Flow-MER Basin-scale research: Summary 2024

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

November 2024

Australian Government
Commonwealth Environmental Water Holder

FLOW Monitoring Evaluation Research

The Flow-MER Program

Flow-MER is the Commonwealth Environmental Water Holder's (CEWH) on-ground Monitoring, Evaluation and Research Program. The Program's objective is to monitor and evaluate environmental outcomes from the delivery of Commonwealth environmental water in the Murray–Darling Basin. It provides the CEWH with evidence to inform our understanding of how water for the environment is helping maintain, protect, and restore the ecosystems and native species across the Murray–Darling Basin. This work will support environmental water managers, demonstrate outcomes, inform adaptive management, and fulfil the legislative requirements associated with managing Commonwealth owned environmental water.

The Flow-MER Basin-scale Project is being undertaken from July 2019 to June 2025 and is led by CSIRO in partnership with the University of Canberra, collaborating with Alluvium, Charles Sturt University, Deakin University, South Australian Research and Development Institute, Arthur Rylah Institute, NSW Department of Primary Industry, University of New England, Australian River Restoration Centre and Brooks Ecology & Technology. The Program delivers to the Science Division of the Commonwealth Environmental Water Holder, Department of Climate Change, Energy, the Environment and Water.

Citation

Cuddy SM*, Thurgate N*, King AJ*, Brooks S, Doody TM, Flett D, Hitchcock JN, McGinness HM, Tonkin Z (2024) Flow-MER Basin-scale research: Summary 2024, Report prepared for the Commonwealth Environmental Water Holder (CEWH), Department of Climate Change, Energy, the Environment and Water, Australia.

Alphabetical order after *. This summary draws on research material and reports prepared by members of the Flow-MER Basin-scale research teams. We acknowledge the valuable contribution of these reports (listed in References) and their authors, all core members of the Basin-scale Flow-MER team. We thank David Post and Jane Thomas of CSIRO for their reviews of the report.

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Document history

Date	Status
31 July 2024	First draft circulated for internal review
August–October 2024	Review and revise period
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Important disclaimer

ACKNOWLEDGEMENT OF COUNTRY

The Flow-MER research team acknowledges the Traditional Owners of the lands and waters of Australia, and in particular the Traditional Owners of the lands and waters of the Murray–Darling Basin. The river and its tributaries are known by many names including: Millewa (Ngarrindjeri name for the main Murray channel in South Australia), Baarka (Barkindji; Darling River, inland New South Wales (NSW), Warring (Taungurung; Goulburn River, Victoria), Kolety (Wamba Wamba; Edwards River, inland NSW), Kalari (Wiradjuri; Lachlan River, inland NSW), Murrumbidjeri (Wiradjuri; Murrumbidgee River, inland NSW) and Guwayda (Kamilaroi; Gwydir River, northern NSW), amongst others. While the European names will be used here, the authors recognise the important associations and history of the Indigenous names for rivers and streams in the Murray–Darling Basin. We express our respect for Elders, past, present and emerging amongst the Nations of the Murray–Darling Basin.

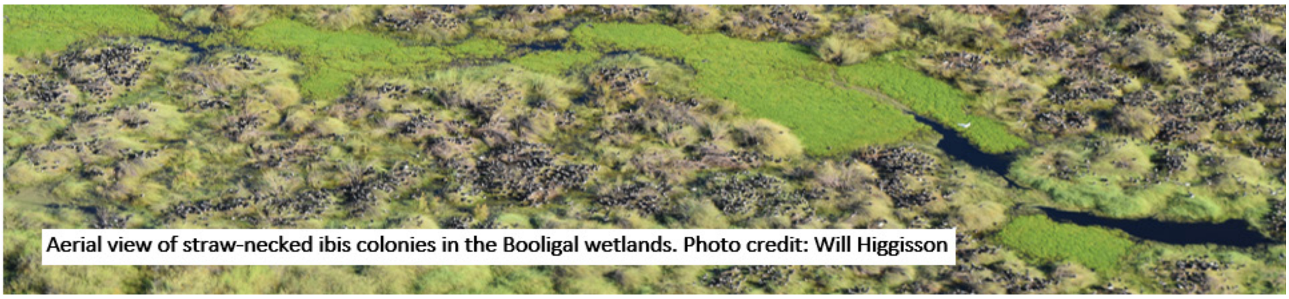
Executive Summary

This report describes the portfolio of research undertaken within the Basin-scale Flow Monitoring, Evaluation and Research Project (Flow-MER). Flow-MER provides the Commonwealth Environmental Water Holder with evidence to inform understanding of how Commonwealth water for the environment is helping maintain, protect, and restore the ecosystems and native species across the Murray–Darling Basin (the Basin). The knowledge Flow-MER generates informs adaptive management so that Commonwealth environmental water can be used to maximise environmental outcomes.

This report presents research summaries for each project in the Basin-scale Flow-MER portfolio, including aims, methods and outcomes, to 30 June 2024 and is an update of the 2023 report.

The Flow-MER Research Plan was informed by a prioritisation and planning exercise undertaken in 2019. Areas of research interest were developed in consultation with the Selected Areas and officers of the CEWH and reviewed by scientific experts from the Science Advisory Group. Thirteen projects were developed, externally reviewed and funded for 2019–22 (see Table 1). The Research Plan was updated and extended for the period 2023–25 in consultation with the CEWH's Science Program and is presented in the Flow-MER Basin-scale Evaluation and Research Plan 2019–2025[1] (ER Plan). Research projects are characterised as:

- **Ongoing –** projects that continue to provide long-term data collection and science partnerships that deliver a continuation of research activities into future programs (to be completed by June 2025). Two projects (**Waterbirds movement** and **Flow-MER Communications and engagement**) are in this category.
- **Extended –** projects where more time and funding have been provided to undertake additional activities within the scope of the original research to refine, generalise or complete outputs, with a particular focus on communication and engagement underpinning adaptive management and evaluation. One project (**Condition**) in this category.
- **Completing –** projects that have completed the planned research activities and are finalising research outputs. Communication, engagement and knowledge exchange activities will continue for many of these projects to ensure the knowledge they have generated will link to adaptive management and evaluation. Three projects (**Scaling, Non-woody plants** and **Ecosystem energetics**) are in this category.
- **Completed** – projects that have completed their research and published their research outputs.



Aerial view of straw-necked ibis colonies in the Booligal wetlands. Photo credit: Will Higgisson

[1] ER Plan V6 (2023-25) submitted to the CEWH 30 June 2024

Table 1 Summary of status @30 June 2024 and (planned or actual) completion dates of Flow-MER research projects

Codes in brackets are those used in earlier reporting.

Project	Short project title	Status @30 June 2024	Planned/actual completion date
	Biodiversity Theme		
1	Waterbird movements (E1)	Ongoing	30 June 2025
2	Refugia (BW1)	Completed	31 December 2023
3	Condition (E2)	Extended	30 March 2025
4	Scaling (E3)	Completing	31 December 2024
	Vegetation Theme		
5	Non-woody plants (V1)	Completing	31 December 2024
6	Remote sensing vegetation (V2)	Completed	31 August 2024
	Fish Theme		
7	Fish populations (F1)	Completed	31 August 2024
8	Fish movement (F2)	Completed	31 August 2023
	Food Webs and Water Quality Theme		
9	Ecosystem energetics (BW3)	Completing	31 October 2024
	Modelling and Visualisation		
10	Flow ecology relationships (BW2)	Completed	31 December 2023
11	Integrative basin modelling (CC2)	Completed	31 December 2022
12	Visualisation (CC1)	Completed	30 June 2022
	Communication and Engagement		
13a	Indigenous engagement	Completed	31 December 2023
13b	Flow-MER communications and engagement	Ongoing	31 August 2025

Research outcome summaries

Project 1 Waterbird movements and site use across the Basin (E1)

Waterbird diversity, populations, and breeding, foraging and refuge sites are managed through decisions affecting water, habitat and other pressures. This research tracks the movements of waterbirds by satellite at local, area and Basin scales. The data show the spatial and temporal scales and drivers of waterbird movements and site use, including breeding, foraging, stopover, refugia and Ramsar sites. Analysis of movement data for straw-necked ibis, royal spoonbill, and Australian white ibis, intermediate egret and great egret is providing information on movement pathways and habitats and their dependency on environmental watering events. This knowledge is directly relevant to planning and management of Commonwealth water for the environment and has contributed to significant improvements to adaptive management of waterbirds in the Basin.

Fieldwork and research are ongoing with the project continuing to collect and analyse movement data and share knowledge to inform adaptive management, evaluation and Basin Plan review through to June 2025. The final report (McGinness et al. 2024) is published, 6 journal papers are at various stages of preparation and visualisations of the tracking data are being developed for delivery through the Flow-MER website.

STATUS: ONGOING

Project 2 Identification and characterisation of refuge habitat (BW1)

Refuges are areas critical for maintaining the resilience of ecosystems during periods of low flow. Key refugia in the Basin have been mapped using geospatial and biodiversity datasets showing how ecological refugia are distributed across the Basin. Research explored options for prioritising locations for water delivery for refugia. The systematic conservation planning approach provides an objective and repeatable process that could be used to prioritise environmental watering of refuges across the Basin.

Research is complete and final report (Bennett et al. 2023) published.

STATUS: COMPLETED

Project 3 Influence of ecosystem condition on responses to environmental water (E2)

Understanding ecosystem condition can help explain environmental outcomes observed in response to environmental watering of different ecosystem types. Research applied measures of ecosystem condition to tailor expected outcomes and evaluation to better match the context under which water is being delivered. Research is linking species outcomes to the ecosystems that support them, and determining how the condition of those ecosystems influences outcomes from water for the environment. The outcomes of this work apply to ecosystem type mapping, environmental water prioritisation frameworks and setting of expected outcomes for watering actions.

The research has developed an evaluation method for describing changes in condition of treed ANAE types that will be described in a research report using case studies (Riverland, Barmah Ramsar sites). The project is extended to early 2025 to finalise reporting.

STATUS: EXTENDED

Project 4 Developing an approach to scaling for evaluating ecosystem diversity (E3)

Flow-MER evaluation needs to be able to evaluate basin-scale ecosystem diversity across different scales and spatial arrangements (related to water delivery). The project team developed methods to scale the evaluation of watering outcomes from the small scale of individual wetlands, up to larger scales, an entire river system and the whole-of-Basin. These methods were used to assess responses to water delivery within and between ANAE ecosystem types.

Research is complete, and final report (Brooks and King 2024) in preparation.

STATUS: COMPLETING

Project 5 Characterising condition for non-woody vegetation in floodplain-wetland systems (V1)

An important part of evaluation is understanding ‘what is good’. Defining what is ‘good’ requires an understanding of what environmental water management is aiming to achieve and why – the objectives, and the functions and values supported; as well as how outcomes will be assessed – such as condition, resilience or thresholds against which to evaluate ‘success’. This research explored the notion of ‘success’ and ‘what is good’; and aimed to rethink the way condition is used to envisage, evaluate and communicate non-woody vegetation outcomes to environmental flows. The resulting structured framework for characterising condition, using both ecological data and societal values, provides practical guidance for water managers to inform condition benchmarks, watering objectives and choice of monitoring metrics. Outcomes have fed into the Flow-MER evaluation of vegetation and are more broadly applicable to monitoring and evaluation of non-woody vegetation outcomes from environmental watering or other management activities.

Research is complete and communicated through PhD journal papers. Final report is in review (Campbell et al. 2024).

STATUS: COMPLETING

Project 6 Remote sensing responses of woody vegetation to environmental water (V2)

Monitoring of the response of ecological function to altered hydrology of woody vegetation is challenging because of the large scales involved and a lack of simple condition metrics. The project team developed a basin-scale remote sensing product to understand changes in tree water stress at a resolution of 30m for each month from 2000–22, for each tree pixel across the Murray–Darling Basin. The remote sensing data is underpinned by robust field data simultaneously collected. This research has improved our understanding of tree response to water availability and allows us to identify water requirement thresholds for woody vegetation. It can then be used to inform the prioritisation of environmental water for woody vegetation and floodplain, wetland and river ecosystems.

Research is complete, journal papers have been written and final report published (Doody et al. 2024).

STATUS: COMPLETED

Project 7 Fish population models to inform Commonwealth environmental watering (F1)

Fish population models are a basin-scale tool for assisting water management and are useful in evaluating different watering scenarios, evaluating likely outcomes, and helping to set monitoring targets for environmental watering. This research explicitly linked flow management to whole-of-lifecycle responses for a suite of native fish species – golden perch, Murray cod and bony herring. Predictive population models are powerful tools for adaptive management, enabling testing of population responses to a range of management scenarios. A research report has been published (Todd et al. 2023) and the Flow-MER fish web pages have been published.

Research was extended to refine the models, address known gaps and undertake sensitivity testing. Outputs are a research note (to the published research report) and a second published report (Todd et al. 2024). Flow-MER webpages will be updated in 2024–25 through the Communication and Engagement project to incorporate dynamic visualisations.

STATUS: COMPLETED

Project 8 Flow, movement and fish population dynamics in the Basin (F2)

Movement is essential for fish population persistence, and in riverine systems, is fundamentally linked to river hydrology and connectivity. Fish movement is also important for resilience and recovery from disturbance events such as hypoxic blackwater events and dry-down. This project evaluated flow triggers for local and regional scale fish movement to improve our understanding of the environmental water requirements among fish species and regions in the Basin. Fish movement datasets were compiled comprising otolith and electronic tagging data from prior projects to model fish movement response in relation to river hydrology and environmental watering. This research improves our understanding of landscape-scale fish movements and population resilience, and informs delivery of environmental water for connectivity, fish passage and maintaining refugia for migrating fish.

Research is complete, Flow-MER webpages updated and research report (Thiem et al. 2023) published.

STATUS: COMPLETED

Project 9 Developing an environmental water energetics response model (BW3)

A bioenergetic model for ecosystem response to environmental water demonstrates how food webs respond to flow, in this case focusing on refuge habitats, wetlands and flowing water habitats. The project team developed an energetics response model to evaluate the contribution of Commonwealth environmental water to food webs, using the Lachlan valley as a case study. This model was used to determine the energetic impacts of different flow scenarios and, in so doing, improve the prediction of ecological outcomes in response to environmental watering. This research is published in technical report (Hitchcock et al. 2024).

This research was extended to model food web responses to environmental flows in the Murray River system using existing data, ultimately informing the utility of this model and the applicability of predictions of ecological outcomes more broadly across the Basin. A technical report and journal papers are in preparation.

STATUS: COMPLETING

Project 10 Using flow-ecology relationships to predict responses to environmental water (BW2)

Flow-ecology relationships describe the relationship between flow and ecological outcomes, in this case, in response to the delivery of environmental water. Understanding these relationships informs adaptive management and evaluation of ecosystem responses to environmental water. The project team developed a novel suite of hydrometrics to identify hydrology and/or inundation metrics driving observed changes in vegetation condition as a case study of the approach. Model outputs identify flow drivers that shape vegetation community patterns. This knowledge improves our understanding of the response of non-woody vegetation to environmental flows.

Research is complete and technical reports published (Repina & Stratford 2020, Lloyd-Jones et al. 2023).

STATUS: COMPLETED

Project 11 Integrative basin modelling (CC2)

This project developed an Integrative Basin Model framework to model ecological response to environmental watering, integrating across desired (or expected) environmental outcomes at the basin-scale. This provides a foundation for future tools to evaluate desired (or expected) outcomes from the delivery of environmental water. The research team developed an integrating basin-scale framework combining Flow-MER information across Basin Themes and Selected Areas. The framework informs our understanding of interactions between thematic areas, scale and locations. Synthesised metrics combine information in space and time, as well as across biotic groups, enabling us to explore scenarios, and test the reasons for observed outcomes at the Basin-scale.

Research is complete, journal paper (Holt et al. 2024) and final technical report (Holt et al. 2023) published.

STATUS: COMPLETED

Project 12 Visualisation (CC1)

This project aimed to develop optimum means of presenting raw and processed data by modelling outputs and research results to inform Flow-MER evaluation, and the adaptive management, decision making and reporting needs of the CEWH. This research integrated data from across thematic areas into data visualization products for communicating the outcomes of basin-scale monitoring, evaluation and research.

The interactive data and mapping prototype illustrates approaches for ’real time’ reporting. Visualisation summaries complement Flow-MER Basin-scale Thematic evaluation reports; annual water year and cumulative summaries show key findings and visualisations of the outcomes of Commonwealth environmental water.

Research is complete, report is published (Nolan and Cuddy 2022) and evaluation summaries have been transitioned to evaluation.

STATUS: COMPLETED

Project 13 Co-designing engagement with Indigenous peoples for better environmental water delivery

This research met a need for contextual information and synthesis of Indigenous perspectives on water management as an input to environmental water management. The approach recognised the challenges in achieving productive and sustainable partnerships with Indigenous people at a national scale and addressed those challenges in narrative form. Research framed engagement of Indigenous perspectives on Australian water management with a particular focus on environmental water, describing successful engagement drawn from Selected Areas and a case study developed in partnership with traditional owners on-country (Woodward et al. 2020, available on request).

Research is complete. Products include report (Woodward et al. 2020), book chapter (Moggridge and Thompson 2024) and guidance on principles and practices for Indigenous engagement (Thompson et al. 2024).

STATUS: COMPLETED

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ABBREVIATIONS AND TERMS

Abbreviation	Definition
ANAE	Australian National Aquatic Ecosystem
BEWS	Basin Environmental Watering Strategy
CEWH	Commonwealth Environmental Water Holder
CMA	Catchment Management Authority
EWKR	Environmental Water Knowledge and Research Project (2014–19)
Flow-MER	CEWH's Monitoring, Evaluation and Research Program (2019–23)
LTIM	Long-Term Intervention Monitoring Project (2015–19)
MDB	Murray–Darling Basin
MDBA	Murray–Darling Basin Authority
MER	Monitoring, Evaluation and Research Program (2019–22)
NWV	Non- woody vegetation
SCP	Systematic conservation planning
The Basin	shortened form for the Murray–Darling Basin
VEWH	Victorian Environmental Water Holder
WERP	Water and Environment Research Project (of the MDBA)

Term	As used in this report
ANAE	Australian National Aquatic Ecosystems is a classification framework which allows groupings of similar ecosystems into a series of classes
Counterfactual	In this context, the hydrological conditions and resulting ecological values that would exist if the Murray Darling Basin Plan had not been enacted (and there were no environmental water releases)
Ecological condition	Condition is an assessment of the presence of ecological communities and processes that would represent the undisturbed state of an ecosystem. Poor condition may indicate individual plants or animals in poor condition, degradation of key ecological processes or loss of species
Ecological community	The living organisms that are present in a place. The community can be described by the number of species (diversity), the number of individuals present (abundance), the physical arrangement of those species (structure) and the distribution of individuals (composition)
Ecosystem diversity	The range of aquatic ecosystem types
Ecosystem functions	Movements of energy and transformations of materials in an ecosystem e.g. denitrification, feeding, respiration
Energetics	The movement of energy between parts of an ecosystem, including processes such as photosynthesis, feeding links, decomposition and respiration
Evapotranspiration (ET)	The process by which water is transferred to the atmosphere by transpiration from plants. This can be measured directly or from satellite imagery and is a measure of plant water stress
Environmental counterfactual	Building on the concept of the hydrological counterfactual, the environmental counterfactual seeks to model what the condition of environmental assets would have been had the Basin Plan not been enacted
Food webs	A map of the movement of energy between organisms in an ecosystem, usually as feeding links
Refugia	An area of habitat where a species or group of species can be sheltered from the effects of stressful conditions. These refugia may be short-term or persist for millennia. Refuges are a critical component of resilience

Term	As used in this report
Remote sensing	Data collected at a distance via satellite imagery or aerial imagery of various types from drones or other aircraft
Resilience	An ecosystem’s stability and capability of tolerating disturbance (resistance) and restoring itself (recovery).
Scaling	In an ecological context scaling represents the ability to predict ecological values into the future (temporal scaling), at unmonitored locations (extrapolating) or over larger regions than sampled (scaling up)
Species Diversity	The number and relative abundance of species
Stream metabolism	The movement of energy into (via photosynthesis), through (by feeding links) and out of (via respiration) a food web. In this project continuous monitoring of oxygen concentrations across day/night cycles is used to model rates of gross primary production (carbon uptake) and ecosystem respiration (carbon release as CO_2).
Water quality	The concentrations of biologically important materials in natural waters, e.g. dissolved oxygen, pH, nitrate, phosphorus, salts

1 INTRODUCTION

1.1 FLOW-MER

The Commonwealth Environmental Water Holder (CEWH) is responsible under the *Water Act 2007* for managing Commonwealth environmental water holdings. The CEWH's Science Program invests in monitoring, evaluation and research (Flow-MER) building on the Long-Term Intervention Monitoring (LTIM) and Environmental Water Knowledge and Research (EWKR) Projects (2014–2020). Flow-MER monitors and evaluates the contribution of Commonwealth environmental water to environmental outcomes in the Murray-Darling Basin (the Basin) for 6 Basin Matter Themes described in the Environmental Water Outcomes Framework. The framework provides the scientific rationale for Theme indicators that address the environmental objectives contained within Chapter 8 of the Basin Plan and the Basin-wide Environmental Watering Strategy. Each Theme has a set of evaluation questions outlined in Foundation Reports.

