Identifying and characterising refugia habitat for target organisms across the Murray–Darling Basin

Commonwealth Environmental Water Holder's Science Program:
Flow Monitoring, Evaluation and Research (Flow-MER)

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Acknowledgement of country

The project team and the Commonwealth Environmental Water Holder (CEWH) respectfully acknowledge the traditional owners of the land on which this work is conducted, their Elders past and present, their Nations of the Basin, and their cultural, social, environmental, spiritual and economic connection to their lands and waters.

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Cover photograph

The Goulburn River downstream of the fish-friendly weir at Shepparton, Victoria, part of the lower Goulburn River Selected Area. Photo credit: Australian River Restoration Centre.

Important disclaimer

Executive summary

We applied systematic conservation planning (SCP) to prioritise areas in the Murray-Darling Basin that may act as climate refugia for different taxa and ecosystem productivity. The overall aim was to inform the delivery of water for the environment for refugia protection.. The SCP approach provides an objective and repeatable process that can be applied broadly across the Basin at multiple scales to support Annual Environmental Watering Priorities.

The spatial framework used to define planning units was the wetlands and lakes identified in the Australian National Aquatic Ecosystem (ANAE) classification as being located on the managed floodplain.

We applied SCP to prioritise planning units that can be feasibility managed with environmental water and may provide refugia during dry periods and from other disturbance (e.g., land-use and infrastructure).

The SCP prioritisation of planning units was tuned to protect a range of ecological assets including ecosystem productivity, target taxa and ecosystems for the least cost.

Key findings and recommendations

- Environmental water is supporting the majority of ecosystem and species diversity. It is also supporting higher productivity and contributing to ecosystem services.
- The systematic conservation planning approach provides an objective and repeatable process to support Annual Environmental Watering Priorities across the Murray–Darling Basin.
- Prioritisation of sites for watering is sensitive to the selection of ecological assets and management constraints, highlighting the importance of setting clear goals and objectives for the prioritisation.
- Environmental water delivery targeted towards the conservation of vertebrate or ANAE diversity may not be protecting invertebrate taxa.
- Invertebrate taxa are underrepresented in environmental watering actions despite many being recognised as keystone species.
- For targeting specific management objectives at multi scale and Basin wide, sub-basin or valley prioritisations may be required.
- Management constraints in addition to those included in this study need to be considered in the prioritisation, especially if they are required to meet environmental obligations, for example, for Ramsar sites.
- Species trait data, which is often lacking for many invertebrates, should be used to refine the prioritisation of locations for environmental watering.
- More data on ecological traits are needed to determine the spatial and temporal location of refugia habitats for target species.
- Better data on the feasibility of environmental water delivery and on the flow of environmental water are needed to improve the reliability of the outcomes.

Overview of Flow-MER

The Commonwealth Environmental Water Holder (CEWH) invests in monitoring, evaluation and research activities delivered through an integrated program called the Flow Monitoring, Evaluation and Research (Flow-MER). This program builds on work undertaken through the Long-Term Intervention Monitoring (LTIM) and Environmental Water Knowledge and Research (EWKR) Projects (2014–19) to monitor and evaluate the contribution of Commonwealth water for the environment to environmental outcomes in the Murray–Darling Basin. Flow-MER:

- monitors and evaluates ecological responses to Commonwealth environmental water in 7 Selected Areas and at Basin-scale using established metrics and methodologies
- undertakes best-practice science in 7 Selected Areas and at Basin-scale to research ecological processes and thus improve capacity to understand and predict how ecosystems respond to water management
- demonstrates outcomes from Commonwealth environmental water and documents these via a regular reporting schedule and engagement and extension activities
- facilitates a regular, timely and effective transfer of relevant knowledge to meet the adaptive management information requirements of Commonwealth environmental water decision-makers.

Up-to-date information on and outcomes from Flow-MER are available from the Flow-MER website[1].

Flow-MER Basin-scale research

Flow-MER is the primary means by which the Science Program of the CEWH undertakes research to deliver improved methods and a richer evaluation of environmental outcomes from Commonwealth environmental water. Flow-MER Basin-scale research aims to improve Basin-scale understanding of the contribution of Commonwealth environmental water within and outside of Selected Areas, develop new approaches to evaluating outcomes, support adaptive management and develop a richer understanding of ecological processes and responses to Commonwealth environmental water.

The Research Plan has evolved from the LTIM and builds on the EWKR research priorities together with a large body of previous work, resulting in 13 research projects: Flow-ecology (BW2) , Condition response (E2), Non-woody plants (V1), Woody plants (V2), Fish population models (F1), Fish movement (F2), Waterbirds (E1), Refugia (BW1), Scaling and condition (E3), Bioenergetics (BW3), Visualisation (CC1), Modelling (CC2) and Indigenous engagement (CC3).

This report is the final report from the Refugia team (BW1).

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[1] https://flow-mer.org.au/

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Abbreviations and terms

Abbreviation/terms	Description
ANAE	Australian National Aquatic Ecosystems (classification)
CEWH	Commonwealth Environmental Water Holder
CEWO	Commonwealth Environmental Water Office
EWKR	Environmental Water Knowledge and Research (project)
HEVAE	High ecological value aquatic ecosystems
LTIM	Long Term Intervention Monitoring (project)
RDI	River Disturbance Index
SCP	Systematic conservation planning
the Basin	the Murray–Darling Basin
WIT	Digital Earth Australia Wetlands Insight Tool

1 Introduction

1.1 Background

Maintaining the health of the Murray–Darling Basin, is a complex challenge. The climate across the Basin is highly variable in space and time and many parts of the Basin are described as boom-and-bust systems of water availability (Bunn et al. 2014). Anthropogenic climate change has caused substantial warming and has led to an increase in the intensity and duration of dry periods as well as an increase in the intensity of floods across the Basin (Whetton and Chiew, 2021). Drought effects in the Basin are superimposed over increasing human water needs including extraction for agriculture, manufacturing and communities (Prosser et al. 2021).

The Commonwealth's *Basin Plan 2012* (the Plan) was developed as a direct response for the need to manage the Basin in a sustainable way that supports communities, the environment and industry. The Basin Plan is a agreement between State and Territory governments and the Commonwealth in recognition of the need to manage the Basin as a connected system. One of The Basin Plan's key objectives is protecting and restoring water-dependent ecosystems and biodiversity. Achieving this aim requires identifying, characterising and managing key aquatic ecological assets that contribute to biodiversity, ecosystem diversity and ecosystem functions in the Basin.

The Basin is home to more than 30,000 wetlands and lakes (Bino et al. 2015). The Basin's wetlands and lakes are found across diverse physical and climatic environments and support a diverse range of plants, animals and ecosystems (Rogers and Ralph, 2010). Wetlands and lakes provide some of the Basin's most productive and biodiverse habitats. They supply feeding and breeding habitats to a wide range of taxa including waterbirds, fish, turtles, invertebrates, and plants. Many are important migratory bird habitats and are recognised under the Ramsar Convention, an intergovernmental treaty for international cooperation and national action for the conservation and sustainable use of wetlands (Bino et al. 2015). Wetlands have an essential role in regulating water quality through a process of absorbing, recycling and releasing nutrients and sediments (Boulton et al. 2014). Wetlands and lakes are also sites of many recreational and cultural activities, and many of the Basin's wetlands and lakes are culturally significant to Aboriginal and other communities (Humphries 2007).

The high biodiversity value of wetlands and lakes and their ability to buffer against climate disturbance has led to their frequent recognition as climate refugia (Morelli et al. 2020; Selwood and Zimmer, 2020).

Here we refer to the general ecological definition of refuge/refugia as the spatial contraction of an individual, population or species range due to adverse conditions such as drought (Keppel and Wardell-Johnson 2012).

Drought refugia are areas of higher resource availability and/or habitat quality than elsewhere in the landscape, supporting plants and animals during dry times. Wetlands and lakes can buffer against multiple climate stressors by providing more permeant water, natural cooling and by dispersing flood peaks and storing floodwaters and releasing them gradually (DCCEEW 2016). The Basin's wetlands and lakes provide a natural buffer against the Basin's commonly dry and highly variable climate and provide climate refugia for the Basin's rich freshwater and terrestrial biodiversity and even grazing stock (MDBA 2021). Effective management of wetlands and lakes as refugia habitats many provide an effective tool to assist species survival and recovery from climate disturbances including protracted droughts and intense floods.

A key lever for sustainable environmental management in the Basin is water for the environment (Wassens et al. 2021). Management of water for the environment aims to deliver planned flows or wetland inundation when and where it is needed to sustain and restore the environment. Water for the environment is often targeted to achieve specific environmental objectives for biodiversity (Wassens et al. 2021), for example to support breeding events, create foraging habitat and restore vegetation condition. During drought years, it has become common across multiple catchments in the Basin for the objectives of environmental water delivery to be for the maintenance of refugia habitats to support the survival of specific or multiple taxonomic groups (Wassens et al. 2021).

The Commonwealth’s commitment to water for the environment is outlined in section 8 of the Basin Plan and is managed by the Commonwealth Environmental Water Holder (CEWH), an independent statutory position established under the Water Act 2007. The CEWH’s on-ground Flow Monitoring, Evaluation and Research (Flow-MER) program aims to fulfil CEWH legislative requirements under the Basin Plan, demonstrate Basin-scale outcomes of Commonwealth environmental water, and support adaptive management. The delivery of environmental water to refugia is relevant to multiple sections of the Plan, particularly sections:

- 8.05 Protection and restoration of water-dependent ecosystems
- 8.06 Protection and restoration of ecosystem functions of water-dependent ecosystems. Specifically subsection (7) has an objective to protect and restore ecological community structure, species interactions and food webs that sustain water-dependent ecosystems, including by protecting and restoring energy, carbon and nutrient dynamics, primary production and respiration.
- 8.07 Ensuring water-dependent ecosystems are resilient to climate change and other risks and threats.

In the context of refugia management there are multiple benefits from the delivery of water for the environment. Water for the environment can be used to maintain the quantity and quality of flow regimes and provide cooling via cool water inputs that can extend the life of existing refugia or create new refugia in key areas of the landscape. Freshwater ecosystems are dendritic and relatively isolated within landscapes, which limits the ability of freshwater taxa to access cooler areas and leaves them exposed to drying (Woodward et al. 2010). Species that are unable to shift their range in response to changes in climate will require in-situ management to ensure their survival (Greenwood et al. 2016). Identifying, prioritising, creating, and managing areas that provide refuge to biodiversity from drought may be an effective strategy for conservation managers (Greenwood et al. 2016; Selwood and Zimmer, 2020). However, in large Basins, such as the Murray-Darling Basin, prioritising wetland refugia for the delivery of environmental water remains a major challenge.

1.2 Systematic conservation planning

Conservation management of refugia requires that managers understand the unique needs of different target species and ecosystems, and the different approaches to selecting potential refugia for conservation (Ashcroft 2010; Reside et al. 2014). Systematic conservation planning (SCP) is the most commonly applied prioritisation approach for selecting areas for conservation. Although originally developed for protected area selection, the SCP approach could be applied to any spatial prioritisation process; here is used for prioritisation of watering for the environment.

In the past, conservation planning and reserve design were often ad-hoc. It was common for nature reserves to be confined to areas with limited economic value (e.g. unsuitable for agriculture or urban development), or areas that hold cultural or scenic value to humans rather than for biodiversity conservation (Pressey et al. 1994). When biodiversity was the focus, a common approach was the protection of charismatic flagship species.

Systematic conservation planning was developed to improve the representation of regional biodiversity in reserve systems. The aim of SCP is to adequately represent biodiversity in a reserve network in a complementary and cost-effective way to minimise species risk and support long-term persistence.

> Complementarity is the gain in biodiversity represented when a site is added to a reserve system (Vane-Wright et al. 1991).

Incorporating complementarity in reserve planning inherently leads to more effective representations of biodiversity and more cost-efficient solutions than ad hoc methods such as scoring, or ranking strategies (Pressey and Nicholls 1989; Margules et al. 2002). Since their development in the 1980s, complementarity planning methods have shaped on-ground conservation management, policy, and legislation and have been implemented by major international conservation non-governmental organisations such as The Nature Conservancy (e.g. Game et al. 2011). Complementarity methods are usually implemented using Complementarity-based algorithms based on the research of Kirkpatrick (1983). Kirkpatrick (1983) identified priority areas to add to a reserve system to represent plant species diversity. Kirkpatrick observed that highly diverse areas often contained the same species compositions and that a combination of high and low diversity sites with a large spatial distribution are needed to represent all the species in the conservation reserve network.

Systematic conservation planning adheres to the principles of conservation planning: connectivity, adequacy and representativeness (CAR), sometimes referred to as CARE principles, with E standing for efficiency (Possingham et al. 2006). The SCP approach is highly relevant to the Basin Plan (MDBA 2014) as connectivity and representativeness are principles within its objectives.

> Connectivity refers to movement of individuals and materials across the landscape between habitat patches, populations, communities and ecosystems (Daigle et al. 2020).

Connectivity is important to conservation planning as it improves population resilience to disturbance via source and sink dynamics (Linke et al. 2011b). Adequacy in conservation contends that enough habitats and species should be protected to ensure long-term persistence. The aim of representativeness is to ensure all regional biodiversity, including species, habitats ecosystem and ecological processes is represented and replicated in conservation planning (Linke et al. 2011b). Efficiency refers to cost, where cost can be cultural, social, or economic. It reflects real world constraints on conservation management decision making that need to balance competing stakeholders (Linke et al. 2011b). The optimal plan is the one with the lowest impact on stakeholders and interest groups, with the lowest cost, that offers the most comprehensive protection of biodiversity and other ecological assets. Accordingly, the overarching aim of the CARE principles is to design a resilient reserve system that comprehensively captures an adequate representation of biodiversity features to be viable based on available biodiversity data and knowledge in the most cost-effective way (Possingham et al. 2006).

