

River Murray Channel Monitoring Plan 2021-22 to 2025-26



Planning,
Industry &
Environment



Commonwealth Environmental Water Office



Government of South Australia
Department for Environment
and Water



Environment,
Land, Water
and Planning



Australian Government
Department of Agriculture,
Water and the Environment

Acknowledgements

This plan was developed by the monitoring sub-group of the Southern Connected Basin Environmental Watering Committee (SCBEWC): Paul Childs, Paula D'Santos, Sean Kelly, Anthony Moore, Andrew Sharpe, Tracey Steggles, Tom Stewart, Gill Whiting, Alana Wilkes, Jan Whittle.

Citation: Southern Connected Basin Environmental Watering Committee (2021) River Murray Channel Five-Year Monitoring Plan 2021-22 to 2025-26, SCBEWC Monitoring sub-group, Canberra.

The authors would like to thank the following people who contributed to the work:

- Darren Baldwin, Nick Bond, Iwona Conlan, Iain Ellis, Jarod Lyon, Paul McInerney, Gavin Rees, Rod Oliver, Ivor Stuart, Jason Thiem, Todd Wallace, Robyn Watts, Ben Wolfenden, Qifeng Ye, Brenton Zampatti.
- Peer reviewers, Lee Baumgartner and Ban Gawne

The SCBEWC monitoring sub-group was guided through the development of the plan by Jennifer Hale, Michelle Dickson, Shane Brooks and Enzo Guarino.

DISCLAIMER

The contents of this publication do not purport to represent the position of the agencies that form the monitoring sub-committee of the Southern Connected Basin Environmental Watering Committee in any way and, as appropriate, are presented for the purpose of informing and stimulating discussion for improved management of the Basin's natural resources. To the extent permitted by law, the copyright holders (including its employees and consultants) exclude all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this report (in part or in whole) and any information or material contained in it. The authors warrant that they have taken all reasonable care in producing this report. The SCBEWC monitoring sub-group does not warrant that the information in this report is free from errors or omissions and does not warrant or make any representation regarding the use, or results of the use, of the information contained herein as regards to its correctness, accuracy, reliability and currency or otherwise. Use of the information and data contained in this report is at the user's sole risk. If users rely on the information, they are responsible for ensuring by independent verification its accuracy, currency or completeness.

© Copyright Commonwealth of Australia, 2021

This work is copyright. Apart from any use as permitted under the *Copyright Act* 1968 (Cth), no part may be reproduced by any process, electronic or otherwise, without the specific written permission of the copyright owner. Neither may information be stored electronically in any form whatsoever without such permission. With the exception of the Commonwealth Coat of Arms, the Murray-Darling Basin Authority, VEWB, NSW DPIE EES and SA DEW logos, all material presented in this document is provided under a Creative Commons Attribution 4.0 Australia licence (<https://creativecommons.org/licenses/by/4.0/>). For the avoidance of any doubt, this licence only applies to the material set out in this document.



The details of the licence are available on the Creative Commons website (accessible using the links provided) as is the full legal code for the CC BY 4.0 AU licence ((<https://creativecommons.org/licenses/by/4.0/legalcode>)).

Table of contents

Acknowledgements	i
Abbreviations	iii
Summary	iv
1 Introduction	1
1.1 Context	1
1.2 How the monitoring plan was developed	1
1.3 Principles of the Program	2
2 River Murray Channel	4
2.1 Overview	4
2.2 Ecological values	4
2.3 Water for the Environment in the River Murray Channel	6
2.3.1 Objectives and expected outcomes of environmental water	6
3 Key evaluation questions	9
3.1 Themes	9
3.2 KEQ hierarchy	11
3.3 Indicators to answer evaluation questions	13
3.3.1 Productivity	13
3.3.2 Large-bodied native fish	17
4 Monitoring design	20
4.1 Monitoring locations	20
4.2 Sample design	20
4.3 Monitoring requirements	22
4.4 Preferred package of monitoring	23
4.4.1 Productivity	23
4.4.2 Large-bodied native fish	24
5 Evaluation, review and reporting	26
5.1 Evaluation of outcomes	27
5.1.1 Foundational information	27
5.1.2 Productivity	28
5.1.3 Large-bodied native fish	28
5.1.4 Integrated evaluation	31
5.2 Monitoring program review	32
5.3 Environmental water management review	32
5.4 Reporting and communication	32
6 How to implement this monitoring plan	34
6.1 Governance	34
6.2 Co-design	34
6.3 Risk assessment	36
6.4 Data management	37

7	References	39
	Appendix A: LTWP Objectives and targets and KEQs.....	44
	Appendix B: Review of indicators and existing monitoring.....	48
	Foundational information: gap analysis	48
	Productivity: indicators and gap analysis	50
	Evaluation questions	50
	Conceptual understanding	50
	Dissolved organic carbon and nutrients	53
	Stream metabolism	56
	Biofilms	59
	Phytoplankton.....	60
	Zooplankton / microinvertebrates	63
	Higher tropic levels (e.g., decapods, Murray cod).....	65
	Fish: indicators and gap analysis.....	66
	Evaluation questions	66
	Conceptual understanding	66
	Expected responses	69
	Existing monitoring	69
	Gaps	69

Abbreviations

ANAE	Australian National Aquatic Ecosystem
ARI	Arthur Rylah Institute
BWS	Basin-Wide Environmental Watering Strategy
CEWH	Commonwealth Environmental Water Holder
CEWO	Commonwealth Environmental Water Office
DELWP	Department of Environment, Land, Water and Planning
EPBC Act	Environment Protection and Biodiversity Conservation Act 1999
ER	Ecosystem Respiration
Flow-MER	Flow-Monitoring, Evaluation and Reporting program
GPP	Gross Primary Production
KEQ	Key Evaluation Question
LTIM	Long Term Intervention Monitoring program (now Flow-MER)
MDBA	Murray-Darling Basin Authority
MERI	Monitoring, Evaluation, Reporting and Improvement
NSW DPI	New South Wales Department of Primary Industries
NSW DPIE EES	New South Wales Department of Planning, Industry and Environment: Environment Energy and Science
MERI	Monitoring, Evaluation, Reporting and Improvement
OEH	Office of Environment and Heritage
SA DEW	South Australian Department of Environment and Water
SCBEWC	Southern Connected Basin Environmental Watering Committee
TLM	The Living Murray
VEFMAP	Victorian Environmental Flows Monitoring and Assessment Program
VEWH	Victorian Environmental Water Holder

Summary

This River Murray Channel Five Year Monitoring Plan (2021–22 to 2025–26) was developed by a multijurisdictional group of water managers to monitor system-scale responses to water regimes in the River Murray. The monitoring plan covers approximately 2000 kilometres of river channel from Hume Dam in NSW to Wellington in South Australia. The primary objective of the Plan is to better understand ecological responses to flow to inform adaptive management of environmental water. The Plan will also seek to demonstrate outcomes environmental water management, understand the potential benefits of relaxing constraints and to learn from and contribute to other environmental monitoring and research programs in the Basin.

The monitoring plan is underpinned by current science and an understanding of flow-ecology relationships in the River Murray Channel. The monitoring plan is focussed on two themes: productivity and large-bodied native fish; selected based on the types of coordinated flow events in the River Murray Channel and the expected outcomes from those flow events. The major features of the monitoring plan are:

- **Key Evaluation Questions (KEQs)** – developed by water managers to address fundamental knowledge gaps in the body of information needed to optimise environmental water use and thus maximise ecological outcomes.
- **Indicators** – of productivity and large-bodied native fish, specifically selected to answer KEQs.
- **Monitoring design** – a multiple before, during and after intervention approach has been adopted, with potential monitoring site locations chosen to include tributary inflows and floodplain return waters that influence river flows.
- **Sampling** – efficient use of existing monitoring that is directly relevant to answering KEQs with new data collection to fill gaps.
- **Evaluation** – that uses data collected from other programs in conjunction with the information collected under implementation of this monitoring plan to answer KEQs and management questions annually and integrating the results from multiple years over time.
- **Review** – annually to ensure monitoring is fit for purpose with respect to planned water delivery; independent review of the program after five years.
- **Governance** – how this program will be implemented; co-design principles; roles and responsibilities, data management and sharing arrangements.

The monitoring plan identifies priorities for monitoring in the first year of the program that were chosen to help answer KEQs and inform adaptive management of environmental water in the River Murray. Indicators selected for productivity include dissolved organic carbon, nutrients, chlorophyll-a, phytoplankton species and abundance, zooplankton abundance/biomass and nutritional value (stream metabolism optional if budget allows). Indicators for large-bodied native fish include larval sampling (eggs and larvae) and if spawning is detected, a population census (length, weight and potentially natal origin via otoliths) is suggested.

1 Introduction

1.1 Context

Environmental water management has become a significant tool for the protection and restoration of aquatic ecosystems in the Murray-Darling Basin (the Basin). For more than a decade, adaptive management, underpinned by intervention monitoring and numerous research projects, has improved the efficiency and effectiveness of managed flow events for ecological outcomes. Through improved understanding and a need to make the most of limited water in a drying climate, there is an increasing use of coordinated flow management for multiple outcomes along connected river and floodplain ecosystems. This includes large-scale watering events in both the Northern and Southern Basin, where water is reused through a series of rivers, floodplains and wetlands providing multiple benefits as it moves downstream.

In the past, many monitoring programs have focussed on evaluation of the outcomes of water for the environment at specific sites or for discrete watering events. While information gathered in these programs is undoubtedly useful for informing the management of larger-scale events, there is both an opportunity and a recognised need to augment these programs with intervention monitoring that addresses and integrates larger scale outcomes.

In recent years, environmental flows in the River Murray Channel have been coordinated with flows in key tributaries to create flow pulses along the length of the river. Coordinated flow management includes consideration of dam releases, channel flows, floodplain inundation and use of return flows (water draining off the floodplains back to the channel) to improve ecological outcomes across multiple ecosystems.

To date these large-scale coordinated watering events have been monitored through short-term intervention monitoring projects. This River Murray Channel Five-Year Monitoring Plan (the monitoring plan) provides the framework for monitoring responses to flows in the channel from the Hume Dam to Wellington in South Australia for the five-year period 2021 to 2026. The Plan aims to inform improved management of environmental water at the system-scale (the entire River Murray Channel), providing environmental water managers with the information they need to make evidence-based decisions.

The primary objective of the monitoring plan is:

To better understand how key ecological indicators respond to flow to inform improved decision making and adaptive management of environmental water in the River Murray Channel.

It is expected that implementation of the monitoring plan will also contribute to secondary objectives, including:

To demonstrate system-scale outcomes of environmental water in the River Murray Channel.

To understand the potential ecological benefit to be gained from relaxing current constraints to environmental water flow delivery in the River Murray.

To inform and enhance the value of other monitoring, research and modelling programs.

1.2 How the monitoring plan was developed

Monitoring, Evaluation, Reporting and Improvement (MERI) is a process by which information collected through monitoring is used to evaluate the impact and effectiveness of management activities to support continuous improvement and evidence-based decision making. The MERI process established in this document was developed, and will be implemented, through a co-design process. The monitoring plan was developed by environmental water managers to provide evidence to directly inform water planning and delivery decisions. The monitoring design team comprised a multi-jurisdictional Steering Committee with representatives of the Commonwealth Environmental Water Office (CEWO), Murray Darling Basin Authority (MDBA), NSW Department of Primary Industry and Environment: Environment Energy and Science (NSW DPIE EES), SA Department for Environment and Water (SA DEW), and the Victorian Environmental Water Holder (VEWH). The Steering Committee was a sub-group of the Southern Connected Basin Environmental Watering Committee (SCBEWC).

The co-design process began with the identification of objectives and key evaluation questions (KEQs) based on information needs of water managers, the management of water in the River

Murray Channel and the current conceptual understanding of flow-ecology relationships. Indicators and evidence required to fill knowledge gaps and answer KEQs were identified and explored using the scientific literature and the outcomes of previous short-term monitoring projects in the Murray and comparable rivers.

Existing monitoring in the River Murray Channel was reviewed to identify complementary data sets that could contribute to answering KEQs. Opportunities to leverage off existing programs and share data and findings, including with teams developing productivity and fish population models, were identified to ensure new monitoring is pragmatic and efficient. A program that integrated new monitoring with existing monitoring networks was developed and documented.

Technical expertise was gathered from a range of scientists in a virtual workshop, individual collaborations and through peer review of the monitoring plan.

The co-design process will continue through implementation with the service providers working closely with the Steering Committee to derive annual expected outcomes and hypotheses to be tested, complete the monitoring and evaluate the data, develop adaptive management messages and the review of the monitoring program (see sections 5, 6 and 7).

1.3 Principles of the Program

The Basin-Wide Environmental Watering Strategy (BWS, MDBA 2019) establishes an adaptive management process that operates at multiple spatial and temporal scales (Figure 1). This is relevant also to the River Murray Channel where system-scale responses are to be evaluated from multi-site monitoring and evaluated at both annual and five-year timeframes.

Consistent with the adaptive management focus of the BWS, the monitoring plan is underpinned by the following principles:

- The purpose of the monitoring plan is to confirm responses and directly inform future adaptive management of coordinated environmental water delivery, as represented by the KEQs, and this drives the monitoring design and evaluation (noting that a non-response is a monitoring outcome that is useful for understanding eco-hydrological relationships at a system-scale).
- Monitoring and evaluation need to be suited to detecting system-scale changes as a result of coordinated channel environmental water delivery. The monitoring needs to be suited to reaches with differing hydraulic conditions as a result of river regulation (i.e., lotic and lentic reaches).
- The monitoring plan seeks to build on existing monitoring within the system to answer the KEQ's (noting that the continuation of existing programs is not guaranteed, and contingencies will need to be considered).
- Where possible, monitoring of different indicators will be undertaken at the same locations to allow for integration of data and analysis across metrics.
- Depending on the indicator, the timing of sampling must capture not only the watering event (or natural flow), but the baseline before and after.
- The monitoring plan will be flexible to allow for the introduction of new indicators as research progresses and the efficacy and suitability of new indicators is tested.
- The Steering Committee is responsible for the development and oversight of implementation of the monitoring plan including annual review and improvement.
- Information collected will be shared with modelling projects being conducted by other organisations (e.g., CSIRO productivity models and CEWO Flow-MER project fish modelling; see Text Box 1).
- Regular data analysis and evaluation (annual and after five years) will underpin learning and improvement.
- There is a collective commitment to data sharing and making data from the monitoring plan available through creative commons licence.



Figure 1: Multi-scale adaptive management (MDBA 2019).

Improving predictive models with data

Predicted responses to flow regimes underpin the planning and management of environmental water. To deliver flow regimes to meet objectives and outcomes, the links between key watering parameters, or levers and desired ecological outcomes need to be well understood. This requires strong conceptual and empirical knowledge of the processes that maintain aquatic values, the key drivers of these and their interaction with flow and non-flow related factors. While there is now a large amount of data from monitoring and research programs about the effects of environmental watering events on the two themes of this monitoring plan: productivity and native fish, environmental water planning and allocations are still largely informed by expert opinion (Webb et al. 2015).

Ecological models are being developed to improve predictive capacity for the management of environmental water for productivity and native fish outcomes. Examples include the development of fish population models for golden perch and Murray cod to evaluate Murray and Murrumbidgee River constraints in NSW; Flow-MER fish population models for Murray cod, golden perch and bony herring; Flow-MER foodweb models exploring trophic interactions and basal food quality linkages to flow and non-flow factors; and ecosystem response models related to productivity being developed by CSIRO.