The Program is the primary means by which the CEWH invests in research to deliver improved methods and a richer evaluation of environmental outcomes from Commonwealth environmental water. The Flow-MER Basin-scale Project commenced in July 2019 and runs to June 2025 and is led by CSIRO in partnership with the University of Canberra, collaborating with Alluvium, Charles Sturt University, Deakin University, South Australian Research and Development Institute, Arthur Rylah Institute, NSW Department of Primary Industry, University of New England, Australian River Restoration Centre and Brooks Ecology & Technology.

Basin-scale research under Flow-MER invests in activities designed to improve scientific understanding of ecological responses to environmental watering in the Basin. Research at the Basin-scale complements research undertaken at Selected Areas.

1.2 RESEARCH PORTFOLIO

The research portfolio was developed through a prioritisation and planning process undertaken in 2019. Areas of research interest were developed in consultation with the Selected Areas and the CEWH. Proposed research was then reviewed by scientific experts from the Flow-MER Basin-scale Science Advisory Group. The portfolio aims to enhance evaluation by improving approaches and methods, including scaling outcomes across Selected and non-Selected Areas in the Basin, and improving understanding of the outcomes of Commonwealth environmental watering. Research was funded that would:

- continue and leverage research already being undertaken in the Basin
- inform the evaluation of outcomes of Commonwealth water for the environment
- build on and complement science networks across Selected Areas
- integrate across physical scales as well as across Basin Themes.

The research portfolio contains 13 projects listed in Table 1.1. The activities associated with managing the portfolio are documented in the Flow-MER Basin-scale Evaluation and Research Plan 2019–2025[2] (ER Plan).

The Flow-MER research portfolio was extended for the period 2023–25 in consultation with the CEWH's Science Program. Extended/ongoing research addresses at least one of the following priorities:

- foundation research funded under Flow-MER and delivering ongoing benefits to the program

[2] ER Plan V6 (2023-25) submitted to the CEWH on 30 June 2024 for publication.

- transition to, and improve, evaluation of outcomes of Commonwealth environmental water delivery
- knowledge exchange to improve communication and inform adaptive management of Commonwealth environmental water.

This document outlines the Basin-scale Flow-MER research portfolio – research outcomes and how these inform evaluation, reporting and adaptive management are summarised. This document complements 2 documents prepared by the Basin-scale project and published by the CEWH – the Flow-MER Basin-scale Evaluation and Research Plan 2019–2025 (ER Plan) and the Flow-MER Basin-scale Evaluation and Research Synthesis (Flett et al. 2024).

Table 1.1 Flow-MER Basin-scale research projects, project leaders and their status

Project and leader(s)	Research summary
Waterbirds Heather McGinness	Waterbird movements and site use across the Basin This project quantifies spatial and temporal scales of waterbird movements and habitat selection across the Murray-Darling Basin. It uses satellite tracking technology and advanced analysis and modelling approaches to investigate relationships between waterbird movements, habitat selection, environmental watering, flooding, and other variables. Outputs include a research report, internal status reports, Flow-MER Friday webinar(s), web-based communications, conference and learning by doing presentations and associated journal papers. 2023–25: Ongoing data collection, data analysis, reporting and communications
Refugia Joanne Bennett	Identification and characterisation of refuge habitat This project helped us understand how ecological refugia are distributed across the Basin and the potential for water management of these areas to support diversity. Research outputs include a research report, web-based communication and Flow-MER Friday webinar. Research complete and research report published
Condition Shane Brooks Tanya Doody	Influence of ecosystem condition on ecological responses to environmental water This project identified ecosystem condition attributes that help to explain watering outcomes in different ecosystem types. It identified measures of ecosystem condition that could be used to adjust expected outcomes and tailor evaluation to better match the context under which water is being delivered. Research outputs included Flow-MER Friday webinar, web-based communications, conference and workshop presentations.
Tanya Doody Shane Brooks	2023–early 25 extension: This project has developed an evaluation method for describing how environmental water impacts the condition of ecosystems (treed ANAE types) that will be described in a research report using case studies (Riverland, Barmah Ramsar sites). Parts of this research have been delivered via a Flow-MER Friday webinar. Data collection and analysis completing, research report and journal papers in preparation
Scaling Shane Brooks	Developing an approach to scaling for evaluating ecosystem diversity This project developed approaches for scaling evaluation of watering outcomes from individual habitat patches to the whole Basin. This work has provided tools for evaluating ecosystem diversity at spatial scales aligned to the scale of watering actions. Output is a research report, Flow-MER Friday webinar, Forum presentations, and spatial layers. Research complete and research report in preparation
Non-woody plants Cherie Campbell Fiona Dyer	Characterising condition for non-woody vegetation in floodplain-wetland systems This research developed a framework of hierarchical condition and a process for evaluating success of outcomes for non-woody vegetation at a Basin-scale. Output is a series of journal papers, Flow-MER Friday webinars, web-based articles, conference and workshop presentations (PhD thesis). Research complete and overview report in preparation
Remote sensing vegetation Tanya Doody	Remote sensing responses of woody vegetation to environmental water The project developed a basin-scale remote sensing product to understand changes in tree water stress at a resolution of 30m for each month from 2000–22, for each tree pixel across the Murray–Darling Basin. Research outcomes have improved our understanding of tree response to water availability and allow us to identify water requirement thresholds for woody vegetation. Research outputs include a Flow-MER Friday webinar, web-based articles, conference and workshop presentations and journal articles.

Project and leader(s)	Research summary
	Research complete and research report published
Fish populations Zeb Tonkin	**Fish population models to inform Commonwealth environmental watering** Population models demonstrate the benefits of environmental water to fish populations. Improving the robustness of the population models. This research explicitly linked flow management to whole-of-lifecycle responses for a suite of native fish species. Research outputs include a research report, Flow-MER Friday webinar, web-based articles and presentations. **2023–24 extension:** Population models were reviewed for sensitivity and uncertainty, addressing known knowledge gaps. Models were updated and results of the model review reported. **Research complete and two research reports published**
Fish movement Brenton Zampatti Jason Thiem	**Flow, movement and fish population dynamics in the Murray–Darling Basin** Research evaluated flow triggers for local and regional scale fish movement to standardise environmental water requirements among fish species and regions in the Basin. This research improves our understanding of landscape-scale fish movements and population resilience and informs delivery of environmental water for connectivity, fish passage and maintaining refugia for migrating fish. Research outputs include a research report, interactive webpage, Flow-MER Friday Webinar, conference and learning by doing presentations. **Research complete and research report published**
Ecosystem energetics Paul McInerney	**Developing an environmental water energetics response model** This project developed a bioenergetic model for food web response to flow, initially focussing on refuge habitats, then extended to wetlands and flowing water habitats. Research outputs include interactive webpage, Flow-MER Friday Webinar, conference and workshop presentations. **2023–24 extension:** To test the energetics model using comprehensive data from the Murray River to test whether the model can be applied beyond the case studies used in the initial research. **Research complete and initial research report published with extension research report in preparation**
Flow ecology relationships Danial Stratford	**Developing flow-ecology relationships to predict responses to environmental water** This project undertook data analysis to understand flow-ecology responses and developed these into a scientifically sound modelling method for Flow-MER evaluation. Research outputs include Flow-MER Friday webinar, web communications and presentations. **Research complete and research report published**
Integrative modelling Rebecca Lester	**Integrative basin modelling** The research project developed an integrative basin modelling framework to inform our understanding of interactions between thematic areas, scale and locations. The model combines information in space and time, and across biota, to explore scenarios, and test reasons for observed outcomes at the basin-scale. Research outputs include Flow-MER Friday webinar, web communications and presentations. **Research complete and research report published**
Visualisation Martin Nolan	**Data visualisation** This project integrated data across Themes to develop data visualisation products for communicating the outcomes of basin-scale monitoring, evaluation and research. It develops optimum means of presenting raw and processed data, modelling outputs and research results to inform policy and decision making. Research outputs are being used in web communications for each research theme in the form of 'dashboards' showing water actions at Basin scale. **Research complete and research report published**
Indigenous engagement Bradley Moggridge	**Co-designing engagement with Indigenous peoples for better environmental water delivery** This project described Indigenous engagement practices and experiences drawing on Selected Areas and a case study in the Gwydir catchment developed in partnership with traditional owners on-country. Selected Area survey report completed and available. Research outputs include Flow-MER Friday webinar, web-based communications and conference presentations. **Research complete, and research report available**

2 BIODIVERSITY THEME

2.1 RESEARCH OVERVIEW

Australia's aquatic ecosystems support nationally and internationally significant plant and animal species. Many water-dependent species and ecosystems found in Australia are adapted to and require natural cycles of wetting and drying. In a climate of increasing pressures on water resources, environmental watering plays a crucial role in maintaining biodiversity. Important reproduction and movement cues are often tightly linked to water regime. Research in this Theme addresses knowledge gaps related to waterbird movement, protection of refugia, condition assessment and scaling (from site to valley and Basin scales). All research activities are ultimately aiming to improve evaluation and/or inform adaptive management of environmental water in the Basin.

2.2 PROJECT 1 WATERBIRD MOVEMENTS AND SITE USE ACROSS THE BASIN

Waterbird diversity, populations, and breeding, foraging and refuge sites, are managed through decisions affecting water, habitat and other pressures. This research tracks the movements of waterbirds by satellite at local, area and Basin scales. The data show the spatial and temporal scales, as well as drivers of waterbird movements and site use, including breeding, foraging, stopover, refugia and Ramsar sites. Analysis of movement data for straw-necked ibis, royal spoonbill, Australian white ibis, intermediate egret and great egret is providing information on movement pathways and habitats, and their dependency on environmental watering events. This knowledge is directly relevant to the planning and management of Commonwealth water for the environment and has already contributed to significant improvements in the adaptive management of water for the environment focusing on waterbird outcomes in the Basin. **This project will continue to collect and analyse data, and conduct knowledge exchange activities through to June 2025.**

Figure 2.1 A royal spoonbill carrying a satellite transmitter fitted to track bird movements
Illustration by artist Nina Rupena prepared for Flow-MER website (flow-mer.org.au)

2.2.1 RESEARCH QUESTIONS

- How do waterbirds move across the Murray–Darling Basin and beyond? Are they moving in response to environmental water or flooding? What does this mean for our perceptions and predictions of waterbird responses to environmental water management?
- Where are birds feeding, roosting and nesting, when and why? What movement and habitat cues, preferences and limitations should be taken into account in water planning for waterbirds?

- How connected are Australian waterbird populations, spatially and temporally? What are the implications for environmental water management to prevent further population declines?

2.2.2 PROJECT OVERVIEW

This project uses satellite transmitters to track the movements of waterbirds at local, area and Basin scales. It provides data describing explicit spatial and temporal scales and patterns of waterbird movements and site use, including identification and use of important sites and routes. This information assists with interpreting how site or area scale waterbird responses to environmental watering are influenced by basin- and national scale waterbird responses and drivers.

SATELLITE TRACKING WATERBIRD MOVEMENTS? WHAT CAN IT TELL US?

- Where, when, how far, how high, and how fast they move
- Foraging – locations, distances, times
- Nesting – locations, behaviour, timing, duration
- Habitats – feeding, sleeping, nesting, shelter
- Site fidelity – nesting, natal, foraging, overwintering
- Differences – species, sexes, age groups
- Populations – boundaries and connectivity
- Survival and mortality – rates, drivers
- Cues and triggers – movement, breeding

Informing where, when and for how long to manage water

2.2.3 METHODS

Satellite tracking transmitters were deployed during the period 2016 to 2023 in 8 key waterbird breeding wetland locations across the Basin. Six species were successfully tracked: Straw-necked Ibis (*Threskiornis spinicollis*, 'SNI'); Australian White Ibis (*Threskiornis moluccus*, 'AWI'); Royal Spoonbill (*Platalea regia*, 'RSB'); Great Egret (Eastern Great Egret, *Ardea alba*, 'GE'); Plumed Egret, previously known as the Intermediate Egret (*Ardea plumifera, previously Ardea intermedia*, 'PE'); and a single individual Musk Duck (*Biziura lobata*, 'MD'). Birds captured for satellite tracking were weighed and measured, with biological samples taken when possible, including feathers, oropharyngeal and cloacal swabs, blood, and opportunistic regurgitate and scat. These samples and measurements may be used in future or complementary projects to assess diet, genetics, toxins, disease, or energetics.

While many birds are still 'in the air' sending data from their transmitters and satellite data processing, mapping, classification, analysis and modelling is ongoing, significant outcomes have been achieved, particularly for the following key knowledge gaps:

1. Ibis and spoonbill movements post-dispersal from breeding sites
2. Common movement routes
3. Habitat selection
4. Environmental watering benefits

5. Nesting cycles and foraging patterns
6. Flight heights and modes
7. Egret dispersal movements

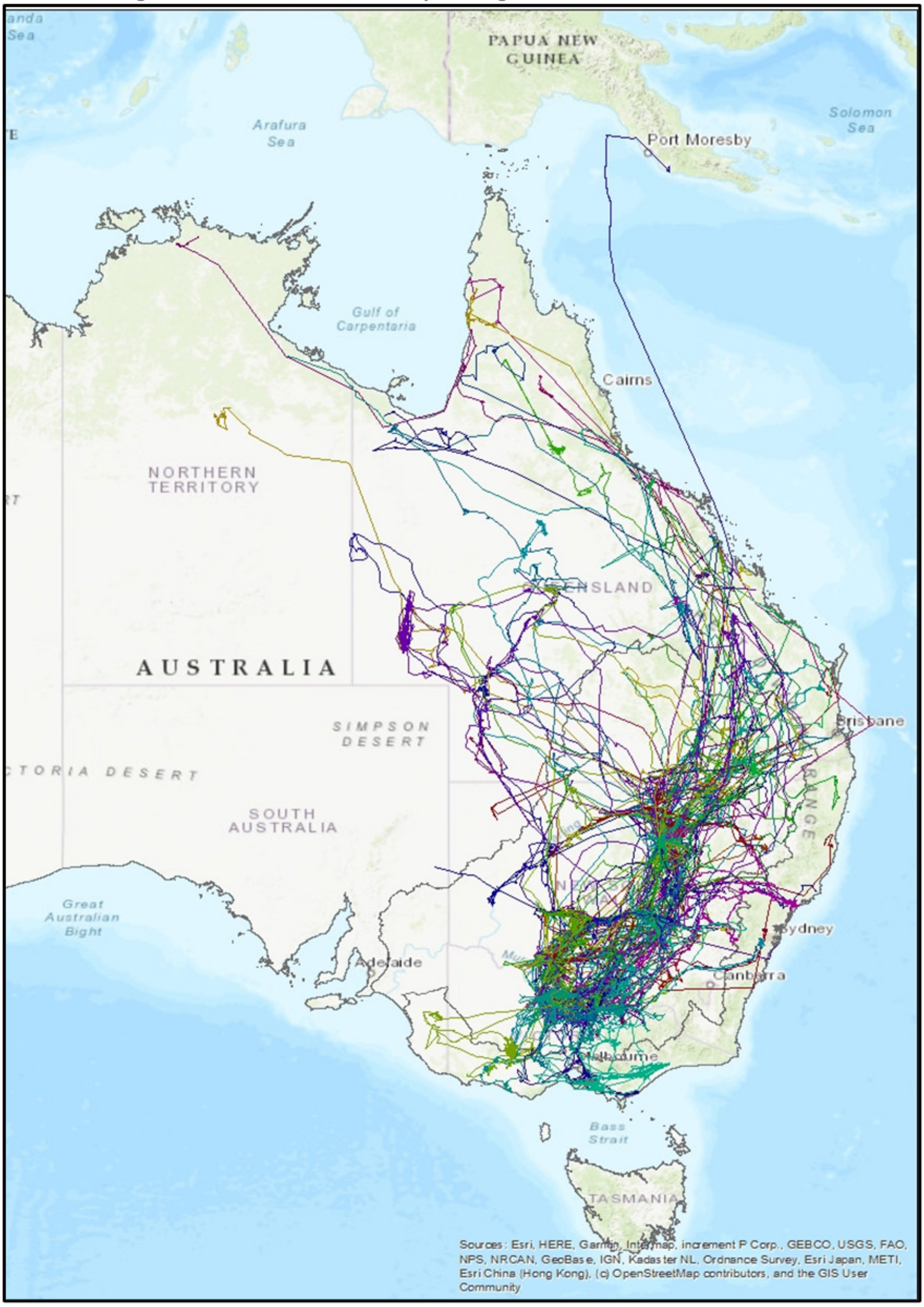
Examples of outputs include maps showing individual and grouped waterbird movements at a range of spatial and temporal scales for multiple purposes; and movement statistics and models describing distances travelled, residency, home ranges, common routes, habitat use, and nesting behaviour. Statistical models of movements and habitat use have been developed for colonial-nesting straw-necked ibis, royal spoonbill, and Australian white ibis. This represents significant progress in waterbird movement ecology in Australia, progress which in future can be built on by including new data, new questions, new analyses, and importantly, new species.

The results of this work have been used to support redrafting of the Basin Environmental Watering Strategy and CEWH and State watering plans. The project has also directly informed and contributed data to multiple projects commissioned by a range of end-users, including the Murray-Darling Basin Authority (MDBA), the Victorian Environmental Water Holder and CEWH. Data from this project have been used by: the MDBA/CEWH Basin Ecosystem Functions Project to model distances travelled and connectivity for straw-necked ibis across the Basin, including modelling the influence of wind on movement distances; the MDBA/CEWH Basin-Wide Vulnerability Project to assess waterbird vulnerabilities; and the MDBA's Water and Environment Research Project (WERP) Waterbird Foraging Habitat Mapping and Prioritisation project.

Figure 2.2 A straw-necked ibis fitted with a satellite tracker

Illustration by artist Nina Rupena prepared for Flow-MER website (flow-mer.org.au)

Figure 2.3 Satellite-tracked movements of straw-necked ibis, royal spoonbill, Australian white ibis, great egret and intermediate egret individuals from the Murray–Darling Basin between 2016 and 2023



2.2.4 RESEARCH OUTCOMES

This study is the first to track multi-year movements of ibis, spoonbills and egrets in Australia using satellite telemetry. The dataset comprises over 50,000 days of tracking from 213 birds of six species, with 30 transmitters still active on mobile birds. Outcomes to-date include:

- identification of new breeding, foraging, roosting, stopover and refugia sites and events, including events in sites not monitored as part of any on-ground activities
- quantification of critical ecological information on breeding timing, duration, stages, and site selection through satellite tracking of breeding bird movements (e.g. Figure 2.4)
- quantification and mapping of spatial and temporal foraging patterns and foraging habitat selection during and after nesting, including changes in foraging and nest attendance patterns, and potential drivers of changes
- quantification and mapping of post-breeding dispersal timing, routes, distances and habitat use for both juveniles and adults, with implications for environmental watering of foraging habitats to support these life stages.
- identification of spatially explicit common routes for waterbird movement and connectivity, including the identification of a major 'flyway' crossing the Basin (Figure 2.5)
- the first GPS-tracked migration of a juvenile intermediate egret from the Macquarie Marshes to Papua New Guinea, including identification of stopover sites
- the first multi-year data for individual waterbirds in the Basin, with movements of some individuals tracked continuously for 5+ years
- waterbirds tracked throughout their full-life cycle, with movements of juveniles tracked from their hatching site to their first nesting event as adults years later
- adult waterbirds moving between important breeding and Ramsar sites, revealing patterns in breeding site connectivity and including the timing and duration of site visits and site abandonments
- mapping of individual and grouped waterbird movements at a range of spatial and temporal scales for multiple purposes
- statistical models developed for colonial-nesting straw-necked ibis, royal spoonbill, and Australian white ibis, including:
  - movement statistics of use for environmental water site selection and prioritisation (e.g. nesting, foraging and nomadic/migration distances, home ranges, breeding movements)
  - modelling of habitats used by species and age groups, during both nesting and non-nesting periods.

