species different at the four locations	Barmah–Millewa Forest
Fish	F2.3.1 — Thermal and nutritional regimes between channel and floodplain habitat	Comparison of the thermal and nutritional regimes among main channel and floodplain habitat patches	Ovens River
Fish	F2.3.2 — Thermal and nutritional zones	Identification of optimal thermal and nutritional zones, and the scales at which they function within a lowland river system	Ovens River
Fish	F2.4 — Relationship of structure and hydrodynamics to patterns of larval settlement and retention	Investigating the relationship between flow, structural habitat, hydrodynamics and patterns of larval settlement and retention	Ovens River
Fish	F2.5 — Population dynamics of golden perch and Murray cod	Basin-scale population dynamics of golden perch and Murray cod: relating flow to provenance, movement and recruitment in the Murray–Darling Basin	Loddon, Campaspe, Goulburn and Murray Rivers
Waterbirds	B2.4 — Field research analyses	Tagged nests, water depths and nesting habitat data analyses	Reed Beds, Millewa
Waterbirds	B2.4 — Field research analyses	Colony mapping	Reed Beds, Millewa
Waterbirds	B2.4 — Field research analyses	Similarities and differences in breeding ecology of straw-necked ibis and Australian white ibis in response to environmental flows (Honours thesis)	Barmah–Millewa Forest
Waterbirds	B2.4 — Field research analyses	Satellite tracking bird movements	Kerang wetlands, Kow Swamp, Barmah–Millewa Forest
Waterbirds	B2.4 — Field research analyses	Motion-sensing and time-lapse camera nest monitoring	Reed Beds, Millewa
Waterbirds	B2.4 — Field research analyses	Waterbird chick energy sources: Food Web cross-theme collaboration project	Kerang wetlands, Kow Swamp, Barmah–Millewa Forest
Waterbirds	B2.4 — Field research analyses	Ibis and spoonbill chick energy requirements	Reed Beds, Millewa
Food webs	Component W2 — Identifying critical basal resources	2.1 — Fish field program	Ovens River
Food webs	Component W2 — Identifying critical basal resources	2.2 — Waterbird food requirements research program	Barmah–Millewa Forest
Food webs	Component W2 — Identifying critical basal resources	2.4 — Basin scale resource use by fish	Edward-Wakool and Goulburn Rivers
Food webs	Component W3 — Identifying important sites of production		Ovens River
Food webs	Component W4 — Modelling bioenergetics within identified production sites		Ovens River

## 4.2. Lower-Murray Site research activity

Fieldwork undertaken in the Lower Murray was predominantly in the Chowilla–Lindsay–Wallpolla floodplain but also included Hattah Lakes and Lower Murray River. Three themes undertook fieldwork at this site, as shown in Table 3. Sites by theme are shown in Figure 4.