Modelling outputs are strengthened by quality data collected from sites across the Basin. Experts have identified data this monitoring plan could potentially contribute:

- Fish:
 - fish larval sampling in the River Murray Channel between Torrumbarry and the South Australian border
 - population structure
 - population size/abundance (using capture-mark to enable capture-mark-recapture techniques)
 - estimations of sampling efficiency
- Productivity
 - biomass at multiple trophic levels
 - productivity hotspots in the River Murray Channel

Text box 1: Improving ecological models.

2 River Murray Channel

2.1 Overview

The River Murray rises in the Great Dividing Range and flows west then south to discharge to the sea in South Australia. Despite being Australia's longest river, natural flows are, on a world-scale, low and highly variable as a result of high interannual variability in rainfall (Maheshwari et al. 1995). The river is highly regulated with the large Hume Dam upstream of Albury, a high-level weir at Yarrawonga, 13 low-level weirs extending from Euston in NSW into South Australia and barrages across the estuary near the river mouth. Diversions have resulted in a reduction in end of system discharge by over 50% (Maheshwari et al. 1995) and generally slower, less variable flows. There has also been a change to the seasonality of flow in the mid-Murray, with the majority of river flows in this section of the river occurring in summer and autumn during peak irrigation demands (Overton et al. 2009). In contrast, annual flows in the lower Murray are much reduced in volume. The seasonality of flows is retained, with flows peaking in spring/summer, but their magnitude is less, reducing the extent and frequency of floodplain inundation.

This monitoring plan covers 2152 kilometres of the River Murray Channel from Hume Dam to Wellington (the River Murray Channel Icon Site; Figure 2). Thoms et al. (2000) described the zones of the River Murray with respect to geomorphology and hydrology. The zones relevant to the River Murray Channel Icon Site are:

- Hume Dam to Yarrawonga – where the river is characterised by a complex system of anabranches with multiple channels carrying a portion of the flow. Includes the Victorian tributaries of the Kiewa and Ovens Rivers.
- Yarrawonga to the confluence of the Edward/Kolety-Wakool – where the river has a wide floodplain, including the large floodplain forests of Barmah-Millewa and Gunbower, Koondrook-Perricoota. Includes the Victorian tributaries of the Broken, Goulburn and Campaspe Rivers and the NSW Edward/Kolety-Wakool anabranch system.
- Edward/Kolety-Wakool to the Darling Confluence – where the river has a single wide channel and includes the Hattah-Kulkyne Lakes floodplain site and the tributaries of the Loddon River (Victorian) and the Murrumbidgee River (NSW). This section contains locks 11 and 15.
- The Darling/Baaka River confluence to Overland Corner – where the river flows in a wide valley and passes the Chowilla floodplain. There are seven locks (4 to 10) in this section of the river
- Overland Corner to Mannum – where the river is confined to a limestone gorge, with a narrow (two to three kilometre wide) floodplain. This section contains locks 1 to 3.
- Mannum to Wellington – where the river remains confined to a narrow floodplain, a large part of which has been developed for agriculture and is disconnected from the river by levee banks.

2.2 Ecological values

The River Murray Channel supports significant ecological values including riparian vegetation, native fish, macroinvertebrates and important ecosystem functions. Large areas of floodplain, in particular, influence the ecosystem functions and processes of the River Murray Channel (Baldwin and Mitchell 2000, Gawne et al. 2007, Baldwin et al. 2016, Nielsen et al. 2016). Inundation of floodplain ecosystems can mobilise large amounts of carbon and nutrients which enter riverine food webs with return waters. Return flows can also mobilise secondary production on the floodplain flushing phytoplankton and zooplankton into the river that supplements river food webs (Furst et al. 2014, Nielsen et al. 2016). River regulation has decreased floodplain river connectivity altering the flow of energy through food webs. Restoring some of these energy pathways is a key objective for environmental watering.

Aquatic vegetation is not a common feature of most of the central Murray (Hume Dam to the Darling/Baaka River) due to high turbidity and unstable sediments (Thoms et al. 2000). The weir pools in both NSW and South Australia, however, provide stable water conditions that encourage the growth of emergent macrophytes such as common reed (*Phragmites australis*) and Typha, as well as submerged species including eel grass (*Vallisneria spiralis*), water milfoil (*Myriophyllum* spp.) and pondweed (*Potamogeton* spp.) (Gehrig and Nicol 2010, Ecological Associates 2015 p. 15). The riparian zone along the length of the River Murray Channel is dominated by river red gum (*Eucalyptus camaldulensis*), with some invasion by willows particularly where water levels are stable.



Figure 2: Location of the River Murray Channel Icon Site (MDBA 2019).

At least 25 species of freshwater native fish (excluding estuarine species) are expected to occur in the River Murray Channel Icon Site (Ellis et al. 2016) including several threatened species. Murray cod (*Maccullochella peelii*), trout cod (*M. macquariensis*) and silver perch (*Bidyanus bidyanus*) are all listed as threatened nationally under the *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC Act). Several other species such as freshwater catfish (*Tandanus tandanus*) and olive perchlet (*Ambassis agassizii*) are protected under state legislation.

The Sustainable Rivers Audit rated fish populations in the Murray between Hume Dam and the Darling River/Baaka as poor, and downstream of the Darling River as very poor (MDBA 2012). The poor condition reflected that less than half of the expected number of native species were recorded in each region and that there was a high number (and biomass) of introduced species. More recent assessments indicate that the fish communities in the Lower Murray are typical of low flow conditions, with a higher abundance and diversity of small-bodied native fish species and low recruitment of native large-bodied flow-cued spawners (Ye et al. 2020). A study of fish populations in the River Murray in NSW indicated that fish communities in the reaches between the Hume Dam and the Edward/Kooley-Wakool confluence were in generally poor condition and in fair to good condition in the reaches between the confluence of the Murrumbidgee River and the South Australian border (Riches et al. 2016).

Environmental watering aims to improve the abundance, richness and distribution of native fish communities in the River Murray system by increasing the frequency of hydrologic spawning triggers, improving hydraulic conditions for nesting fish and drifting larvae during breeding seasons and increasing the availability of high-quality food resources for larvae and juvenile fish as they develop.

For First Nations in the southern Basin, all waterways, communities, plant and animal species exist as an interconnected whole. First Nations people have an intricate and enduring connection to water. Cultural traditions, stories and knowledge are entwined in First Nations custodianship of water resources. The common goal of improving and sustaining the health of our waterways can be better achieved through collaboration.

2.3 Water for the Environment in the River Murray Channel

SCBEWC is the coordination committee that supports the delivery of water for the environment in the River Murray system across multiple environmental water holders, managers and jurisdictions. In recent years, SCBEWC has increasingly focused on targeting environmental outcomes for the River Murray Channel and its floodplain from Hume Dam to the sea. The River Murray receives the most environmental water of any asset within the Murray-Darling Basin. Water delivery options are evaluated each year, informed by watering proposals developed for the channel downstream of Yarrawonga and Torrumbarry weirs, and the SA section of the River Murray. Watering needs of the channel, important wetland sites along the River Murray Channel and opportunities to leverage from natural flows, operational deliveries and environmental flows from tributaries are all important considerations in water delivery planning.

Water delivery in the River Murray at this point of time is constrained by several factors:

- Operational and management constraints as a result of sharing channel capacity with consumptive users and conflicting priorities for the release of held water (MDBA 2013).
- The Barmah Choke, which has a channel capacity of 10,600 ML/day during summer and autumn (to protect the forest from unseasonal flooding).
- Current limitations on maximum flow rates due to the potential impacts to third parties:
 - Regulated flows from the Hume Dam, are limited to < 25,000 ML/day at Doctor's Point (located downstream of the Kiewa River confluence) (MDBA 2013)
 - Regulated flows downstream of Yarrawonga Weir when inundation of Barmah-Millewa Forest is desirable can be delivered up to 3.0m AHD at the Tocumwal Gauge (approximately 15,000 ML/day downstream Yarrawonga), with the option of flow up to 3.3m AHD at Tocumwal (approximately 18,000 ML/day downstream Yarrawonga, subject to consultation with affected landholders and Basin Officials Committee support). A trial of flows up to 3.3 metres AHD at Tocumwal may occur in coming years, subject to seasonal conditions, water availability and the outcomes from consultation with potentially affected landholders.
- Limitations to the magnitude of environmental releases that can be made from various tributaries due to flow constraints within those tributaries.
- Limitations to the magnitude of releases that can be made from Lake Victoria, to top up flows to South Australia.

Basin states are contributing to works under the Constraints Management Strategy (MDBA 2013) that aim to address/relax these limitations to improve outcomes that can be achieved from water for environment delivery.

2.3.1 Objectives and expected outcomes of environmental water

Ecological objectives and targets for environmental water delivery in the River Murray Channel are established in two regional Long-Term Watering Plans (LTWP; see Appendix A): Long-Term Environmental Watering Plan for the South Australian River Murray Water Resource Plan Area (Department of Environment, Water and Natural Resources 2015); Murray–Lower Darling Long Term Water Plan (Department of Planning, Industry and Environment 2020) and informed by the Basin-wide Environmental Watering Strategy (2019).

On an annual basis¹, considerations of antecedent conditions, climate, river flow predictions and water resource availability are used to identify ecological objectives of environmental water delivery for the River Murray Channel for a range of possible climate conditions. As an indicative example, the objectives for environmental watering in the River Murray Channel during 2020-21 are as follows (MDBA 2020):

River connectivity and native vegetation

- Improve longitudinal connectivity through the River Murray, supporting ecologically important functions through shaping the pattern of how the river is flowing.
- Improve lateral connectivity to the wetlands and floodplains either side of the river where overbank flows are targeted.

¹ While a review of the environmental water objectives is undertaken each year as part of the planning process, it is recognised that not all objectives are required to be achieved each year. For example, long-lived fish species do not necessarily recruit every year.

- Mitigate against water quality issues resulting from stratification of weir pools under low flow conditions, especially in the lower Murray.

Native fish

- Create or maximise opportunities to increase the distribution and abundance of short to moderate-lived native fish species.
- Provide conditions for the improvement in population structure of moderate to long lived native fish species such as golden perch, Murray cod and freshwater catfish.
- Support Murray cod breeding in the mid-Murray through increased habitat and stable flows with no sudden drops in river level during spring (supported by River Murray flows and regulator opening strategy to provide off-river access).
- Support flow pulse specialist fish spawning and recruitment through the delivery of a spring pulse of sufficient magnitude and duration.

Priority ecosystem function

- Provide and protect a diversity of refugia across the landscape.
- Create quality instream, floodplain and wetland habitat.
- Provide movement and dispersal opportunities for water dependent biota to complete lifecycles and disperse into new habitats.
- Support nutrient, carbon and sediment transport along channels, and between channels and floodplains/wetlands.
- Support instream and floodplain productivity.

Environmental watering is also expected to provide benefits for species and locations of cultural significance. SCBEWC includes representatives of First Nations people to improve the alignment between environmental water coordination and cultural values. Guidance has been sought from First Nations people on key messages and principles that can be incorporated into environmental water planning for the River Murray on an annual basis. As engagement and collaboration continues to evolve in coming years, cultural outcomes will be better reflected in this monitoring plan.

Environmental objectives and watering actions within the year are generally scaled depending upon seasonal conditions and water resource availability. For example, during extremely dry conditions, the main ecological objectives will be related to supporting key refuge sites and avoiding severe impacts to ecological values. During moderate conditions the objectives may relate to maintenance of communities and ecosystem health and during wet periods, environmental water can be used to augment natural flows to improve ecological health and build resilience (Figure 3).

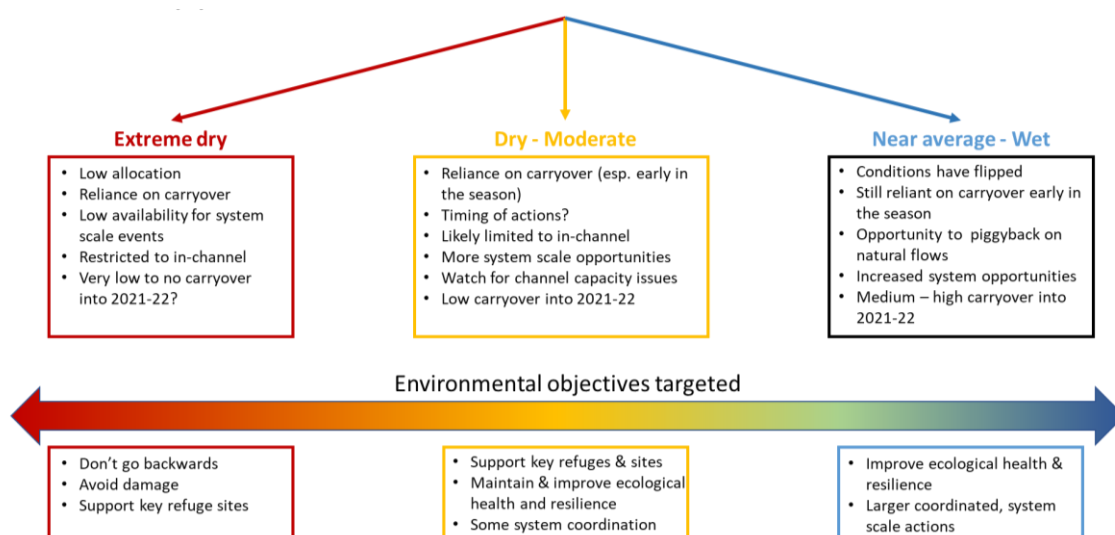


Figure 3: Example of the use of resource availability scenarios in environmental water planning (MDBA 2020).

An example of coordinated spring flow planning in the River Murray, including monitoring results, is provided in Text box 2. It is expected that there is scope to enhance outcomes within a constrained environment via adaptive management, underpinned by monitoring that moves from site-based to integrated whole of system-scale monitoring.

Southern Spring Flow 2019

In 2019, SCBEWC coordinated a 330 GL system-scale environmental watering event along the River Murray Channel. A small natural overbank flow in winter 2019 prompted the use of environmental releases from Hume Dam in August that were planned to augment a predicted natural flow pulse. The predicted rainfall, however, did not eventuate, and flow targets were not met. Adaptive management decisions were made, and a small winter pulse of 10,500 ML/day downstream of Yarrawonga was sustained to inundate emerging vegetation in Barmah-Millewa Forest. In September, spring releases were increased and a 15,000 ML/day flow target downstream of Yarrawonga was delivered during September and October 2019. This resulted in around 25% of the Barmah-Millewa Forest being inundated, supporting ecosystem processes, native fish, floodplain vegetation and waterbirds, including the threatened Australasian bittern.

Flows reached a further six Ramsar listed wetlands including Gunbower Forest, Koondrook-Perricoota Forest, Hattah Lakes, Riverland (Chowilla) and the Coorong. The spring release from Hume Dam was coordinated with releases from Lake Eildon in the Goulburn River to create a pulse along the length of the River Murray Channel. This resulted in flows above 15,000 ML/day at the South Australian border for 11 days (Figure 4).

Short-term intervention monitoring indicated that the inundation of Barmah-Millewa Forest and return flows to the River Murray Channel resulted in improved productivity outcomes in the central Murray below the forest (Furst et al. 2020; Rees et al. 2020). In addition, the in-channel pulse in the lower Murray increased flow velocity and inundated littoral habitat, also resulting in increases in zooplankton (Furst et al. 2020). While only short-lived increases in carbon and nutrients were detected downstream of Echuca, and no increases in the Lower Murray, it is likely that any new carbon entering the river was quickly incorporated into the food web, and hence not detected in sampling (Rees et al. 2020). This illustrates the importance of multiple indicators of productivity and the integration of information across indicators to gain a more complete understanding of the trophic responses to environmental flows.