Figure 2.4 The movements of a nesting adult Royal Spoonbill from a nest site in Yanga National Park in the Lower Murrumbidgee floodplain, NSW

Lines show movements and colours show nesting stage, including nest establishment, incubation, immobile chicks and mobile chicks. The background is the true colour image average over the nesting period generated from the Sentinel Copernicus Sentinel-2 satellite imagery and accessed from SentinelHub. The top left inset shows the moving average of distance travelled to forage (km).

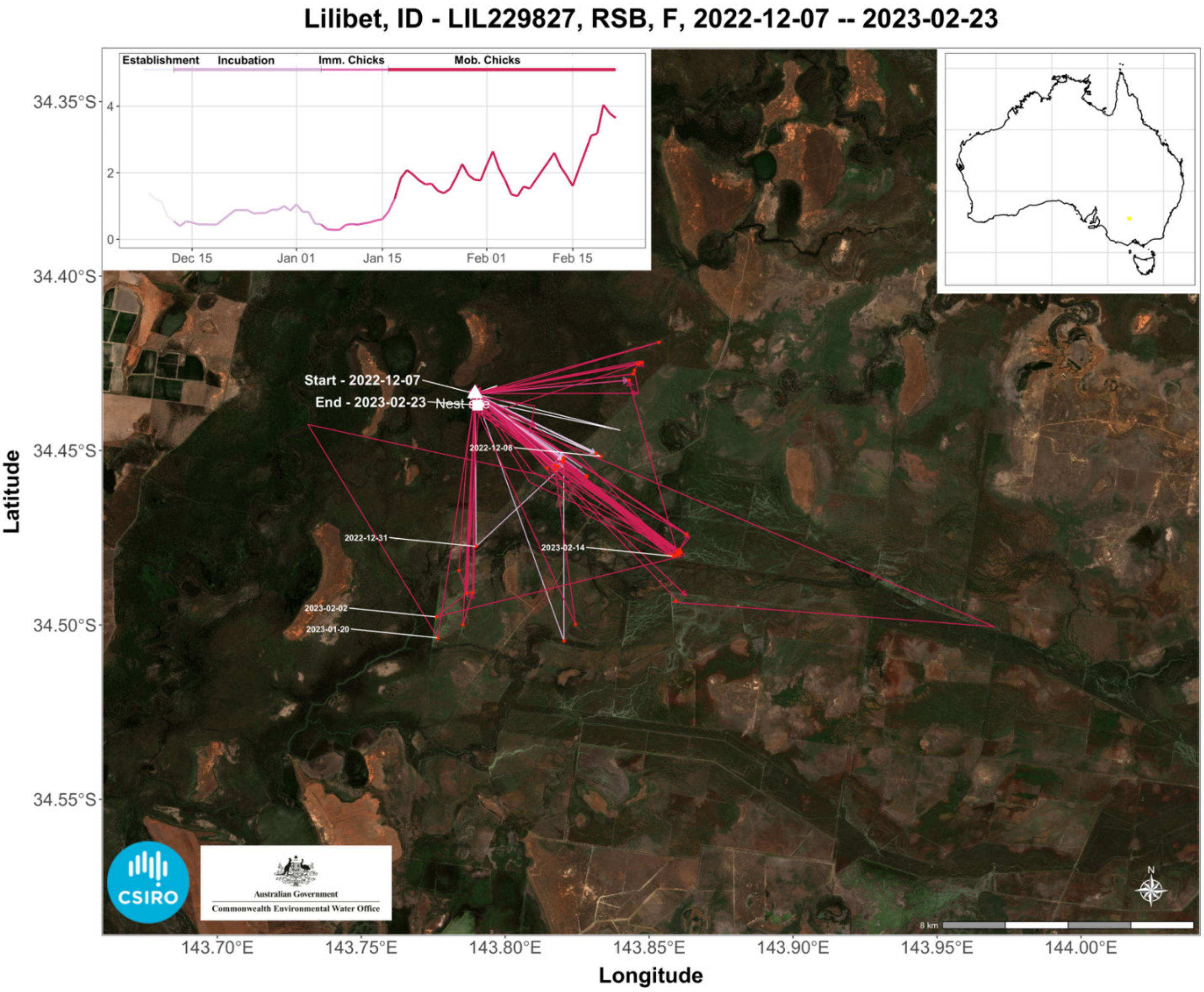
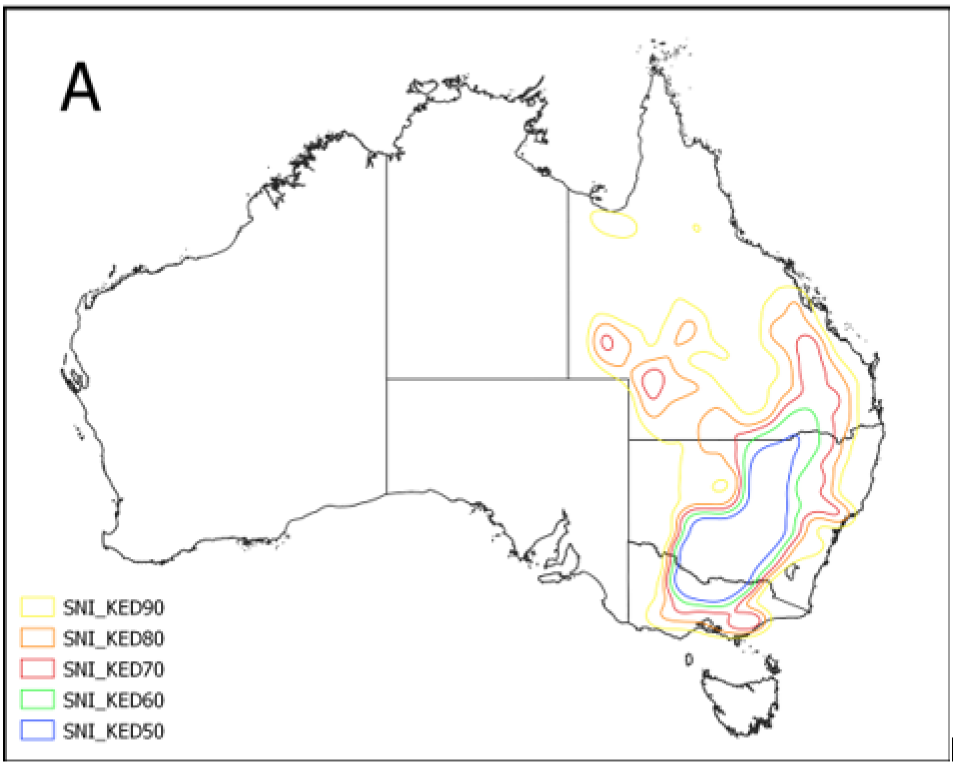
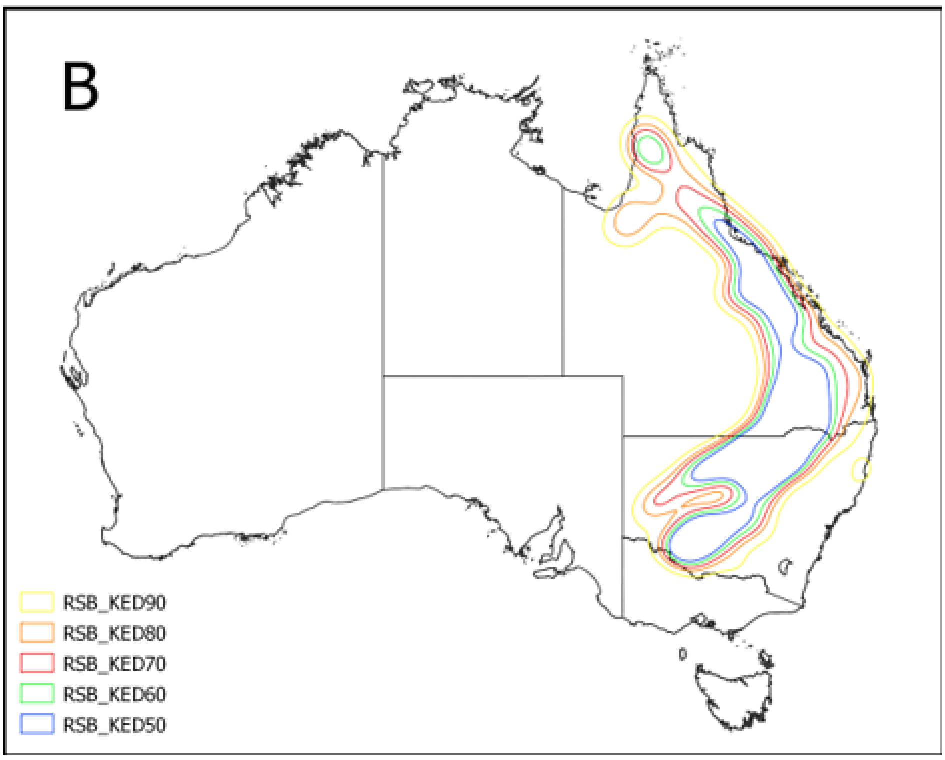


Figure 2.5 Maps of the 'Murray-Darling Basin Flyway', separating common movement routes along the flyway of A) Straw-necked Ibis and B) Royal Spoonbill between 2016-2023

Long-distance movement kernel density contours are shown for KED90, KED80, KED70, KED60 and KED50 (see waterbird research final report and attachments for explanations of the kernel density method). Contours were generated using a dataset of long-distance movements, subset from a dataset of lines of the maximum distance that a bird had travelled in the 24 hours from midday to midday based on the sixth movement class from a six-state Hidden Markov Model.





Links to evaluation

Better understanding of spatial and temporal scales and drivers of waterbird movements and site use helps to explain monitored site scale responses to environmental water and natural flooding. It supports more accurate and nuanced assessment of local waterbird abundance and breeding responses, by presenting a broader perspective of basin- and national-scale waterbird responses and drivers. Monitoring of waterbird movements is also useful for the direct evaluation of when and where environmental watering is supporting different bird species and age groups for foraging, breeding, stopovers or refuge.

Informing adaptive management

Restoring waterbird populations is reliant on completion of full species lifecycles, including breeding initiation, successful incubation of eggs and chicks, and survival of juvenile, sub-adult and adult birds post-breeding. This project provides information describing waterbird movements and habitat use for all life cycle stages.

For adaptive management, it provides this information in:

- spatially and temporally explicit forms in real-time to inform immediate management at site scales (e.g. maps of where birds are breeding, maps of where breeding birds go to get food for their chicks, and reports on physical condition of birds in breeding sites and environmental conditions on-ground)
- general patterns based on statistical modelling across all individuals and sites to guide longer-term planning.

Research report: McGinness et al. (2024)

Manuscripts: McGinness et al. (submitted-a; submitted-b, submitted-c, submitted-d), McGinness et al. (in prep), Nicol et al. (2023), Robinson & McGinness (in prep)

Knowledge catalogue: https://flow-mer.org.au/basin-theme-biodiversity/

2.3 Project 2 Identification and characterisation of refuge habitat

Refuges are areas critical for maintaining the resilience of ecosystems during periods of low flow. Key refugia in the Basin have been mapped using geospatial and biodiversity datasets showing how ecological refugia are distributed across the Basin. Research explored options for prioritising water delivery for refugia. The systematic conservation planning approach provides an objective and repeatable process that can be used to prioritise environmental watering of refuges across the Basin. Research is complete and the final report published.

2.3.1 Research questions

The project aimed to support managers in their decision-making processes in providing environmental water to support refugia. Refuges support ecosystem resilience and maintain habitat condition and connectivity for multiple taxa, particularly during low flow or drought periods. Specifically, we asked:

- Where are the high ecological value depressional wetlands and lakes?
- Where would watering actions deliver the highest ecological value at the lowest cost?
- Have past watering actions captured ecological diversity?

2.3.2 Project overview

Systematic conservation planning (SCP) is a prioritisation approach for selecting areas for conservation that represent biodiversity in the most cost-effective way. SCP is an iterative process that can be continually updated as new ecological and management information becomes available. Although commonly applied to protected area design on land and at sea, SCP has been less commonly applied to freshwater management.

Despite SCPs infrequent application in freshwater systems, there is a history of SCP in the Basin to identify priority habitats for conservation. Linke et al (2015) conducted a pilot study prioritising sub catchments (basin scale) and wetlands (single catchment) for protection and restoration of aquatic ecological assets. For the Linke et al. 2015 study, prioritisation of wetlands at the basin scale was not possible due to a lack of accurate wetland mapping. Since 2015 updates to the Australian National Aquatic Ecosystem (ANAE) have delivered consistent mapping of wetland and lakes across the Basin which allowed us to significantly expand the application of SCP in the Basin for the prioritisation of depressional wetlands and lakes.

In dry years, a common objective of watering management actions in the Basin is the maintenance of refugia habitats. As water resources are becoming increasingly scarce the need for watering actions for the protection and creation of refugia is likely to increase. Discrete watering actions to wetlands and lakes often involve Commonwealth environmental water and are targeted at supporting the survival and maintaining habitat conditions for multiple taxa.

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. Thus, it is now possible to estimate changes in the condition of ANAE features as a product of changes in water resource availability allowing for an assessment of their refugia qualities (e.g., their resilience as a function of condition in relation to drought).

This project characterises refugia and refugial values as the likely best predictor of resilience within the Basin.

2.3.3 Methods

This project commenced in March 2020, with literature reviews completed in Year 1. In parallel to the literature reviews a process of stakeholder engagement with managers and researchers working on refugia in the Basin was undertaken to develop consistent definitions of refugia. Geospatial analyses were then completed to identify refugia, their spatial context and ecological values.

Refugia were identified using the conservation planning software Marxan (Ball et al. 2009). The optimisation algorithm within Marxan seeks for a near-optimal combination of sites that represent all species in a minimum required area while accounting for the constraints of cost and connectivity. In Marxan costs can be used to negatively or positively weight sites during the selection process. That is, each site can be discounted because of its positive attributes, or the cost can be increased because of its negative values. A cost can be monetary (e.g. water price), ecological (e.g. site condition) or social (e.g. cultural value). An algorithm can support this site selection because it can consider all possible combinations of sites, species, and costs.

Marxan was used to select a suite of sites that represent all species and ecosystem types and to target areas with high basal resource availability. The area targets were based on a minimum watering area estimated from known volumes of water delivered by the CEWH. Cost was based on multiple scenarios including volume/area and water permeance. The ecological value of each planning unit was based on representing sites that represented all species of fish, frogs, crayfish, molluscs, Odonata and plants considered, ecosystem diversity based on ANAE category, and allochthonous organic matter availability.

2.3.4 Research outcomes

Contextual work

- A review of habitat condition metrics and biodiversity data in the Basin has been completed.
- A systematic literature review has been completed developing definitions of refugia that are consistent with existing definitions used by the states and other management authorities.

Spatial analyses – locations of refugia

- Refugia mapping models have been identified which can be used to relate hydrological metrics to persistence of refugia through time and space.
- Map of key refugia in parts of the Murray–Darling Basin. A spatial layer of refugia planning units has been created, where planning units are defined as freshwater depressional wetlands and lakes in the ANAE. This data layer was then separated into 2 spatial layers for analysis; one containing sites on the managed floodplain and another containing sites that are actively managed by the CEWH.
- Planning units in the managed floodplain of the Basin were isolated by intersecting the generated planning unit data layer with the MDBA's floodplain spatial layer and the CEWH inundation spatial data.
- Planning units that are actively managed by the CEWH have been extracted based on the CEWH inundation spatial data.

Spatial analyses – connectivity of refugia

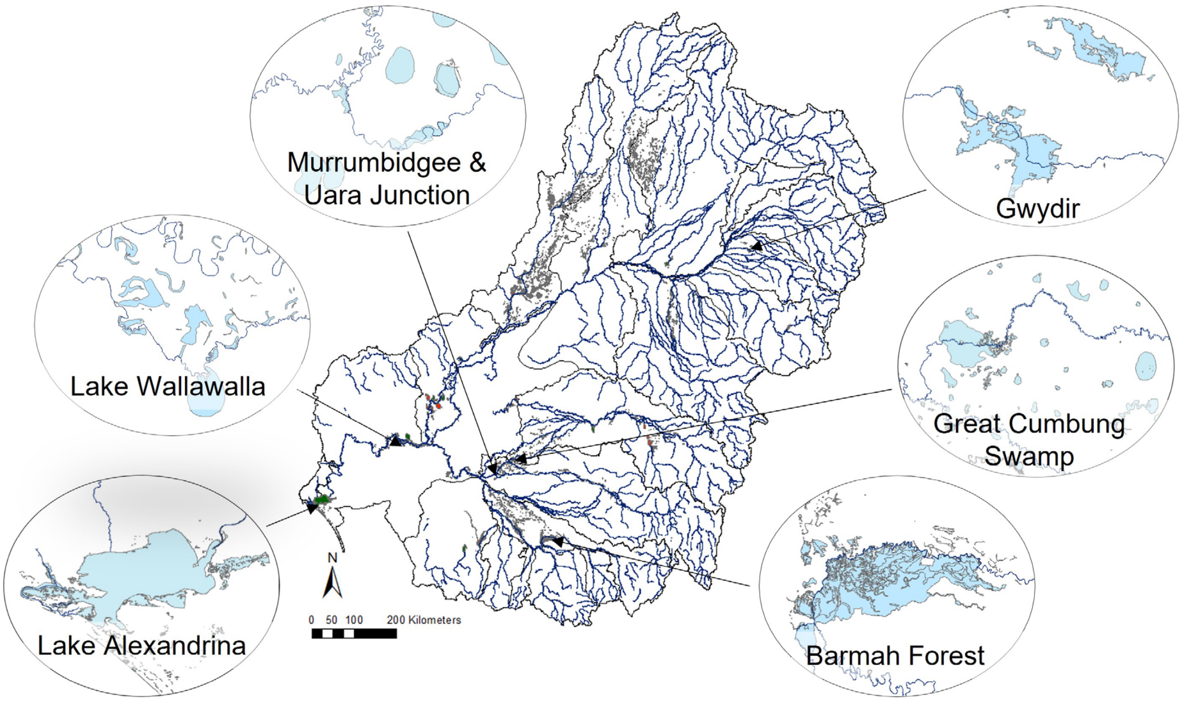
- A connectivity dataset was generated using spatial analysis to calculate the distance of each planning unit to the nearest major and/or minor watercourse in the Geofabric version 3 dataset.
- A spatial dataset of wetland complexes has been generated that corrects for artificial boundaries that may be present (e.g., bridges, pipelines, and roads) between water bodies. Spatial statistics were performed on the wetland complexes layer to measure the shared boundary between adjoining wetland and lakes.

Ecological uniqueness and value of refugia

- Ecological uniqueness and value of refugia have been estimated by determining the identity of ANAE classes within the sphere of influence of a depressional wetland or lake. The probability of occurrence and identity of target wetland species of fish, frogs, molluscs, Odonata and plants was determined from species distribution maps. The mean density of terrestrial biomass surrounding each depressional wetland or lake is an estimate of available basal resources. The value of each ecological asset is then multiplied by the area the planning unit contributes to that asset.
- Analysis has been completed in Marxan and projected as maps (Figure 2.6).

Figure 2.6 Depressional wetlands on the managed floodplain of the Murray–Darling Basin currently managed with Commonwealth water for the environment (Fig 3.2 in Bennett et al. 2023)

Areas identified as priority areas for the conservation of animal, plant and ecosystem diversity and ecosystem productivity are shown in light blue; major waterways are shown in dark blue; and major catchments are delineated by grey.



Links to evaluation

This project informs our understanding of how refugia and resilience may be managed. In the future, evaluation metrics which describe, for example, the percentage of refugia supported by environmental water, could be developed.

Informing adaptive management

The maps of refuges produced within this project can assist water managers in identifying priority areas for targeted environmental watering. The development of assessments of refugia values provides additional information for prioritising watering actions to support refugia which support particularly important ecological values.

Research report: Bennett et al. (2023)

2.4 Project 3 Influence of ecosystem condition on responses to environmental water

Understanding ecosystem condition can help explain environmental outcomes observed in response to environmental watering of different ecosystem types. Research applied measures of ecosystem condition to tailor expected outcomes and therefore tailor evaluation to better match the context under which water is being delivered. Research is linking species outcomes to the ecosystems that support them and determining how the condition of those ecosystems influences outcomes from water for the environment. The outcomes of this work apply to ecosystem type mapping, environmental water prioritisation frameworks and setting of expected outcomes for watering actions. This project continues to March 2025.