To improve efficiency, the SCP is an iterative and unidirectional management process, which allows for decisions to be refined as new information and knowledge becomes available through stakeholder evaluation. The SCP decision framework was developed by Shea (1998), Possingham et al. (2001) and Margules and Pressey (2000), and has been refined and applied to freshwater systems by Linke et al. (2011a). Here we apply the framework in 5 steps as described by Linke et al. (2011a):

1. Select the types of ecological assets to be managed (e.g. species, ecosystem types or processes), the target levels of conservation, and the costs and degree to which they are considered.
2. Identify spatially explicit data on ecological assets for conservation and define the spatial planning units. Planning units are areas that contain the desired conservation features (e.g. species, ecosystems, or ecological process) within the landscape (e.g. sub-catchments, wetlands).
3. Identify conservation management options. This is achieved via a SCP algorithm, which aims to prioritise sites for conservation actions based on a site's complementarity ecological value while constrained by its cost.
4. Stakeholder negotiation and re-evaluation.
5. Consensus conservation plan.

The SCP approach has been widely applied to terrestrial and marine systems, however freshwater habitats are under-represented within systematic conservation planning on a global scale (Darwall et al. 2011). This is concerning because freshwater habitats support a disproportionate amount of the world's taxa, given they represent only 0.8% of the Earth's surface (Dudgeon et al. 2006). In conservation planning, freshwater habitats are often used as a boundary or considered to be a feature rather than the target of conservation (Abell et al. 2007). The traditional terrestrial focus of reserve system design is unlikely to protect freshwater taxa due to the unique threats they face such as hydrological modification and this may in part explain why freshwater species declines are outpacing their terrestrial and marine counterparts (Pimm et al. 2014).

1.3 Relevance to other studies in the Basin

There have been notable previous applications of SCP for selecting protected areas within the Basin (e.g., Bino et al. 2015; Linke et al. 2015). Bino et al. (2015) used long-term aerial surveys of water birds and applied the SCP methods to identify important wetlands acting as waterbird refugia in wet and drought periods. Linke et al. (2015) piloted the use of SCP for prioritising subcatchments at the Basin-scale and wetlands within the Murrumbidgee River for conservation using a wide range of taxa including birds, fish, invertebrates, and plants. In their study, Linke et al. (2015) were unable to apply SCP to wetlands at the Basin-scale due to a lack of consistent wetland mapping at that time. The release of the Australian National Aquatic Ecosystems (ANAE) classification for the Basin (Brooks, 2021) provides a consistent cross-jurisdictional mapping of wetlands, lakes and other aquatic ecosystems with specific relevance to the management of Commonwealth environmental water. The recent linking between the ANAE classification and the Digital Earth Australia Wetlands Insight Tool[2] (WIT) developed by Geoscience Australia, which contains data on the amount of water, green vegetation, dry vegetation, and bare soil, means that it is now possible to assess changes in condition with ANAE features through time. The combination of these two datasets means it is possible for the first time to both apply SCP to wetlands at the Basin scale and incorporate an assessment of their condition as a product of changes in climate as a critical assessment of their physical refugia qualities (e.g. their resilience as a function of condition in relation to drought).

The systematic prioritisation of environmental watering to maintain and protect refugia habitat during drought may be an effective management strategy to support the survival and recovery of water-dependent ecological communities (Selwood and Zimmer 2020). The long-term persistence of populations under disturbance is not only determined by their ability to persist (resistance) but also their ability to recover (resilience) (Bennett et al. 2014). Refugia habitat that facilitate resilience as well as resistance are

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[2] https://cmi.ga.gov.au/data-products/dea/669/dea-wetlands-insight-tool-ramsar-wetlands

likely to be those where resource availability is consistently high compared to other areas. This is because these areas will enable individuals to persist during drought and then increase their reproduction to potentially re-colonise the surrounding landscape when conditions improve (Selwood and Zimmer 2020). All refugia that facilitate resistance may not facilitate resilience as habitat that improves survival in dry times may not be the same habitat once the water returns. For populations to persist, recover and recolonise following drying it is important that refugia are identified not just in high-quality areas which may be spatially clumped but are instead located in a variety of ecosystems and in critical nodes of the river network to facilitate dispersal (Mouquet et al. 2013).

Many wetlands and lakes in the Basin are managed for the benefit of charismatic and recreationally important species such as waterbirds and fish (Wassens et al. 2021). Such species are highly mobile and often move over relatively large ranges compared to other important but potentially less charismatic and underrepresented taxa such as invertebrates. Dispersal ability is linked to climate risk, and species that are unable to move in response to changes in condition will be the most in need of in situ protection (Sandel et al. 2011). Invertebrates are important food resources for high tropic groups such as birds and fish and are an essential component of biodiversity in their own right with many considered to be keystone species in freshwater systems (Sheldon and McCasker 2020; Whiterod and Zukowski 2019).

1.4 Project aim

To prototype using the systematic conservation planning (SCP) method to identify wetlands and lakes in the Murray–Darling Basin that may be acting as refuges to drought conditions. These refugia may then be represented with higher priority in management frameworks using water for the environment to protect and restore Basin ecosystems.

Specifically the project identifies:

- Which conservation values (species, ecosystems and ecosystem productivity) are supported by Commonwealth environmental water?
- Which lakes and wetlands may act as refugia for specific conservation values and are therefore a high priority for environmental water delivery during dry periods?
- What is the feasibility of management based on different cost constraints to management, including the feasibility of environmental water delivery and other management costs (such as the area of inundation and site condition)?

2 Approach

The systematic conservation planning (SCP) is an interactive approach which follows a decision-theoretic framework developed by Shea (1998), Possingham et al. (2001) and Margules and Pressey (2000) (Figure 2.1). Here we:

1. Define a spatial framework that considers the constraints on delivering water for the environment across the Basin (Section 2.1)
2. Identify spatial data on ecological assets relating to species diversity, ecosystem diversity and ecosystem process (Section 2.2)
3. Identify costs and impediments to the delivery of water to the environment for the systematic delivery of water for refugia management (Section 2.3)
4. Run a range of scenarios for prioritisations of wetlands and lakes at the Basin scale based on their ecological value, management constraints and refugia capacity. Specifically, we aim to determine if where we currently deliver environmental water is adequate for representing regional diversity across the managed floodplain or if alternative sites could better represent regional diversity and better protect ecosystem processes (Section 0 and Chapter 3)
5. Identify knowledge gaps and study limitations to improve future implementation of ecological prioritisation of the Basin Annual Environmental Watering Priorities (Chapters 4 and 5).

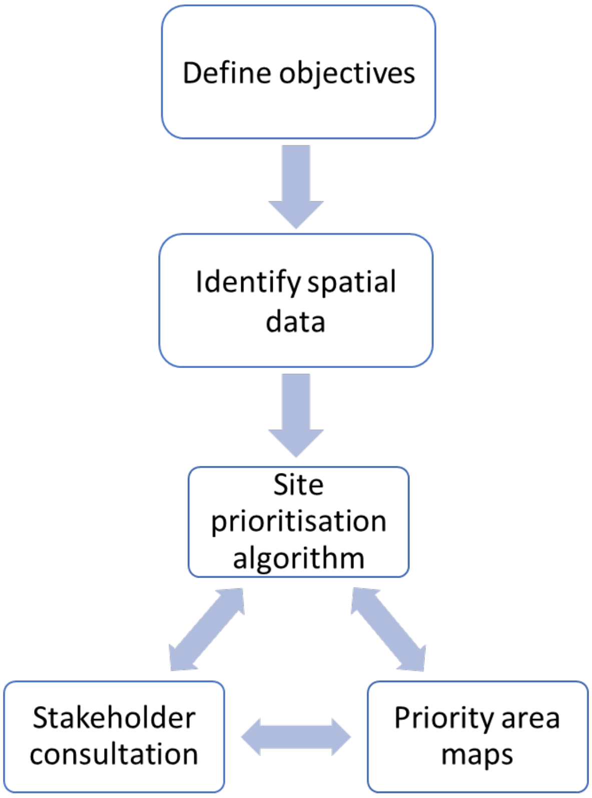

Figure 2.1 The decision framework for implementing systematic conservation planning
The framework was developed by Shea (1998), Possingham et al. (2001) and Margules and Pressey (2000) and applied to freshwater systems by Linke et al (2011a).
Source of figure: modified from Linke et al. (2011a).

2.1 Spatial framework

For the spatial framework, we adopted the Australian National Aquatic Ecosystems (ANAE) v3.0 Classification of the Basin (Brooks, 2021). We used the ANAE ecosystem classifications because they are based on the best available spatial data for rivers, floodplains, wetlands and lakes from the States, the Murray Darling Wetlands Working Group, and the Australian Government National mapping including the Australian Hydrological Geospatial Fabric (Geofabric, BOM 2020). The ANAE provides a consistent cross-jurisdictional classification of aquatic ecosystems across the Basin and has specific relevance to the management of Commonwealth water for the environment. The classification is broadly applied by relevant management authorities across the Basin including the Murray–Darling Basin Authority (MDBA) and the officers of the Commonwealth Environmental Water Holder (CEWH) to support monitoring, evaluation, and adaptive management of water resources. For analysis, planning units (i.e. the areas to be considered for the prioritisation of environmental water) were defined as freshwater depressional wetlands and lakes (e.g. 'Lacustrine', 'Palustrine') in the ANAE v3.0 (Figure 2.2).

Management recommendations need to be restrained by a realistic interpretation of outcomes that can be achieved. Accordingly, we tempered our analysis to reflect the constraints on where held environmental water can be delivered. Using attributes in the ANAE classification, planning units were refined into 2 subsets for further analysis: (1) planning units identified to be on the managed floodplain and (2) planning units that have received CEWH environmental water according to available records (Figure 2.3). The managed floodplain was defined as per the Basin-wide Environmental Watering Strategy (MDBA 2014) and includes areas in the Basin where water for the environment could likely be recovered within current operational constraints. Regions of the Basin where water for the environment can generally be delivered include areas downstream of large headwater storages such as the Macquarie, Murrumbidgee and Murray regions; the River Murray floodplain via The Living Murray ‘environmental works’ sites; and other areas via flow rules in water resource plans (MDBA 2014). Actively watered planning units were identified as those that have historically received Commonwealth environmental water since records began (i.e. at any time between the 2014–15 to 2019–20 water years). The unmanaged floodplain is generally reliant on natural large flow events for inundation and as such is beyond the scope of environmental watering under the Plan (MDBA 2014). The unmanaged floodplain was not included within our spatial framework and was excluded from analysis. The aim of using these 2 sets of planning units was to determine if where Commonwealth environmental water is delivered is adequate for representing regional diversity across the managed floodplain; or if alternative sites could better represent regional diversity and better protect ecosystem processes.