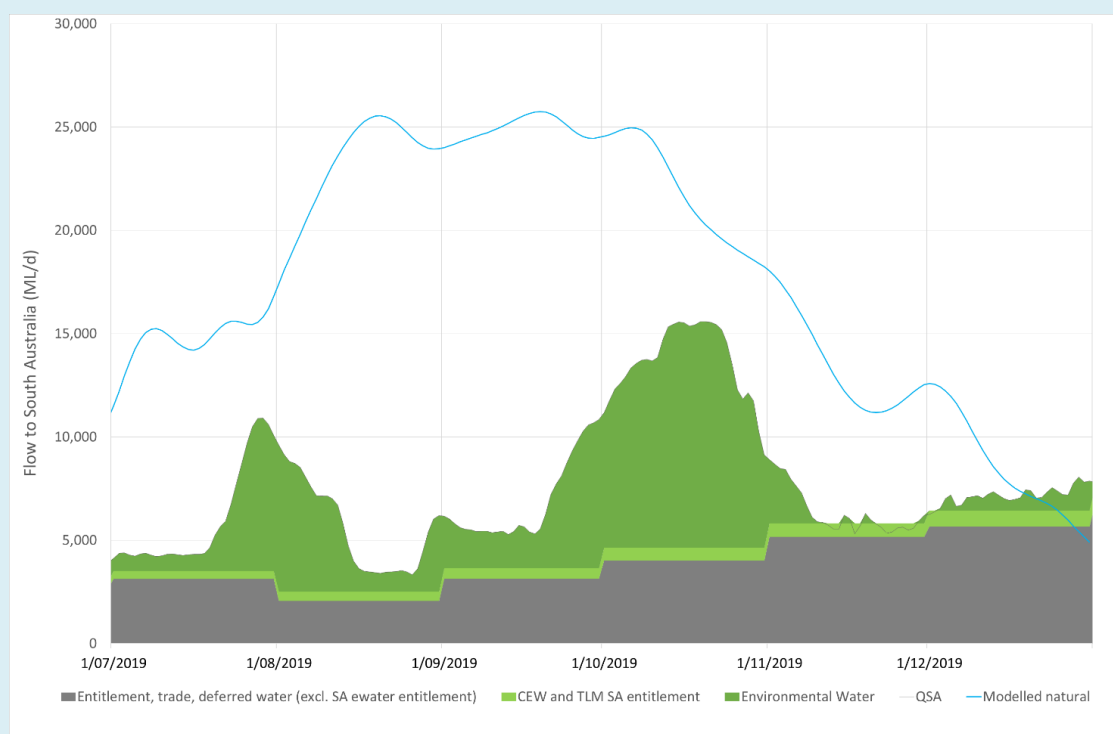


Figure 4: Hydrograph at the South Australian border during the Southern Spring Flow 2019 (MDBA 2020).

Text box 2: River Murray Channel Southern Spring Flow 2019.

3 Key evaluation questions

Key evaluation questions (KEQs) have been used to guide the development of the monitoring plan in accordance with the program objectives. The KEQs inform the selection of monitoring indicators and the timing and frequency of their measurement. They also direct the analysis and evaluation by focussing on the evidence that is required to answer the questions. This approach helps ensure that monitoring undertaken is relevant and appropriate to the program objectives. As the monitoring plan evolves an important adaptive management step will be for environmental water managers to assess the collected evidence to decide if the KEQs have been adequately answered to inform decisions about how to direct future monitoring efforts.

3.1 Themes

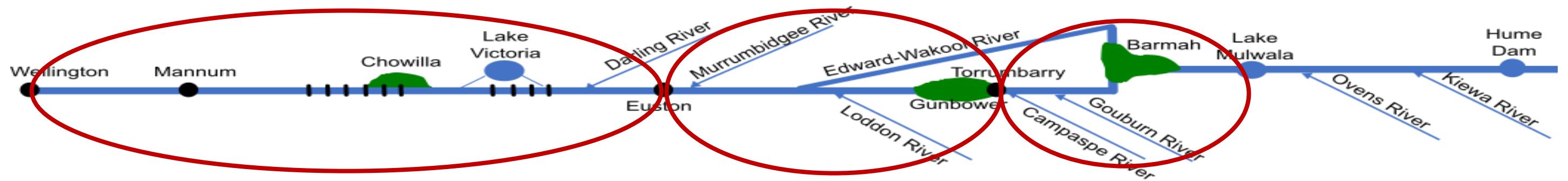
Productivity and native fish (specifically breeding of golden and silver perch and Murray cod) were chosen as themes to focus the monitoring plan. These themes reflect the expected system-scale outcomes from flow events that are planned to be delivered through the River Murray Channel (as opposed to individual sites or wetland focus). Fish and productivity outcomes are key targets for River Murray Channel watering actions, influencing. Information from monitoring and evaluation that refines delivery decisions regarding flow rates, durations and volumes is expected to enhance these outcomes.

While there is established science that underpins the relationship between hydrology, productivity and outcomes for fish, knowledge gaps remain. Many of the KEQs developed for the monitoring plan aim to better understand these connections to inform adaptive management of water for the environment. The results also have the potential to inform delivery of operational flows and/or the management of river infrastructure.

Coordinated spring flow events are expected to have detectable increases in ecosystem productivity (basal food resources through to higher trophic levels), trigger fish spawning and enhance larval development in various parts of the River Murray channel. Implementation of the monitoring program aims to quantify the effect that coordinated spring flows have on various productivity and larval fish indicators and compare those effects to what may happen without the coordinated event as well as responses to natural events.

The selected indicators are expected to provide useful information without having to rely on extensive co-variates. They are also considered to be relatively cost effective and provide an opportunity to leverage off and complement existing state, CEWO, TLM and MDBA monitoring and evaluation programs.

A general description of the expected ecological outcomes for the focus themes from spring flow delivery in different parts of the River Murray Channel (Figure 5), provides the basis for the development of KEQs and identification of indicators to address those KEQs.



Lower Murray (See Bice et al. 2014 for more detail) (Euston to Wellington)	Mid Murray (downstream Torrumbarry to Euston)	Barmah-Millewa Forest and river reach immediately downstream
<p><i>Hydraulic conditions</i></p> <ul style="list-style-type: none"> This reach of the River Murray is characterised by a series of weir pools and is influenced by flows from the Mid Murray and tributaries, the Darling/Baaka and Lake Victoria operations. During regulated conditions, the weir pools have the effect of slowing down water velocities. High flow events and/or lowering weir pool water levels can increase flow velocities (note detailed relationships between weir pool height and in-channel flow velocities have been established for many of the weir pools in this reach; Ye et al. 2020). Conversely, weir pool raising has the effect of improving lateral connectivity with low-lying floodplain wetlands and anabranches while decreasing water velocities. Coordinated spring flows in the Lower Murray creates hydraulic diversity within weir pools and provide some water level variation in the tailwaters that would not occur otherwise. Substantial increases in lotic habitat (>0.3 m/s) are observed across the upper parts of the Lower Murray River weir pools when flows to South Australia are in the order of 15,000 ML/day, but lotic conditions in the lower parts of the weir pools are still not achieved at this flow (Ye et al. 2020). To achieve lotic conditions in the lower weir pools flow pulses of ~20,000 ML/day are needed or coordinated weir pool lowering of 1m at each weir pool between locks 1-6 (not achievable in the near term or life of the monitoring plan) (Ye et al. 2020). <p><i>Productivity response</i></p> <ul style="list-style-type: none"> Productivity in this reach is expected to primarily be generated locally, via influences such as coordinated delivery of spring pulses and weir pool level variation successively wetting and drying fringing low-lying areas. Recent monitoring has highlighted that stable weir pool levels strongly constrain local production (Ye et al. 2020). Transportation of carbon, nutrients and zooplankton from upstream sources is not expected to be a significant source of increased productivity during managed environmental flow events within current constraints (Furst et al 2020). Return flows entering from floodplain sites such as Hattah, Lindsay-Mulcra-Walpolla and Chowilla following managed inundations are expected to generate a localised productivity response, however this is expected to be relatively small for managed events as the volume returning will be small relative to the flow rate in the main channel (Wallace and Furst 2016, Furst et al. 2019). <p><i>Fish response</i></p> <ul style="list-style-type: none"> Sustained flows greater than 18,000 ML/d (possibly higher e.g., 20,000 ML/d) with water temperature above threshold levels (~late spring) are needed at the SA border to cue golden and silver perch spawning (Zampatti et al. 2015). Downstream drift of golden and silver perch larvae into the Lower Murray is expected to occur under high flow conditions to leading to enhanced recruitment. Contributions from the Darling/Baaka may be of particular significance for golden perch larvae distribution when water is available and timed with elevated Murray flows to promote dispersal into the Murray including u/s towards Torrumbarry. Such flows may also attract fish from the Murray into the Baaka system (Koehn et al. 2020). Murray cod are expected to spawn and recruit locally in the lower Murray each year. However, research has shown that that Murray cod recruitment is limited under predominantly lentic conditions and that there is a positive association between recruitment and flow in the main River Murray Channel (Ye et al. 2020). Providing elevated flows above 20,000 ML/day at the South Australian border will increase the quantity of lotic habitat in the lower Murray and therefore should improve Murray cod recruitment. 	<p><i>Hydraulic conditions</i></p> <ul style="list-style-type: none"> This reach of the River Murray is largely free-flowing without the influence of weir-pools. Significant inflows (either managed or natural) enter this reach via the Goulburn, Campaspe, Edward/Kolety-Wakool and Murrumbidgee rivers. Water may be diverted into floodplain sites of Gunbower-Koondrook-Perricoota and other smaller forests, however the volume of water returning to the river from managed events is expected to be relatively small compared to return flows from floodplain sites in other zones. Coordinating spring environmental flows in the River Murray Channel with tributary inflows results in a small increase in water levels in the Channel inundating small areas of the riverbank. Flow timing and magnitude can be shaped to provide flow variability or pulses to improve in-channel velocity and hydraulic diversity. <p><i>Productivity response</i></p> <ul style="list-style-type: none"> Productivity in this section of the River is influenced by return flows through Barmah-Millewa Forest and flows from the Goulburn, Edward/Kolety-Wakool and the Murrumbidgee Rivers (Gawne et al. 2017). While higher flows will wet more areas of the riverbank releasing small amounts of carbon and nutrients, the main source of productivity in this reach is expected to be via run-off from upstream floodplain sites and tributary inputs. Productivity responses to managed flows in this zone are expected to be most evident immediately downstream of input sources (e.g., floodplain return flows and tributary inflows). More widespread productivity responses will likely require larger flows (Furst et al 2019; Rees et al 2020; Rees et al 2021) that cannot be actively delivered within current operating constraints. <p><i>Fish response</i></p> <ul style="list-style-type: none"> There is a significant knowledge gap about spawning and recruitment of native fish species in this section of the river (I. Stuart pers. comm). Golden perch spawning has been detected in upstream tributaries, such as the lower Goulburn with these larvae thought to drift downstream to the River Murray where their fate remains unknown (Zampatti and Lee 2013). A flow pulse of sufficient magnitude and velocity is expected to trigger localised spawning of golden and silver perch within this reach King et al. 2009). Higher in-channel flow rates increase flow velocities facilitating larvae dispersal from upstream to downstream sites. Natal origin studies indicate that some strong cohorts of golden perch in the Lower Murray originated in the Mid Murray (Zampatti et al. 2015). Murray cod are expected to establish nests in spring within the river channel. Maintaining stable water levels during the nesting period to keep nests submerged and to avoid rapid drops in water levels, will enhance the survival of eggs and larvae (Tonkin et al. 2020). 	<p><i>Hydraulic conditions</i></p> <ul style="list-style-type: none"> Higher flows delivered overbank in winter-spring will inundate areas of the Barmah-Forest floodplain, with return flows passing downstream in the River Murray Channel and to the Edward/Kolety-Wakool system. Flow rates of ~15,000ML/d downstream of Yarrawonga Weir inundate around 25% of the Barmah-Millewa Forest with water entering the forest via a series of regulators. Higher flows will inundate a greater extent. Managed overbank flows using environmental water will have gradual rates of rise and fall. Multiple effluent channels distribute water onto and across the floodplain with water gradually returning back in-channel downstream of Barmah Lake and 200km downstream at the Wakool junction. Higher flows will result in a small increase in water levels inundating small areas of the riverbanks, with flow variability or pulses improving in-channel velocity and hydraulic diversity <p><i>Productivity response</i></p> <ul style="list-style-type: none"> The main contributor to productivity increases in this reach will be return flows from inundated parts of Barmah Millewa Forest (Nielsen et al. 2016). Inundation of the forest mobilises floodplain carbon and nutrients and provides conditions for zooplankton to grow in wetlands and creek lines. The quality and quantity of basal food resources produced on the floodplain differs from that produced within the main river channel and therefore are important contributors to riverine food webs (Gawne et al. 2007). Carbon, nutrients and zooplankton are transported from the forest floodplain to the River Murray Channel via floodplain return flows. These are expected to increase the abundance and diversity of basal food resources in the River Murray channel downstream of the forest (Gawne et al. 2007). The effect on the River Murray channel food web is expected to vary in the following ways (Gawne et al. 2007): <ul style="list-style-type: none"> Area of floodplain inundated – greater inundation extent within the forest is expected to have a larger productivity response in the river downstream. Time between inundation events – wetting events following a long dry interval are expected to deliver larger productivity outcomes in the downstream river channel than inundation after a short dry interval. Season – productivity responses are expected to be larger in warm weather/seasons than cool seasons. <p><i>Fish response</i></p> <ul style="list-style-type: none"> Murray cod are expected to establish nests in spring within the river channel and creeks of the forest. Maintaining stable water levels during the nesting period to keep nests submerged and to avoid rapid drops in water levels, will enhance the survival of eggs and larvae (Tonkin et al. 2020). Providing some variability in flows (e.g., increasing from 12,000 ML/d d/s Yarrawonga to 14,000 ML/d followed by gradual recession) once water temperatures are above threshold levels are expected to generate silver perch spawning within the river channel (Tonkin et al. 2020).

Figure 5: General description of expected ecological outcomes (associated with environmental water releases).

3.2 KEQ hierarchy

The KEQs were developed by a multi-jurisdictional group of environmental water managers with significant operational experience in planning and delivering system-scale environmental water events along the River Murray. Information that informed the KEQs included:

- The likely magnitude, timing and duration of coordinated spring flow events in the River Murray Channel.
- Environmental objectives of coordinated spring flow events in the River Murray Channel.
- Likely response time and extent to which a response relies on other factors that cannot be controlled.
- Environmental and management importance of expected response.
- NSW and SA River Murray Long-Term Watering Plans.
- Knowledge gaps identified through operational experience and past monitoring and research.

This led to the development of evaluation questions (Figure 6) using the following hierarchy:

- Aspirational goal / vision – overarching goals to which information collected across multiple programs (monitoring, research and modelling) will contribute.
- Long-term questions – that will be answered by information from a range of monitoring and research programs to which the River Murray Channel Monitoring Plan will contribute.
- Intermediate questions – questions to be answered from data collected over the five years of the program, hopefully spanning a range of climatic and flow conditions.
- Immediate questions – to be answered annually from conditions experienced before, during and after environmental watering.
- Foundational information – baseline information about hydrology that supports the evaluation of ecological responses.