2.4.1 Research questions

- How does condition of an ecosystem influence responses to environmental water?
- What are the critical indicators of ecosystem condition (using vegetation indicators to evaluate different ANAE ecosystem types at Basin-scales)?
- Do we need to understand condition as an ecosystem integrity measure or is it sufficient to understand the antecedent 'state' of ecosystems?
- When does condition need to be evaluated over a long duration versus in the present only?
- Adaptive management - It is critical to understand when ecosystems can respond to provision of environmental water. This project seeks to develop metrics for assessing the sensitivity to environmental watering through time.

2.4.2 Project overview

Condition metrics may have value as surveillance tools to identify and prioritise water delivery to ecosystems in most need. The ANAE classification of wetlands and rivers has been identified for use as a template for extrapolating monitoring outcomes within ecosystem types. This provides context for similar watering actions and ecosystems elsewhere in the Basin. Condition indices help to define the contexts under which extrapolation of monitored outcomes to other areas is valid, leading to more robust evaluation of responses to environmental water at the Basin-scale.

This project examines how ecosystem condition or patch quality influences watering outcomes across a range of targets (e.g. varied species groups, vegetation communities) and explores whether ecosystem types can be used for extrapolating monitored outcomes to unmonitored areas. At present, the ANAE classification used to quantify ecosystem diversity is a static template. Inclusion of patch quality/starting condition may provide a way to parameterise variability for modelling outcomes and contribute to evaluating Basin Plan objectives for improving resilience to climate change and extreme events (such as drought).

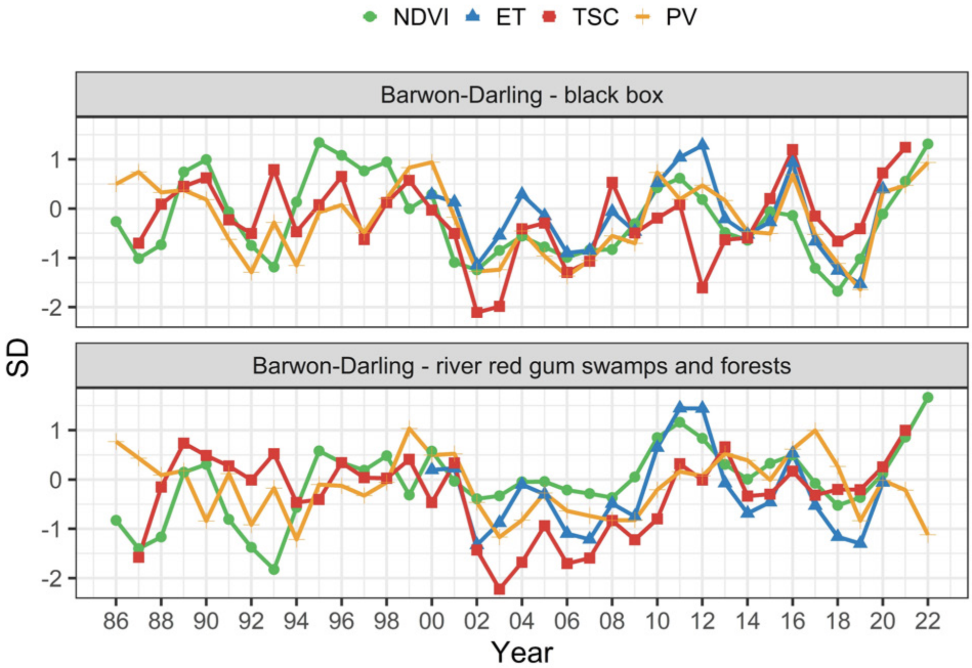
2.4.3 Research outcomes

- Collaboration with Geosciences Australia and the Flow-MER Vegetation Theme (Tanya Doody, Steve Gao) have enabled us to compare different measures of vegetation condition at large scales. We have used evapotranspiration as a measure of ecosystem stress and condition to compare with other vegetation condition metrics (including the fractional cover of green and non-green vegetation from Geoscience Australia's Wetland Insights Tool, MDBA's Tree Stand Condition Tool (Cunningham et al. 2014) and satellite derived vegetation NDVI (Normalised Difference Vegetation Index). From this, we have developed a method for scaling up from experimental plots to larger ANAE wetland complex and valley scales to permit alignment with the Basin Environmental Watering Strategy. Preliminary response trajectories were presented at the Flow-MER Research forum in Canberra (March 2023).
- Current work has used annual time steps for tracking condition. We are now reducing the annual time step to monthly, with the aim of testing the hypothesis that evapotranspiration is a condition metric that responds to environmental water more quickly because it is based on the physiology of the trees. Satellite products rely on growth or senescence of the canopy before changes can be observed in satellite imagery.

Figure 2.7 Trajectories of change in vegetation condition metrics that have been aggregated from ANAE polygons to represent changes at the valley scale

This example is for the Barwon-Darling valley, showing changes in NDVI (green line), evapotranspiration (ET) (blue line), MDBA Tree Stand Condition (TSC) (red line) and fractional cover of photosynthetic vegetation (PV) (orange) from the Wetland Insights Tool (WIT) for black box (top plot) and river red gum swaps and forests (bottom plot)

Plots prepared by Shane Brooks



Links to evaluation

Some evaluation activities assess responses of ecosystems to Commonwealth water for the environment and would benefit from a more sophisticated understanding of why responses may or may not be observed at particular times. This analysis seeks a temporal scale (antecedent year or years for example) that drives condition and the potential for vegetation to respond to watering.

An initial outcome from the scaling project (Section 2.5) (see Figure 2.7) is a framework to group the condition of ANAE polygons to larger scales, including watering assets and whole valleys. This allows localised condition metrics (provided by the evapotranspiration measurement and Wetland Insights Tool), to report at any scale. The condition work can then 'hind-cast', with the aid of satellite data to develop trajectories, that reveal the antecedent ecosystem condition and trajectory of change leading up to the time of watering, and in response to water.

Informing adaptive management

- Analysis of trends in combination with ecosystem condition provides important context to interpret ecosystem vulnerability and adjust watering priorities. Watering to halt or reverse a declining trend may be a higher priority for management in some cases than using environmental water to support locations in similar condition that are improving unassisted. Similarly, a short-term outcome showing no improvement may be a positive response if halting a declining trend ('holding the line' in the face of adversity).

- Understanding the sensitivity of different condition metrics and time lags in the expression of condition changes will inform and guide their appropriate use for water planning and evaluation. This will in turn improve our ability to ascribe observed changes in condition as an outcome of environmental water management.

2.5 Project 4 Developing an approach to scaling for evaluating ecosystem diversity

Flow-MER evaluation needs to be able to evaluate basin-scale ecosystem diversity across different scales and spatial arrangements (related to water delivery). The project team developed methods to scale the evaluation of watering outcomes from the small scale of individual wetlands, up to large scales, an entire river system and the whole-of-Basin. These methods were used to assess responses to water delivery within and between ANAE ecosystem types. Research is complete; the final report is in preparation.

2.5.1 Research questions

- How diverse are the sampling locations from which we are drawing inference about the role of Commonwealth environmental water in supporting biodiversity in the Murray–Darling Basin?
- Does the spatial scale at which ecosystem diversity is defined change our perception of outcomes from water delivery at local versus catchment scales?
- Can ecosystem types be aggregated to larger spatial scales to improve evaluation of environmental water delivered to wetland and floodplain complexes (i.e. developing a framework for evaluating within and between 'patch' diversity where patches can be defined at multiple scales)?
- Adaptive management - To what degree can we make management decisions at one unmonitored site based on information or data we know about another site? This research addresses the degree to which we can generalise our information from one site to inform adaptive management at another.

2.5.2 Project overview

This project examined the importance of scaling for evaluating the influence of environmental water on ecosystem diversity. Here, scaling represents the ability to predict ecological values into the future (temporal scaling), at unmonitored locations (extrapolating) or over larger regions than sampled (scaling up). The project team sought a multi-scale approach for integrating ecosystem types to larger patches (or catchments) to evaluate ecosystem diversity outcomes from watering actions at different scales. The project team incorporated temporal aspects of environmental water management into evaluation (timing of delivery, duration of inundation). The research evaluated how representative the distribution of sampling locations is within LTIM/MER and EWKR research sites with respect to ecosystem diversity, watering regime and other landscape attributes.

2.5.3 Research outcomes

- This project has developed multiscale ecosystem diversity metrics that link to the ANAE classification mapping, at multiple spatial scales ranging from asset to whole-of-Basin. The team have completed the GIS framing to quantify landscape ecology metrics (patch diversity, evenness, connectivity, contiguity, aggregation, dispersion) at a range of spatial scales that will be linked to scales of delivery of

Commonwealth environmental water. Alignment of monitoring sites to ANAE polygons and assembly of polygons to represent Assets (e.g. Macquarie Marshes is 1,000 ANAE polygons), valleys (BEWS vegetation regions are valleys) and Basin has been undertaken.

- Ecosystem richness has been used as a test case to refine the methods for carrying out assessments at different scales (Figure 2.8). This has indicated the most appropriate scales for assessment of trends in important metrics. Finer scale measures of diversity (Figure 2.9) are being used to support visualisation of local scale responses to environmental watering. Our framework for 'scaling up' from ANAE polygons to larger asset scales is being tested in the condition project (above) and is showing we can aggregate local building blocks (ANAE polygons in this case) to report at any scale.

Figure 2.8 Ecosystem richness measured at different scales for the Murray–Darling Basin, showing the detected richness as scale of investigation increases
Image: Shane Brooks

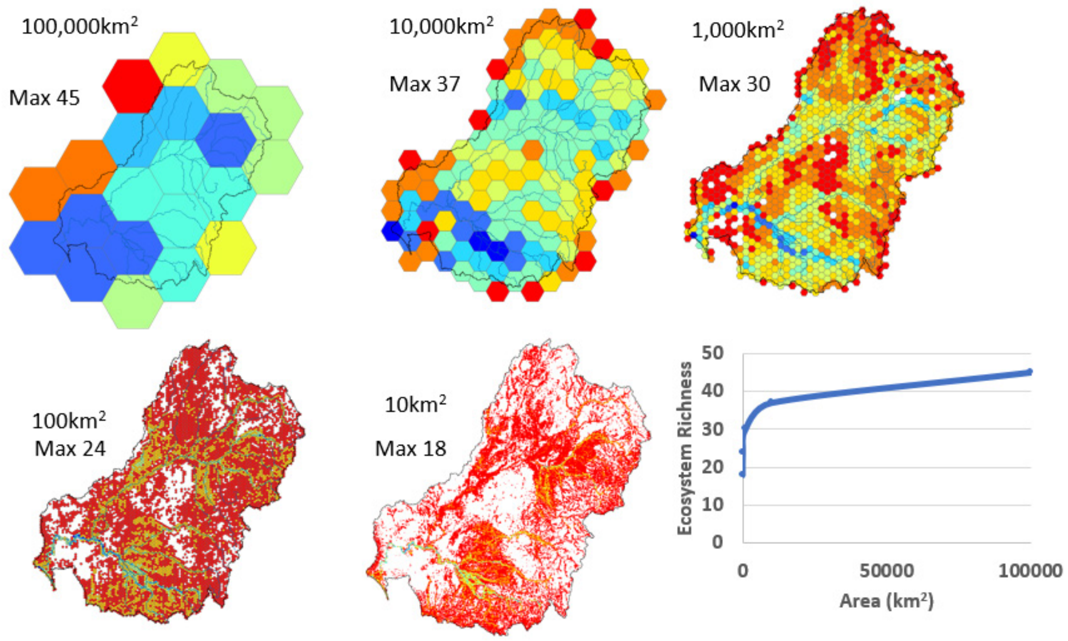
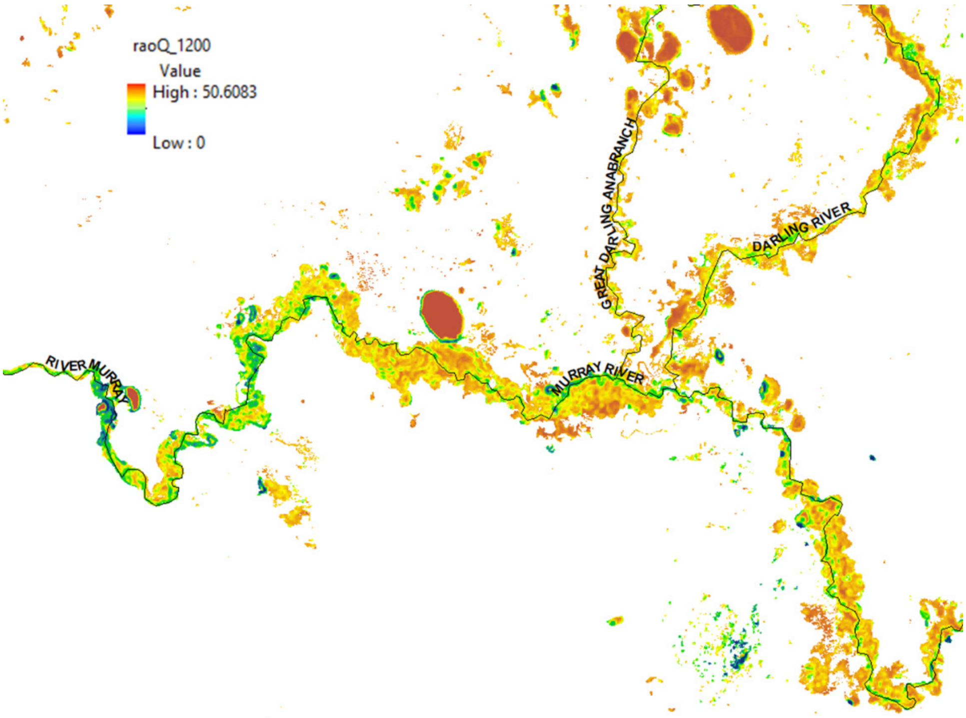


Figure 2.9 Fine-scale measure of diversity (Rao's Q) from Landsat reflectance of the mid-Murray
Image: Shane Brooks



LINKS TO EVALUATION

An outcome from this work is a code module programmed using Python to aggregate data spatially using an area weighting to representing larger scale assets of interest that can be delineated in GIS shape files. This is designed primarily to use remote sensing data and metrics calculated for individual ANAE mapping units to evaluate aggregate outcomes at larger spatial scales of wetland complexes, waterbird breeding areas, or entire river valleys that are targets of water management.

INFORMING ADAPTIVE MANAGEMENT

The primary purpose of this work is to support calculation of asset condition at multiple scales through the lens of different remote sensing metrics (e.g. surface water, soil moisture and vegetation condition; refer Project 3). Assessment of asset condition can then inform water planning and the quantification of outcomes from water delivery at the spatial scales of the assets of interest.

Research report: Brooks and King (in prep)

Knowledge catalogue: https://flow-mer.org.au/basin-theme-ecosystem-diversity/

3 VEGETATION THEME

3.1 RESEARCH OVERVIEW

The Vegetation Theme aims to assess the contribution of Commonwealth water for the environment to achieving vegetation species and community diversity outcomes across wetland, floodplain and riverine habitats. Composition and structure are important components of vegetation diversity. Vegetation diversity is considered through all phases of the flow regime relevant to a riparian, wetland or floodplain ecosystem (i.e. dry, base flow, fresh, bankfull, overbank). Changes in flow regimes are likely to significantly impact vegetation diversity across multiple scales, from the presence and abundance of local plant species to vegetation composition and structure at landscape scales.

The vegetation research program focuses on providing an improved ability to evaluate and predict responses to Commonwealth environmental water for both woody (trees) and non-woody (groundcover) vegetation across the Basin. This is achieved through 2 projects: 'non-woody plant responses' and 'remote sensing vegetation'. The research within the Theme improves our understanding of how best to use Commonwealth environmental water to achieve outcomes for both non-woody and woody vegetation, which includes iconic tree species such as river red gum and black box.

3.2 PROJECT 5 CHARACTERISING CONDITION FOR NON-WOODY VEGETATION IN FLOODPLAIN-WETLAND SYSTEMS

Figure 3.1 Diverse non-woody vegetation found in floodplain-wetland systems
Photo credit: Cherie Campbell, Fiona Freestone, Deb Bogenhuber, Caitlin Johns

An important part of evaluation is understanding 'what is good'. Defining what is 'good' requires an understanding of what environmental water management is aiming to achieve and why – for example, the objectives, and the functions and values supported– as well as how outcomes will be assessed – such as condition, resilience or thresholds to evaluate 'success' against. This research explores the notion of 'success' and 'what is good' and aims to rethink the way condition is used to envisage, evaluate and communicate non-woody vegetation outcomes to environmental flows. The resulting structured framework for characterising condition, using both ecological data and societal values, provides practical guidance for water managers to inform condition benchmarks, watering objectives and choice of monitoring metrics. Outcomes feed into the Flow-MER evaluation of vegetation and are more broadly applicable to monitoring and evaluation of non-woody vegetation outcomes from environmental watering or other management activities.

This research was extended in 2023–24 to define resilience and transition states for floodplain-wetland vegetation communities using selected area case studies. However it did not proceed due to departure of key staff.

3.2.1 Research questions

The project aim was to rethink the way condition is used to envisage, evaluate and communicate non-woody vegetation (NWV) outcomes to environmental flows; specifically to:

- Conceptualise the components of condition that are integral to adaptively manage non-woody vegetation outcomes to flow in social-ecological systems such as floodplain-wetlands.
- Better understand the practice of environmental water management for non-woody vegetation outcomes by gathering practitioners' perspectives on outcomes and benefits, influences and risks to achieving outcomes, challenges associated with monitoring and evaluation, and how to improve outcomes in the future.
- Explore how non-woody vegetation responses to flow have been characterised in the published literature in terms of hierarchical biodiversity, functions and values, and resilience.
- Better understand community perspectives on the value of non-woody vegetation in river-floodplain environments to inform processes that foster shared understanding and just management of environmental water.
- Investigate the bounds of resilience for non-woody vegetation communities through variable wet-dry cycles.
- Synthesise a framing of condition to envisage and evaluate non-woody vegetation outcomes to environmental water to help maintain a range of functions and values.

3.2.2 Project overview

Basin-scale monitoring and research projects are providing insights into just how diverse, unique, and complex wetland and floodplain plant communities are at a landscape scale. Given the unique species level responses of non-woody vegetation, research is needed to seek patterns in non-woody vegetation responses that can inform predictions for future water management. The challenge is to develop a Basin-scale process for evaluating non-woody vegetation outcomes that incorporates diversity and variability of responses, has clear links to the functions and values supported, and can predict expected outcomes in unmonitored areas.

3.2.3 Methods

This project was completed as a PhD (Cherie Campbell) with the title *Characterising condition for non-woody vegetation in wetland floodplain systems: multi-scale approaches for evaluating restoration outcomes*. The project comprised 5 related pieces of work (see the aims above), and a final chapter to address the aim of characterising condition for non-woody wetland and floodplain vegetation.

The project characterised the condition of non-woody wetland and floodplain vegetation. A combination of expert opinion, societal values, ecological data, literature and conceptual understanding was used to rethink the way condition is used to measure and evaluate vegetation responses to environmental water.

3.2.4 Research outcomes

Conceptual modelling

- A peer-reviewed publication has been produced which conceptualises the components of condition that are integral to adaptively manage non-woody vegetation outcomes to flow in floodplain-wetlands, namely hierarchical biodiversity, functions and values, and resilience (Campbell et al. 2022).

Practitioner survey

- An online survey was undertaken to better understand the practice of environmental water management for non-woody vegetation outcomes. This gathered perspectives on outcomes and benefits, influences and risks, challenges associated with monitoring and evaluation, and how to improve outcomes in the future. The survey captured knowledge and expert opinion from 98 practitioners in environmental water management. Survey responses identified 6 key themes: 1) flow regimes, 2) vegetation attributes, 3) non-flow drivers, 4) management-governance considerations, 5) functions and values, and 6) monitoring, evaluation and research. These diverse themes highlight the need for 'more than just water' when it comes to the restoration and management of non-woody vegetation. The survey identified the need for more integrated land-water governance and management to address the impacts of non-flow drivers, such as pest species, land-use change, and climate change, along with a need to tackle physical, operational and social constraints to improve outcomes to environmental flow management (Campbell et al. 2023).