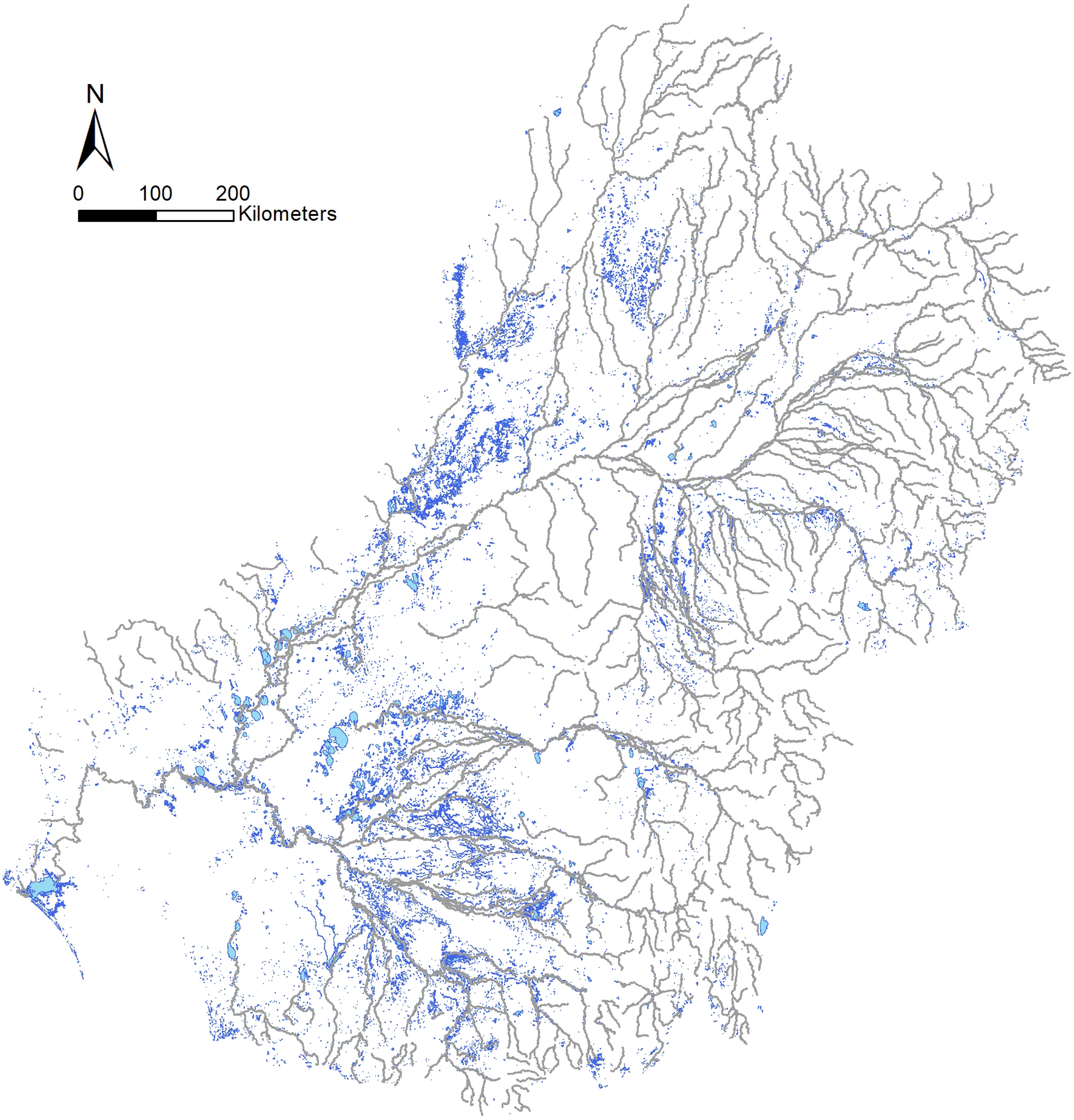

Figure 2.2 Map of depressional wetlands and lakes in the ANAE

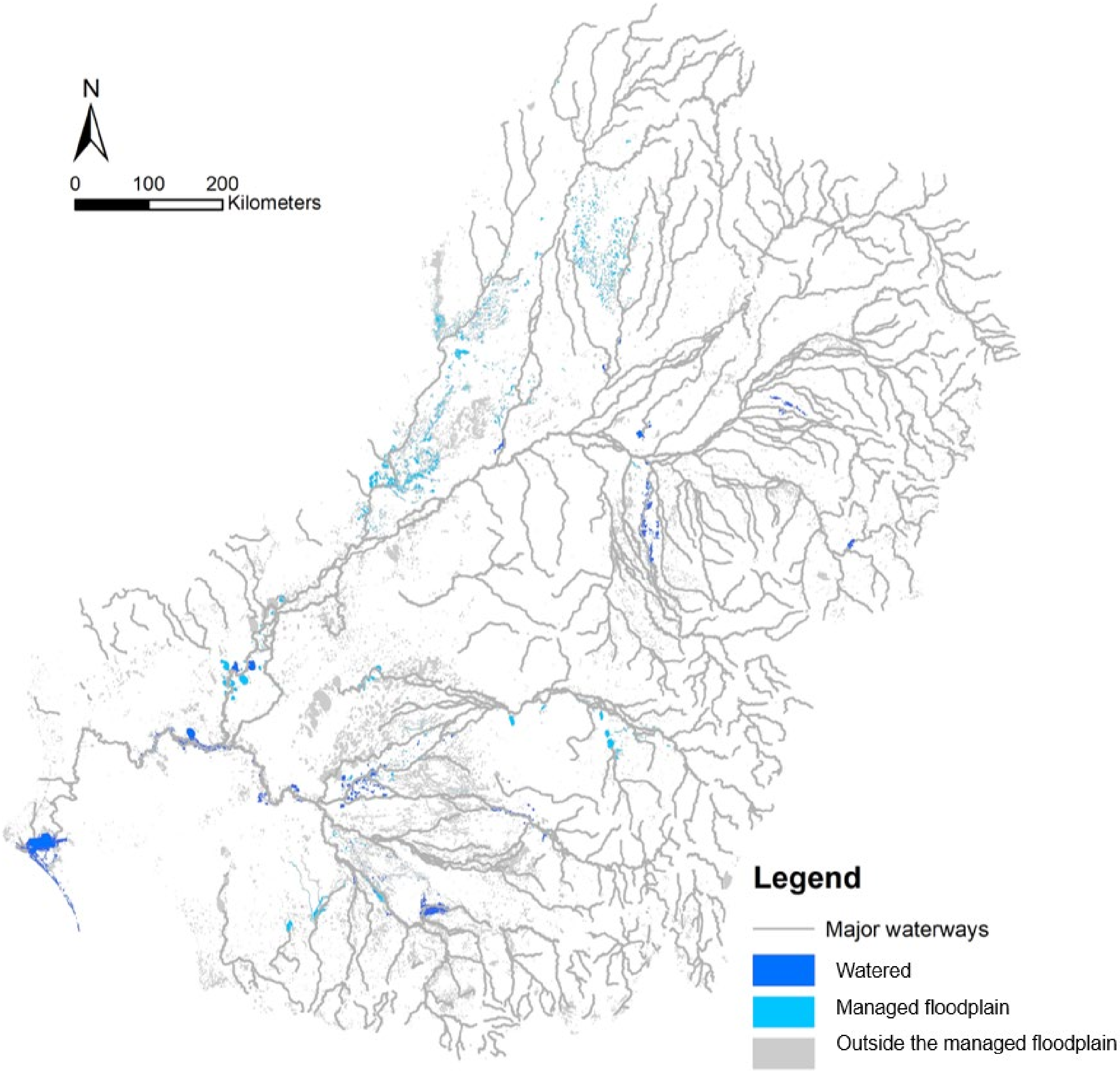

Figure 2.3 Depressional wetlands and lakes in the ANAE that are on the managed floodplain (light blue) and have received CEWH delivered water for the environment (dark blue); and those outside the managed floodplain (grey)

2.2 Ecological assets

We developed a spatial database of ecological assets and ecosystem function for each planning unit. Our methods adhere to the guidelines for identifying high ecological value aquatic ecosystem (HEVAE) (Aquatic Ecosystems Task Group 2012). The HEVAE identifies high ecological value aquatic ecosystems based on key attributes including diversity, distinctiveness, vital habitat, naturalness, and representativeness – all of which are also considered under the SCP framework applied here. The spatial data used in our analysis captures both biodiversity and landscape complexity and aims to represent a range of species.

2.2.1 Ecosystem diversity

Increased landscape complexity, including high ecosystem and habitat diversity, is linked to greater species diversity. Ecosystem diversity is also seen as an important aspect of biodiversity in its own right because there is an assumption that preserving different ecosystem types also protects the inherent biodiversity living within those ecosystems. The inundation of a particular planning unit may benefit surrounding habitat types and facilitate different species to use multiple habitats. Accordingly, we aimed to identify the other ecosystems surrounding each planning unit.

We defined the **value of a planning uni**t to each ecosystem in the ANAE classification by identifying each ANAE and its area within a 500 m circle of influence of each planning unit (Figure 2.4).

The ANAE uses a rules-based approach to classify aquatic ecosystems using attributes relevant to the structure and function of each system (Brooks 2021). The ANAE has a hierarchical structure designed to capture the spatial patterns at the regional and landscape scale and ecological diversity at the local scale. The regional and landscapes levels, levels 1 and 2, capture large-scale and mid-scale attributes associated with landform, climate, topography, hydrology and water influence. Level 3 captures more local scale attributes such as aquatic ecosystem classes (surface water and subterranean), system (e.g. estuarine, lacustrine, riverine, and floodplain) and habitats (e.g. red gum forest). A typology is applied to distil these attributes into distinct aquatic ecosystems classes (e.g. ‘permanent paperbark swamps’ or ‘temporary lakes’). In total the ANAE contains 7,948 lakes classified into 8 ecosystem types and 51,830 Palustrine wetlands of 29 different ecosystem types.

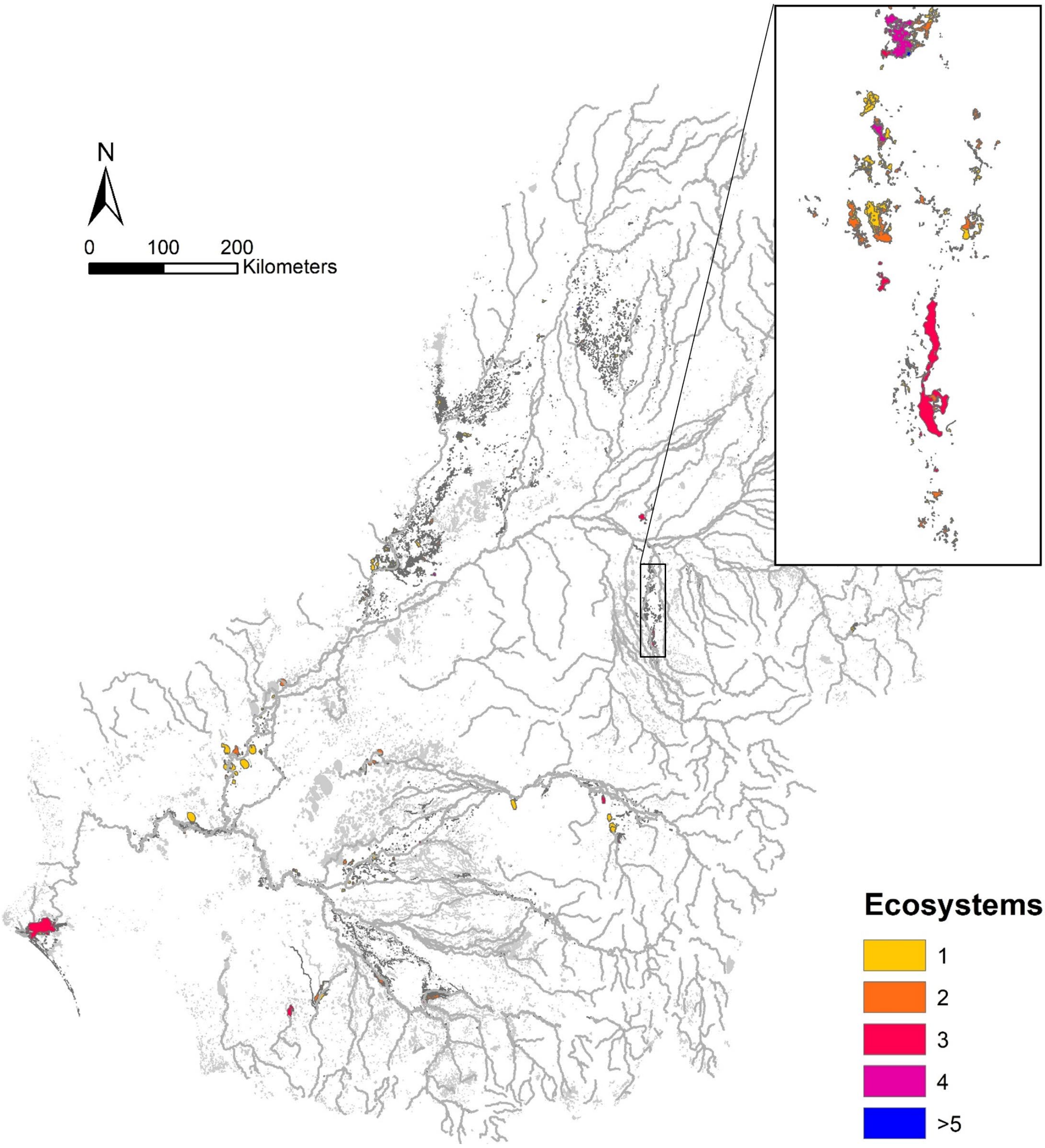

Figure 2.4 The diversity of ANAE Lacustrine and Palustrine ecosystems within a 500m buffer of each planning unit on the managed floodplain

Ecosystem diversity of each planning unit is defined as the number of unique ANAE classifications in that planning unit

2.2.2 Species diversity

The Basin supports a rich diversity of water-dependent plants and animals. We used the subset of species defined by Rogers and Ralph (2010) for which spatial distributions in the Basin are available. This includes 17 species of wetland dependent fish, 73 species of frogs, 87 species of dragonflies, 36 species of crustacea, 33 species of molluscs and 48 species of plants.

We used available species distribution maps that mapped the probability of occurrence for each taxon at the scale of the Geofabric Level 15 subcatchments (e.g. Figure 2.5). The Geofabric maps the Murray–Darling Basin as hierarchically nested catchments, where scale basins divisions are sub-divided into successively finer sub-catchments. The lowest level delineates the sub-catchments draining directly to a stream segment (BOM 2019). For fish, species distribution models combined state fisheries presence/absence data with spatial data on environmental suitability including climate and catchment physiography. For a full description of model development see (Bond et al. 2014). Habitat suitability models for all other taxa were fit using a combination of 5 common algorithms; generalised linear models, generalised boosted models, generalised additive models, Maxent and multivariate adaptive regression splines (Elith et al. 2006).

We assumed that the probability of a species occurring in any planning unit was the same as the probability of it occurring in the Geofabric Level 15 sub-catchment where the planning unit occurred. We therefore assigned the probability of a species occurring to each planning unit to be the same as that of the surrounding Geofabric Level 15 sub-catchment. When planning units spanned multiple sub-catchments, we assigned the mean probability of occurrence from the surrounding sub-catchments to that planning unit. To calculate the habitat value of each planning unit to a particular taxon, we multiplied the probability of occurrence by the area of each planning unit. This was done so that larger planning units, that contained more habitat, were deemed more valuable that smaller planning units with the same probability of occurrence.

2.2.3 Ecosystem process

The ability of lake and wetland planning units to act as refugia for higher trophic taxa such as fish and birds is dependent on a consistently adequate supply of basal energy resources. Areas with consistently high productivity in the landscape can support higher biodiversity (Waide et al. 1999). High ecosystem productivity is positively linked to diversity through multiple mechanisms. Simply, highly productive habitats can support more diversity because they can support more individuals and more trophic levels.