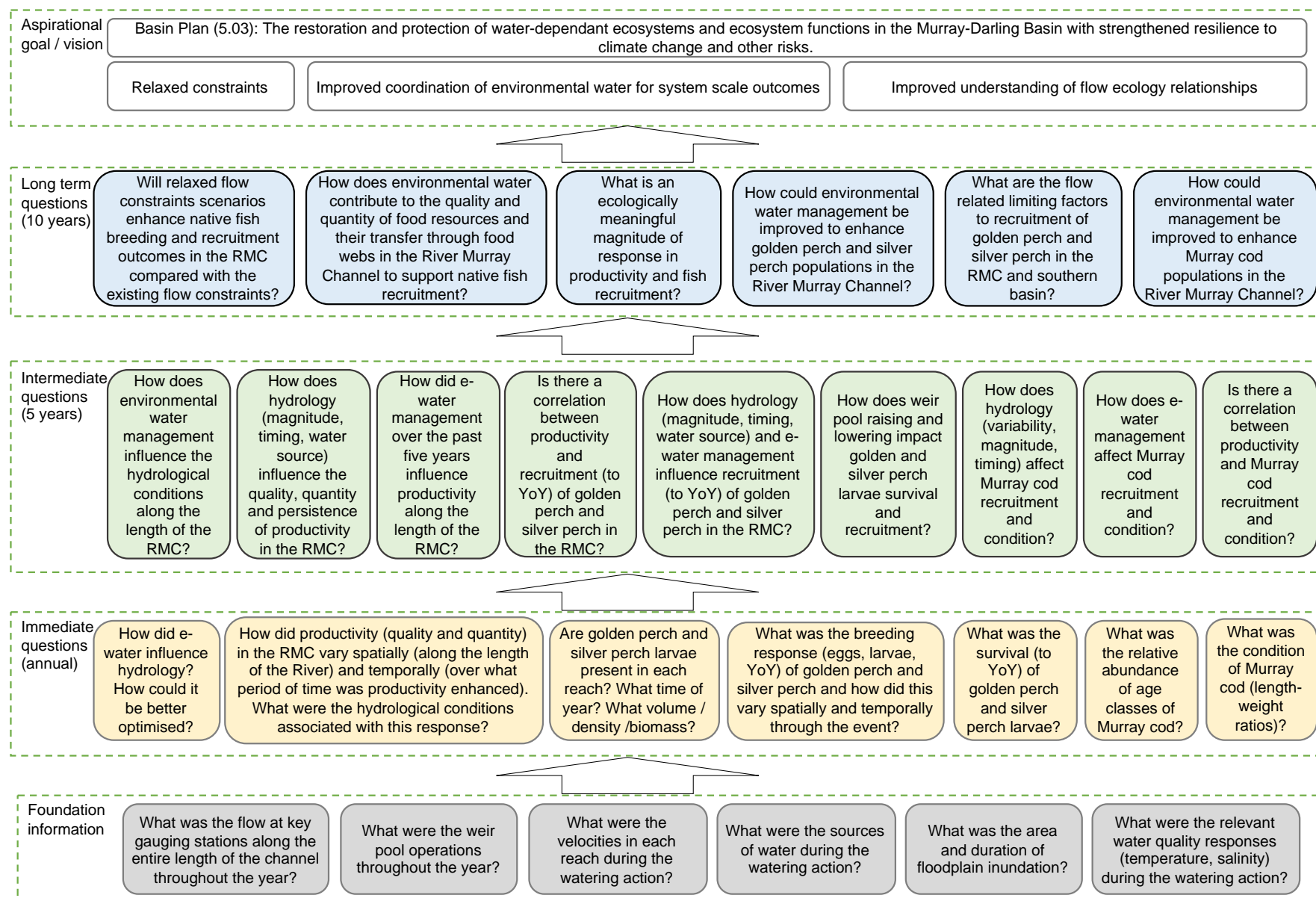


Figure 6: Key Evaluation Questions for the Program.

3.3 Indicators to answer evaluation questions

Indicators have been reviewed with respect to their strengths and limitations to address the KEQs, known flow-ecology relationships, expected responses to flow in the River Murray Channel, cost and leverage opportunities. The results of this brief review are provided in Appendix B and summarised below.

3.3.1 Productivity

Riverine productivity is the flow of energy and essential nutrients through food webs from basal food resources such as organic carbon, through trophic levels to apex predators such as fish and waterbirds (Robson et al. 2017). Hydrology is a driver of aquatic food webs in terms of production of food resources and transport of those resources between floodplains and rivers and along river systems (Junk et al. 1989, Brookes et al. 2012). There is evidence that managed flows both instream and through floodplain inundation can influence riverine productivity outcomes through the mobilisation of carbon and nutrients, but also through the transfer of biota such as phytoplankton and microcrustaceans (Baldwin and Mitchell 2000, Gawne et al. 2007, Nielsen et al. 2016). Productivity outcomes are targeted by environmental water in the River Murray Channel and the Basin Plan contains two environmental objectives specifically targeting productivity:

- 8.04 (2) *An objective is to protect and restore a subset of all water-dependent ecosystems of the Murray-Darling Basin, including by ensuring that:...(c) water-dependent ecosystems are able to support episodically high ecological productivity and its ecological dispersal.*
- 8.07 (7) *An objective is to protect and restore ecological community structure, species interactions and food webs that sustain water-dependent ecosystems, including by protecting and restoring energy, carbon and nutrient dynamics, primary production and respiration.*

The conceptual understanding of flow-productivity relationships in Figure 7, formed the basis for selecting potential indicators for the productivity theme of the program; with a number of indicators across trophic levels selected to explore in more detail. Investigating responses at multiple trophic levels is a key focus for this monitoring plan to determine whether specific flows i) provide the fundamental ingredients for increased productivity, and ii) whether any observed increase in productivity is transferred to higher trophic levels. The productivity theme KEQs relate to both the quality and quantity of the food resource and the intermediate to long-term KEQs link productivity outcomes to improved native fish recruitment and populations. The review of potential indicators (Appendix B) suggests that no single indicator of productivity will adequately address all KEQs.

While the lower trophic order indicators (dissolved organic carbon, nutrients) provide the most direct link between hydrology and productivity responses, they provide no information on the quality of food resources or even if increased mobilisation of carbon and nutrients had a productivity outcome. Similarly, while stream metabolism is the only direct measure of production, provides a measure of the rate of productivity and one that is not influenced by food web interactions, it provides no information on food quality, nor if there were improved outcomes up the food chain to fish. Phytoplankton, in different groups are enumerated, provides an indication of food quality, as does zooplankton and biofilms if a measure of nutritional value is analysed. These indicators, however, have a less direct link to hydrology and are confounded by food web interactions whereby a low abundance may mean poor productivity, or it may mean stimulated productivity, but consumption by biota higher on the food chain. As a consequence, multiple indicators of productivity will be required to adequately address the immediate and intermediate questions and contribute to the evaluation of long-term KEQs.

In addition, it is recognised that there are a number of research programs currently exploring indicators of productivity and relationships with hydrology in the Basin (e.g., Flow-MER, CSIRO Ecosystem Function Project). It is possible that within the five-year timeframe of the monitoring plan that sufficient evidence is provided for the inclusion of additional or alternative indicators to address the productivity theme KEQs. This will be considered in the annual review and adaptive management of the monitoring program (see section 6).

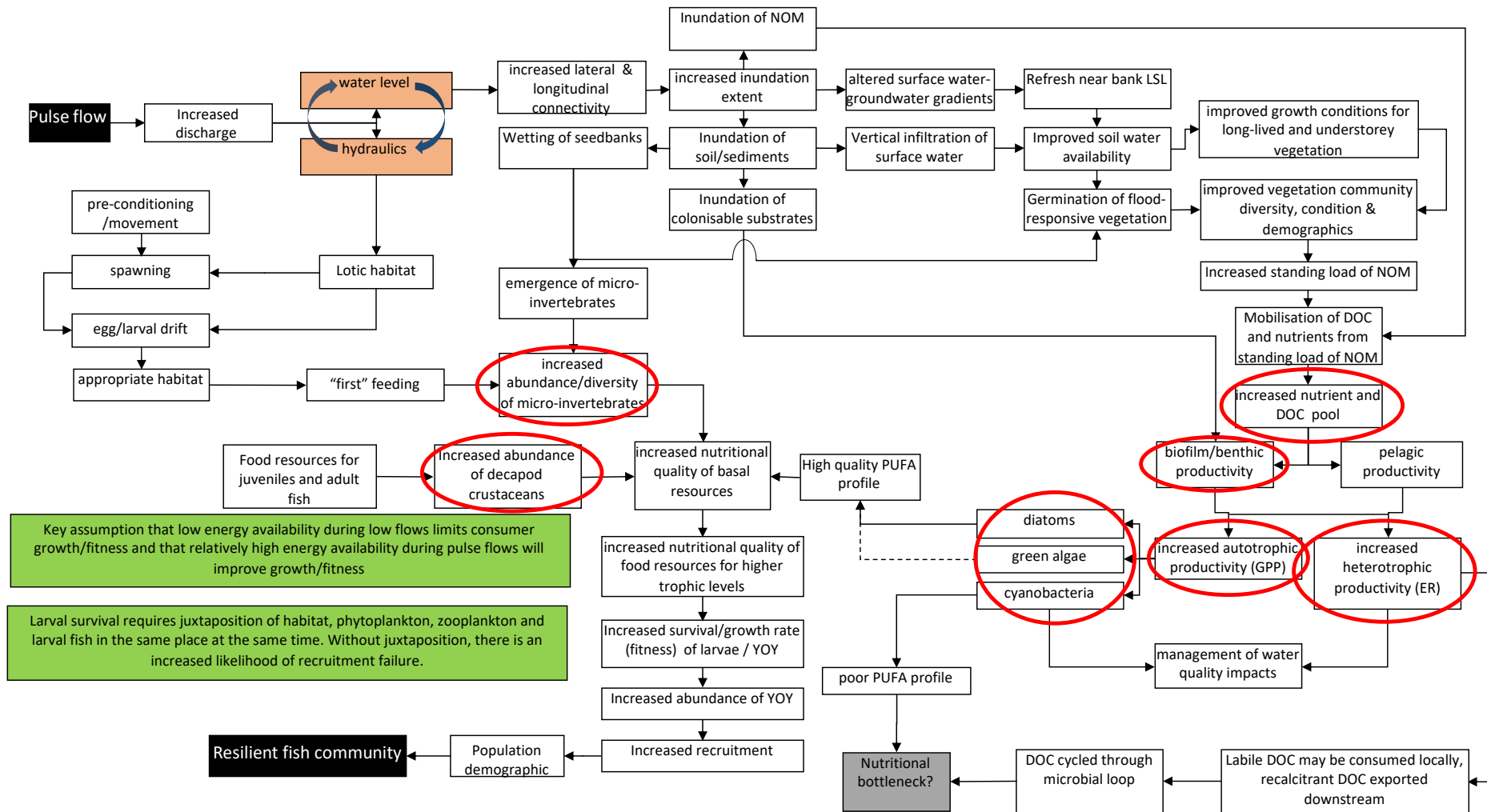


Figure 7: Chain of consequence model linking hydrology to productivity and native fish outcomes (Wallace unpublished). Red circles illustrate the indicators selected for consideration in the monitoring plan. The selection of indicators was informed by technical experts and chosen to reflect a spread of productivity indicators across trophic levels.

Table 1: Summary of the strengths and limitations of productivity indicators (see Appendix B for more detail).

Indicator	Strengths	Limitations
Dissolved organic carbon and nutrients	<p>Foundational information with a direct causal link with hydrology.</p> <p>Proven responses to the types of flows that occur in the mid Murray (Hume to the Darling River/Baaka) from both in-channel increases in flows and floodplain return waters.</p> <p>Existing monitoring program that can be leveraged off.</p> <p>Large long-term data set would allow for retrospective analysis for trends and causal relationships to flow.</p> <p>System scalable.</p> <p>Established methods and protocols.</p>	<p>Provides no information on outcomes for biota.</p> <p>Limited responses expected from the types of flow currently delivered in most years below the Darling River/Baaka in the Lower Murray.</p> <p>Effect size in the mid-Murray (Hume to the Darling River) may be low and of limited extent and duration during years where there is little return of water to the river from floodplain inundation.</p>
Stream metabolism	<p>Provides a direct measure of the basics of productivity and the only measure that provides an indication of rate of change.</p> <p>Has been shown to be responsive to both floodplain inundation (return waters) and in channel flows.</p> <p>Methods are well established</p> <p>Provides an opportunity to leverage off existing monitoring.</p> <p>Moderate costs – especially if it can be integrated with a higher trophic order sampling regime.</p>	<p>Provides no information on outcomes for biota.</p> <p>Limited responses expected from the types of flow delivered in most years below the Darling River/Baaka, particularly in South Australian weir pools.</p> <p>Effect size in the mid-Murray (Hume to the Darling River) may be low and of limited extent and duration during years where there is little return of water to the river from the floodplain.</p> <p>Utility in informing adaptive management may be low.</p>
Phytoplankton (biomass and functional groups)	<p>Provides a more direct measure of the quantity of food produced than stream metabolism and water quality measurements.</p> <p>Has been shown to be responsive to flows in the mid and lower Murray River.</p> <p>Methods are well established.</p> <p>Low cost – especially if leveraged off existing programs</p>	<p>It is unknown whether the types of flows delivered in the River Murray would illicit a detectable response.</p> <p>There are a large number of covariates (nutrients, temperature, grazing pressure) that may make linking back to hydrological regimes difficult.</p>
Biofilms	<p>Provides a more direct measure of the quality of food produced than stream metabolism and water quality measurements.</p> <p>Represents a short food chain pathway from allochthonous carbon to shrimp and other macroinvertebrates.</p> <p>Some flow-ecology relationships established.</p> <p>Moderate costs.</p>	<p>Does not offer any direct leveraging opportunities on existing monitoring.</p> <p>It is unknown whether the types of flows delivered in the River Murray would illicit a detectable response.</p> <p>There are a large number of covariates (nutrients, temperature, grazing pressure) that may make linking back to hydrological regimes difficult.</p>
Zooplankton	<p>Zooplankton are important components of the diet of several native fish species and so provide a more direct link between productivity and fish food resources.</p> <p>Zooplankton abundance/biomass and nutritional value have shown to be responsive to the types of flow that occur in the Murray, including moderate floodplain inundation.</p> <p>Methods are established.</p> <p>Moderate costs – particularly if leveraged off existing monitoring in the lower Murray.</p>	<p>It is unknown whether the types of flows delivered in the River Murray would illicit a measurable response in the absence of significant floodplain inundation.</p> <p>There are a large number of covariates (nutrients, temperature, grazing pressure) that may make linking back to hydrological regimes difficult.</p> <p>Zooplankton abundance potentially does not provide an indication of the nutritional value of the food resource. This would require analysis of fatty acid content (for which sample volumes required may be large).</p>
Higher trophic levels (e.g., decapods, Murray cod)	<p>Provides a direct measure of the quality of food produced at a higher level in the food chain</p>	<p>Methods need to be tested.</p> <p>No guarantee that it would be responsive to environmental water or changes in hydrology throughout the system within the timeframe of monitoring.</p> <p>Potentially high cost and high risk.</p>

Productivity responses to flow in the River Murray Channel

There have been several studies evaluating the effect of hydrology on productivity in the River Murray Channel (see Appendix B). Collectively they illustrate some key points:

There is good evidence linking productivity responses to natural floods

Studies from the large flows following prolonged drought in 2010 and 2011 indicate that large flows in-channel and floodplain return waters stimulate the movement of floodplain carbon, nutrients and zooplankton into the River Channel, resulting in significant (orders of magnitude) increases in production (see graphic below). Although this may be accompanied by black water and negative impacts to obligate aquatic biota.