Values survey

- This survey sought to ascertain community perspectives on the value of non-woody vegetation in river-floodplain systems via an online survey. The survey found that participants valued non-woody vegetation for its provision of a range of ecosystem functions and services, with strong emphasis on ecological aspects such as regulation functions, habitat provision and biodiversity. However, the inclusion of a question reframed to focus on stories or narratives resulted in a shift in emphasis, highlighting values based on the way non-woody vegetation and rivers, wetlands and floodplains more broadly made people feel through lived experiences such as recreational activities, personal interactions with nature, educational and research experiences. This highlights the important role of storytelling in navigating complex natural resource management challenges and ascertaining a deeper understanding of values that moves beyond provision of function to feeling (Campbell et al. 2024).

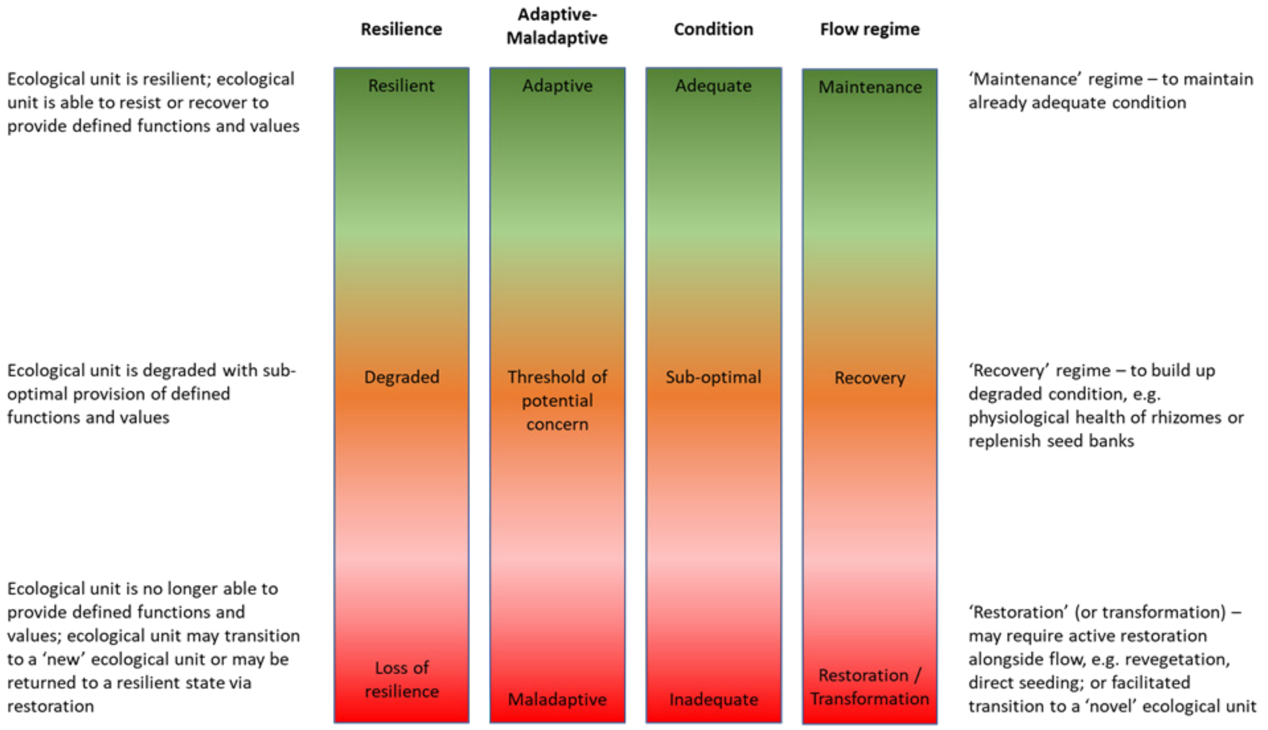
Resilience response models

Resilience is defined here as the ability to resist or recover from disturbances, including natural disturbances such as wetting and drying. A resilient vegetation community will have the ability to resist or recover (i.e. a level of condition) that is adequate to maintain defined functions and values (Figure 3.2). The resilience or condition state also has implication for the environmental flow regime managers may seek to implement (Figure 3.2).

- Conceptual resilience response models have been developed for 5 broad non-woody vegetation types: submerged benthic herbfields, tall reed beds, sedge-rushlands, aquatic grasslands, and ephemeral herbfields. Vegetation responses, considering composition, structure and processes, have been hypothesised for different hydrostates (i.e. wetting, wet, drying, dry) under 'exemplar' (typical), drier and wetter hydrological scenarios. These conceptual models have been applied to case-studies using understorey vegetation data from the Flow-MER program. For broad non-woody vegetation types, these resilience models help define expected outcomes (e.g. what are the characteristics of a functioning reed bed?), bounds of resilience (e.g. when is a reed bed no longer a reed bed?) and restoration goals (e.g. how do we reinstate a reed bed?).

Figure 3.2 Relationship between resilience, adaptive-maladaptive space, and condition

The upper (green) end of the scale represents a high degree of resilience with condition adequate to maintain defined functions and values. The lower (red) end of the scale represents a loss of resilience with a level of condition that is inadequate to maintain defined functions and values.



Links to evaluation

This project identifies ways to define non-woody vegetation condition to inform evaluation of vegetation outcomes in response to environmental flows, in both Flow-MER and more broadly. Specifically outcomes will help inform:

- watering objectives and an overarching vision for the maintenance and recovery of non-woody vegetation
- identifying monitoring indicators and metrics
- definitions of condition and the development of resilience models
- evaluation approaches and a quantifiable definition of success.

Informing adaptive management

Non-woody vegetation can be effectively managed using environmental water in many locations in the Basin. However, there are no clear benchmarks or definitions of success for non-woody vegetation condition that would provide simple targets for monitoring and adaptive management. This research will develop condition frameworks which allow an assessment of the effects of environmental watering. By characterising condition in a structured framework, practical guidance can be given to water managers to help inform the development of benchmarks, watering objectives and monitoring metrics.

Research report: Campbell C (2024, in prep)

Knowledge catalogue: https://flow-mer.org.au/basin-theme-vegetation/

3.3 Project 6 Remote sensing responses of woody vegetation to environmental water

Monitoring of the ecological function of woody vegetation to altered hydrology is challenging because of the large scales involved and a lack of simple condition metrics. The project team developed a basin-scale remote sensing product to understand changes in tree water stress at a resolution of 30m for each month from 2000-2022, for each tree pixel across the Murray-Darling Basin. The remote sensing data is underpinned by robust field data simultaneously collected. This research improves our understanding of tree response to water availability and allows us to identify water requirement thresholds for woody vegetation. It can then be used to inform the prioritisation of environmental water for woody vegetation and floodplain, wetland and river ecosystems. Research is complete and final report published (Doody et al. 2024a).

3.3.1 Research questions

- What do existing remotely sensed models tell us about the prior and current condition of long-lived woody floodplain vegetation at regional and basin-scales?
- How can we translate remotely sensed evapotranspiration into basin-wide condition information and identification of key thresholds?
- How is vegetation condition and trends related to hydrology across various scales, including at basin-scale?
- What was the condition of long-lived woody floodplain vegetation prior to the involvement of Commonwealth environmental water and how has this changed?

3.3.2 Project overview

Native woody vegetation in the Murray–Darling Basin contributes important resources and services to support ecosystem function of rivers, wetlands and floodplains. Woody vegetation includes tree species such as the iconic river red gum (*Eucalyptus camaldulensis*) (Figure 3.3), black box (*E. largiflorens*) and coolibah (*E. coolibah*) and the lesser-known river cooba or native willow (*Acacia stenophylla*).

Environmental water is often allocated to ensure that condition of key tree species in the Basin is maintained and restored. However, it is difficult to measure tree responses at various scales (individual – region – Basin or population outcomes) and also determine the benefit of Commonwealth environmental water in unmonitored regions across the Basin. This project developed basin-scale spatial data products which will improve our ability to investigate long-term ecological responses of trees to water availability and to develop new knowledge to aid in decision making and evaluation. A broad-scale remote sensing model, related to tree water use, demonstrating changes in water stress levels and underpinned by robust field measurements, has been developed for River red gum and Black Box in both saline and non-saline areas across the Murray-Darling Basin.

Tree water use is governed by canopy density and is thus an accurate alternate surrogate for tree condition via demonstrating ecological responses to hydrological change. It has been made scalable by measuring total woody vegetation evapotranspiration. This project has developed innovative methods to generate new fine temporal and spatial basin-scale data to determine water use trends and temporal responses in saline and non-saline regions for both River red gum and Black box across the Murray-Darling Basin.

Figure 3.3 Flooded red gum forest at Yanga National Park
Photo credit: Tanya Doody

3.3.3 Methods

Development of AMLETT model

This task aimed to create regression models between remote evapotranspiration (ET) and field ET to build remote sensing models for red gum and black box, in saline and non-saline environments. For each field location, ET remote sensing data have been extracted and we have investigated how to scale field measured tree evapotranspiration across the Basin for river red gum and black box trees in both saline and non-saline environments. The resulting innovative Basin scale and 24-year temporal scale data provide monthly tree response information for both species in both environments for the last 20+ years, enabling timeseries analysis. The model developed is called AMLETT (Australian Machine Learning EvapoTranspiration for Trees) These datasets are available from the CSIRO Data Access Portal.

Understand trends in remote sensing vegetation responses (based on ET) in relation to Commonwealth environmental watering actions

Inundation layers and metrics such as timing of flow, duration of higher flow/inundation were collated across years. Remote sensing imagery and the normalized difference vegetation index (NDVI) were used to understand how woody vegetation responds to different inundation frequencies in 2 case study regions, one for river red gum and one for black box. The same methods will be applied to ET data to show when woody vegetation may change into a different ecological community in response to water availability (or lack thereof).

3.3.4 RESEARCH OUTCOMES

VALIDATION OF AMLETT OUTPUTS

A new approach was undertaken to that proposed at the beginning of the research project. This new approach is detailed in Doody et al. (2023) with a clear advantage being that one model (AMLETT – **A**ustralian **M**achine **L**earning **E**vapo**t**ranspiration for **T**rees) could accurately predict woody vegetation ET across the Murray-Darling Basin when validated with substantial long-term field measurements of ET, irrespective of species and salinity/freshwater situations. The resulting dataset[3] provides woody vegetation ET values monthly ($mm^{month-1}$), for 24 years across the entire Basin for river red gum and black box.

Estimates are provided for coolibah[4], however, these are not underpinned by the same field measurements as the other 2 species and results should be treated with caution. A method was developed to map fine scale (20m) fractional tree canopy cover across the Basin, to ensure ET estimates were accurate across the heterogenous woody vegetation estate (Gao et al. 2021).

COMPARE REMOTE SENSING ET OUTPUTS WITH FIELD COLLECTED TREE CONDITION DATA [TREE CANOPY INDEX]

Research indicated that there was little relationship between tree ET and Tree Condition Index (TCI) as TCI is collected at a much finer scale (individual tree) compared to the 250 m ET outputs. We have concluded that ET needs to be converted to a functional index that represents tree responses to altered hydrology and considers trajectory of change. We have developed a preliminary method for this using the 30m AMLETT product for woody vegetation. Visualisation products have been created for ET modelled outputs from 2000 for each pixel within 100-year Basin flood extent for Barmah National Forest and Calperum/Chowilla Station case study sites.

UNDERSTAND TRENDS IN REMOTE SENSING VEGETATION RESPONSES (BASED ON ET) IN RELATION TO CEWH WATERING

Final spatial ET layers are complete (ET, 30m, monthly from 2000–24) and a preliminary response index developed. A detailed conceptualisation of expected drivers and responses to water for the environment using field collected data has been produced (see Wallace et al. 2020a, 2020b). Substantial spatial data are now available to commence data mining to elucidate trends in vegetation responses in relation to Commonwealth environmental watering. This work is ongoing and a focus of the 2023–24 extension.

FLOODPLAIN TREE CARBON ESTIMATION USING REMOTE SENSING

Using multiple sources of spatial data, the research created basin-scale layers that provide monthly Gross Primary Productivity estimates[5] across the Basin from 2015–20. This was produced in collaboration with the MDBA's Ecosystem Functions project.[6] An example of outputs is provided for Barmah National Park and Calperum Station (Figure 3.4).

[3] https://doi.org/10.25919/nxr8-9z06

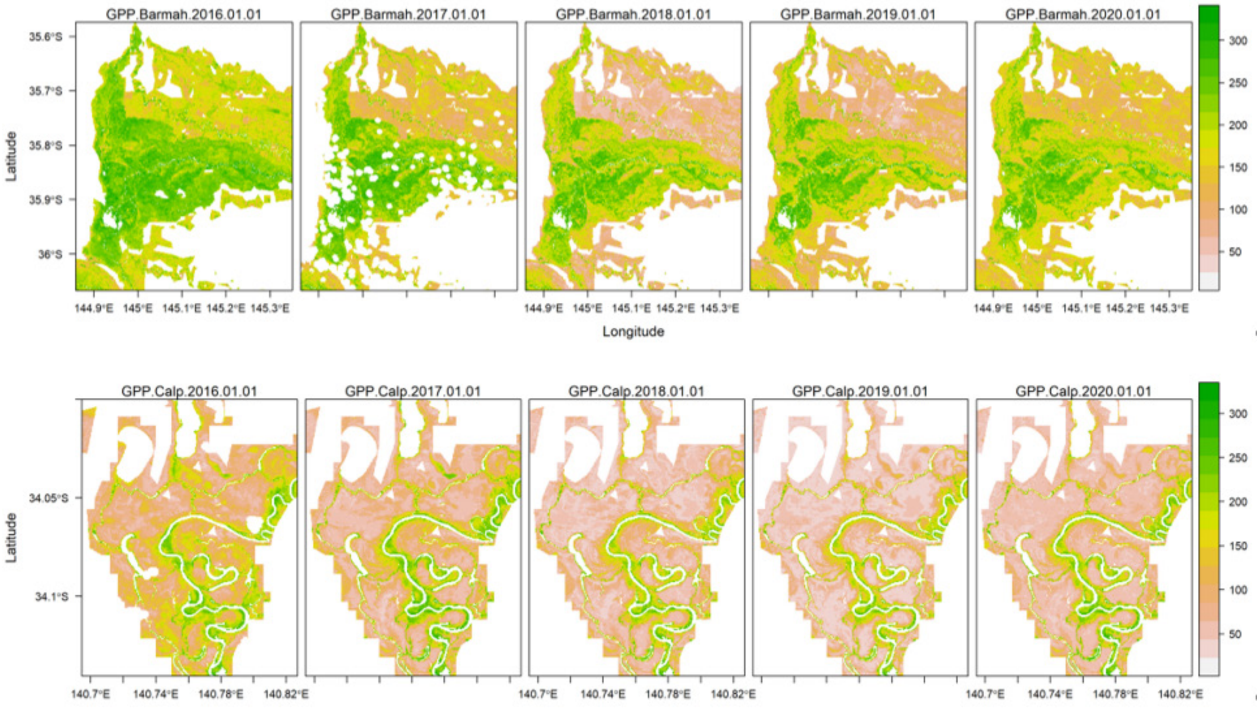
[4] https://doi.org/10.25919/9w38-8268

[5] https://doi.org/10.25919/sv92-0j64

[6] Information on the Ecosystem Functions project is available at https://research.csiro.au/mwe/investing-in-ecosystem-functions-knowledge-to-improve-adaptive-management-of-water-for-the-environment-in-the-murray-darling-basin/#:~:text=The%20Department%20of%20Agriculture%2C%20Water,connection%20to%20the%20health%20and

Figure 3.4 Example of gross primary productivity annual timeseries data for Barmah National Park and Calperum Station within the Murray–Darling Basin

Image: Tanya Doody/Steve Gao, CSIRO/University of Canberra



LINKS TO EVALUATION

This research project has generated monthly, finescale (30m) spatial data of woody vegetation condition, from 2000-2024. This output is intended to be immediately applicable to evaluation of the effects of environmental watering on several species of woody vegetation.

INFORMING ADAPTIVE MANAGEMENT

The outcomes of this research contribute to an improved understanding of how vegetation responds to water availability and will enable identification of water requirement thresholds for flow management, to benefit vegetation and floodplain, wetland and river ecosystems. It also provides an ability to understand how resilient a region may be via a trajectory of change approach coupled with past and current inundation frequency.

Research report: Doody et al. (2024a)

Manuscripts: Doody et al. (2023), Doody et al. (2024b), Gao et al. (2021)

Knowledge catalogue: https://flow-mer.org.au/basin-theme-vegetation/

4 FISH THEME

4.1 RESEARCH OVERVIEW

The Murray–Darling Basin historically supported a unique fish community with a diverse array of sizes and species of native fish. Since European settlement, the distribution and abundance of native fish species has declined and over half are now listed as threatened or of conservation concern (MDBA 2020). The vision of restored fish populations in the MDB is intrinsically linked to recovering functioning riverine ecosystems and will assist in maintaining strong connections between people and their rivers.

Freshwater fish are important indicators of ecosystem health and have critical life history processes linked to hydrology and hydraulics. Fish are influenced by flow characteristics directly, by habitat provision and water quality, and indirectly through cues to migration and reproduction, and biotic interactions such as feeding, competition and predation. Theme research focuses on critical life history processes (growth, spawning, recruitment, survival, migration and dispersal) and their intrinsic links to hydrology.

4.2 PROJECT 7 FISH POPULATION MODELS TO INFORM COMMONWEALTH ENVIRONMENTAL WATERING

Fish population models are a basin-scale tool for assisting water management and are useful in evaluating different watering scenarios, evaluating likely outcomes, and helping to set monitoring targets for environmental watering. This research explicitly linked flow management to whole-of-lifecycle responses for 3 key native fish species.

This project aimed to develop basin-scale metapopulation models for golden perch (*Macquaria ambigua*) and bony herring (*Nematalosa erebi*), and local reach-scale models for Murray cod (*Maccullochella peelii*), which enable predictions about responses to specific flow management scenarios. These models can then predict the contribution of Commonwealth water for the environment to key native fish populations.

Figure 4.1 A juvenile golden perch detected in the Lower Murray River
Photo credit: Lower Murray selected area team.

Predictive population models are powerful tools for adaptive management, enabling testing of population responses to a range of management scenarios. Research was extended to refine the models to address known gaps and undertake sensitivity testing, and completed in June 2024 with publication of results in Todd et al. (2024).

4.2.1 Research questions

- What is the contribution of Commonwealth environmental water to key native fish population processes including movement, reproduction and survival at the selected area scale?
- How could this contribution be improved to enhance native fish populations?

4.2.2 Project overview

The ecological connection between attributes of river flow (e.g., discharge, water level, water velocity) and ecological processes (e.g., fish spawning, survival, movement) are known as flow-ecology relationships. Where there are strong empirical data that reveal the nature of these relationships, then seasonal and annual watering regimes can be designed to benefit such, and ultimately fish populations. One of the greatest challenges is a lack of knowledge about the degree to which flow-ecology relationships can be transferred to unmonitored sites, or at larger spatial or temporal scales.

Population models are a mathematical construct based on underlying ecological processes. They provide a structured, quantitative method for integrating existing knowledge and data to predict fish responses to management actions. The models can be used to explore region-specific responses (i.e. by population) or for a particular process (e.g. recruitment). The models can also be used to set fish recovery targets (timelines and spatial areas), while also helping to devise optimal watering scenarios and complementary management measures (e.g., fishways, recreational fishing regulations and habitat restoration).

System-scale flow planning is a step towards whole-of-basin planning and helps recover these fish species. Population modelling offers a whole-of-Basin approach to test and refine multi-year watering scenarios. A strength of these models is their ability to be applied beyond the selected monitoring areas for predicting broad-scale population responses to flow events.

4.2.3 Methods

The underlying approach uses stochastic population models for each species, with life history guiding model structure. The models were developed to capture current knowledge of flow-ecology relationships, explicitly including flow and temperature effects on spawning timing and success, egg, larval, fingerling and adult survival, and movement of juveniles and adults. The population modelling used data collated from a variety of State and Commonwealth (including Flow-MER and its predecessors) monitoring programs and from several expert workshops. Basin-wide metapopulation models were developed for golden perch (14 populations areas) and bony herring (9 populations) and individual Murray cod population models were developed for 6 Flow-MER Selected Areas. All models for Murray cod were run using observed flows at corresponding river gauge sites and then used to assess population trajectories modelled against flow scenarios with and without Commonwealth water for the environment (a counterfactual approach).