To quantify productivity in each planning unit, we estimate carbon sequestration from harmonised global maps of above ground living biomass carbon density for the year 2010 (Spawn et al. 2020, Figure 2.6). Above ground biomass maps usually focus on trees and non-tree plant communities separately. The harmonised above ground living biomass carbon density map integrates published remotely sensed maps on all major components of living biomass (e.g. woody, herbaceous and crop biomass) from all above ground living plant tissues (stems, bark, branches, twigs) and therefore allows for a holistic accounting of diverse vegetation carbon stocks. For each planning unit, productivity was estimated as the mean carbon sequestration (mg per hectare) for the perimeter of each planning unit multiplied by the area of the planning unit. Larger planning units such as wetlands and lakes may contain deep open water in the middle and, therefore may have zero carbon sequestration despite being highly productive and potentially important habitat and refugia. For this reason, we used the mean carbon sequestration for the perimeter of each planning unit so as to not devalue large planning units.

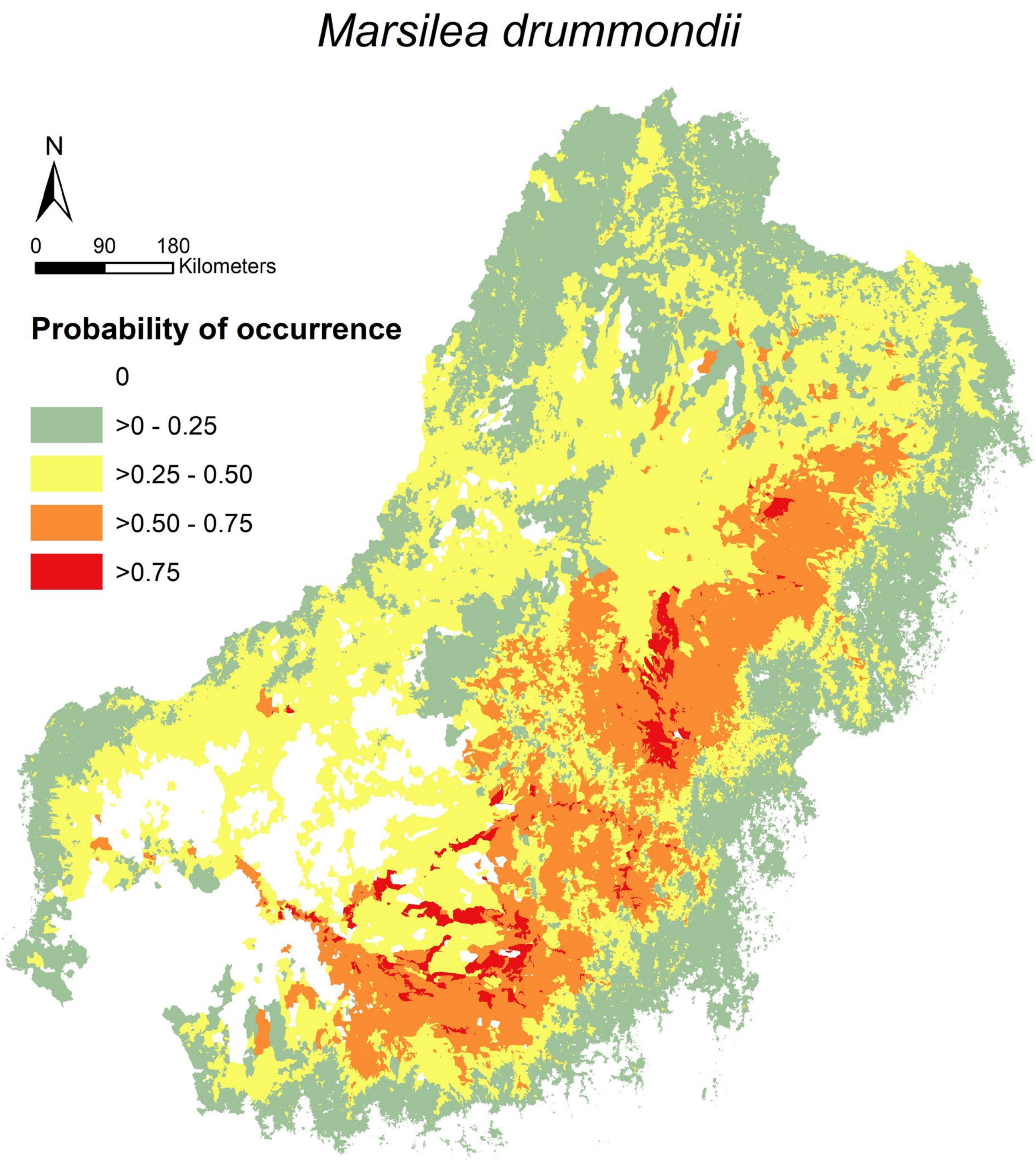

Figure 2.5 Species habitat suitability model for nardoo *Marsilea drummondii,* a native rhizomatous perennial aquatic fern of cultural and ecological importance

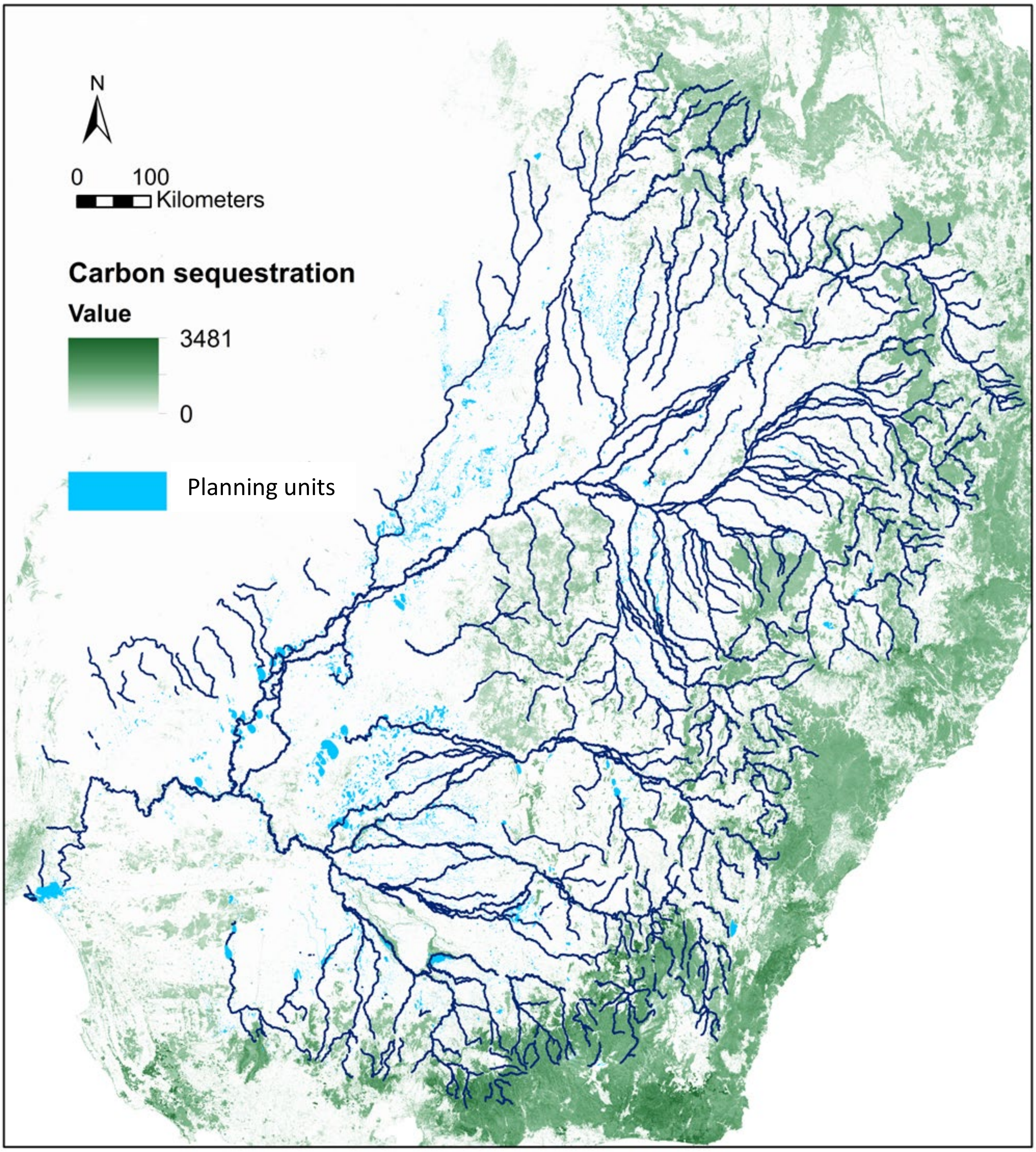

Figure 2.6 Carbon sequestration (Mg/ha) as per the harmonised global maps of above ground living biomass carbon density for the year 2010 at 300-m spatial resolution (Spawn et al. 2020)

2.3 Management constraints

Management costs can include a broad range of factors. Here we consider the amount of water needed to deliver environmental water to the planning unit, the presence of other threats and refugia capacity. These factors not only relate to real world management constraints but are also relevant to species conservation as habitat quality and connectively are all relevant to species population viability.

2.3.1 Habitat area

Large planning units contain more habitat. However, larger planning units also require more water to achieve the same standing water level compared to small planning units. Therefore, the area of each planning units was used as a major management constraint.

2.3.2 Habitat condition and connectivity

More disturbed areas have a lower conservation value because degraded habitats are less suitable and/or less available to species. Further, highly disturbed sites may have other associated ecological, social or economic costs that need to be considered before conservation actions can successfully achieve their goals. For example, disturbed sites may need considerable restoration before they can support viable species populations and in-turn diverse communities. For our SCP process we therefore quantify the habitat condition of a planning unit.

Measuring the habitat condition of a planning unit requires a multi-scale prospective. The condition of the surrounding landscape in which a wetland or lake is located will likely have the largest effect on condition; however, upstream catchment condition will also play a role due to hydrological connectivity. Simply, flow through dendritic freshwater systems means the negative effects of anthropogenic disturbance, and conversely, the positive effects of more natural areas in upstream catchments can propagate downstream (Hermoso et al. 2012). Further, allocating water for the environment could have unintended consequences if it reconnects degraded sites to the network and causes disturbances (e.g. pollution) to propagate downstream (Hermoso et al. 2012).

Here we accounted for river condition using the River Disturbance Index (RDI, Stein et al. 2014) which has been calculated consistently for all catchments in the Basin. The RDI numerically characterises anthropogenic river disturbance assigning a value ranging between 0 and 1, from near-pristine to severely disturbed (Figure 2.7). The RDI is an estimate of the extent and intensity of anthropogenic disturbances in a river catchment e.g. land-use and infrastructure such as roads and flow-regime disturbance due to impoundments, flow diversions and levee banks. To account for hydraulic connectivity, the disturbance index calculated for sub-catchments is then weighted by the mean disturbance of all upstream sub-catchments. The RDI has been calculated for all catchments of the Australian Hydrological Geofabric (Bureau of Meteorology 2015). We assumed that the condition of a lake/wetland planning unit was the same as the condition of the Geofabric Level 15 sub-catchment in which the wetland or lake occurs. Therefore, we assigned to each planning unit the RDI value of the surrounding Geofabric Level 15 sub-catchment.

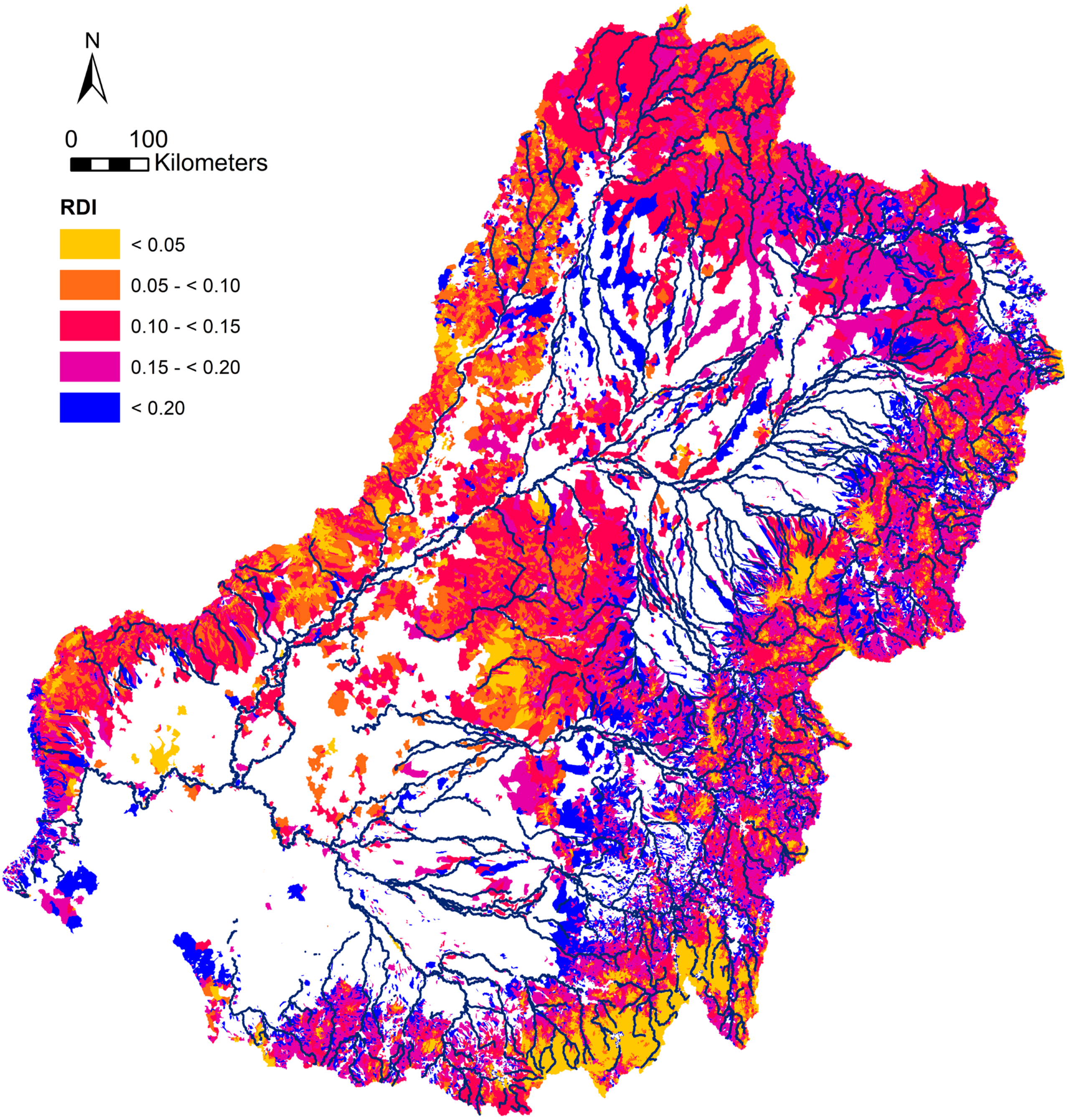

Figure 2.7 River Disturbance Index (RDI) for each Murray–Darling Basin sub-catchment in the Australian Hydrological Geofabric Level 15

2.3.3 Resistance to drought

Many of the Basin's wetlands are as dynamic as they are diverse. Wetting and drying phases create boom-bust-cycles of resource availability which in turn affects species abundance, recruitment and distributions, and habitat availability, water quality and ecosystem processes (Bunn et al. 2006). Inter-annual flow variability in the Basin is primarily driven by the El Niño Southern Oscillation (ENSO), however, under climate change the intensity of drought periods and severity of floods is increasing (Whetton and Chiew 2021). Refugia habitats can be considered to be areas in the landscape where resource availability is consistently high. Habitats that are relatively resistant to bust periods support survival and facilitate resilience by providing a base for recruitment and re-colonisation when conditions improve in the surrounding landscape (Selwood and Zimmer 2020).