**Lower Murray Field sampling sites**

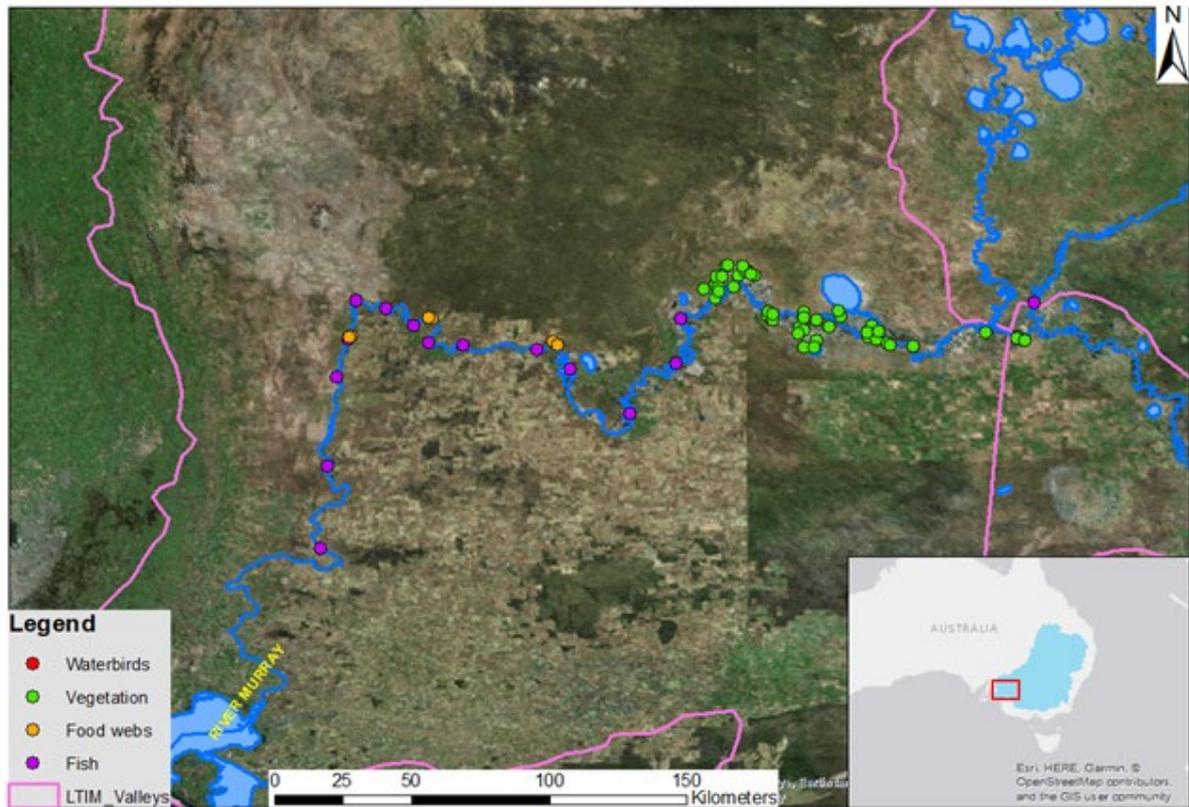


Figure 4. Field sampling sites undertaken during the EWKR project in the Lower Murray.

Table 3. Research activities undertaken by themes in the Lower Murray with the activity and question listed for reference to EWKR reports.

Theme	Component – Activity	Research question	Location
Vegetation	V2 — Data integration and synthesis	Disentangling flow-vegetation relationships and legacy effects to inform environmental flows	Hattah Lakes
Vegetation	V3 — Field site assessments and germination trials	Are species unique to locations and are the relatively assemblages of species different at the four locations	Chowilla–Lindsay–Wallpolla floodplain
Fish	F2.5 — Population dynamics of golden perch and Murray cod	Basin-scale population dynamics of golden perch and Murray cod: relating flow to provenance, movement and recruitment in the Murray–Darling Basin	Lower Murray River
Food webs	Component W2 — Identifying critical basal resources	2.4 — Basin scale resource use by fish	Lower Murray River

### 4.3. Macquarie Marshes Site research activity

Fieldwork undertaken was predominantly in the Macquarie Marshes but also included the Macquarie River. Three themes undertook fieldwork at this site, as shown in Table 4. Sites by theme are shown in Figure 5.

**Macquarie Marshes Field sampling sites**



Figure 5. Field sampling sites undertaken during the EWKR project in the Macquarie Marshes.

Table 4. Research activities undertaken by themes in the Macquarie Marshes with the activity and question listed for reference to EWKR reports.

Theme	Component – Activity	Research question	Location
Vegetation	V1 — Conceptualisation	Evaluating wetland vegetation responses to environmental flows	Macquarie Marshes
Vegetation	V2 — Data integration and synthesis	Disentangling flow-vegetation relationships and legacy effects to inform environmental flows	Macquarie Marshes
Vegetation	V3 — Field site assessments and germination trials	Are species unique to locations and are the relatively assemblages of species different at the four locations	Macquarie Marshes
Vegetation	V4 — Mesocosm study	Establishment strategies of dominant trees of highly variable floodplains	Macquarie Marshes
Fish	F2.5 — Population dynamics of golden perch and Murray cod	Basin-scale population dynamics of golden perch and Murray cod: relating flow to provenance, movement and recruitment in the Murray–Darling Basin	Macquarie River
Waterbirds	B2.4 — 2018–19 Field research analyses	Satellite tracking bird movements	Macquarie Marshes

#### 4.4. Lower Balonne and Narran Lakes Site research activity

Fieldwork undertaken was predominantly undertaken in the Narran Lakes but also included the Narran and Culgoa Rivers and the Queensland Floodplain Vegetation Water Requirements Project Lower Balonne sites. Two themes undertook fieldwork at this site, as shown in Table 5. Sites by theme are shown in Figure 6.