There is some evidence that managed floodplain inundation can stimulate riverine productivity responses

Managed floodplain inundation events that are augmented or entirely produced by environmental water have been shown to increase the mobilisation of carbon, nutrients and zooplankton from the floodplain to river systems and to stimulate riverine phytoplankton abundance. These effects are, however, usually localised (within 50 kilometres of the discharge) and short-lived, weeks after the event.

Increases in in-channel flows can stimulate productivity and enhance basal food quality

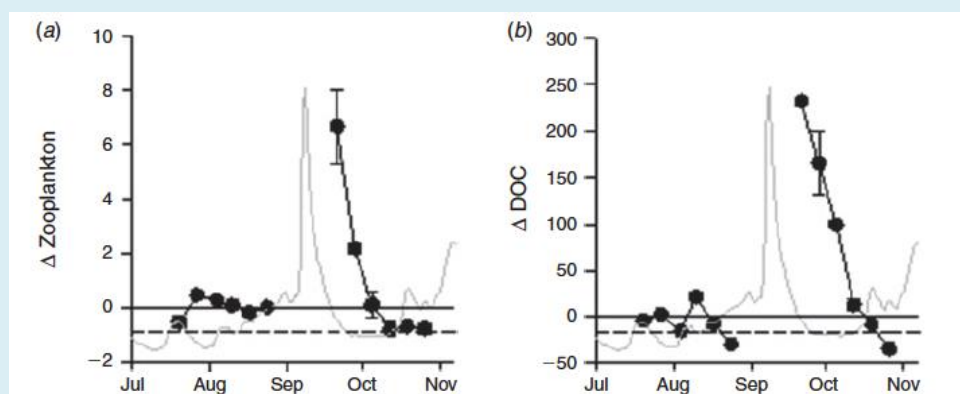
Increases in in-channel flows can also affect productivity in river systems. There are small, but measurable increases in stream metabolism in response to inundation of in-channel features such as benches and backwaters, mobilising carbon and nutrients and increasing productivity. In addition, moderate increases in flow (base flow to fresh) can have an effect on phytoplankton communities, increasing the proportion of diatoms, which have higher nutritional value and decreasing poor food quality blue-green algae. This in turn can influence the zooplankton community, increasing diatom grazers, which also represent a high-quality food resource for higher trophic levels.

There are constraints limiting what can currently be achieved with water for the environment

Delivery of water for the environment in the River Murray is constrained by a number of factors including competition with operational flows for limited channel capacity during peak times and minimising the risk of third-party property impacts. As a result, there are currently limitations on the range of flows that can be delivered and capacity to add water for the environment to natural unregulated flows. Productivity responses are limited in the weir pools of the lower Murray, where water levels remain largely stable. Locks 7 to 9 weir pools are constrained in drawdown depth by fishway functionality, which potentially affect productivity outcomes that may be able to be achieved etc.

There are still many knowledge gaps

There is still much that we do not know about the relationship between hydrology and productivity in large, regulated rivers like the River Murray. One of the key pieces of missing information is how much of a productivity response (magnitude, spatial and temporal extent) represents an ecologically meaningful increase. Similarly, do the smaller managed water events that result in some increases in quality and quantity of food in river systems move through the food chain to benefit higher end predators such as large bodied native fish? There are several research programs currently in place addressing these questions, the outcomes of which can be used to both improve our monitoring programs and the way we manage water for the environment.



Change in zooplankton and dissolved organic carbon (tonnes / day) upstream and downstream of Barmah Forest in 2010 (dots) and flow at Tocumwal (grey line). Small natural winter flood had little effect, but the large inundation in spring resulted in the mobilisation of large amounts of carbon and zooplankton (Nielsen et al. 2016).

3.3.2 Large-bodied native fish

Hydrological influences on large-bodied native fish populations in the Basin have been studied for several decades (Humphries et al. 1999, King et al. 2009, Koehn et al. 2014, Ellis et al. 2016). As research and monitoring have progressed, our conceptual understanding and models of flow-fish relationships have been updated (e.g. Chee et al. 2006, DELWP 2017) and a generalised conceptual model illustrates the links between drivers (flow regime, habitat, water quality and connectivity); modifiers (altered flow and habitat; introduced species and barriers to connectivity) with fish life-history processes and population outcomes (Figure 8). In particular, a reduction in the frequency and magnitude of spring flow pulses and overbank flows and a reduction in flow variability in the River Murray Channel has impacted large-bodied native fish populations (Zampatti and Leigh 2013, Tonkin et al. 2019).

Three species of large-bodied fish are targeted by coordinated large-scale environmental water releases in the River Murray Channel², two of which are listed threatened species under the EPBC Act (Murray cod and silver perch) while golden perch has experienced low recruitment in recent years, including in several tributaries of the mid-Murray (Shams et al. 2020, Stuart and Sharpe 2020). The Basin Plan has several objectives that are relevant to these three species including:

- 8.05 (3) *An objective is to protect and restore biodiversity that is dependent on Basin water resources by ensuring that:...(a) water-dependent ecosystems that support the life cycles of a listed threatened species or listed threatened ecological community, or species treated as threatened or endangered (however described) in State law, are protected and, if necessary, restored so that they continue to support those life cycles.*
- 8.06 (6) *An objective is to protect and restore ecosystem functions of water-dependent ecosystems that maintain populations (for example recruitment, regeneration, dispersal, immigration and emigration).*

Despite several decades of study, significant knowledge gaps remain. In particular the influence of flow on survival rates between life stages is largely unknown as is the importance of flow on the rate of movement of eggs, larvae and adults (Koehn et al. 2019).

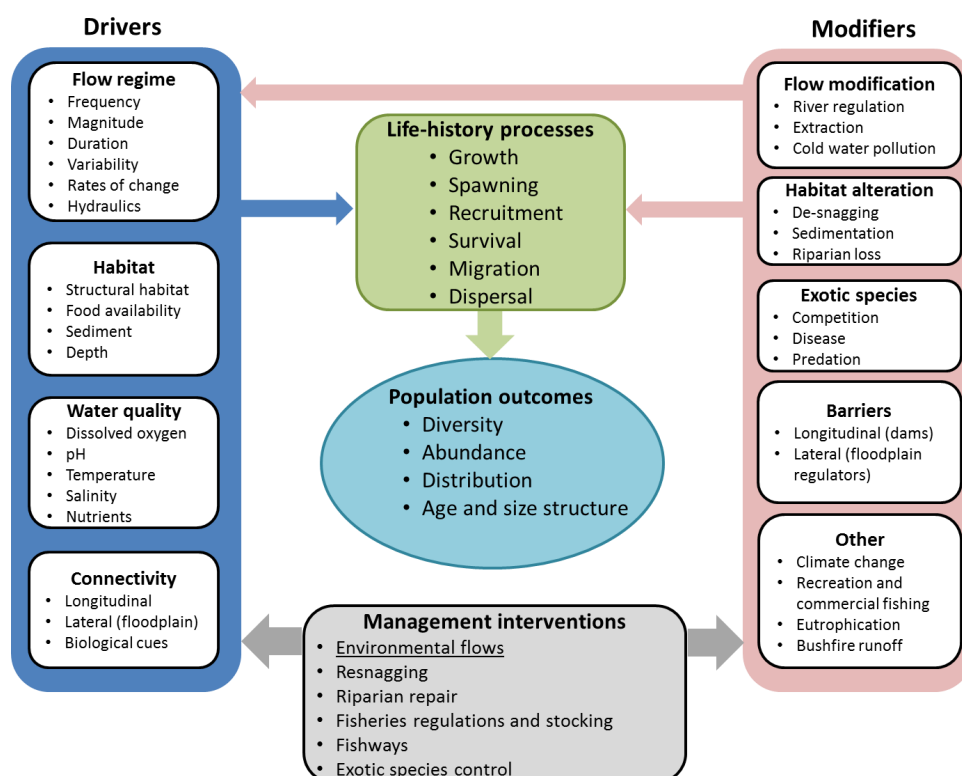


Figure 8: Overarching conceptual model of native fish population outcomes to drivers, modifiers and management interventions (DELWP 2017).

² While freshwater catfish are targeted in the Lower Murray, they are not the focus of water management across the entire system.

Unlike the productivity KEQs, which could be answered through the measurement of a number of different indicators, in many respects the KEQs for fish (Figure 6), define the indicator to be measured:

- Golden perch and silver perch:
 - Abundance of eggs, larvae, Young-of-the-Year (YoY)
 - Population structure and recruitment
- Murray cod
 - Condition (length: weight)
 - Population structure and recruitment

One consideration is whether destructive sampling may be required to collect otoliths of fish, which can be used to determine the age of individual fish with a greater degree of accuracy than length measurements (Wright et al. 2020) and can also, with matched strontium isotope samples³ from river water, determine the natal origin of larvae and YoY (Harris et al. 2020). The need for this information will need to be carefully weighed against the destructive sampling required to collect otoliths, particularly for the EPBC listed threatened species Murray cod and silver perch. Consideration should be given to alternative methods for the collection of otoliths from adult target fish species, including the use of citizen science programs where anglers can submit otoliths with location data for laboratory analysis (Tonkin et al. 2020) provided such alternatives provide suitably robust data.

³ Strontium levels in the River Murray Channel and tributaries have been previously characterised and appear stable over time. The need for additional sampling would need to be explored and justified.

Perch spawning and flow in the Lower Murray

Spawning and recruitment of native flow-cued spawning species, particularly golden and silver perch, is a key targeted outcome for environmental water delivery in the Lower Murray. While success has been elusive in recent years and there remains a lot to learn, adaptive management and monitoring since 2012 has significantly improved the understanding of the flow requirements and the role of environmental water in meeting them.

Refining the perch flow demand

Successive years with negligible recruitment during the low-flow Millennium Drought emphasized the importance of flow for perch in the Lower Murray. Post Basin Plan reforms, hopes were high that if newly recovered environmental water could increase flows to around 15,000 ML/d at the SA border during spring, it may be enough to support spawning and recruitment of new perch cohorts. For several seasons (2013-18) environmental water contributed to spring pulses of that size, however monitoring typically detected no or low numbers of eggs and larvae, with very limited evidence of recruitment to YOY. Modelling to understand the influence of flow on riverine hydraulics added to the emerging picture, demonstrating that even at 15,000 ML/d, the flowing water habitat needed to support perch recruitment is patchy and disconnected in the Lower Murray. For strong spawning responses and successful recruitment, perch evidently needed more flow, and best-available science indicated that several weeks in the 18-20,000 ML/d range may be needed.

Coordinating flows across catchments to meet demand

In 2019, water managers carefully coordinated spring deliveries from Hume with a pulse from the Goulburn in a concerted effort to raise and extend the spring flow for a range of outcomes in the Murray, including perch recruitment. In SA, this generated a spring pulse peaking at 15,600 ML/d, but again there was no evidence of recruitment of golden or silver perch, lending further support to the argument that higher flows would be crucial.

In spring 2020, water managers took this coordinated approach a step further, with concurrent environmental water deliveries from the Goulburn River, Murrumbidgee River and Hume Dam. Forecasts in the weeks leading up to the event suggested that with flows from these catchments combining in the Murray, flow rates at the SA border would potentially exceed 20,000 ML/d and remain above 18,000 ML/d for several weeks. With perch spawning a realistic target outcome, resources were mobilised to monitor and detect spawning activity.

As the event approached, a series of factors combined to reduce the size of the forecast flow pulse at SA, including reduced environmental water deliveries from Hume and Goulburn, and hot, drier than expected conditions. By the time the pulse neared the SA border in mid-November, it was no longer clear whether it would reach even 18,000 ML/d and was forecast to rapidly recede back below 15,000 ML/d. In the meantime, monitoring detected good numbers of perch eggs in South Australia on the rising limb of the pulse. Clearly, perch were responding to the bigger flow on a scale not seen in almost a decade, but the past learnings indicated that a rapid drop in flow would likely compromise chances of recruitment success.

Real-time adaptive management

With all upstream catchments already delivering at their upper flow thresholds, options to provide more support for the South Australian perch spawning activity were very limited. A decision was made to bring forward the delivery of some water that had been planned for summer and supplement river flows with immediate releases from Lake Victoria. Water managers, scientists and river operators worked together to identify and respond to this demand in an extremely short timeframe; an order for 40,000 ML of Commonwealth environmental water was placed and delivery commenced within days. This water helped ensure that flow rates could be maintained above 15,000 ML/d for several weeks and subsequent monitoring continued to detect perch eggs and larvae from several monitoring locations in the Lower Murray. Surprisingly, later lab analysis found that most larvae were the threatened silver perch, with only a few goldens, and genetic analysis is underway to identify egg species. Despite the spring spawning response, surveys in autumn have not yet detected YOY fish and work is ongoing to provide further insight into the responses of golden and silver perch to 2020 flows. While there are plenty of questions still to answer, integrated science and adaptive water management is steadily improving the understanding of how environmental water can enhance flows and support perch spawning and recruitment in the Lower Murray.

Text box 4: Perch spawning and flow in the Lower Murray.

4 Monitoring design

Funds available for implementation of the monitoring plan are not yet committed and are likely to vary over time due to budgets and changes to complementary monitoring programs. A monitoring design that explores a full suite of potential monitoring locations, with respect to flow influences (storages, tributaries, return flows from major floodplain inundations) and a range of indicators is preferred. While the preferred approach set out in this monitoring plan applies over a five-year period, work will be contracted on an annual basis (at least in the first instance) with monitoring service providers to plan monitoring activities based on the planned watering and the expected outcomes of that watering. This monitoring plan does not contain the detailed design features of exact methods for sampling and analysis. It is expected that service providers would develop Standard Operating Procedure (SOPs) within the framework of this Plan, that explicitly address the KEQs (see section 7).

4.1 Monitoring locations

Delivery of water for the environment in the River Murray varies each year. Releases can be made from both the Hume Dam and Lake Victoria and where possible is coordinated with tributary flows, which may consist of water for environment or operational releases, or both. Coordinated flows aimed at achieving objectives in the River Murray Channel (typically in spring; but with priming flows also in late winter) may pass through a number of floodplain wetlands with return flows moving downstream. This may include Barmah-Millewa Forest, Gunbower Forest; Koondrook-Perricoota Forest, Hattah Lakes, Lindsay-Mulcra-Wallpolla, Chowilla, Pike and Katarapko floodplains. In addition, significant tributary flows from the Goulburn, Murrumbidgee, Darling/Baaka and Edward/Kolety-Wakool Rivers, Lake Victoria operations and weir pool raising and lowering can also influence outcomes in the River Murray Channel.