To identify wetlands that may maintain their condition during low flow periods we calculated a dryness anomaly using data from the Digital Earth Australia (DEA) Wetlands Insight Tool (WIT) (Dunn et al. 2019). The WIT contains the proportion of open water, wet vegetation, green vegetation, dry vegetation, and bare soil in each wetland in the Basin between the years 1986 until 2022 (Hale et al. 2023). We calculated a dryness anomaly for each planning unit, as the medium increase in bare soil for the period 2017 until 2019 compared to the medium bare soil since records began (1986) to 2022 (Figure 2.8). We used the recent dry conditions of 2017 to 2019 to investigate wetland resistance to drought as it was one of the most extreme Basin-scale multiple-year rainfall deficits (Figure 2.9, BOM 2022, 2019). The dryness anomaly was calculated for wetlands and lakes > 1 ha, as ANAE polygons smaller than 1 ha are considered too small to be reliably measured using the Landsat data sets that are incorporated into the WIT.

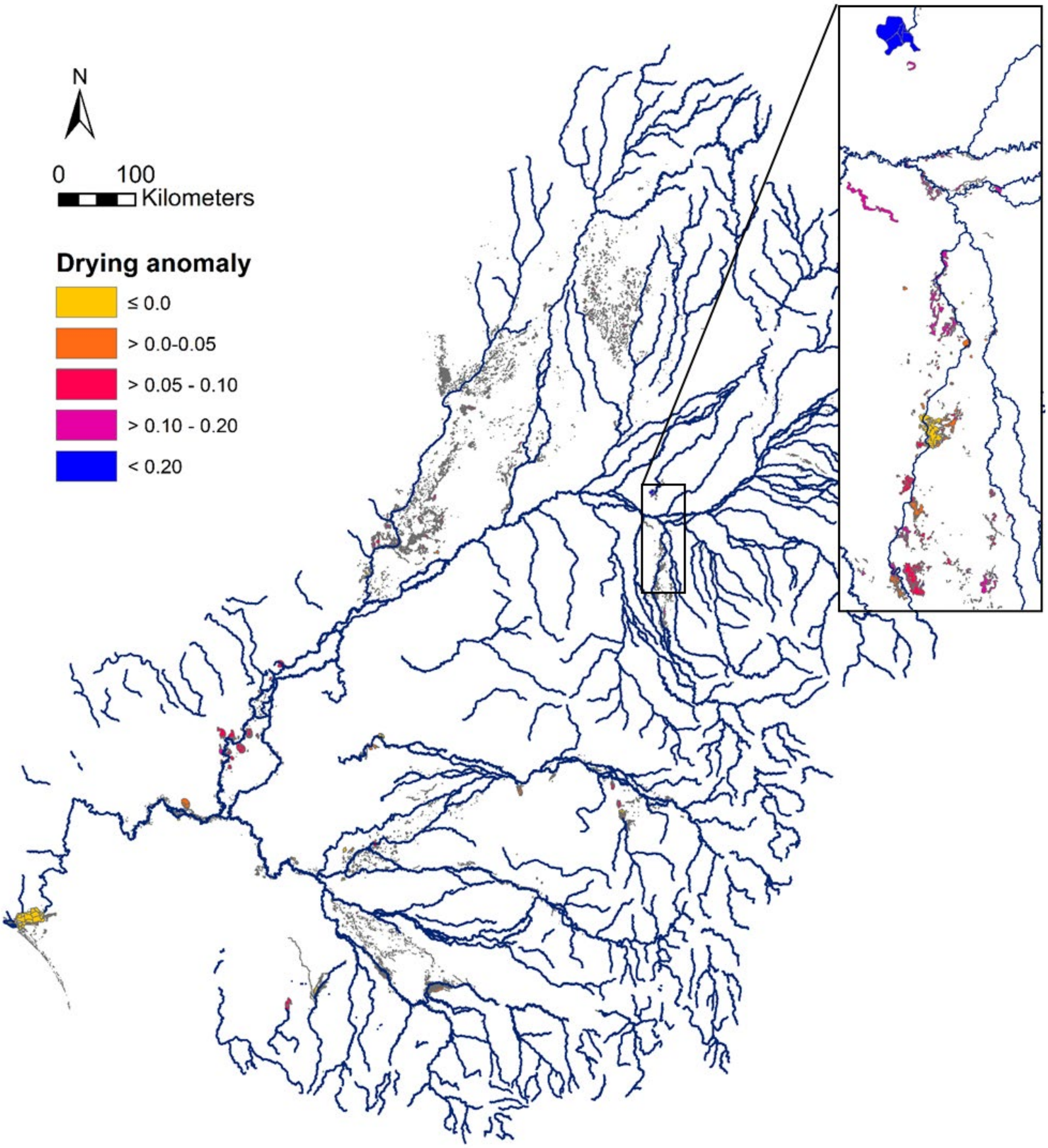

Figure 2.8 Dryness anomaly for each planning unit, calculated as the medium increase in bare soil over the period 2017 to 2019 compared to the medium since records began (1986) to 2022

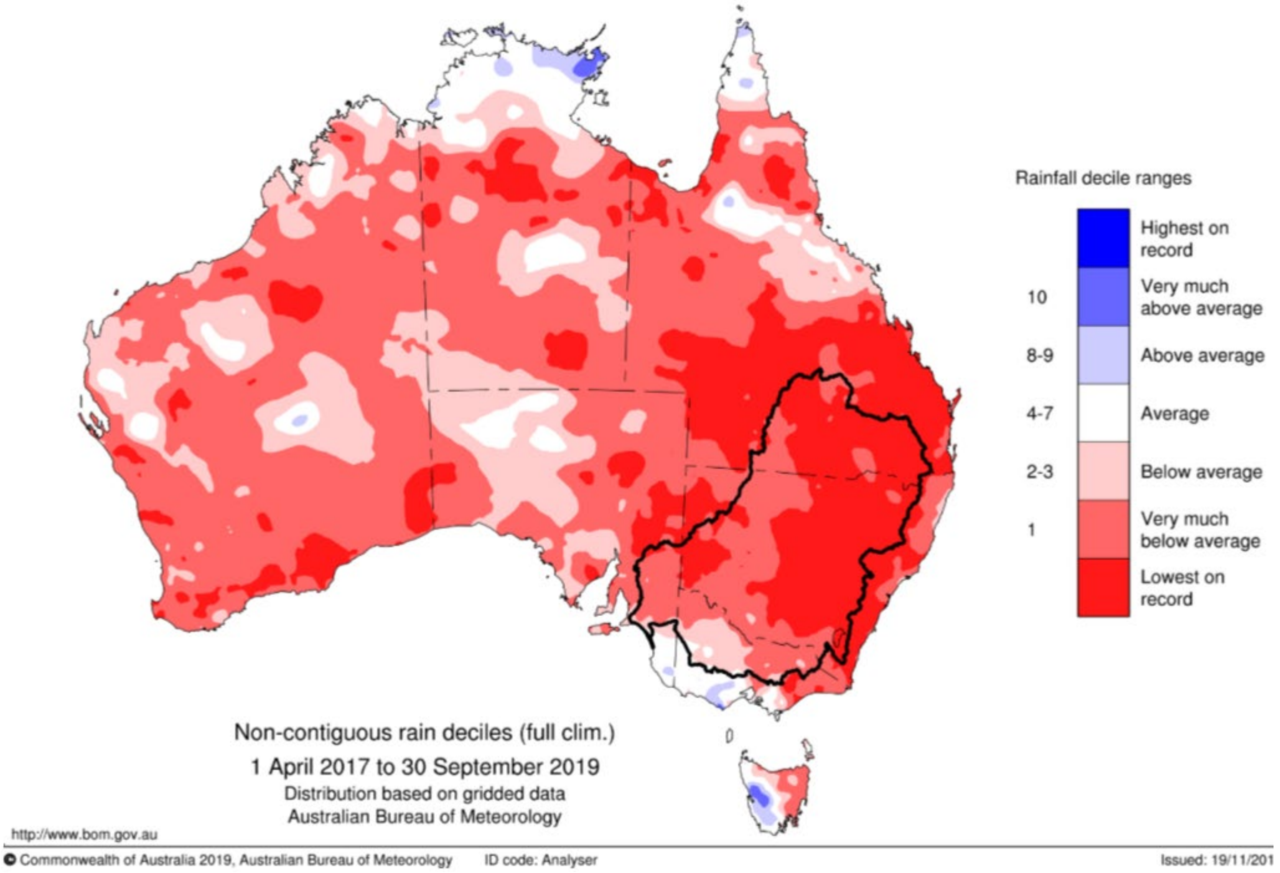

Figure 2.9 Rainfall deciles for the period April 2017 until September 2019 compared to a baseline of all years since records began (1900) to 2019
Source: BOM 2019

2.3.4 Combined constraints layer

In systematic conservation prioritisation analysis, management constraints surrounding each planning unit are usually combined into a single adjusted ‘cost layer’. Following Linke et al. (2012), the ‘cost’ of a planning unit was weighted by its capacity to act as a refuge (dryness anomaly), catchment condition and connectivity (RDI) and management feasibility (previous environmental water delivery). First, the RDI value, and the dryness anomaly of each planning unit was scaled between 0.3 and 1. The 0.3 to 1 range was chosen, as it has been shown to allow for effective comparison been planning units, without overriding the prioritisation (Linke et al. 2012). For the managed floodplain only, planning units that had previously been inundated with environmental water were assigned a weighting value of 0.3, while planning unit that had not revived environmental water were assigned a value of 1. The rationale being that it must be feasible to deliver environmental water to a planning unit if it had received environmental water in the past. The cost of each planning unit can then be calculated as a weighted average of area multiplied by the scaled RDI, dryness anomaly and/or management feasibility on the managed floodplain. The rationale for the weighting is that when planning units are of equal biodiversity value, the algorithm will prioritise planning units that dry out less, in low disturbance catchments, that can be watered, over planning units that are less resistant to drying, are in more disturbed catchments and have no prior history of watering suggesting watering delivery may be difficult. If a planning unit is important to a highly unique asset, the weighting will not affect its selection as the goal of representativeness and complementarity will override the weighting.

2.4 Analyses

2.4.1 Prioritisation used the MARXAN algorithm

For the prioritisation of planning units that are most likely to be refugia for the conservation of target taxa, ecosystem and ecosystem productivity that should be considered as a priority for environmental water, we used the program MARXAN (Ball et al. 2009). MARXAN uses a simulated annealing algorithm to identify a set of planning units that maximises the representation of ecological asset, while aiming to capture a defined target for each asset and minimise cost. To account for the importance of connectivity, we included a boundary layer in MARXAN to identify adjoining planning units. To force the algorithm to preferentially select adjoining planning units the maximum boundary penalty was applied in all analyses.

The targets for conservation were based on the average inundated area of wetlands by Commonwealth environmental water per year. In the water years between 2014 to 2019, on average ~150,000 ha (range 117,965 to 171,296 ha) of wetlands and lakes in the Basin received environmental water per year. Therefore, the MARXAN conservation targets were adjusted until a scenario in which inundated planning units collectively totalled approximately 150,000 ha in area.

2.4.2 Scenarios

We aimed to identify high priority lakes and wetlands that may act as refugia for target taxa, ecosystems and ecological processes that could be targeted by environmental water management. We also aimed to understand what was driving the site selection prioritisation by conducting prioritisations under separate cost scenarios, different levels of feasibility and for individual ecological assets as follows:

1. We considered how different cost constraints influence conservation planning solutions:
    a. **Area scenario**: Area as the only management cost.
    b. **Degradation refugia scenario**: Cost is estimated as the planning unit area weighted by the RDI.
    c. **Climate refugia scenario**: Cost is estimated as the planning unit area weighted by the dryness index.
    d. **Degradation and climate refugia scenario**: Cost is estimated as the average of scenarios 2 and 3.
2. We considered how feasibility of environmental water delivery influences conservation planning solutions. Here we only prioritised planning units that had previously received environmental water (watered planning units), as we considered this to be the best indication that a planning unit can receive environmental water. The prioritisation included all ecological assets, and the cost of planning units was calculated as per scenarios 1.4 above.
3. We determined which primary conservation features are driving the prioritisation of the refugia across the managed floodplain when all management constraints are considered. To achieve this aim we performed analysis on specific taxonomic groups, ecosystem diversity and ecosystem services: Crayfish; frogs; molluscs; Odonata; fish; plants; ANAE ecosystem classes; productivity measured as carbon sequestration.