**Lower Balonne and Narran Lakes Field sampling sites**

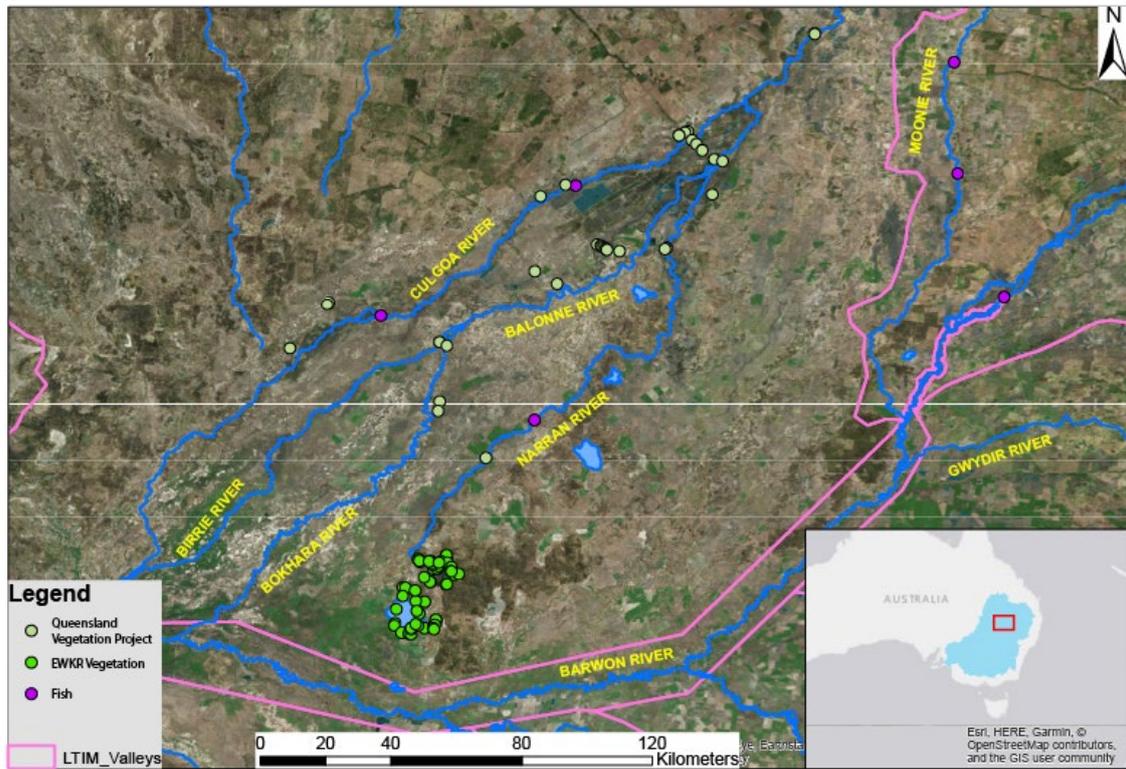


Figure 6. Field sampling sites undertaken during the EWKR project in the Lower Balonne and Narran Lakes.

Table 5. Research activities undertaken by themes in the Lower Balonne and Narran Lakes with the activity and question listed for reference to EWKR reports.

Theme	Component – Activity	Research question	Location
Vegetation	V1 — Conceptualisation	Evaluating wetland vegetation responses to environmental flows	Narran Lakes
Vegetation	V2 — Data integration and synthesis	Disentangling flow-vegetation relationships and legacy effects to inform environmental flows	Narran Lakes
Vegetation	V3 — Field site assessments and germination trials	Are species unique to locations and are the relatively assemblages of species different at the four locations	Narran Lakes
Vegetation	Queensland Floodplain Vegetation Water Requirements Project	Watering requirements of floodplain vegetation asset species of the Northern Murray-Darling Basin	Lower Balonne floodplain
Fish	F2.1 — Larval fish	Understanding the feeding requirements of larval fish in the northern Murray–Darling Basin	Narren and Culgoa Rivers
Fish	F2.5 — Population dynamics of golden perch and Murray cod	Basin-scale population dynamics of golden perch and Murray cod: relating flow to provenance, movement and recruitment in the Murray–Darling Basin	Upper Balonne and Condamine Rivers