Monitoring locations should be selected to capture these important influencing factors and the timing of monitoring matched both to the delivery of environmental water and critical lifecycle timings. An Idealised list of sites in the main channel could comprise (Figure 9):

- Upstream of Barmah-Millewa Forest
- Downstream of Barmah-Millewa Forest, upstream of the Goulburn River confluence
- Downstream of Barmah-Millewa Forest on the Edward/Kolety River
- Downstream of Goulburn River, upstream of Gunbower Forest
- Downstream of Gunbower Forest
- Upstream of the Murrumbidgee River
- Downstream of the Murrumbidgee River
- Upstream of the Darling River/Baaka
- Downstream of the Darling River/Baaka
- Downstream of Lake Victoria, upstream of Chowilla
- Downstream of Chowilla upstream of Overland Corner
- Downstream of Overland Corner upstream of Mannum
- Downstream of Mannum to upstream of Wellington

The actual number of monitoring locations for each selected indicator may be tailored to the expected outcomes of planned watering in a given year and available resources. For example, in years where there is floodplain watering, sites upstream and downstream of return waters may be required to capture the effect on productivity and / or large-bodied native fish. Implementation will need to balance the power of fixed sites over time against the need for flexibility in response to planned environmental water and natural flows.

4.2 Sample design

A Multiple Before—During—After Intervention approach has been adopted as the sample design for the monitoring plan. In the absence of a reference river (identical to the River Murray Channel in all ways except for the delivery of environmental water), it will be difficult to separate the effects of flow on productivity and fish indicators from non-flow factors operating at the same time (e.g., exotic species, water quality changes, climatic conditions)..It may be possible to understand the influence of these confounding factors using complementary data collected by other monitoring programs in tributary systems that are not receiving water for the environment. Evidence to explain flow responses will be strengthened by inclusion of multiple monitoring locations along the river, and the cumulative evaluation of responses to multiple flow interventions over the duration of the monitoring program.

Monitoring is to commence prior to the flow intervention and should capture both during and after intervention phases. The spatial and temporal complexities of monitoring along the system are illustrated in Figure 9. Monitoring commences before the intervention (T1), during storage release (T2), after incorporating floodplain return water (T3), and tributary inflows (T4). As the flow pulse moves downstream some sites move into the “during” intervention phase, while upstream sites move into the “after” phase. In any given year the sample design may be complicated by multiple interventions along the river (e.g., floodplain return water from Hattah, and inflows from the Darling/Baaka River) resulting in a complex pattern of before, during and after interventions. This needs to be carefully scheduled in conjunction with water delivery on an annual basis and respond to conditions as the flow event is managed. Over the course of the monitoring plan’s implementation, it is likely that there will be some years where flows are mostly regulated (in-channel) during spring, while there may also be opportunities to enhance or extend unregulated flows for outcomes in the channel during moderate to wet years. Therefore, implementation of the monitoring plan needs to be adaptable in order to enable detection of responses (and lack of response) from environmental water delivery over a range of conditions.

It is expected that along with detailed design, service providers will justify the monitoring design with statistical analysis of existing data. In particular, it is important that the magnitude of response that could be detected through implementing the proposed sample design is explicitly stated using a power analysis or similar statistical tool. If there is likely to be insufficient statistical power to detect the expected level of response of an indicator to the flows that are planned, alternatives to the monitoring design will need to be proposed.

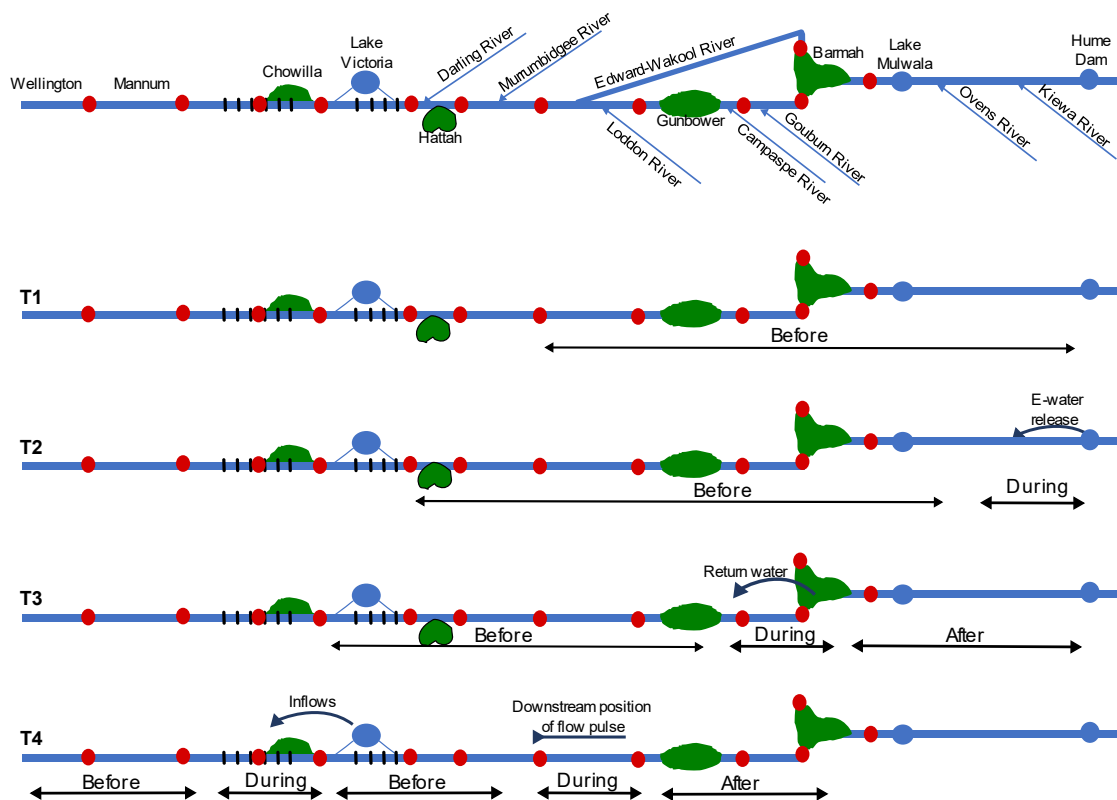


Figure 9: Schematic of the monitoring design, red dots are indicative of potential sampling locations, between potential intervention sites. T1 to T4 represent four successive time periods from before release (T1), during (T2) and after as the pulse moves downstream and incorporates return flows (T3) and tributary inflows (T4). The timing and location of before, during and after intervention sites will vary annually depending on planned and natural inundation events.

4.3 Monitoring requirements

Following the principle of leveraging off existing programs, a review of existing monitoring that could address the KEQs has been completed (see Appendix B). There are a number of ongoing and current programs that collect data that is fit for purpose to address, or partially address, the identified KEQs. Information gaps with respect to indicators, locations, frequency, timing and frequency have been identified and are provided in Appendix B. A preferred monitoring design that accounts for current resource limitations is provided in section 4.4.

A summary of current monitoring locations and indicators identifies gaps and alignment to requirements to answer KEQs (Table 2). The partially met (orange) indicators represent instances where existing, active monitoring collects some but not all the data that may be required to adequately answer KEQs:

- Stream metabolism – continuous dissolved oxygen and temperature loggers in place, but light loggers need to be added.
- Phytoplankton – currently cyanobacteria are identified and counted, but not other groups.
- Zooplankton – Flow-MER covers species and abundance, but not a measure of basal food quality such as polyunsaturated fatty acids.
- Larval fish – ARI (Arthur Rylah Institute) and TLM sampling for larval fish (mid-Murray sites) is often an annual survey in spring. For example, riverine larval drift for TLM Barmah-Millewa icon site (Raymond et al. 2019); a higher sampling frequency may be required to answer evaluation questions related to before and during. Flow-MER larval fish monitoring in the Lower Murray is seasonal for Murray cod, but is implemented by discretion for golden and silver perch when a positive response is considered a realistic targeted outcome of a forecast flow (e.g., if flows exceed 20,000 ML/day at the South Australian border).

Table 2: Summary of existing monitoring in the main channel: green indicates data requirements to answer KEQ are likely to be fully met by existing programs; orange is partially met but would require either additional metrics or sampling frequency; red is no existing monitoring available.

Location	Hydrology	DOC, nutrients, Chl-a	Stream metabolism	Phytoplankton	Zooplankton	Biofilms	Higher trophic levels	Fish - populations	Fish - larvae
Upstream of Barmah Forest	Green	Green	Orange	Green	Red	Red	Red	Green	Orange
Downstream of Barmah Forest, upstream of the Goulburn River confluence	Green	Red	Red	Orange	Red	Red	Red	Green	Orange
Downstream of Millewa Forest on the Edward/Kooley River	Green	Orange	Orange	Red	Red	Red	Red	Orange	Red
Downstream of Goulburn River, upstream of Gunbower	Green	Green	Orange	Green	Red	Red	Red	Green	Orange
Downstream of Gunbower	Green	Green	Orange	Green	Red	Red	Red	Red	Red
Upstream of the Murrumbidgee	Green	Green	Red	Green	Red	Red	Red	Red	Red
Downstream of the Murrumbidgee	Green	Red	Red	Green	Red	Red	Red	Green	Red
Upstream of the Darling River/Baaka	Green	Green	Red	Green	Red	Red	Red	Green	Red
Downstream of the Darling River/Baaka	Green	Green	Red	Green	Red	Red	Red	Red	Red
Downstream of Lake Victoria, upstream of Chowilla	Green	Green	Red	Orange	Orange	Red	Red	Green	Orange
Downstream of Chowilla	Green	Green	Green	Orange	Orange	Red	Red	Green	Orange
Overland Corner to Mannum	Green	Green	Green	Green	Orange	Red	Red	Green	Orange
Mannum to Wellington	Green	Green	Red	Green	Red	Red	Red	Green	Red

4.4 Preferred package of monitoring

Considering the principle of leveraging off the existing monitoring network and the types of watering actions and expected outcomes from those watering actions, a preferred approach to monitoring in the River Murray Channel has been identified. Annual procurement will be dependent of available funds and so the exact nature of the monitoring in any given year may differ. In addition, in some years (e.g., if a major inundation event occurs) contingency funds may become available to opportunistically include additional monitoring.

4.4.1 Productivity

The KEQs specific to productivity are:

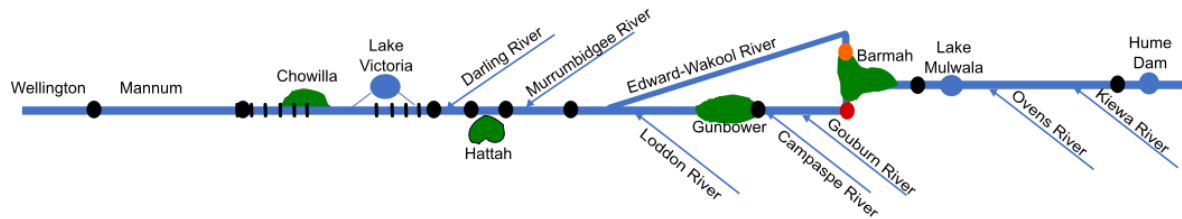
- Immediate:
 - How did productivity (quality and quantity) in the River Murray Channel vary spatially (along the length of the River) and temporally (over what period of time was productivity enhanced)? What were the hydrological conditions associated with this response?
- Intermediate:
 - How does hydrology (magnitude, timing, water source) influence the quality, quantity and persistence of productivity in the River Murray Channel?
 - How did environmental water management over the past five years influence productivity along the length of the River Murray Channel?
- Long-term
 - How does environmental water contribute to the quality and quantity of food resources and their transfer through food webs in the River Murray Channel to support native fish recruitment?
 - What is an ecologically meaningful magnitude of response in productivity and what flows (magnitude, timing, duration) are needed to achieve them?

The existing monitoring network includes weekly monitoring of several productivity indicators as part of the MDBA Water Quality Monitoring Program. This includes dissolved organic carbon, nutrients, chlorophyll-a and phytoplankton abundance and species. These measures provide information to address KEQs at the base of the food web and, through the phytoplankton indicator, allow for some measure of the quality of the food resource. Stream metabolism is collected in the Lower Murray and Edward/Kooley-Wakool under the Flow-MER program. The preferred approach for River Murray Channel monitoring is to:

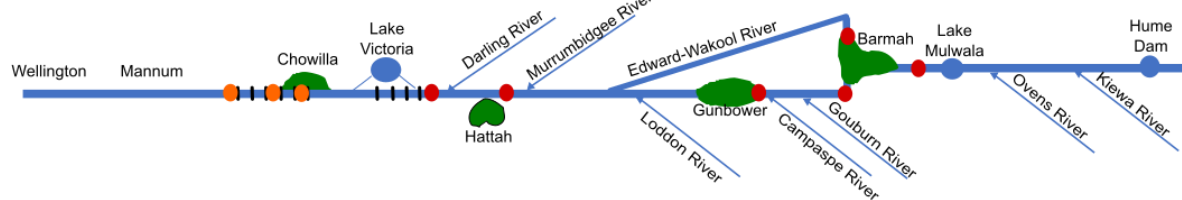
1. Add zooplankton abundance/biomass and a measure of food quality (e.g., poly-unsaturated fatty acid content) to the existing monitoring. This would require new sample collection at up to six sites in the River Murray Channel above the South Australian border, and the addition of nutritional value to the zooplankton sampling collected under Flow-MER in the Lower Murray Selected Area (Figure 10).
2. The reach between the Barmah-Millewa Forest and the Goulburn River is also a monitoring gap and ideally (if it could be included inexpensively), the base trophic levels (dissolved organic carbon, nutrients, chlorophyll-a and phytoplankton groups) would be collected at this site as well during zooplankton sampling.
3. There is a desire, if possible, to include measures of stream metabolism in the NSW Murray. At a minimum, this could include adding light loggers to locations that have existing continuous dissolved oxygen and temperature logging (Edward River at Deniliquin, Murray River at Barham, below Wakool Junction, at Boundary Bend and at Colignan⁴). As a secondary priority (to be implemented only if sufficient resources are available), new stream metabolism sites could be established at other NSW Murray locations.

⁴ In addition to CEWO MER sites in South Australia for stream metabolism, there are several dissolved oxygen logging water quality points in South Australia, however these do not have temperature. There was also a dissolved oxygen logging station downstream of Yarrawonga, that may be reinstated. Sites would have to be chosen to best match the needs of the monitoring plan, and the existing logging sites may not all be relevant but should be included for consideration.

Productivity: dissolved organic carbon, nutrients, chlorophyll-a, phytoplankton species abundance; weekly, MDBA



Zooplankton: abundance, nutritional value, before, during and after the event; existing monitoring Flow-MER, lower Murray; fortnightly spring and summer, abundance but not nutritional value.



Stream metabolism: continuous light, temperature and dissolved oxygen loggers.

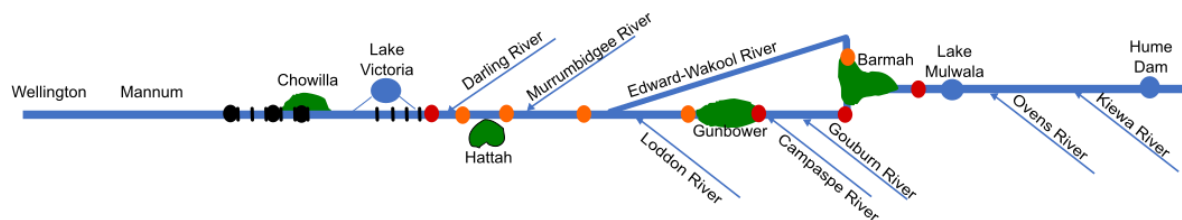


Figure 10: Preferred monitoring to address productivity KEQs in the River Murray Channel. Black circles are existing sites, orange require additional tests to existing sampling, red indicates new data to be collected under this program. Note the exact location and number of new sites to be determined by service providers.