3 Results

3.1 Conservation values supported by Commonwealth environmental water

- Within the managed floodplain. more than 80% of species associated with depressional wetlands and lakes considered in this study have potentially benefited from Commonwealth environmental watering actions.
- More than 75% of ecosystem types in the ANAE may benefit from watering actions as they are represented within the sphere of influence of wetlands and lakes that have received CEWH water for the environment.

3.1.1 Ecosystem diversity

- There are 46 freshwater ANAE ecosystem types within the sphere of influence of all freshwater depressional waterbodies in the Basin; 42 of these are represented within the managed floodplain, and 32 (of these 42) have potentially benefited from environmental water delivery (Table A.1).
- All ANAE ecosystem types have at least one ANAE type within their circle of influence i.e., themselves. Most planning units have one other ecosystem within their circle of influence – mean 1.864, range 1–9 and SD 0.937. Planning units with the highest surrounding wetland diversity include Wetlands and lakes in the Edward/Kolety–Wakool and Paroo River systems.
- The wetland with the highest diversity of ecosystems within its circle of influence was on the Murrumbidgee River, surrounded by 9 unique ANAE types (Figure 2.2).

3.1.2 Species diversity

At the Basin level we considered 294 species with distributions overlapping the depressional wetlands and lakes that comprised the planning units.

- Within the managed floodplain, 266 species had distributions overlapping with planning units and 219 species had distributions that intersected planning units that had previously received environmental water (Table A.2 to Table A.7).
- Wetland species with distributions within the Basin but not found within the managed floodplain included 9 species of frog, one species of plant, 10 species of crayfish and 8 Odonata.
- Distributions of all species of wetland-dependent fish and molluscs were found within the managed floodplain.
- Species with distributions within the managed floodplain that have not received Commonwealth environmental water included 20 species of frog, 13 species of Odonata, 11 species of crayfish and 3 species of mollusc.
- All of the plant and fish species considered with distributions within the managed floodplain have received Commonwealth environmental water.

3.1.3 Productivity

- The mean rate of carbon sequestration was higher in watered planning units (i.e., those that have received environmental water) than the mean rate of carbon sequestration across the managed floodplain (i.e., watered and unwatered planning units on the managed floodplain), 302.37 Mg/ha ± 320.46 SD compared to 165.16 Mg/ha ± 255.16 SD respectively.

3.2 High priority lakes and wetlands

The MAXAN algorithm prioritises (ranks) planning units for their conservation value and then selects the highest rankings for inclusion in the ‘network’ while minimising costs. Here we identify the lakes and wetlands that are a high priority for conservation based on their importance to different taxa, and ecosystems productivity and may act as refugia to drying and should be considered in the prioritisation of environmental water.

3.2.1 Prioritisation using all conservation features under different cost constraints for all planning units in the managed floodplain

- The ranking of planning units was highly consistent across all cost scenarios, with ~80% of planning units either consistently selected as either in or out of the best prioritisation networks.
- Catchment condition and connectivity had the largest effect on planning unit selection, with a 20–22% change in planning unit ranking.
- Management feasibility (as indicated by previous environmental water delivery) had the smallest effect on prioritisation.
- There was no apparent geographic effect of the different cost scenarios on the selection of planning units in the best conservation scenarios, with changes in planning unit selection occurring within wetland systems rather than between wetland systems and catchments.
- Areas identified as high priority refugia, under all cost constraints for all taxa, productivity and ANAE diversity, included the wetlands around Lake Alexandrina, the region of Barmah Forest, Lake Wallawalla, Great Cumbung Swamp and surrounding wetlands, Lake Buloke and the Macquarie Marshes (Figure 3.1), many wetlands and lakes along the Paroo, Murrumbidgee, Warrego, and Murray rivers (Figure 3.1) and some wetlands on the Gwydir, Namoi and Merivale rivers were also identified as high priority.

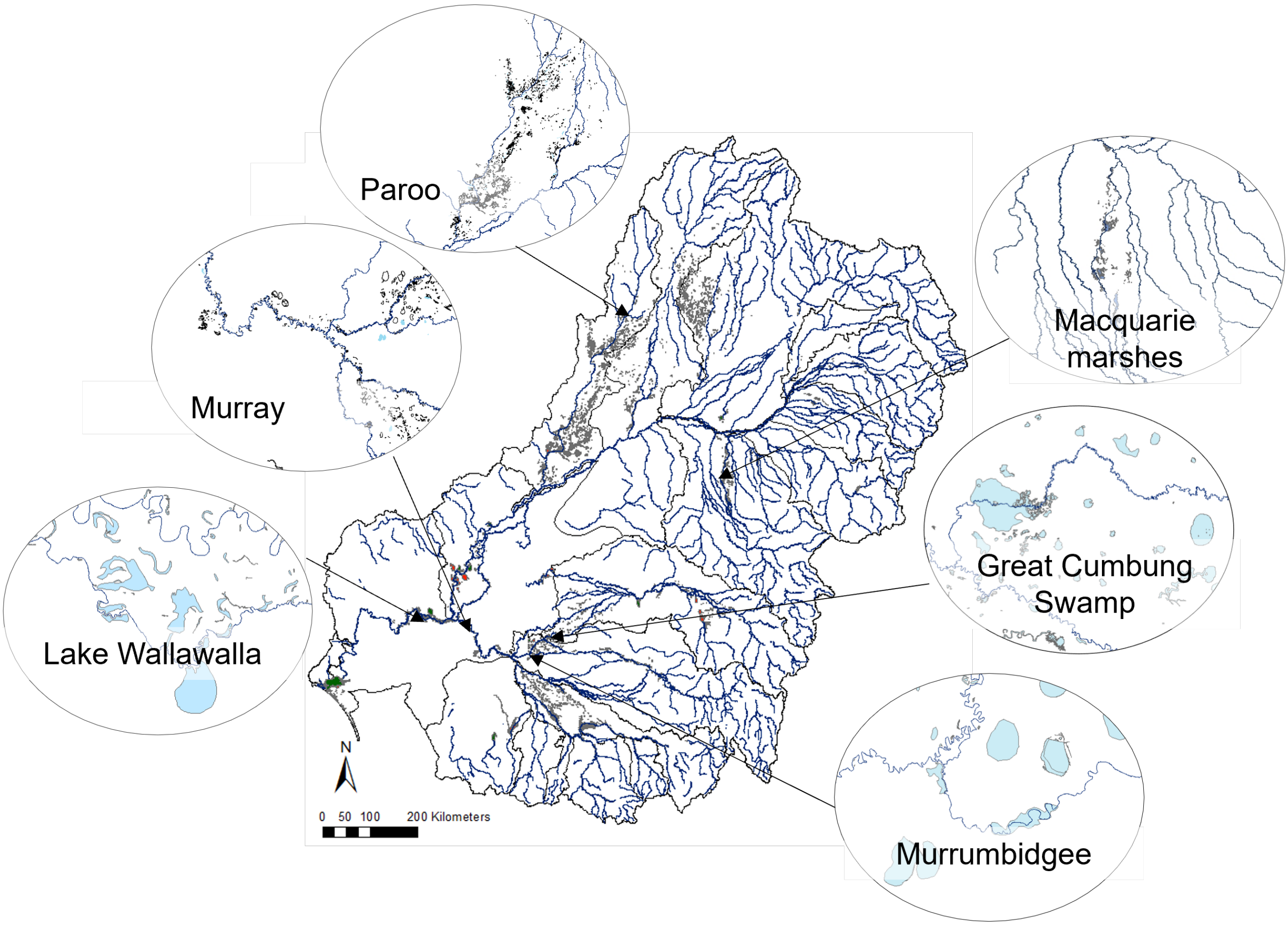

Figure 3.1 Key areas prioritised as refugia from disturbance and drying accounting for management feasibility for the conservation of animal, plant and ecosystem diversity and productivity
Areas identified include Lake Walla Walla and the Great Cumbung Swamp and surrounding wetlands, the Macquarie Marshes, and Wetlands and lakes along the Murrumbidgee, Warrego and Paroo Rivers.

3.2.2 Prioritisation scenarios including prior watered planning units only

The various SCP scenarios were re-evaluated using only those planning units that have received Commonwealth environmental water since 2014 to identify potential high priority refugia among the locations that we know can be managed with certainty. Using RDI and water permeance as a discount cost, selecting for more pristine areas and with higher water permeance. The areas prioritised for the conservation of all target taxa, ANAE, and productivity that had received prior environmental water were Barmah Forest, Lake Alexandrina and Wallawalla and surrounding wetlands (Figure 3.2). Many wetlands and lakes along the Murrumbidgee, Warrego, Murray and Namoi Rivers (Figure 3.2) were also identified and some wetlands on the Gwydir River.

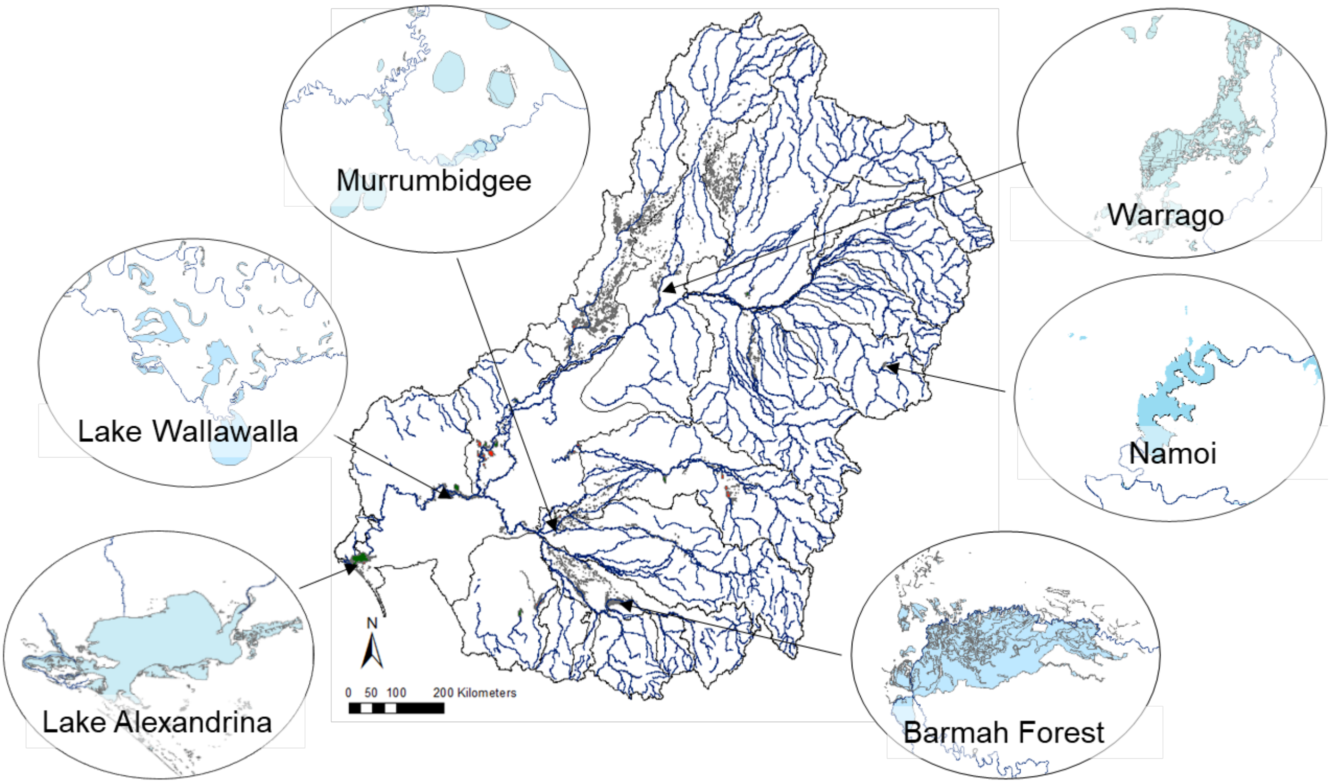

Figure 3.2 Key areas prioritised as refugia from disturbance and drying for the conservation of animal, plant and ecosystem diversity and productivity that have received CEWH water
Areas include Lake Alexandrina, Barmah Forest, Lake Wallawalla and surrounding wetlands, Wetlands and lakes along the Murrumbidgee, Warrego and Namoi Rivers and some on the Gwydir.

3.2.3 Prioritisations for primary conservation feature classes for all planning units in the managed floodplain

To determine which primary conservation features were driving the prioritisation of the refugia for biodiversity conservation across the managed floodplain when all management constraints are considered, 8 comparative prioritisation scenarios were run for ecological feature subsets including ANAE classes, terrestrial productivity, and wetland-taxa.