4.2.4 Research outcomes

- Overall population trajectories for Murray cod were predicted to be highly sensitive to hypoxic events, causing a significant drop in the modelled adult population. These events were predicted to occur every 7 years in most of Selected Areas.

- Murray cod model predictions demonstrated that for most of the Selected Areas, there were generally increased recruitment in population responses to Commonwealth water for the environment delivery (using our counterfactual comparison between with and without Commonwealth water for the environment). However, this enhanced recruitment only translated into a predicted increase in adult population size in 2 of the Selected Areas (Gwydir and Lachlan River populations).
- Murray cod model predictions showed the greatest responses to Commonwealth water for the environment were in circumstances where a moderating process, such as hypoxic blackwater or cold-water pollution, was occurring.
- The meta population models developed for golden perch (at a whole-of-basin-scale) showed broadly stable population dynamics across the modelled time period, despite large increases in population sizes in the middle years of the study and subsequent declines (Millennium drought).
- The latest outputs generated from the golden perch population model predicted basin-scale benefits of Commonwealth environmental water for golden perch, highlighting that these benefits were robust to uncertainty in key model parameters (movement rates among populations).
- The meta population models developed for bony herring (at a whole-of-basin scale) predicted a general decline since 2010.
- For both golden perch and bony herring, the modelling demonstrates responses to flow and temperature with marked fluctuations in both the southern Basin and northern Basin (i.e., major increases and decreases) in response to flow, resulting in relatively greater levels of recruitment occurring during periods of high flow and flooding.
  - The modelling predicts greater numbers of golden perch in the southern Basin compared to the northern Basin, whereas greater numbers of bony herring were predicted in the northern compared to the southern Basin. This demonstrates species differences between the metapopulation models highlighting that the models capture different aspects of the species life history.

LINKS TO EVALUATION

While the model outputs have had no formal application in the evaluation portfolio as yet, the models for golden perch and Murray cod are advanced and could be used for such. The latest output from the golden perch metapopulation model generated counterfactual outputs (with and without Commonwealth environmental water) at a basin scale and thus could be a useful tool for Basin scale evaluation (where empirical data is lacking).

INFORMING ADAPTIVE MANAGEMENT

Predictive population models can be powerful tools for adaptive management as they assist in predicting population responses to a range of management scenarios. For example, well parameterised fish population models could be used to test scenarios of different delivery strategies (the timing and duration of environmental flows), including sequences of flows.

Research reports: Todd et al. (2023), Todd et al. (2024)

Knowledge catalogue: https://flow-mer.org.au/basin-theme-fish/

4.3 Project 8 Linking flow and movement of native fish in the Basin

Movement is essential for fish population persistence, and in riverine systems, is fundamentally linked to river hydrology and connectivity. Fish movement is important for resilience and recovery from disturbance events such as hypoxic blackwater events and drought conditions. Research evaluated flow triggers for local and regional scale fish movement to refine our understanding of the environmental water requirements among fish species and regions in the Basin. Fish movement datasets were compiled comprising otolith and electronic tagging data from prior projects to model fish movement response in relation to river hydrology and environmental watering. This research improves our understanding of landscape-scale fish movements and population resilience and informs delivery of environmental water for connectivity, fish passage and maintaining refugia for migrating fish. Research is complete and final report published.

Figure 4.2 A tagged golden perch being released in the lower Murray River
Photo credit: South Australian Research and Development Institute

4.3.1 Research questions

- What is the role of river hydrology in determining regional and inter-regional fish movements in the Murray–Darling Basin?
- How does this vary by life-history stage and species in different Murray–Darling Basin rivers?

4.3.2 Project overview

Movement is fundamental to animal population persistence and provides opportunities to exploit variable resources, determines fitness and, ultimately, drives population dynamics. For fish occupying riverine environments, the interplay between hydrology and geomorphology determines micro- and meso-scale hydraulics that, in turn, influence habitat availability and suitability for different species. Coupled with seasonal changes that control biological rhythms, such as day-length and temperature; hydrology and associated hydraulics provide cues and physically enable fish to move and complete essential life-history processes.

4.3.3 Methods

This project collated fish movement data comprising a time series spanning several decades from existing telemetry and otolith datasets to analyse regional (>5 km) and inter-regional (>100 km) fish movements in relation to river discharge in the Murray–Darling Basin. Data were compiled for 2 native freshwater fish species, with a combined sample size of 2,696 individual tagged golden perch (*Macquaria ambigua*) and Murray cod (*Maccullochella peelii*), and a separate sample of 1,126 individual otoliths.

The objective was to use these complementary datasets to quantify the role of river hydrology in determining regional and inter-regional fish movements in the Basin. Using our current understanding of the factors affecting golden perch and Murray cod movement, we estimated a population-level flow-movement relationship for each species. Using this model, we generated transferable flow-ecology relationships and subsequently predicted non-sampled study areas of the Basin to demonstrate the utility of this approach for management. We highlight key aspects of the hydrograph that maximise the movement responses of these 2 species of lowland river fish.

4.3.4 Research outcomes

- Complementary electronic (telemetry) and natural (otolith) data revealed that event-based river discharge positively influences both regional and inter-regional movement of golden perch and Murray cod.
- Across their broad geographic range, both golden perch and Murray cod undertook regional (>5 km) and inter-regional movements that were substantially influenced by the magnitude of river discharge.
- Increasing discharge resulted in a net positive increase in the probability of both regional and inter-regional movement occurring.
- Analysis of telemetry data revealed that every 1-unit increase in standardised discharge was associated with a 4.86-fold increase in the odds of golden perch moving compared with a 1.44-fold increase for Murray cod.
- Analysis of otolith chemistry showed that golden perch moved extensively between the delineated regions, although there was substantial regional variability both within and between the northern and southern Basin.
- Abundances of fish that moved into and out of specific regions was also variable, with some regions acting as distinct sources of fish (emigration most prominent), such as the Warrego and Lower Darling rivers, and other as sinks (immigration was most prominent), such as the Lower Murray and Upper Murray rivers.
- Analysis of otolith data revealed that every 1-unit increase in standardised discharge was associated with a 2.6-fold increase in the odds of emigration occurring.
- Despite examples of large-scale movements, a large proportion of the golden perch populations remained within their natal (birth) region throughout their entire lifetime.
- Statistical models were generated that enabled prediction of golden perch and Murray cod short-term movements in relation to river discharge events from the telemetry dataset and golden perch immigration/emigration in relation river hydrology. We applied these predictions to a region of the mid-Murray River as a single example demonstrating the utility of the technique and data.

Links to evaluation

While this work has no direct application to Basin-scale evaluation as yet, discussions are underway to include a movement evaluation question within future evaluations (thereby meeting one of the Basin Evaluation Watering Strategy objectives). As such, the Basin scale movement model generated in this work may be a useful tool to undertake this (where empirical data is lacking which is likely at a basin scale). The results generated in this work have also recently been used to refine transition rules embedded in the golden perch population model, which may also be used for basin-scale evaluation in the future.

Informing adaptive management

- Fish populations are connected to one another via movement of individuals along river systems. These movements are likely to be an important part of resilience and recovery from disturbance events such as hypoxic blackwater events and dry-down. Understanding fish movement enables management for fish passage, supports important refugia for migrating fish and improves our understanding of the role of landscape scale fish movements to promote population resilience.
- Both regional and interregional movement of Murray cod and golden perch can be facilitated by increased river discharge. This is highly relevant when considering flow connectivity and barriers to fish movement such as weirs.
- Modelled movement of both species was found to be highly variable among river catchments, thus understanding of regional movement probabilities is an important consideration for fish and flow management.
- Region specific models can be used to understand how flow and life-stage may mediate movements. For example, what is the likelihood of movement of adult or juvenile.
- Given that movement can substantially restructure populations as a reflection of source-sink dynamics, the extension of the current approach includes integration into population dynamics models.

Research report: Thiem et al. (2023)

Knowledge catalogue: https://flow-mer.org.au/basin-theme-fish/

5 FOOD WEBS AND WATER QUALITY THEME

5.1 RESEARCH OVERVIEW

Food webs provide a useful way to think about life in rivers and wetlands. Food webs describe the interactions between organisms – who is eating who, from the smallest bacterium to the largest Murray cod. They can illustrate how much energy is moving between organisms or groups, and the role of individual animals or connections in sustaining life across an ecosystem. Flows and flooding provide food and sustain life in river and wetland ecosystems. Inundating a wetland helps plants grow by wetting dry areas and creating habitat for algae to flourish. Flows transport floodplain organic matter into rivers, fueling growth of microbes and zooplankton. They allow fish to move, forage and spawn, as well as helping insects grow, which, in turn, enables birds to forage and flourish.

The energy that drives riverine food webs is a fundamental requirement for all organisms. Without energy, organisms have no capacity for growth or reproduction. Food webs describe the pathways along which energy is transferred from resource to consumer. The strength and direction of these pathways are sensitive to impacts from changes to river flows and their landscapes. Although complex, food web studies can identify critical parts of an ecosystem that influence energy production and transfer, that in turn influence the size and structure of our iconic native fish and waterbird populations.

The Food Webs and Water Quality Theme evaluates how Commonwealth environmental water influences water quality and stream metabolism under the Flow MER Evaluation program. For Research, the Food Webs and Water Quality Theme conduct a program that explores trophic transfer efficiency and the responses of basal resources and their quality to different watering regimes to aid the development of a bioenergetic food web model.

5.2 PROJECT 9 DEVELOPING AN ENVIRONMENTAL WATER ENERGETICS RESPONSE MODEL

A bioenergetic model for ecosystem response to environmental water demonstrates how food webs respond to flow, in this case focusing on riverine habitats. The project team developed an energetics response model to evaluate the contribution of Commonwealth environmental water to food webs, using one valley as a case study. This model was used to determine the energetic impacts of different flow scenarios and in so doing, improve the prediction of ecological outcomes in response to environmental watering. This research is extended to October 2024 to model food web responses to environmental flows in the Murray River system using existing data, ultimately informing the utility of this model and the applicability of predictions of ecological outcomes more broadly across the Basin.

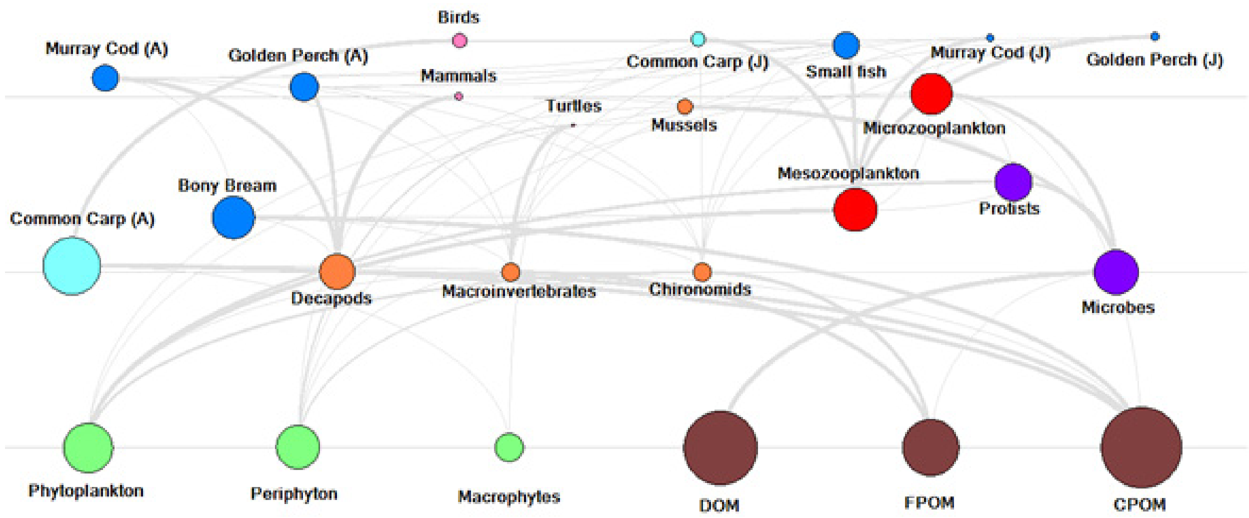
5.2.1 RESEARCH QUESTIONS

- How does environmental watering influence the flow of energy through to vertebrate consumers such as fish and birds?
- How can the energetics response model support the prediction of the trophic-carrying capacity of rivers and wetlands in response to environmental water delivery?

5.2.2 Project overview

It is well understood that environmental flows can be used as a cue to trigger breeding of some native fish species. Food web modelling work provides information about the biomass of food web groups. Food webs describe not only the organisms that live within a habitat but the relationships between them, including how they grow and change and how they eat and are eaten. The amount of growth by the organisms within a food web is conceptualised as productivity, which is essentially a measure of how much life there is. Understanding how aquatic food webs work and the influence of hydrology is therefore critical to maintaining and restoring the health and productivity of individual populations of animals and the whole ecosystem. An example food web derived for the Lachlan River is shown in Figure 5.1.

Figure 5.1 Food web diagram of the Lachlan River created as part of the bioenergetics model
Each circle corresponds to a different functional group, the size of each circle its biomass, and lines between circles food web connections



The food web research project has 2 main parts:

- Empirical research to address critical knowledge gaps on the functioning of food webs in the Basin with an emphasis on flow dynamics (components 1, 2 and 3)
- Development of a food web modelling framework to estimate the contribution of Commonwealth environmental water to food web production (component 4). An energetics response model was developed to predict the trophic carrying capacity of rivers and wetlands in response to environmental water delivery.

5.2.3 Methods

Empirical research

1. The first component of the project reviewed existing data and literature to assess knowledge gaps on food web structure and functioning. This included sourcing data for total abundance for different food web groups, diet preferences of important taxa, and information on growth and consumption rates. Field data were collected and assembled into information for building food web models.
2. Experiments used larval golden perch to assess how the structure of the food web changes under different resource conditions and how this impacts fish growth. Small-scale experiments were used to

test the hypothesis that if the right microzooplankton food resources (Figure 5.2) are unavailable following spawning, recruitment outcomes will be poor. A second experiment tested the trophic upsurge theory, that resource increases at the base of the food chain lead to energy flowing through to higher trophic levels.

3. Two experiments were conducted with NSW Department of Primary Industry and Environment to assess changes to organic matter and food web productivity during flow events. The first experiment focused on the potential role of overbank flows in mobilising organic matter with different bioavailability. The second experiment focused on how various size in-channel flow events inundate distinct sections of riverbanks and the potential implications for food web productivity via different inputs.

Figure 5.2 Planktonic microbes play a critical role in processing and transforming organic material and nutrients in aquatic ecosystems

Illustration by artist Nina Rupena prepared for the Flow-MER website (flow-mer.org.au)

Food web model

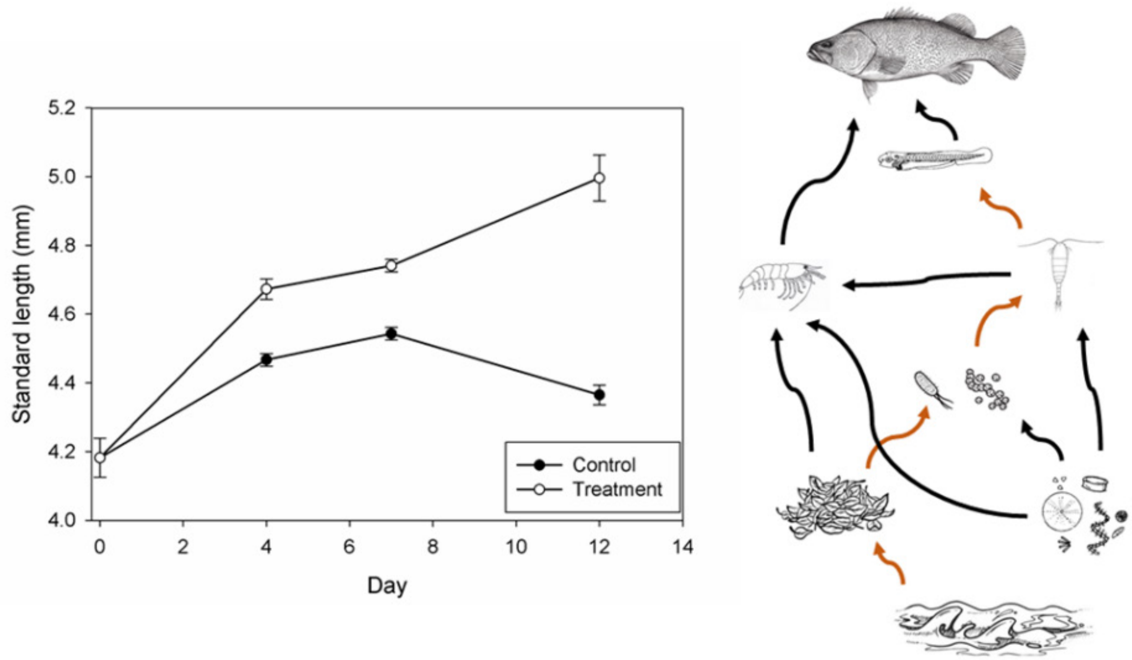
A case study bioenergetic food web model for the river channel is complete using data generated from the empirical research. The modelling framework has been designed to integrate core metric outputs from Selected Areas, including dissolved organic carbon and chlorophyll concentrations, fish and other biota abundance measures. The robustness of the model relies on long-term time series data collected in Flow MER and other programs. Using the fitted models, scenarios will be simulated in the presence and absence of environmental water allocations to see how changes in flow influence the structure and productivity of food webs. The model demonstrates rates of carbon transfer and production in food webs under different environmental flows, to illustrate the changes in productivity and fish outcomes. This provides the capability to predict the trophic carrying capacity of river channels and floodplain wetlands in response to Commonwealth environmental water delivery. The approach developed was then further validated and parameterised with data obtained through the River Murray Monitoring Program, an allied monitoring program to Flow MER, also funded by the CEWH and focused on ‘whole of system’ assessment of a large-volume annual spring pulse in the River Murray.

5.2.4 RESEARCH OUTCOMES

- During overbank flooding, the concentration and total load of organic carbon entering the river system increases, as do the relative amount of carbon consumed by organisms and therefore entering into the food web. Inundation of the mid- and upper sections of lowland riverbanks was shown to lead to significantly higher concentrations of organic matter and zooplankton abundances within the river channel compared to base flows.
- The growth of larval golden perch can be limited by the availability of microzooplankton (see Figure 5.3). Inputs of organic matter associated with flow events may provide additional resources for increasing microzooplankton and relieving food limitation (Figure 5.3). Therefore, resource pulses associated with flow events can lead to substantial short-term increases in zooplankton with measurable increases in fish biomass weeks later.
- The model can provide estimates of food web production between different flow scenarios. For example the biomass of Murray Cod was 8.3% higher and Golden Perch 15.3% higher in the scenario with CEW compared to the scenario without for the period 2017 to 2021.
- The modelling approach was applied to the River Murray, parametising and fitting models for the period 1978 to 2023. The outcomes showed that the approach is broadly applicable with the models able to explain changing biomasses observed across the food web well.

Figure 5.3 Growth rates of golden perch larvae with (treatment) and without (control) the addition of organic matter mimicking the delivery of resources that occur during a flow event (left)

During the early stages of life, golden perch larvae rely on microzooplankton such as rotifers and copepod nauplli to survive and grow; environmental flows can help promote the growth of these important food resources.



LINKS TO EVALUATION

This bioenergetic model has provided a framework and example of how the influence of Commonwealth environmental water in the Basin can be evaluated at the ecosystem scale. The outcomes can support the evaluation of other themes, for example how Commonwealth environmental water may influence the population of a fish species. It also helps link and integrate themes, such as flow regimes and birds/fish, highlighting their connections, important ecological components and knowledge gaps.

Informing adaptive management

The bioenergetic model can be used to explore how different flow scenarios may influence the structure and population of different organisms within the food web. In the case study of this work (to date), we have focused on scenarios that have included with and without Commonwealth environmental water. Outcomes of this work have shown that even small amounts of environmental water can contribute to significant increases in biomass of taxa within rivers. Empirical work has highlighted the importance of the environmental flows as events that lead to successional changes in food webs from initial pulses in basal resources that lead to increased growth and production of higher trophic animals such as birds and fish.