4.4.2 Large-bodied native fish

The KEQs relevant to large-bodied native fish are:

- Immediate:
 - Are golden perch and silver perch larvae present in each reach? What time of year? What volume / density / biomass?
 - What was the breeding response to environmental water delivery or natural flow (eggs, larvae, YoY) of golden perch and silver perch and how did this vary spatially and temporally through the event?
 - What was the survival (to YoY) of golden perch and silver perch larvae?
 - What was the relative abundance of age classes of Murray cod?
 - What was the condition of Murray cod (length-weight ratios)?
- Intermediate:
 - How does hydrology (magnitude, timing, water source) and e-water management influence recruitment (to YoY) of golden perch and silver perch in the River Murray Channel?
 - How does weir pool raising and lowering impact golden and silver perch larvae survival and recruitment?
 - How does hydrology (variability, magnitude, timing) affect Murray cod recruitment and condition?
 - Is there a correlation between productivity and recruitment (to YoY) of golden perch and silver perch in the River Murray Channel?
 - Is there a correlation between productivity and Murray cod recruitment and condition?
- Long-term:
 - Will relaxed flow constraints scenarios enhance native fish breeding and recruitment outcomes in the River Murray Channel compared with the existing flow constraints?

- How does environmental water contribute to the quality and quantity of food resources and their transfer through food webs in the River Murray Channel to support native fish recruitment?
- What are the flow related limiting factors to recruitment of golden perch and silver perch in the River Murray Channel and southern basin?
- How could environmental water management be improved to enhance golden perch and silver perch populations in the River Murray Channel?
- How could environmental water management be improved to enhance Murray cod populations in the River Murray Channel?
- What is an ecologically meaningful magnitude of response in fish recruitment?

While the immediate and most of the intermediate KEQs are specific to large-bodied native fish, there are several intermediate (and long-term) questions that link fish and productivity outcomes. For that reason, the preferred approach for monitoring of native fish builds on the existing network with respect to both fish and productivity (Figure 11). Fish population data is collected as annual census under TLM, MDBA Native Fish Strategy and Flow-MER program, which can be used to assess recruitment over time. Larval fish are monitored in the Lower Murray via the Flow-MER program, every year for Murray cod and for golden and silver perch when flow conditions are suitable for spawning. The preferred approach for River Murray Channel monitoring is to:

1. Collect new data for fish spawning at up to six sites in the River Murray above the South Australian border.
2. In addition, if significant spawning is detected, contingency fish population monitoring to detect YoY in the following autumn could be considered if resources allow.

Productivity: dissolved organic carbon, nutrients, chlorophyll-a, phytoplankton species abundance; weekly, MDBA

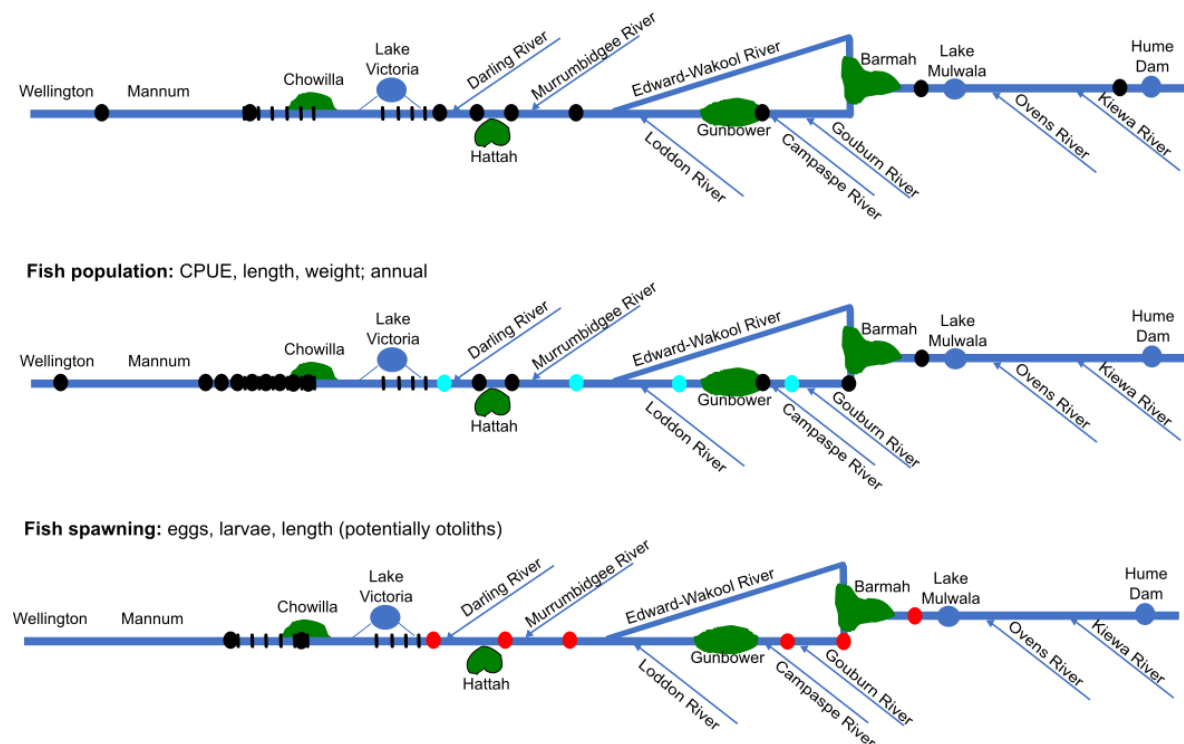


Figure 11: Preferred monitoring to address native fish KEQs in the River Murray Channel. Black circles are existing sites, red indicates new data to be collected under this program; blue circles represent potential additional autumn fish population sampling in the event spawning is triggered. Productivity sites are included to emphasise the links between the two themes and the desire, where possible to measure the themes at the same or similar locations.

5 Evaluation, review and reporting

There are three types of evaluation that will inform adaptive management under the River Murray Channel Five-Year Monitoring Plan:

1. Assessment of the outcomes associated with hydrology, productivity and fish will be conducted by service providers annually (and cumulatively in each subsequent year) and be focused on answering the KEQs and providing information to improve the management of environmental water in the River Murray Channel. This should occur based on the following logic:
 - a. Identifying relevant KEQs and articulating why they are important for informing adaptive management of environmental water use at a River Murray system-scale (Section 3.1 and 3.2). Specific expected outcomes of environmental water will be determined annually. The service provider will be required to identify hypotheses around magnitude of expected response to test, including quantification of what magnitude of response would be considered negligible, minor, moderate or significant.
 - b. Identifying indicators to answer those KEQs. These are set out in Section 3.3, with some tailoring required via the annual monitoring design.
 - c. Analysing data collected under this monitoring plan and other programs in a robust and scientifically rigorous manner to answer KEQs.
 - d. Comparison of monitoring outcomes with expected magnitude of responses and known ecological thresholds to determine if ecologically meaningful levels of responses are being achieved (see Text box 5).
 - e. Providing advice for management response considering the detected compared with expected response, including to confirm or refine hypotheses.
2. Monitoring program evaluation will be conducted by service providers and water managers annually (with consideration to having a review by an independent party in year five), to review the efficacy of the monitoring to address KEQs, test hypotheses, quantify the magnitude of ecological response to flow, and inform water management.
3. Environmental water management review will be conducted by the Steering Committee at year five to ensure that adaptive management messages are translated into management and policy.

How much of a response is enough?

Past monitoring and investigations have provided an indication of the magnitude of change in productivity and large-bodied native fish indicators that can occur from a variety of different flow scenarios. There are very large responses that occur from widescale natural floodplain inundation both on the floodplain and in the river channel (Nielsen et al. 2016; Wallace and Furst 2016). The response of productivity and fish indicators to more modest, in-channel flows is considerably smaller (Rees et al. 2020; Tonkin et al. 2020). What we do not yet fully understand, is how much of a boost in productivity is required to make an ecologically meaningful impact on the river system and result in benefits to higher trophic biota such as native fish.

The energy transfer within multi-trophic food webs is quantified by the trophic transfer efficiency, which is the proportion of resource production converted into consumer production. It has traditionally been assumed that trophic transfer efficiency between adjacent trophic levels is roughly 10% (Lindeman 1942). So that a 20 % increase in phytoplankton, would translate to a 2% increase in zooplankton grazers and a 0.2 % increase in larval fish production. While some investigations have found trophic transfer efficiencies of lower than 10%, there is evidence that consumption of high-quality food resources (e.g., high poly-unsaturated fatty acid) increases trophic transfer efficiency (Robson et al. 2013).

We also do not know what scale of fish response to flow (e.g. fish spawning or recruitment to YoY is meaningful. One of the KEQs to be addressed through this Plan is “What is an ecologically meaningful magnitude of response in productivity and fish recruitment?”. Answering this question will provide water managers with the information required to make evidence-based decisions to improve outcomes from environmental water.

5.1 Evaluation of outcomes

The major focus of the annual evaluation is to answer KEQs and provide information to water managers for improved water management in the River Murray Channel. There are also the secondary requirements of reporting on the outcomes of environmental water for stakeholders, including the general community, informing other relevant monitoring, research and modelling programs and informing programs such as those related to constraints relaxation. The evaluation is framed around inputs, analysis and outputs as follows:

- Inputs
 - KEQ's, annual expected outcomes of environmental water and finer scale hypotheses / management questions
 - foundational information with respect to hydrology, water quality and water source (addressing foundational KEQs)
 - data on productivity and large-bodied native fish from the existing monitoring network (addressing immediate KEQs)
 - data on productivity and large-bodied native fish collected under this program (addressing immediate KEQs)
 - complementary data on response modifiers (non-flow factors that may influence the response).
- Analysis
 - patterns in response among sites
 - correlations between hydrology (including floodplain inundation), productivity and fish responses
 - results with respect to expected outcomes and finer scale hypotheses / management questions,
 - proportion of variability in ecological responses that could be explained by hydrology and other response modifiers
 - evidence for thresholds or magnitude of hydrological events (flow, floodplain inundation) to elicit significant responses.
- Outputs
 - assessment against KEQs at a site, reach and system-scale, including quantification of magnitude of response (negligible, minor, moderate or significant)
 - outcomes of water management (were expected outcomes achieved)
 - distillation of adaptive management messages (specific to water management in the River Murray Channel)
 - refinements to hypotheses for future watering if appropriate.

There will be annual collaboration between the Monitoring Plan Steering Committee and service providers to design the evaluation. While the KEQs are established and need to be addressed, expected outcomes of environmental water and finer scale hypotheses / management questions will vary according to natural conditions and planned water delivery each year. Examples of the sorts of questions / expected outcomes that could be developed annually are provided in Table 4 and Table 5.

5.1.1 Foundational information

Several evaluation questions have been identified at the foundational level. These are largely related to hydrology (the management lever and primary influencing factor of interest), but also include several other indicators that are important co-variables for the biotic indicators of productivity and native fish (e.g., temperature, salinity). These evaluation questions can be answered using data from existing programs (Table 3).

Table 3: Existing monitoring against foundational information requirements.

Evaluation question	Existing sites	Frequency of measurement	Parameters	Custodian
What was the flow at key gauging stations along the entire length of the channel throughout the year?	40 active gauging stations (see Figure 14); larger number measuring water level	Continuous	Discharge	Water NSW, MDBA, SA DEW
What were the weir pool operations throughout the year?	Weir pools 1 -5	Daily	Modelled - velocity, water level	CEWO

What were the velocities in each reach during the watering action?	3 - Loxton, Wilpunda, Morgan	Continuous	Velocity	SA DEW
What were the sources of water during the watering action?	Operational detail from SCBEWC members			
What was the area and duration of floodplain inundation? ⁵	GeoScience Australia Wetlands Insight Tool – for each ANAE polygon	Various (Landsat record)	Open water, wet vegetation, green vegetation, dry soil	MDBA / GeoScience Australia
What were the relevant water quality responses (temperature, salinity) during the watering action?	>60 stations along the entire channel from Hume to the Mouth	Continuous ⁶	Temperature, electrical conductivity	Water NSW, MDBA, SA DEW

The exception to this is velocity. There are currently just three active stations directly measuring velocity in the River Murray Channel (all in South Australia); noting that velocity could be modelled at other sites. In addition, the Lower Murray Selected Area as part of the former LTIM now Flow-MER models hydraulic regimes (discharge, velocity, water level and area inundated for weir pools 1 to 5).

The majority of the metrics required to address foundation information are collected (or modelled) at continuous or daily time steps, indicating that frequency of measures is adequate. The distribution of sites includes upstream and downstream of major tributaries and floodplain ecosystems as well as all the weir pools in the Lower Murray, indicating that spatial coverage is also likely adequate.

5.1.2 Productivity

The productivity KEQs concern both the quantity and quality of food resources in the River Murray Channel. Annual evaluation is expected to report on the outcomes of water management in the given year as well as link hydrological and other response modifiers to productivity outcomes, distilling the information into lessons learned to inform water management in subsequent years (Table 4).

Only a portion of the data required to be analysed for evaluation of productivity KEQs will be collected under this program, much of the data will come from the existing monitoring network:

- Foundation information with respect to hydrology, hydraulics and water quality (see Table 3)
- Dissolved organic carbon, nutrients, phytoplankton (MDBA water quality monitoring program)
- Stream metabolism in the lower Murray and Edward/Kooley River (Flow-MER)
- Hydrology, productivity, water quality metrics from tributary inflows (Flow-MER, MDBA water quality monitoring Program, Water NSW and SA DEW water quality monitoring networks).

Service providers will be expected to source this data and include it in the analysis and evaluation of productivity outcomes at site and whole of system scales. SCBEWC members will aid service providers in sourcing this data.

5.1.3 Large-bodied native fish

The fish KEQs concern spawning and recruitment in the River Murray Channel. Annual evaluation is expected to report on the outcomes of water management in the given year as well as link hydrological and other response modifiers to fish outcomes, distilling the information into lessons learned to inform water management in subsequent years (Table 5).

⁵ There are also several modelled / measured site-specific tools, such as inundation mapping at Gunbower Forest and Barmah Forest using field measurements and MDBA BIG-MOD modelling).

⁶ There are a number of additional locations that measure periodically (rather than continuous) and several of the telemetered stations also have regular spot / lab samples for other water quality parameters.

Table 4: Annual evaluation of productivity outcomes (using data collected under this Plan and from other programs).

KEQ	Indicators	Data	Response modifiers	Example hypothesis / management questions
How did productivity (quality and quantity) in the River Murray Channel vary spatially (along the length of the River) and temporally (over what period of time was productivity enhanced). What were the hydrological conditions associated with this response?	DOC, nutrients, chlorophyll-a, Stream metabolism Phytoplankton Zooplankton abundance and nutritional value	Concentration and loads of carbon, nitrogen and phosphorus Rate of gross primary productivity (GPP) and ecosystem respiration (ER) Abundance of different types of phytoplankton (diatoms, green, cyanobacteria, dinoflagellates); concentrations and loads of chlorophyll-a Abundance and nutritional value of zooplankton	Foundational information (see Table 3), temperature, turbidity, time since last floodplain inundation, prior water regime, inflows from tributaries (including water quality, phytoplankton)	How did productivity response for this year vary compared to previous responses to different flow magnitudes? Does managed and natural flow events of similar magnitude produce similar productivity response? Did repeated annual partial floodplain inundation elicit a productivity response in the downstream river channel? Over what time frame? Over what distance? Do productivity responses improve with inundation of floodplain areas that have been dry for two or three years, rather than inundated annually? Do flows need to be timed with increased temperature to result in improved productivity outcomes? What types of weir pool manipulation elicited productivity responses? How has the source, timing and magnitude of flows impacted resulted in: <ul style="list-style-type: none"> • mobilisation of carbon • increases in GPP and ER • increases in higher value food resources (i.e., diatoms, higher trophic levels)?