- While there were some clear differences in the prioritisation of planning units when considering representativeness in different features, overall, the prioritisations of planning units were fairly consistent, with planning units being located in similar geographic locations.
- ANAE classes changed the ranking of planning units the most, followed by wetland fish.
- The importance for carbon sequestration and the representativeness of mollusc species changed the ranking of planning units the least.
- The largest differences between the selection of planning units were between prioritisations for (i) ANAE classification and fish, (ii) ANAE classification and Odonata and (iii) ANAE classification, and plants, with 26%, 25% and 25% planning units changing in the ranking of planning units, respectively.
- The smallest difference was between biomass, and plant diversity, and crayfish, and mollusc diversity, both with a ~17% change in the ranking of planning units.
- Among the top ranked planning unites, the prioritisation for the ANAE was the most inconsistent (e.g., a planning unit was not selected, even though it was in the other 7 prioritisation scenarios).
- In sites that were rarely selected in the ecological prioritisations (e.g., planning units that were selected only once across the 8 prioritisations), ANAE classification accounted for the most ~40%,

followed by the fish 23% prioritisation with prioritisation of all other taxa groups accounting for >6% and biomass only 3%.

- Planning units that receive Commonwealth environmental water were well represented in the subset of high conservation value planning units selected by our SCP process. In the lower Murray, many sites that frequently received Commonwealth environmental water were identified as important for all ecological assets, except ANAE classifications. Planning units in the Murrumbidgee and Warrego Rivers that regularly receive environmental water were also well represented.
- However, sites that had not received Commonwealth environmental water in the past were also identified in the Warrego, Lachlan, Border Rivers and Condamine-Culgoa.
- Multiple wetlands and lakes in the Paroo River were highlighted as important for all or the majority of taxonomic groups; for example, either all or 7 of the 8 scenarios used to determine which taxonomic groups were driving the prioritisation of planning units as refugia for biodiversity conservation. These sites in the Paroo system have not previously received Commonwealth environmental water.

4 Discussion

Here we applied a systematic conservation planning (SCP) method to identify wetlands and lakes in the Murray–Darling Basin that are essential refugia habitats for the target conservation features considered here. The important refugia habitats identified by the prioritisation should be considered when managing environmental water during drought conditions. The ranking of planning units was influenced more by their importance as refugia for different conservation features than their cost as refugia (i.e., size, condition (RDI), water permeance and the feasibility of management).

Current actions for delivering water to the environment are reaching the majority of ecosystems (as defined by the ANAE) and supporting species diversity on the managed floodplain. For example, all the species of wetland fish are found in planning units identified as refugia that have received environmental water. However, diversity of some species on the managed floodplain is not as well targeted by environmental water, most notably some invertebrate species such as frogs and crayfish.

4.1 Drivers of the prioritisation networks

River condition had the largest effect on the ranking of planning unites as potential refugia in our SCP process, and feasibility had the least effect. The different cost scenarios did not appear to strongly affect where selected planning unit were located across the Basin. This result is likely due to a spatial correlation between feasibility and water permanence. Previous delivery of water for the environment was used as an indication of 'feasibility', and locations that regularly receive environmental water will also likely experience greater water permanence as a result. Alternatively, environmental water is often used to top-up permanent waterbodies to prevent drying. A correlation between feasibility and RDI is also likely because sites that are less disturbed may be more likely to managed (e.g., watered) for biodiversity.

The SCP-rankings of planning units were relatively consistent across taxonomic groups and productivity but was less consistent between taxonomic groups and productivity and ANAE classes. Of the different taxonomic groups considered, fish had the largest effect on the planning units identified as priority areas as refugia for biodiversity conservation. This is consistent with previous prioritisations within the Basin. For example, Linke et al. (2015) conducted SCP using sub-catchments in the Basin and found the largest influences to planning unit selection were from fish and vegetation.

Overall, ANAE type had the largest effect on the prioritisation, causing the largest difference in site selection when considered alone. Even the prioritisation of planning units for ecosystem diversity (ANAE) and targeted vegetation species was not well correlated despite vegetation types contributing to the ANAE classifications. The lack of a correlation between the ANAE and vegetation prioritisations is likely due to the additional complexity included in the ANAE and the broad dominate vegetation categories used in the ANAE (e.g. Aquatic grass/sedge/forb, Black box, Bogs and fens, River red gum, etc). We recommend that ecologically and culturally important plant species such as *Marsilea drummondii* should be separately targeted if they are the aim of conservation watering actions.

4.2 Environmental water

Over three quarters of the ecosystem types within the managed floodplain have received water for the environment or are proximal to a planning unit that has received Commonwealth environmental water.

Consequently, the distinct ecosystems and communities within these ANAE types may benefit from environmental water. Our result suggests a large proportion of the ecosystem diversity in the Basin is already serviced by environmental water (Table A.1). There are some temporary ANAE ecosystem types on the managed floodplain that have not previously received environmental water and that could benefit from delivery and should be considered in future environmental water planning.

We found planning units that have previously received environmental water had higher productivity in terms of carbon sequestration on average than planning units that had not received managed water. This suggests management is supporting higher productivity sites, i.e., more productive sites are more likely to receive environmental water. Thus, environmental water may be supporting greater species abundances, more diversity and higher trophic levels as these are known to be driven by high productivity (Waide et al. 1999).

Current actions to deliver environmental water are supporting the majority of the wetland species diversity on the managed floodplain that we quantified. This is particularly true for the fish and molluscs as all were found in wetlands and lakes that have received environmental water. Many of the same wetlands and lakes identified as priority areas for biodiversity conservation in this study were similarly identified in a systematic conservation plan specifically for the waterbirds in the Basin (see Bino et al. 2015). However, watering actions targeted towards the protection of fish and birds may not protect other taxa and by comparison, frogs and many invertebrates including molluscs, crayfish, and odonates on the managed floodplain are not currently in areas that have received Commonwealth water for the environment. Many of the Basin’s invertebrate species including mussels and crayfish are considered to be keystone species and important components of a healthy riverine and terrestrial food-weds (Noble et al. 2018; Sheldon and McCasker 2020). Generally ecological and life-history information are often limited for many invertebrate taxa (Bennett et al. 2018; Marsh et al. 2022) and the environmental water needs of many of the Basin’s invertebrate taxa are poorly understood (Marsh et al. 2022). For example, little is known about the ecology and life-cycle of the small range endemic crayfish species *Engaeus orientalis* which is found within the managed floodplain but has not been recorded in an area receiving environmental water. Further study is needed to determine if the species that are not currently receiving environmental water would benefit from its delivery now or in the future. Many species of wetland frogs, crayfish and Odonata are underrepresented on the managed floodplain and additional management levers other than environmental water may need to be considered for their conservation.

Our analysis is restricted to the areas where environmental water can currently be delivered, i.e. the managed floodplain. As part of the basin plan reforms, the Murray Darling Basin Authority developed the Constraints Management Strategy that aims at expanding the area environmental water can be delivered to in seven regions of the basin. In the future, this analysis can be expanded to include new areas and habitats that environmental water can reach. The SCP approach could also be used to prioritise which habitats and potential refugia would benefit most from future environmental water deliveries and relaxation of constraints.

4.3 Limitations and knowledge gaps

Here we used individual wetlands and lakes mapped by the ANAE as our spatial planning units. Although there are many benefits to using the ANAE as a spatial framework, it also presents a number of challenges. Firstly, little is known about inundation patterns to individual wetlands (Linke et al. 2015), although recent developments in the wetland insights tool (WIT) are a promising advancement in this area. Water for the environmental will likely flow between wetland complexes and further work is needed to understand and incorporate these patterns into conservation planning. This is especially necessary when accounting for re-use of environmental water in return-flows. Secondly, the resolution and spatial extent of this study may need to be tailored for implementation in management decisions. For example, management decisions may be made at the catchment scale or sub-basin scale, when only a proportion of the Basin is under water stress. In this instance, SCP could be conducted at multiple scales to ensure basin and catchment level diversity is captured by watering plans. Finally, the difference scales of the data sources may also affect the outcomes of prioritisation. For example, there are often multiple ANAE wetlands within each of the Level 15 Geofabric subcatchments and ANAE wetlands and lakes can also span multiple Level 15 Geofabric subcatchments. In future work, RDI and species distribution models at the subcatchment scale could be refined to the wetland scale by enhancing the existing data via expert knowledge.

Future work should incorporate species trait data into the analysis. What habitats will act as refugia for a given organism will depend on their traits, especially life history traits. For example, species with long generation times will take longer to respond to environmental water and may need multiple watering events or longer wettings to complete their life cycle. Furthermore, species with distinct life stages may require multiple refugia habitats to complete their life cycle (Wilbur 1980). For example, some frog species are only water dependant for half the year and some for the other half (Rogers and Ralph 2010). In these cases, the most logical way to easily adapt the prioritisation process would be to conduct seasonal SCP optimizations.

One of the major objectives of the Ramsar Convention on Wetlands (1971) is that the ecological character of Wetlands of International Importance be preserved. Many of the wetlands and lakes in the Basin are experiencing altered wetting regimes due to flow regulation. Therefore, the dryness anomaly used here may not reflect the natural drying patterns of the wetlands and lakes and therefore may not represent the original characteristics of the wetlands. In future analysis, refugia could be identified using climate-tracking and microclimate approaches. Climate tracking is used to project where current climate conditions will be spatially redistributed under future climate scenarios to identify in situ (where climate remain stable) and ex situ refugia (where suitable climatic conditions will be in the future) (Ashcroft 2010). This approach can incorporate information on microclimate to identify environments where the local climate is decoupled from the regional climate due to topography (Ashcroft et al. 2012) or groundwater inputs (Davis et al. 2013).

5 Conclusion and recommendations

Here we piloted the use of systematic conservation planning (SCP) tools and readily available data for the prioritisation of water for the environment with the aim of protecting refugia habitats for biodiversity and ecosystem function in the Basin. The approach provides an objective and repeatable process that can be applied broadly across the Basin at multiple scales to support Annual Environmental Watering Priorities. While there were many similarities in the areas included in the prioritisations under different cost scenarios and for different ecological assets, there were also marked differences showing the importance of setting clear goals and objectives for the prioritisation. Prioritisations for different conservation features caused clear changes in the ranking of planning units. Further, more data on ecological traits is needed to identify spatiotemporal changes in refugia for target species. Better data on the feasibility of water delivery and on the flow of environmental water is needed to improve the reliability of the outcomes. We recommend applying a systematic approach to support future water delivery action that can target specific objects, ecological assets and scales. We show this could be done to inform the management of environmental water delivery in the Murray–Darling Basin using open access, readily available, data and systematic conservation planning tool.

5.1 Contribution to Flow-MER objectives

This project aimed to inform management capacity to:

- target environmental flows towards keystone ecosystems for diversity and dispersal
- consider ecosystem function in conjunction with biodiversity when allocating e-flows
- target e-flows to protect and promote specific species groups or life stages.

Project outcomes are relevant to a wide range of Flow-MER themes and objectives including:

- Biodiversity Theme
  - Ecosystem diversity
    - Is Commonwealth environmental water supporting representative ecosystems?
  - Species diversity
    - What did Commonwealth environmental water contribute to species diversity?
- Water quality and Food webs Theme
  - What did Commonwealth environmental water contribute to patterns and rates of primary productivity?
- Vegetation Theme
  - What did Commonwealth environmental water contribute to plant species diversity?
- Fish theme
  - What did Commonwealth environmental water contribute to sustaining native fish at the Basin-scale?

5.2 Recommendations

- Detailed mapping of the flow of environmental water and where environmental water can be delivered is needed at the Basin scale. We recommend building on and improving the accuracy of the managed floodplain mapping and using tools like the geofabric directional flow networks to quantify flows of environmental water as it traverses the catchment.
- More data on the distribution of important taxa and their ecological needs is needed to refine predictions. Flow-MER has made some significant advances in collating and analysing species traits for vegetation and for fish. However, there is less trait data available for Invertebrate taxa, which are often recognised as keystone species and underrepresented in environmental watering actions. Species trait data should be used to refine and improve the SCP process, for example, prioritisations could be run seasonally to consider the arrival of critical migratory species. We recommend prioritising the collection of trait data for other important taxonomic groups.
- For targeting specific management objectives, multi-scale basin-wide, sub-basin or valley prioritisations may be required. The approach demonstrated here for the Basin-scale should be replicated at other scales, for example, the catchment scale.
- Additional cost constraints should also be examined, especially if they are required to meet environmental obligations, for example, Ramsar sites. This can be easily incorporated into a SCP process by designating planning units that are Ramsar sites as sites that are always including in prioritisation network.

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Appendix A Conservation features associated with depressional wetland and lakes across the Basin that are represented on the managed floodplain and those that receive environmental water

Table A.1 Distinct ecosystems as classified under the ANAE that are within the circle of influence of depressional water bodies in the Basin that are represented (indicated by X) on the managed floodplain (column 2 Managed floodplain) and those that have received Commonwealth environmental water (column 3 Watered).