Research report: Hitchcock et al. (2024b)

Manuscripts: Hitchcock et al. (2024a, 2024c, 2024d), Hitchcock et al. (in prep)

Knowledge catalogue: https://flow-mer.org.au/basin-theme-food-webs-water-quality/

6 Basin modelling and Visualisation

6.1 Research overview

The Modelling and Visualisation Themes developed methods and tools to evaluate the benefits of environmental water. Research activities aimed to develop predictive models which describe the basin-scale benefits achieved with Commonwealth environmental water and assist in planning of future actions. Two key benefits of modelling are the ability to compare outcomes between different scenarios and the ability to extrapolate outcomes to locations beyond current monitoring sites or other periods of time.

The key to modelling is identifying the important environmental drivers (e.g., flow requirements or temperature envelopes) and quantifying the expected response occurring across drivers through space and time. The most widely used approach to doing this is to use indicator metrics that change in response to flow and environmental watering and provide an understanding of the relationships in monitored locations under a broad range of environmental conditions. Basin-scale predictive modelling seeks to provide a basis to:

- identify knowledge gaps in our understanding of ecosystem responses and develop recommendations on how to address these gaps
- enable integration of hydrological information with ecological models for evaluating ecological outcomes for a range of scenarios
- extend predictive approaches to areas of the Basin outside of Selected Areas.

Visualisation explores ways of creating data dashboards to enable real time reporting and interpretation of complex data spatially, temporally and from the perspective of multiple outcomes.

6.2 Project 10 Using flow-ecology relationships to predict responses to watering

Flow-ecology relationships describe the relationship between flow and ecological outcomes, in this case, in response to delivery of environmental water. Understanding of these relationships informs adaptive management and evaluation of ecosystem responses to environmental water. The project team developed a novel suite of hydrometrics to identify hydrology and/or inundation metrics driving observed changes in vegetation condition as a case study of the approach. Model outputs identify flow drivers that shape vegetation community patterns. This knowledge improves our understanding of the response of non-woody vegetation to environmental flows. Research is complete and technical report published.

6.2.1 Research questions

- What are the relationships between flow and ecological outcomes, how can these be extrapolated to unmonitored locations, and how can they be scaled up?
- How to enable integration into a common framework and identify commonalities?
- How to understand the ‘ecological counterfactual’?
- How to contribute to Basin-scale and Basin-wide evaluation?

6.2.2 Project overview

The flow-ecology modelling research project sought to understand flow-ecology relationships for the purpose of developing a scientifically sound modelling method to support Flow-MER evaluation. This research integrated data and information across all Flow-MER Themes.

The modelling methods developed in this research provide an 'environmental counterfactual', linking to the hydrology counterfactual described in the Hydrology Foundation Report (Stewardson and Guarino 2019). This allows greater understanding of the relative environmental outcomes under flows both with and without Commonwealth environmental water, considering differences in the magnitude, duration, and timing of flow events between the scenarios.

The objectives for the development of the modelling method were to:

- enable extrapolation to unmonitored locations within the Basin, and scaling to the Basin
- provide the ability to understand the relative benefit of environmental water considering flows both with and without Commonwealth environmental water
- facilitate transparency and communication of environmental decision making and outcomes.

A case study was undertaken, using Vegetation Theme data, to understand the contribution of hydrology or inundation to the condition of understory vegetation. We use statistical models including a generalised additive model (GAM) that asks if percent cover depends on water in a non-linear manner. The resulting model delivered predictive counterfactual modelling to the Vegetation Theme.

6.2.3 Methods

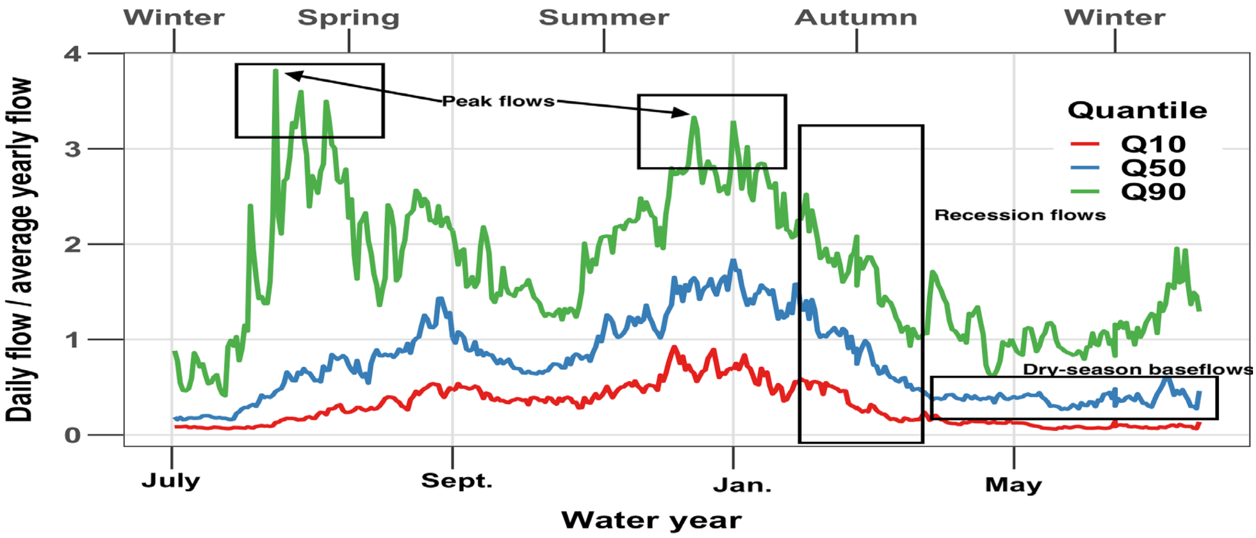
Modelling assessment

A review of methods for analysis of LTIM data was undertaken and exploratory data analyses used vegetation indicators. An assessment of existing modelling frameworks reviewed their suitability for application for an ecological counterfactual for the Basin-scale evaluation. The project team completed sensitivity and suitability testing of ecohydrological modelling tools. This work provided recommendations on the design of integrative and Basin scale modelling frameworks for the environmental counterfactual.

Generalisable hydrometrics

Hydrometrics provide summaries of the flow regime through statistics of key flow components. Outcomes provide a useful summary and description of the actual and counterfactual flows compared to pre-development flows (or unaltered flow regime). We developed a suite of functional flow metrics by adapting the California Environmental Flows Framework (CEFWG 2021). The hydrometrics were re-coded as a statistical R package and repurposed to represent flow regimes in the Murray-Darling Basin. It has been packaged as FFAus (functional flows Australia) available from a bitbucket repository and includes the R code and a User manual (Lloyd-Jones et al. 2024). Figure 6.1 shows the unaltered flow regime at one gauge in Macquarie River.

Figure 6.1 Unaltered flow regime estimated from the modelled pre-development flows at Dubbo, Macquarie River
This plot shows two wet periods – late winter-early spring and late summer. Recession flows are observed during autumn leading to dry season baseflow.



For 51 gauges across the 19 valleys, we estimated 84 hydrometrics on the observed flows, the counterfactual flows and the pre-development flows. Design criteria for final set of hydrometrics included that the hydrometrics were functional (with direct links to ecological outcomes), management relevant (with ability to consider river operations and the counterfactual), versatile (with flexibility to consider a broad range of flow/inundation needs for integration across Themes), generalisable (with applicability across different river templates and regions) and scalable (with consideration of different antecedent conditions or temporal periods). We used the flow requirements described in Baumgartner (2013) and Mallen-Cooper and Zampatti (2018), and Northern Basin Expert Panel Workshop to shortlist the functional flow metrics that met those design criteria. In addition to fish and vegetation, we included other assets, such as riparian vegetation and ecosystem functions as identified in the EWR plans for different Selected Areas (Table 6.1).

Table 6.1 Key functional groups of fish and vegetation in the Basin and functional flow hydrometrics associated with life cycle of these assets (compiled from multiple sources, including EWR plans)

			Flow attributes by life cycle			Corresponding hydrometric		
Category	**Functional**	**Asset**	**Egg/Embroyonic**	**Larval**	**Adult**	**Egg/Embroyonic**	**Larval**	**Adult**
Fish	Flow dependent species	Golden Perch, Hyrtl's Tandan, Silver Perch, Spangled Perch	Requires flow upto 5 days for buoyancy and plelagic, or non sticky and demersel	Larval drift downstream- 20 days, small pulses	flow pulses for spawning trigger (post winter)	Q25 duration>25days (seasonality)	Q25 duration>25 days (seasonality), Q25 frequency	Q50 frequency, spring-summer
	In channel Specialist -flow dependent	Murray Cod, Trout	Eggs are demersel with a relatively long hatch time -14 days, requiring stable flows	larval drift for about 10 days, require stable flows	Increasing flows mid winter-end of spring	Q25 mag, Q25 duration>25	Q25 mag, Q25 duration>25	Q25 mag, Q50 mag, duration, frequency
	Floodplain specialist	Darling River Hardyhead, Flat-headed Galaxies, Olive Perchlet, Rendahl Tandan	Eggs are sticky and demersal with hatch time upto 9 days	Recruitment and dispersal relies on large flow event that can connect to floodplain	increasing flows and specific substrate requirement	Q25>10days	Q90 mag, freq, duration, timing	Q50 mag, duration, frequency
	Generalist	Australia smelt, Bony herring , Flat-headed gudgeon	Eggs are sticky and demersal with hatch time upto 14 days	there is some larval dispersal	multiple spawns a year-with low to medium flow events	Q25>14days		Q25 mag, Q50 mag, duration, frequency
Vegetation	Riparian		Baseflows during spring, Large fresh every 5-10 year, for about 15 days			Q25 mag, Q50 mag, duration, frequency, Q50, duration>15 (every 5 years)		

Statistical analysis of Flow-MER Theme data

Research identified and quantified relationships between environmental assets and flow in order to develop a generalisable model to extrapolate results across the Basin, using the ANAE as a basis for extrapolation. As a case study, the project team identified indicators for vegetation including non-woody vegetation functional groups. These indicators demonstrated model capability in predicting outcomes for 'fast response' (non-woody) indicators that included groups with a broad range of watering needs (Lloyd-Jones et al. 2023).

This activity generated an 'environmental counterfactual'. This was achieved by linking relative outcomes under flows with and without Commonwealth environmental water, as a timeseries of condition values, to the hydrology counterfactual. The project team assessed the effectiveness and suitability of model attributes for assessing Commonwealth environmental water counterfactual flows (Repina and Stratford 2020).

6.2.4 Research outcomes

The method demonstrates the application of the analytical and statistical modelling approach using hydrometrics. The outcomes of this are two-fold:

- identification of important flow drivers for understanding outcomes in non-woody vegetation communities
- development of predictive models to understand and model response of non-woody vegetation communities to patterns of flow.

Statistical analysis was used to 1) identify the hydrology or inundation metrics that are driving observed changes in vegetation condition, 2) quantify the response relationships associated with changes in hydrology across different spatial units, and 3) enable the quantification of outcomes associated with different hydrology inputs (e.g. scenarios including the counter factual).

Key takeaways include:

- flow time series length is important in detecting change
- the ability to detect change is not only related to the volume of Commonwealth water for the environment at a site, but also with the parameter space of the watering needs of biota
- the representation of flow is important, for example:
  - threshold vs gradient
  - aggregated vs point in time
  - in-channel (gauge flow) vs floodplain (inundation)
  - inclusion of diverse watering needs.

Links to evaluation

This project enables important flow attributes that are associated with changes in ecological response to be identified based upon analysis of selected theme data. Through development of models, predicted environmental outcomes associated with flow regimes and environmental flow deliveries can be explored. This work has demonstrated the role of generalisable predictive modelling approaches in exploring outcomes through time and into unmonitored parts of the Basin to estimate the environmental benefits of environmental water.

Informing adaptive management

Predictive modelling provides the ability to explore different flow regimes and scenarios of delivery including 'what if' scenarios. This can be used to support decision making across large and complex systems to ensure that water is used reliably and put to the best purpose given our understanding of the system. Statistical analysis of theme data provides a view to understanding the parts of the flow regime (e.g. season and volume of flows) that can be attributed to the observed environmental outcomes to ensure that we are delivering water in a way that is likely to achieve desired outcomes.

Research reports: Lloyd-Jones et al. (2023, 2024), Repina and Stratford (2020)

Product: FFAus (functional flows Australia) R package (available from bitbucket repository)

6.3 Project 11 Integrative basin modelling

An Integrative Basin Model framework is used to model ecological response to environmental watering, integrating across desired (or expected) environmental outcomes at the basin-scale. This provides a foundation for future tools to evaluate desired (or expected) outcomes from the delivery of environmental water. The research team developed an integrating basin-scale framework combining Flow-MER information across Basin Themes and Selected Areas. The framework informs our understanding of interactions between thematic areas, scale and locations. Synthesised metrics combine information in space and time, as well as across biotic groups, enabling us to explore scenarios, and test the reasons for observed outcomes at the Basin-scale. Research is complete and final report and journal paper published.

6.3.1 Research questions

- How can planning and evaluation at Basin scale over the medium term (3 to 20 years) be conceptualised and expressed in a common framework for use across Selected Areas and between Themes with suitable indicators, parameters and input data?
- What model features, components and structures are required for a common method to be fit-for purpose (considering data inputs, desired outputs and spatial and temporal scales)?

6.3.2 Project overview

This research project built on EWKR to understand the interactions between different Themes and locations. In previous tools, responses have been calculated assuming that each species is independent of others, and that locations are similar and/or independent. This work better represented the complex responses to environmental watering and identifies unifying metrics that synthesise outcomes.

There were 4 main components to the research:

- Defining outcomes relevant at the Basin scale to inform management. Designing a framework with management relevance at the Basin scale requires accounting for a range of management goals.
- Developing an integrative modelling framework to enable environmental drivers (using hydrology as a starting point in combination with new remote-sensing products that are now available) as well as biotic groups and other management targets to be incorporated.
- Developing an appropriate method for considering and integrating time and space across the heterogeneity of the Basin.

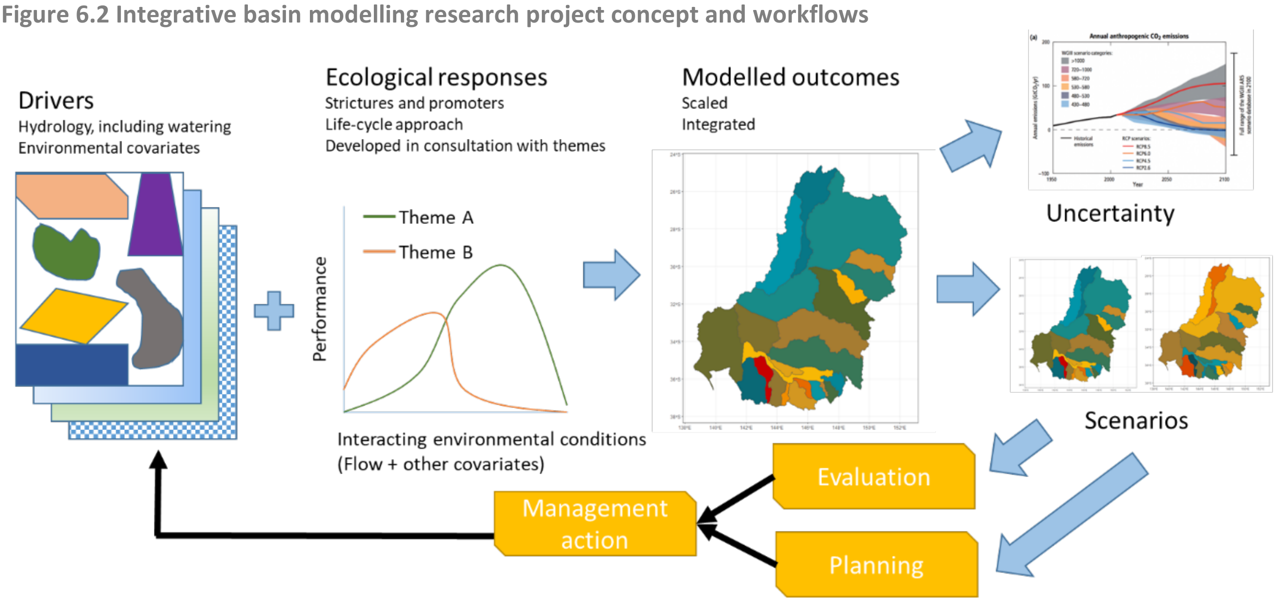
- Identifying a small number of metrics that integrate across species to provide a simpler and more robust analysis of the effects of environmental watering events and other management actions.

6.3.3 Methods

Research integrated across Themes and focused on developing a simplified but working example of an integrating framework to identify challenges and complexities, but also provide examples of possible output for consideration by CEWH. To develop the framework, the team constructed a series of self-contained, but interacting components, describing relationships between hydrology, other environmental variables, and ecological outcomes. In developing this, we have drawn upon products such as remotely sensed layers available from satellite imagery and existing data layers such as the ANAE habitat types.

The research project generated an Integrative Basin Model (IBM) framework to combine knowledge and scale across Themes and Selected Areas. A consistent modelling framework integrates across desired outcomes at the basin-scale, laying the foundation for future tools for evaluating the value and outcomes of environmental water, explore scenarios, and help understand the reasons for those outcomes (Figure 6.2). Key areas of development in this project include greater understanding of the interactions between different Themes and locations and in creating synthesised metrics that combine information in space and time, as well as across biotic groups.

Figure 6.2 Integrative basin modelling research project concept and workflows



6.3.4 Research outcomes

- The ecological response of the individual species or groups of species to environmental conditions has been constructed using a concept known as strictures and promoters. This concept considers the various life history stages of the relevant organism(s) and attempts to distil the key requirements for that organism or group of organisms to reach its next life-history stage.
- Vegetation was used as a case study to demonstrate the framework. This involved understanding which species requirements are likely to be critical in determining favourable environments for that species. Additionally, we demonstrated the ability of the framework to include interdependence between species or groups, where success in one group depends on the status of another species or group.
- A key component of the framework is the inclusion of variables other than hydrology to explain variation in ecological responses to hydrological actions. This approach depends on extrapolation of relationships

and outcomes at Selected Areas, scaled to the catchment and Basin-scale. The structure of this framework allows these processes to interact, and so better addresses scaling.

- The framework can compare scenarios. The structure provides the ability to improve over time as information becomes available. The integration and presentation of outputs is scientifically rigorous and designed to be relevant for management. We have conceptualised what those outputs might look like, with updated, iteratively improved, demonstrations of outputs for socialisation and reporting.
- Further demonstrations were undertaken for wetland metabolism and bird breeding events to demonstrate the capacity of the model for integration across species and in space. Capability exists within the modelling framework to integrate and scale outcomes in space and time to enable reporting at scales suitable for evaluation and planning purposes, which are likely to differ.
- The framework has applicability for the evaluation of the impact of environmental watering via the use of scenario comparisons between current conditions and the counterfactual.

INFORMING ADAPTIVE MANAGEMENT

This project provided a framework to assist with adaptive management of environmental watering via the use of modelled comparisons between potential management or climatic scenarios. The framework seeks to improve both evaluation and research, as they rely on comparisons of responses under different conditions. It provides the ability to investigate the reasons for those responses.

Research report: Holt et al. (2023)

Manuscript: Holt et al. (2024)

6.4 PROJECT 12 VISUALISATION

Visualisation sought to develop optimum means of presenting raw and processed data, modelling outputs and research results to inform Flow-MER evaluation and the adaptive management, decision making and reporting needs of the CEWH. This research integrated data from across thematic areas into data visualisation products for communicating the outcomes of basin-scale monitoring, evaluation and research. The interactive data and mapping prototype illustrates approaches for reporting. Visualisation summaries complement Flow-MER Basin-scale Thematic evaluation reports; annual water year and cumulative summaries show key findings and visualisations of the outcomes of Commonwealth environmental water. Research is complete, a report is available and evaluation summaries have been transitioned to evaluation.

6.4.1 PROJECT OVERVIEW

A critical challenge in integrating many different streams of data into a coherent and accessible framework, is the challenge of effectively visualising data spatially, temporally and from the perspective of multiple outcomes. This project is developing data visualisation products for communicating outputs of the Basin-scale monitoring, evaluation and research. This involves integrating data from across Themes and the results of the Basin-scale evaluation and modelling.

Large volumes of data are collected by LTIM and Flow-MER, and methods of maximising the benefit of the collected data is being explored through visualisation. This research project addresses how best to communicate results of basin-scale monitoring, evaluation and research. The goal of the research is to develop optimum means of presenting raw and processed data, modelling outputs and research results to inform the management of environmental water. The focus of this project was on visualisations for incorporation into Theme and Basin-scale reports and web-based presentation.