ANAE TYPE	Managed floodplain	Watered
F1.10: Coolibah woodland and forest riparian zone or floodplain	X	X
F1.11: River cooba woodland riparian zone or floodplain	X	X
F1.12: Woodland riparian zone or floodplain	X	X
F1.13: Paperbark riparian zone or floodplain	X	X
F1.2: River red gum forest riparian zone or floodplain	X	X
F1.4: River red gum woodland riparian zone or floodplain	X	X
F1.6: Black box forest riparian zone or floodplain	X	
F1.8: Black box woodland riparian zone or floodplain	X	X
F2.2: Lignum shrubland riparian zone or floodplain	X	X
F2.4: Shrubland riparian zone or floodplain	X	X
F3.2: Sedge/forb/grassland riparian zone or floodplain	X	X
F4: Unspecified riparian zone or floodplain	X	X
Lp1.1: Permanent lake	X	X
Lp1.2: Permanent lake with aquatic bed	X	
Lt1.1: Temporary lake	X	X
Lt1.2: Temporary lake with aquatic bed	X	
Pp1.1.2: Permanent paperbark swamp		
Pp2.1.2: Permanent tall emergent marsh	X	X
Pp2.2.2: Permanent sedge/grass/forb marsh	X	
Pp2.3.2: Permanent grass marsh	X	X
Pp2.4.2: Permanent forb marsh	X	X
Pp3: Peat bog or fen marsh	X	

ANAE TYPE	Managed floodplain	Watered
Pp4.2: Permanent wetland	X	X
Pps5: Permanent spring		
Pt1.1.2: Temporary river red gum swamp	X	X
Pt1.2.2: Temporary black box swamp	X	X
Pt1.3.2: Temporary Coolibah swamp	X	
Pt1.5.2: Temporary paperbark swamp		
Pt1.6.2: Temporary woodland swamp	X	X
Pt1.7.2: Temporary lignum swamp	X	X
Pt1.8.2: Temporary shrub swamp	X	X
Pt2.1.2: Temporary tall emergent marsh	X	X
Pt2.2.2: Temporary sedge/grass/forb marsh	X	X
Pt2.3.2: Freshwater meadow	X	X
Pt3.1.2: Clay pan	X	X
Pt4.2: Temporary wetland	X	X
Rp1.1: Permanent high energy upland stream	X	
Rp1.2: Permanent transitional zone stream	X	X
Rp1.3: Permanent low energy upland stream	X	
Rp1.4: Permanent lowland stream	X	X
Rp1: Permanent stream		
Rt1.1: Temporary high energy upland stream	X	
Rt1.2: Temporary transitional zone stream	X	X
Rt1.3: Temporary low energy upland stream	X	
Rt1.4: Temporary lowland stream	X	X
Rt1: Temporary stream	X	X

Table A.2 Plant Species associated with depressional lakes and wetlands in the Basin that are represented (indicated by X) on the managed floodplain (column 2 Managed floodplain) and those that have received Commonwealth environmental water (column 3 Watered)

Species	Managed floodplain	Watered
Acacia pendula	X	X
Acacia stenophylla	X	X
Bolboschoenus caldwellii	X	X
Bolboschoenus fluviatilis	X	X
Bolboschoenus medianus	X	X
Cyperus bifax	X	X
Cyperus concinnus	X	X
Cyperus difformis	X	X
Cyperus exaltatus	X	X
Cyperus gymnocaulos	X	X
Cyperus rigidellus	X	X
Eleochari pusilla	X	X
Eleocharis acuta	X	X
Eleocharis plana	X	X
Eleocharis sphacelata	X	X
Eucalyptus camaldulensis	X	X
Eucalyptus coolabah	X	X
Eucalyptus largiflorens	X	X
Isotoma axillaris	X	X
Isotoma fluviatilis	X	X
Isotoma tridens	X	X
Juncus aridicola	X	X
Juncus flavidus	X	X
Juncus ingens	X	X
Juncus pallidus	X	X
Juncus usitatus	X	X
Lobelia concolor	X	X
Lobelia purpurascens	X	X
Ludwigia octovalvis	X	X
Ludwigia peploides	X	X
Marsilea costulifera	X	X
Marsilea drummondii	X	X
Marsilea exarata		
Marsilea hirsuta	X	X
Marsilea mutica	X	X
Muehlenbeckia florulenta	X	X

Species	Managed floodplain	Watered
Nymphaea caerulea	X	X
Nymphoides geminata	X	X
Nymphoides indica	X	X
Nymphoides montana	X	X
Phragmites australis	X	X
Ranunculus inundatus	X	X
Ranunculus pumilio	X	X
Ranunculus undosus	X	X
Typha domingensis	X	X
Typha orientalis	X	X
Vallisneria australis	X	X
Vallisneria nana	X	X

Table A.3 Fish species associated with depressional lakes and wetlands in the Basin that are represented (indicated by X) on the managed floodplain (column 2 Managed floodplain) and those that have received Commonwealth environmental water (column 3 Watered)

Species	Managed floodplain	Watered
Ambassis agassizii	X	X
Bidyanus bidyanus	X	X
Craterocephalus fluviatilis	X	X
Craterocephalus stercusmuscarum fulvus	X	X
Hypseleotris sp	X	X
Leiopotherapon unicolor	X	X
Maccullochella macquariensis	X	X
Maccullochella peelii peelii	X	X
Macquaria ambigua ambigua	X	X
Macquaria australasica	X	X
Melanotaenia fluviatilis	X	X
Mogurnda adspersa	X	X
Nematalosa erebi	X	X
Philypngrandiceps	X	X
Philypnmacrostomus	X	X
Retropinna semoni	X	X
Tandanus tandanus	X	X

Table A.4 Frog species associated with depressional lakes and wetlands in the Basin that are represented (indicated by X) on the managed floodplain (column 2 Managed floodplain) and those that have received Commonwealth environmental water (column 3 Watered)

Species	Managed floodplain	Watered
Adelotus brevis		
Crinia deserticola	X	
Crinia parinsignifera	X	X
Crinia riparia	X	X
Crinia signifera	X	X
Crinia sloanei	X	X
Cyclorana brevipes	X	X
Cyclorana cultripes	X	X
Cyclorana novaehollandiae	X	X
Cyclorana platycephala	X	X
Cyclorana verrucosa	X	X
Geocrinia victoriana	X	X
Heleioporus australiacus	X	X
Lechriodus fletcheri		
Limnodynastes dumerilii	X	X
Limnodynastes fletcheri	X	X
Limnodynastes interioris	X	X
Limnodynastes peronii	X	X
Limnodynastes salmini	X	X
Limnodynastes tasmaniensis	X	X
Limnodynastes terraereginae	X	X
Litoria alboguttata	X	X
Litoria aurea	X	X
Litoria barringtonensis		
Litoria booroolongensis	X	X
Litoria caerulea	X	X
Litoria castanea	X	X
Litoria chloris	X	
Litoria citropa	X	
Litoria dentata	X	X
Litoria ewingii	X	X
Litoria fallax	X	
Litoria jervisiensis		
Litoria latopalmata	X	X
Litoria lesueuri	X	X
Litoria littlejohni	X	

Species	Managed floodplain	Watered
Litoria nudidigita	X	
Litoria paraewingi	X	X
Litoria pearsoniana	X	
Litoria peronii	X	X
Litoria phyllochroa	X	
Litoria piperata	X	
Litoria raniformis	X	X
Litoria revelata	X	
Litoria rubella	X	X
Litoria spenceri	X	
Litoria subglandulosa		
Litoria tyleri	X	X
Litoria verreauxii alpina	X	
Litoria verreauxii	X	X
Litoria wilcoxii	X	X
Mixophyes balbus	X	
Mixophyes fasciolatus	X	
Mixophyes iteratus		
Neobatrachus pictus	X	X
Neobatrachus sudelli	X	X
Notaden bennettii	X	X
Opisthornatus	X	X
Paracrinia haswelli	X	X
Philoria frosti		
Philoria pughi		
Pseudophryne australis	X	
Pseudophryne bibroni	X	X
Pseudophryne coriacea	X	
Pseudophryne corroboree	X	
Pseudophryne dendyi	X	
Pseudophryne major	X	X
Pseudophryne pengilleyi	X	
Uperoleia fusca	X	X
Uperoleia laevigata	X	X
Uperoleia martini		
Uperoleia rugosa	X	X
Uperoleia tyleri	X	X

Table A.5 Odonta species associated with depressional lakes and wetlands in the Basin that are represented (indicated by X) on the managed floodplain (column 2 Managed floodplain) and those that have received Commonwealth environmental water (column 3 Watered)

Species	Managed floodplain	Watered
Adversaeschna brevistyla	X	X
Aethriamanta circumsignata		
Agrionoptera insignis allogenes	X	X
Apocordulia macrops	X	X
Archaeophya adamsi	X	
Archaeosynthemis orientalis	X	X
Austroaeschna atrata	X	
Austroaeschna cooloola		
Austroaeschna flavomaculata	X	X
Austroaeschna inermis	X	X
Austroaeschna multipunctata	X	X
Austroaeschna obscura		
Austroaeschna parvistigma	X	X
Austroaeschna sigma	X	X
Austroaeschna subapicalis	X	X
Austroaeschna unicornis	X	X
Austroagrion exclamationis	X	X
Austroargiolestes amabilis	X	
Austroargiolestes brookhousei	X	
Austroargiolestes calcaris	X	X
Austroargiolestes christine		
Austroargiolestes isabellae	X	X
Austroepigomphus praeruptus	X	X
Austrogomphus guerini	X	X
Austrogomphus ochraceus	X	X
Austrolestes analis	X	X
Austrolestes cingulatus	X	X
Austrolestes minjerriba	X	
Austrolestes psyche	X	X
Austropetalia tonyana	X	X
Austrophlebia costalis	X	X
Austrothemis nigrescens	X	X
Brachydiplax denticauda	X	X
Caliagrion billinghursti	X	X
Ceriagrion aeruginosum	X	X
Coenagrion lyelli	X	X

Species	Managed floodplain	Watered
Cordulephya montana	X	X
Cordulephya pygmaea	X	X
Dendroaeschna conspersa	X	X
Diphlebia coerulescens	X	X
Diphlebia lestoides	X	X
Diphlebia nymphoides	X	X
Diplacodes melanopsis	X	X
Diplacodes trivialis	X	X
Episynlestes albicauda	X	X
Eusynthemis aurolineata	X	X
Eusynthemis brevistyla	X	X
Eusynthemis guttata	X	X
Eusynthemis nigra	X	
Eusynthemis rentziana	X	
Eusynthemis tillyardi	X	X
Eusynthemis ursula	X	
Eusynthemis virgula	X	X
Griseargiolestes bucki	X	
Griseargiolestes eboracus	X	X
Griseargiolestes fontanus	X	
Griseargiolestes griseus	X	X
Griseargiolestes intermedius	X	
Hemicordulia continentalis	X	X
Hemicordulia superba	X	X
Hemigomphus gouldii	X	X
Hemigomphus heteroclytus	X	X
Hydrobasileus brevistylus	X	X
Ischnura heterosticta	X	X
Lestes concinnus	X	X
Macrodiplax cora	X	X
Micromidia atrifrons		
Nannodiplax rubra		
Nannophya australis	X	X
Nannophya dalei	X	X
Neosticta canescens	X	X
Notoaeschna geminata	X	X
Notoaeschna sagittata	X	X
Orthetrum boumiera	X	X

Species	Managed floodplain	Watered
Orthetrum sabina	X	X
Petalura gigantea	X	X
Procordulia jacksoniensis	X	X
Pseudagrion cingillum	X	X
Spinaeschna tripunctata	X	X
Synlestes selysi	X	X
Synlestes weyersii	X	X
Synthemis eustalacta	X	X
Telephlebia brevicauda	X	X
Telephlebia cyclops		
Telephlebia godeffroyi	X	
Tonyosynthemis ofarrelli	X	
Tramea eurybia		

Table A.6 Crayfish species associated with depressional lakes and wetlands in the Basin that are represented (indicated by X) on the managed floodplain (column 2 Managed floodplain) and those that have received Commonwealth environmental water (column 3 Watered)

Species	Managed floodplain	Watered
Cherax albidus	X	X
Cherax bicarinatus	X	X
Cherax cairnsensis	X	
Cherax cuspidatus	X	
Cherax depressus	X	
Cherax destructor	X	X
Cherax quadricarinatus	X	
Cherax setosus	X	X
Engaeus affinis	X	X
Engaeus cymus	X	X
Engaeus hemicirratulus	X	
Engaeus lyelli	X	X
Engaeus orientalis		
Engaeus quadrimanus	X	X
Engaeus tuberculatus	X	
Euastacus armatus	X	X
Euastacus australasiensis		
Euastacus bidawalus	X	
Euastacus bispinosus	X	X
Euastacus claytoni	X	X
Euastacus crassus	X	

Species	Managed floodplain	Watered
Euastacus diversus		
Euastacus gamilaroi		
Euastacus hirsutus	X	X
Euastacus kershawi	X	X
Euastacus neohirsutus		
Euastacus polysetosus		
Euastacus rieki	X	X
Euastacus simplex		
Euastacus spinichelatus		
Euastacus spinifer	X	X
Euastacus sulcatus	X	
Euastacus suttoni		
Euastacus woiwuru	X	
Euastacus yanga		
Geocharax falcata	X	

Table A.7 Mollusc species associated with depressional lakes and wetlands in the Basin that are represented (indicated by X) on the managed floodplain (column 2 Managed floodplain) and those that have received Commonwealth environmental water (column 3 Watered)

Species	Managed floodplain	Watered
Alathyria jacksoni	X	X
Amerianna truncata	X	
Austropeplea brazieri	X	X
Austropeplea lessoni	X	X
Austropeplea tomentosa	X	X
Austropeplea vinosa	X	
Corbicula australis	X	X
Ferrissia petterdi	X	X
Ferrissia tasmanica	X	X
Gabbia vertiginosa	X	X
Glacidorbis hedleyi	X	X
Glyptophysa aliciae	X	X
Glyptophysa gibbosa	X	X
Gyraulus gilberti	X	X
Gyraulus scottianus	X	X
Gyraulus waterhousei	X	X
Helicorbis australiensis	X	X
Isidorella newcombi	X	X
Musculium tasmanicum	X	X

Species	Managed floodplain	Watered
Notopala kingi	X	X
Notopala sublineata	X	X
Physa acuta	X	X
Pisidium carum	X	X
Pisidium etheridgei	X	X
Pisidium hallae	X	X
Pisidium tasmanicum	X	X
Posticobia brazieri	X	X
Potamopyrgus antipodarum	X	X
Pseudosuccinea columella	X	X
Thiara australis	X	
Thiara balonnensis	X	X
Velesunio ambiguus	X	X
Velesunio wilsonii	X	X

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