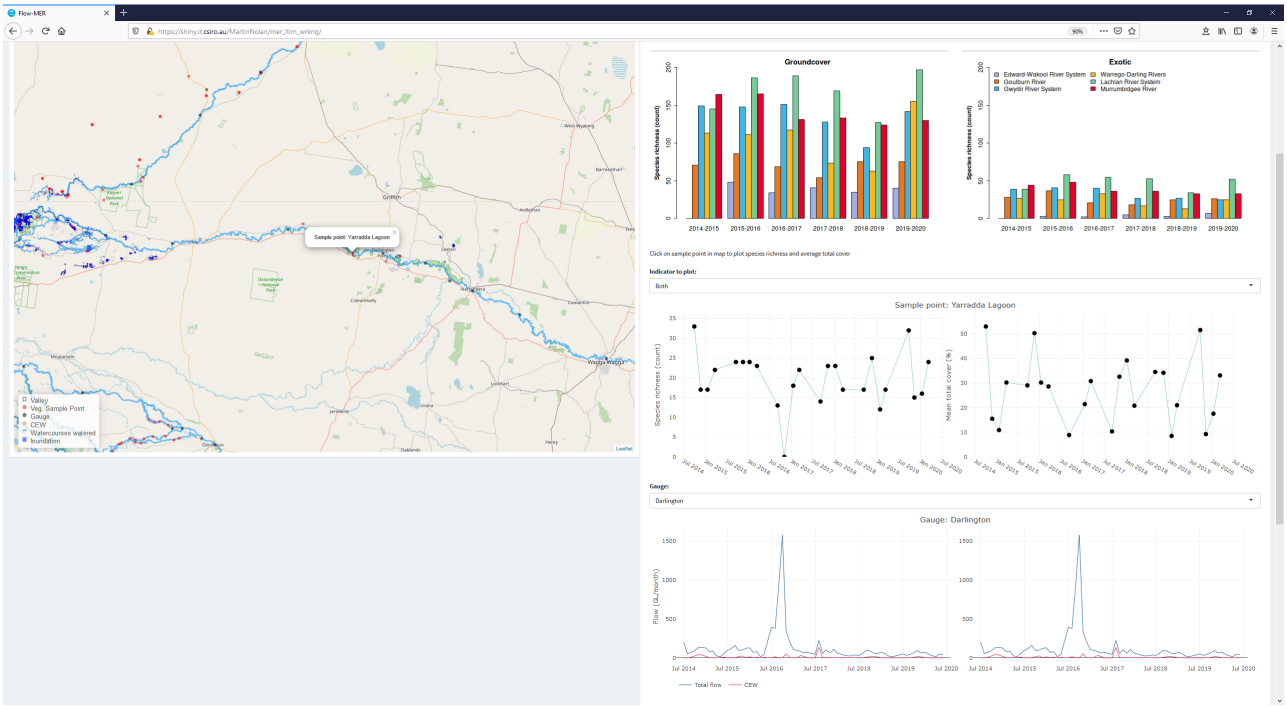
6.4.2 Research objectives

- Develop data visualisation products for communicating the outcomes of basin-scale monitoring, evaluation and research to help inform policy and decision-makers
- Develop optimum means of presenting raw and processed data, modelling outputs and research results. How best to communicate results of Basin-scale monitoring, evaluation and research.

6.4.3 Research outcomes

The 2 focus areas for this data visualisation project were the development of a data and interactive mapping explorer (DIME) (Figure 6.3) and the production of evaluation report summaries. Visualisations for the vegetation research project (V2) were also produced Figure 6.3 and the DIME framework used to present results of the hydrometrics modelling with a demonstration of its potential application to the fish Theme.

Figure 6.3 DIME prototype – sample of Vegetation Theme data visualisations



A dashboard advisory group was established to provide a forum for exploring visualisation options relevant to the CEWH. The core objectives of this project have been met:

- to produce an interactive data and mapping tool prototype
- to engage with potential end-users through the development process
- to produce evaluation report summaries.

Links to evaluation

This project enables the production of report summaries directly linked to the evaluation activity through the provision of water year and cumulative summaries which include key findings and visualisations related to the use and outcomes of Commonwealth environmental water

Informing adaptive management

Considerable data has been collected across the Basin on the outcomes of different management interventions. This project has attempted to develop visualisations of that data in order to inform management decisions in useful time-frames.

Research report: Nolan and Cuddy (2022)

Prototype: Data and Interactive Mapping Explorer (DIME)

7 COMMUNICATIONS AND ENGAGEMENT

Communication and engagement within and across Flow-MER, as well as externally to stakeholders, is central to achieving adaptive management outcomes from water for the environment. It helps improve stakeholder understanding and connection with environmental and cultural watering outcomes in the Basin. It also provides access to evidence of the contribution of Commonwealth environmental water to Murray-Darling Basin Plan environmental objectives.

7.1 PROJECT 13 CO-DESIGNING ENGAGEMENT WITH INDIGENOUS PEOPLES FOR BETTER ENVIRONMENTAL WATER DELIVERY

This research meets a need for contextual information and synthesis of Indigenous perspectives on water management as an input to environmental water management. The approach recognised the challenges achieving productive and sustainable partnerships with Indigenous people at a national scale and addresses those challenges in narrative form. Research framed engagement of Indigenous perspectives on Australian water management with a particular focus on environmental water, describing successful engagement drawn from Selected Areas and a case study developed in partnership with traditional owners on-country. The project is complete and research report (Woodward et al. 2023) is available on request.

7.1.1 PROJECT OVERVIEW

Over the last 2 decades there has been an identified failing in water management around achieving productive and sustainable partnerships with Indigenous people at a national scale. The alienation of Indigenous people from a role in managing Country since colonisation has had a profound effect on the opportunities for engagement. This project will recognise those challenges in narrative form, but take a prospective view, describing examples of successful engagement around environmental water through case studies developed in partnership with traditional owners on-country.

The objective of this activity is framing the engagement of Indigenous perspectives on Australian water management with a particular focus on environmental water. This project will meet a need for contextual information and synthesis around Indigenous perspectives on water management to provide a key input to advancing environmental water management.

7.1.2 RESEARCH OBJECTIVES

- To summarise the Indigenous engagement approaches, perspectives and challenges for the 7 Selected Areas with the aim of detailing current activity and identifying emerging opportunities.
- To develop a case study on Kamilaroi country in northern NSW that:
  − illustrates approaches to engagement around water management
  − seeks an understanding of how Indigenous communities would wish to be engaged with in relation to environmental water management
  − identifies any barrier to engagement
  − seeks to identify any cultural values that could be managed for using environmental water.

7.1.3 Methods

Objective 1: Summarise Indigenous engagement approaches

To summarise Indigenous engagement approaches, perspectives and challenges for the 7 Selected Areas, an online survey was conducted which collated and analysed data on Indigenous engagement activities. This work detailed current activities and identified emerging opportunities. A report on the outcomes of this work is available on request (Woodward et al. 2022). The report provides snapshots of examples of Indigenous engagement, including:

- Down the Track Youth Enterprises Program
- Employment of Cultural Advisors
- Tracking turtles in the Edward/Kolety-Wakool river system Selected Area
- Indigenous Ecology in Action workshop
- Indigenous cadets connecting culture and science
- Murrin Bridge Community Development Program
- Research to support culturally significant native plants (such as nardoo, Figure 7.1)
- Cultural values of the Yellowbelly.

Figure 7.1 Nardoo during extensive flooding at Yanga National Park
Photo credit: Tanya Doody

Objective 2: To develop a case study on Kamilaroi Country in northern NSW

Methods were developed for engagement (published in Moggridge et al. 2022) and the work has been socialised with communities on Kamilaroi country (after an interruption due to Covid-19) (Figure 7.2).

Figure 7.2 Gwydir Wetlands on Kamilaroi Country (Source: Moggridge)

7.1.4 Research outputs

- a review of methods of Indigenous engagement
- a summary and analysis of engagement approaches
- a timeline of indigenous engagement in water management
- a reflective narrative and analysis of Indigenous engagement around water.

Informing adaptive management

Engaging with Indigenous groups is a challenge in many parts of the Murray–Darling Basin. This project used case studies to commence development of approaches to simplify engagement while protecting cultural values and intellectual property of Indigenous people, and conducting engagement in a culturally safe manner.

Report: Woodward et al. (2022)

PhD thesis: Moggridge (2023)

Manuscripts: Moggridge et al. (2019, 2022), Moggridge & Thompson (2021, 2024)

7.2 Flow-MER communications and engagement

The science undertaken throughout Flow-MER needs to be relevant, accessible and meaningful for key stakeholders. The research team developed a range of communication and engagement techniques to inform, share knowledge and connect with target audiences. To do this, a range of communication activities have been used including those that are informative where target audiences are passive consumers of the information made available to them, (for example, social media, website, branding) or consultative where target audiences are active and responsive participants in the communications process (for example, webinars, workshops, consultations, community meetings, social media forums and conferences). At all times the team focused on maximising the research impact of Flow-MER so that environmental water managers could inform adaptive management.

7.2.1 Research objectives

- To meet the needs of the CEWH, enhance the credibility of the Basin-scale MER Project and the positive reputation of the CEWH and the science providers to the CEWH.

- To collaborate with primary users of monitoring and evaluation to ensure that the products from monitoring and evaluation will meet their needs.
- To build relationships with project collaborators and gather information about what they want from the Basin-scale MER Project and how they wish to contribute.
- To undertake communication activities that will inform stakeholders about the project and facilitate users to access Basin-scale MER products and information as they become available.
- To inform a broad stakeholder audience about the Basin-scale MER project to increase community confidence in the science informing environmental watering policy and decisions

7.2.2 Methods

The primary target audience for Flow-MER communications and engagement is the Office of the CEWH, MDBA, the Victorian Environmental Water Holder, NSW Office of Environment and Heritage and other environmental water managers throughout the Basin. With this target audience in mind, communications and engagement has focused on sharing knowledge in ways that environmental water managers can easily access in multiple ways. The Covid 19 pandemic meant that communication approaches needed to shift from face-to-face to online, and this sparked improvements in webinar, social media and web-based engagement techniques.

7.2.3 Outputs

Key communications and engagement research outputs include:

- network of Flow-MER science providers across the Basin, working more closely together to share knowledge to improve adaptive management of environmental water
- Flow-MER brand and logo which is well recognised within the environmental water and wider river management community
- Flow-MER website – a dynamic, attractive and easy to use website that combines awareness raising through story-telling along with detailed analyses and research applications. www.flow-mer.org.au (Figure 7.3)
- 4 Flow-MER Friday Webinar series featuring 19 presentations, recorded and shared via the Flow-MER website. Attendance at Flow-MER Friday started with a small invitation only group that has expanded to several hundred e-water managers.
- Flow-MER Email newsletter – this newsletter goes out to 1400 subscribers whenever a new story, event or research outcome is achieved.
- Flow-MER Facebook and LinkedIn – social media is used to extend reach and complement CEWH communication activities. Facebook reaches a wide audience, whereas the LinkedIn channel is for a profession-based network of people working in river restoration and environmental water management.
- Flow-MER conference and workshop presentations dominating key scientific forums, for example at the recent International Freshwater Science Society conference in Brisbane Flow-MER related work was featured in 20+ presentations.

Figure 7.3 Examples of profiling of Flow-MER Program activities available from flow-mer.org.au

Flow-MER Annual Forum 2024

Insights from the Forum

The Flow-MER Annual Forum was held on the 27th and 28th of August, in Canberra, on Ngunnawal Country. The Forum shared what has been learnt about delivering water for the environment so that it can be practically applied by water managers. Presentations by the Flow-MER team discussed and celebrated the insights and knowledge that has been gained, and reflected on how this can inform future investment and practice. Emphasis was given to how Flow-MER can best provide the Commonwealth Environmental Water Holder with the information needed to inform the upcoming Basin Plan Review.

During the Forum we asked some of the presenters to reflect on their experience of working in Flow-MER, what new knowledge has been learnt, and what future work might be undertaken as the program moves into its next phase of investment. We hope you enjoy the photos from the event, the videos and the feedback participants provided about being involved in the Flow-MER Annual Forum.

What have we learnt through 10 years of Flow-MER?

What does the future hold for Flow-MER?

Reflections from the Commonwealth Environmental Water Holder

INFORMING ADAPTIVE MANAGEMENT

Without investment in communicating and engaging with the end-users of MER work the impact we seek will never eventuate. Over the past 3 years the Flow-MER brand has become well recognised amongst environmental water managers as a trusted source of knowledge, with strong and ever expanding networks, at Basin and Selected Area scales.

Appendix A RESEARCH OUTPUTS

A.1 MANUSCRIPTS SUBMITTED/IN PREPARATION 2024

YEAR	REFERENCE	FUNDED BY
Submitted 2024	McGinness et al. (submitted-a, -b, -c, -d)	Basin-Scale Flow-MER Project 1 (E1), CEWH Short-term Intervention Monitoring Projects, MDB EWKR Project, CSIRO, Lake Cowal Conservation Centre
Submitted 2024	Robinson et al. (submitted)	MDB EWKR Project, Basin-Scale Flow-MER Project 1 (E1)
In prep 2024	McGinness et al. (in prep)	Basin-Scale Flow-MER Project 1 (E1), CEWH Short-term Intervention Monitoring Projects, MDB EWKR Project, CSIRO, Lake Cowal Conservation Centre
In prep 2024-25	Galtbalt B et al. (in prep)	Basin-Scale Flow-MER Project 1 (E1), CEWH Short-term Intervention Monitoring Projects, MDB EWKR Project, CSIRO, Lake Cowal Conservation Centre Deakin University,
In prep 2024	Hitchcock JN et al. (in prep)	Basin-Scale Flow-MER Project 9 (BW3)
Submitted 2024	Hitchcock JN et al. (2024a, 2024b, 2024c, 2024d, 2024e)	Basin-Scale Flow-MER Project 9 (BW3)
Submitted 2024	Balzer MJ et al. (2024)	Basin-Scale Flow-MER Project 9 (BW3)

A.2 PEER-REVIEWED PUBLICATIONS (JOURNAL ARTICLES, BOOK CHAPTERS)

REFERENCE	FUNDER
2024	
Campbell CJ et al. (2024)	Basin-Scale Flow-MER Project 5 (V1)
Doody et al. (2024b)	Basin-scale Flow-MER Project 6 (V2)
Holt et al. (2024)	Basin-scale Flow-MER Project 11 (CC2), Deakin University
Moggridge & Thompson (2024)	Basin-scale Flow-MER Project 13
Thompson et al. (2024)	DFAT, Basin-scale Flow-MER Project 13
2023	
Campbell CJ et al. (2023)	Basin-Scale Flow-MER Project 5 (V1)
Doody et al. (2023)	Basin-scale Flow-MER Project 6 (V2)
Moggridge BJ (2023)	Basin-scale Flow-MER Project 13, University of Canberra, MDBA
Nicol S et al. (2023)	Basin-scale Flow-MER Project 1 (E1), CSIRO, MDBA, MDB EWKR Project
2022	
Campbell CJ et al. (2022)	Basin-Scale Flow-MER Project 5 (V1)
Moggridge BJ et al. (2022)	Basin-Scale Flow-MER Project 13
Thompson RM et al (2022)	Describes functioning of the Basin Scale review process
2021	
Campbell C et al. (2021a)	EWKR, Basin-Scale Flow-MER Project 5 (V1)
Campbell C et al. (2021b)	NSW OEH (related to Project 5 (V1))

REFERENCE	FUNDER
Gao S et al. (2021)	Basin-Scale Flow-MER Project 6 (V2)
Higgisson W et al. (2021)	EWKR, LTIM (SA Lachlan)
Moggridge BJ & Thompson RM (2021)	Basin-scale Flow MER (CC3)
Stewardson M et al. (2021)	Describes case studies from LTIM and Flow MER
Tonkin Z et al. (2021)	Basin-scale Flow MER Project 7 (F1)
Wallace T et al. (2021)	Basin-Scale Flow MER Project 6 (V2)
2020	
Gawne B et al. (2020)	LTIM
Growns I et al. (2020a)	EWKR
Growns I et al. (2020b)	EWKR
Higgisson W et al. (2020)	Conducted in association with but not funded by LTIM (SA Lachlan)
Higgisson W et al. (2020)	Conducted in association with but not funded by LTIM (SA Lachlan)
Humphries P et al. (2020)	EWKR
McInerney PJ et al. (2020)	EWKR, Basin-Scale Flow MER, Project 9 (BW3)
Shams F et al. (2020)	Conducted in association with but not funded by LTIM (SA Lachlan)
Wallace T et al (2020)	Basin-Scale Flow MER Project 6 (V2)
Watts RJ et al. (2020)0	LTIM SA lead collaboration
2019	
Dyer F (2019)	LTIM (SA Lachlan)
Koehn JD et al. (2019)	EWKR
Kopf RK et al (2019)	LTIM
Moggridge B et al. (2019)	Basin-scale Flow MER (CC3)
Schiller D et al. (2019)	Conducted in association with but not funded by LTIM (SA Lachlan)
Shams F et al (2019)	Conducted in association with but not funded by LTIM (SA Lachlan)
Shams F et al. (2019)	Conducted in association with but not funded by LTIM (SA Lachlan)
Shumilova O et al. (2019)	Conducted in association with but not funded by LTIM (SA Lachlan)
Thompson RM et al. (2019)	LTIM, EWKR, Flow-MER Basin Scale

A.3 BASIN-SCALE FLOW-MER RESEARCH REPORTS

Research Project	REFERENCE
1 (E1)	McGinness HM et al. (2024)
2 (BW1)	Bennett J et al. (2023)
6 (V2)	Doody TM et al. (2024)
7 (F1)	Todd CR et al. (2023); Todd CR et al. (2024)
8 (F2)	Thiem JD et al. (2023)
9 (BW3)	Hitchcock JN et al. (2024)
10 (BW2)	Repina O & Stratford D (2020); Lloyd-Jones L et al. (2023)
11 (BW2)	Holt G et al. (2023)
12 (CC1)	Nolan M & Cuddy SM (2022)

Research Project	REFERENCE
13	Woodward E et al. (2022)

A.4 Companion products (fact sheets, datasets, code, web stories)

Year	Product type	Authors	Product title and hyperlink (if available)	Research project
2024	Webinar	Sengupta A & Hladyz S	Flows, fish and connectivity (abstract and recording) Flow-MER Friday Autumn 2024 series	
2024	Webinar	Dyer F	Environmental water: Supporting the right plants in the right places (abstract and recording) Flow-MER Friday Autumn 2024 series	
2024	Webinar	Wassens S & Brooks S	Species conservation in the age of uncertainty (abstract and recording) Flow-MER Friday Autumn 2024 series	
2023	video	Tonkin Z	The importance of fish to river ecosystems and their immense cultural, recreational and conservation value	
2023	Fact sheet	Todd et al., ARI	Modelling the impacts of water for the environment and climate change on native fish populations. A counterfactual modelling approach to inform the delivery of Commonwealth Environmental Water for Golden Perch and Murray Cod	7 (F1)
2023	Fact sheet	Todd et al., ARI	Modelling the impacts of water for the environment and climate change on native fish populations. A counterfactual modelling approach to inform the delivery of Commonwealth Environmental Water for Golden Perch and Murray Cod. Supplementary information	7 (F1)
2023	Web story	Campbell C, ARRC	We're-all-in-this-together-have-your-say-about-evaluating-vegetation-outcomes-to-environmental-flows	5 (V1)
2023	Web story	Campbell C, ARRC	Why are we drawn to rivers, wetlands and floodplains? What role do plants play in making these places special? Tell us what you value (particularly about plants!)	5 (V1)
2023	Dataset	Gao S & Doody T	Fractional tree cover canopy for Murray-Darling Basin wetlands	6 (V2)
2023	Dataset	Gao S & Doody T	Fine-scale Gross Primary Productivity for Murray-Darling Basin wetlands	6 (V2)
2023	Dataset	Gao S & Doody T	Australia-wide Machine Learning Evapotranspiration for Trees (AMLETT) model for Murray-Darling Basin wetlands	6 (V2)
2022	Code	Lloyd-Jones L	Functional Flow Australia R package [R]	11 (CC2)

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Government of South Australia Department of Primary Industries and Regions

SARDI South Australian Research and Development Institute

UNE University of New England

NSW Government Department of Primary Industries

Deakin University

ARRC Australian River Restoration Centre