Table 5: Annual evaluation of large-bodied native fish outcomes (using data collected under this Plan and from other programs).

KEQ	Indicators	Data	Response modifiers	Example hypothesis / management questions
Are golden perch and silver perch larvae present in each reach? What time of year? What volume / density /biomass?	Perch larvae	Abundance (CPUE) and species of larvae; biomass	Foundational information (see Table 3), temperature, turbidity, time since last floodplain inundation, prior water regime, water quality (including blackwater events), thermal pollution, inflows from tributaries (including measures of spawning in tributaries from programs such as Flow-MER); evidence of spawning from TLM monitoring at Barmah-Millewa, Gunbower, Hattah and / or Chowilla; predators; exotic species.	Was the coordinated flow pulse associated with perch spawning in various reaches?
What was the breeding response (eggs, larvae, YoY) of golden perch and silver perch and how did this vary spatially and temporally through the event?	Perch larvae, eggs, YoY	Abundance (CPUE) and species of eggs and larvae; age and size of larvae and YoY; natal origin		Are the Goulburn spawned perch recruiting in the Murray?
What was the survival (to YoY) of golden perch and silver perch larvae?	Golden and silver perch population	Abundance (CPUE), age, weight, length, presence of YoY, natal origin of YoY		How can water management be improved to trigger spawning of perch (e.g., longer pulses, pulses delivered later in the season)?
				Should the Hume Dam release be coordinated with Lake Victoria releases to increase peak flow to SA?
What was the relative abundance of age classes of Murray cod?	Murray cod population	Abundance (CPUE), age, presence of YoY		Is the currently hypothesised flow rate required at the SA border for perch spawning accurate? If yes, is the pulse also adequate to translate spawning to recruitment to YoY? If no, how should the hypothesis be adjusted (timing, magnitude, duration)?
What was the condition of Murray cod (length-weight ratios)?	Murray cod condition	Weight, length ratios		What effect does Lake Victoria and weir pools have on perch drift? How have historic Lake Victoria operations influenced perch recruitment? If there is an impact, can Lake Victoria operations be adjusted during a spring pulse?
				Should flows be delivered to stabilise water levels for Murray cod breeding? At what locations? Over what time period?
				Would trialling a larger flow downstream of Yarrawonga than currently possible lead to increased cod or perch breeding success?
				Is the lack of suitable floodplain nursery habitat a limiting factor in the limited success of GP recruitment for the Murray?

5.1.4 Integrated evaluation

In the final year of the monitoring plan, intermediate KEQs will need to be answered in an integrated evaluation that spans the five years of data collection. This will require analysis of data collected via implementation of the monitoring plan and complementary monitoring over five years and across all locations. Examples of the analyses and outputs for the five-year integrated evaluation are provided in Table 6.

Table 6: Integrated evaluation of productivity and large bodied native fish outcomes

Evaluation question	Example Analyses	Outputs
Hydrology		
How does environmental water management influence the hydrological conditions along the length of the River Murray Channel?	Characterisation of watering actions along the River Murray Channel over the five year period including timing, magnitude, sequencing of events, water source, extent and frequency of floodplain inundation and volume of return waters	Tabulation of system scale environmental water management in the River Murray Channel.
Productivity		
How does hydrology (magnitude, timing, water source) influence the quality, quantity and persistence of productivity in the River Murray Channel?	Correlations between hydrological metrics (e.g., flow magnitude, extent of floodplain inundation, volume and timing of return waters) and productivity indicators of quantity such as loads of carbon, chlorophyll-a, zooplankton biomass and quality such as proportion of diatoms, nutritional value of zooplankton.	Site, reach and whole of system scale quantification of productivity responses. What proportion of the variability in productivity indicators that could be explained by hydrological variables?
How did environmental water management over the past five years influence productivity along the length of the River Murray Channel?	Counterfactual assessment of hydrology without environmental water.	What were the productivity responses with and without environmental water management? How could water have been managed differently for improved productivity outcomes with respect to the quantity and quality of food resources?
Large-bodied native fish		
How does hydrology (magnitude, timing, water source) and management of water for the environment influence recruitment (to YoY) of golden perch and silver perch in the River Murray Channel?	Correlations between hydrological metrics (e.g., flow magnitude, timing, sequencing, water source) and indicators of perch spawning and recruitment across the five years.	What conditions led to spawning? What evidence is there of recruitment to YoY in golden perch and silver perch? Where in the River Murray Channel? What was the origin of YoY perch sampled in the Murray River Channel? What changes to the flow regime would result in improved outcomes for golden and silver perch?
How does weir pool raising and lowering impact golden and silver perch larvae survival and recruitment?	Correlations between weir pool levels, timing, rate of rise and fall and indicators of perch spawning and recruitment.	
How does hydrology (variability, magnitude, timing) affect Murray cod recruitment and condition?	Correlations between hydrological metrics (e.g., flow magnitude, timing, sequencing, water source) and indicators of Murray cod recruitment and condition.	What conditions led to improved recruitment and condition outcomes for Murray cod? What changes to the flow regime would result in improved outcomes for Murray cod?
Integrated		
Is there a correlation between productivity and recruitment (to YoY) of golden perch and silver perch in the River Murray Channel? Is there a correlation between productivity and Murray cod recruitment and condition?	Correlations between productivity and large-bodied native fish metrics.	Are there significant linkages between productivity and large-bodied native fish condition and recruitment in the River Murray Channel? What changes to the flow regime would result in improved productivity outcomes through the food web to large-bodied native fish?

5.2 Monitoring program review

The purpose of program review is to confirm that the monitoring program is on track to meet its objectives. Annual review will:

- Determine if any of the complementary monitoring that the monitoring plan is leveraging off is about to change or discontinue. Loss of key monitoring in the River Murray Channel will require a review of the monitoring program design and potentially an increase or shift in sample locations to cover the system and the required indicators to address KEQs.
- Revise conceptual models with new understanding of flow-ecology relationships in the River Murray Channel and elsewhere based on monitoring and research outcomes.
- Review and potentially refine KEQs to better reflect management needs.
- Review and refine monitoring methods including an assessment of gaps and redundancies with indicators and site locations.
- Review the efficacy of the monitoring to address KEQs, test hypotheses, quantify the magnitude of ecological response to flow, and inform water management.
- Consider opportunities for incorporating First Nations priorities and environmental water guidance into the monitoring plan, including opportunities to actively involve First Nations people in implementation of the monitoring plan.

At the end of the five years of monitoring an independent review of the monitoring plan should review the science underpinning the program as well as objectives and governance arrangements. At the end of the program there may be sufficient data to conduct statistical analyses of monitoring design to look at the power of inference and the ability to detect responses from background variability. This can lead to a more robust program, that will provide greater confidence in adaptive management messages.

5.3 Environmental water management review

At the end of the five-year program, SCBEWC will consider conducting a water management review that ideally includes other policies and programs that are outside this River Murray Channel Monitoring Plan. This could include Flow-MER, TLM monitoring and broader government water policy and programs. The review could be aimed at ensuring that adaptive management messages from the monitoring plan and others are translated into improved water management. The review could:

- Consolidate evidence collected in this program and others to adaptively improve water management in the Basin.
- Improve integration knowledge and data between implementation of this monitoring plan and others.
- Identify priority knowledge gaps for research and monitoring.
- Identify mechanisms to influence policy to improve water management, including consideration of constraints.

5.4 Reporting and communication

There are several communication and reporting products that will be the outputs of the River Murray Five Year Monitoring Program (Table 7). This includes annual evaluation reports, updates to the monitoring program, high level summaries for the stakeholders and the interested community and a five-year integrated evaluation report.

The primary objective of the monitoring plan is to inform water management in the River Murray Channel. This requires reporting of adaptive management messages in a timely manner to inform planning of environmental water in the subsequent year. Annual reporting of the evaluation of outcomes to SCBEWC is required by April of each year. This will allow the lessons learned from water delivery in one year to inform planning and delivery in the next. It is recommended that the service providers present the outcomes of the evaluation to SCBEWC in a session that also allows time for the review of monitoring requirements in the subsequent year to match planned environmental water and any changes to the complimentary monitoring that underpins much of the evaluation. This should be documented in an updated monitoring plan for each year.

A five-year integrated evaluation report is to be delivered after the full five years of monitoring, with the target audience being water managers and policy makers. In recognition that this may take additional time for analysis and evaluation, this report is due six months after the collection of year five data.

Table 7: Reporting requirements.

Report	Purpose	Audience	Timing	Responsibility
Annual evaluation report	Addressing immediate KEQs and management questions; Informing adaptive management and communication of outcomes of environmental water (should include a technical report and plain English summary)	SCBEWC	Preliminary in April; final in December each year	Service providers
Summary / fact sheet	Communication of monitoring outcomes to broader stakeholders (optional)	Community	April each year	Service providers
Monitoring Plan	Update monitoring methods and design to match planned water delivery. Includes review of existing monitoring network and development of management questions / hypotheses for the monitoring in the year ahead.	Monitoring Steering Committee and service providers	August each year	Monitoring Steering Committee and service providers
Integrated evaluation report	Addressing intermediate KEQs and integrating across the portfolio of conditions and outcomes over the five-year period. Informing future monitoring.	SCBEWC, water policy makers	December 2026	Service providers
Program review report	The effectiveness and efficiency of the monitoring plan and recommendations for future monitoring.	SCBEWC	December 2026	Independent reviewers

6 How to implement this monitoring plan

6.1 Governance

The governance of the River Murray Channel Five Year Monitoring Plan is illustrated in Figure 12. The program will be overseen by SCBEWC, with a Monitoring Plan Steering Committee comprised of a sub-group of SCBEWC responsible for the management of the project and a project managing group from CEWO and MDBA who will be the program administrators.

It is recognised that whilst an independent science reviewer or panel would benefit the program, there are insufficient resources to establish this as a formal ongoing role. If a science panel is convened more broadly within CEWO or MDBA, consideration will be given to incorporating that into the River Murray Channel Monitoring Plan. At a minimum, the Steering Committee will consider options for obtaining independent scientific input at key points of the monitoring plan's implementation as required.

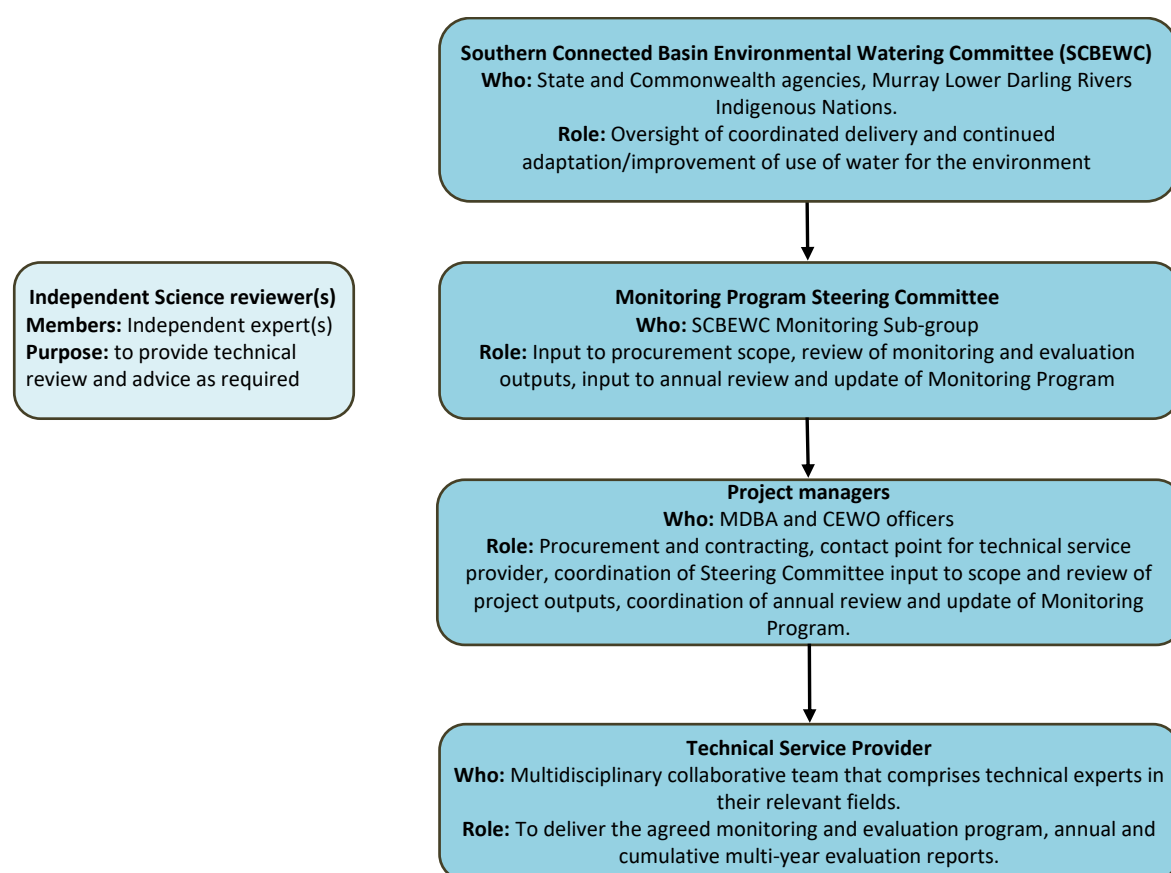


Figure 12: Program governance structure.

6.2 Co-design

The monitoring plan is adopting a co-design approach where the responsibility for various aspects of the monitoring design is shared between the Monitoring Program Steering Committee and service providers. The Monitoring Program Steering Committee is responsible for establishing, reviewing and updating KEQs that underpin the monitoring design. The Steering Committee has also selected the themes of the monitoring plan (productivity and large-bodied native fish) and provided input on the selection of indicators and monitoring design. Service providers will be responsible for the detailed design of monitoring methods to address KEQs (including definition of hypotheses, quantification of expected magnitude of response and fit-for-purpose power analysis or similar statistical assessment based on available data to inform sampling design) and development of Standard Operating Procedures (SOPs) and Health, Safety and Environment Plans (HSEP). The design of the evaluation will be shared between service providers and the Monitoring Plan Steering Committee.

Roles and responsibilities for service providers and the Monitoring Plan Steering Committee are presented in Table 8.

Table 8: Roles and responsibilities.

Monitoring program aspect	Responsibility
Objectives and KEQs for monitoring (including annual review)	Monitoring Plan Steering Committee
Indicators to address KEQs	Monitoring Plan Steering Committee
Management questions / hypotheses (developed annually)	Monitoring Plan Steering Committee with input from service providers
Monitoring locations	Monitoring Plan Steering Committee with input from service providers
Detailed methods (SOPs); including analysis of statistical power.	Service providers
Health Safety and Environment Plans	Service providers
Permits (e.g., EPBC Listed species and ecological communities permits; State jurisdictional permits)	Service providers
Annual evaluation and reporting	Service providers
Annual monitoring program review	Monitoring Plan Steering Committee with input from service providers
Data management infrastructure	Monitoring Project Managers
Data management (QA/QC and upload to system)	Service providers

6.3 Risk assessment

Plan objectives will be successfully achievable through annual and five-yearly evaluation cycles. The following risks to achieving this goal are identified and considered in Table 9 in terms of both probability and consequence.

Table 9: Risk assessment to Program not achieving its objectives.

Event	Risk	Mitigation
Delays in procurement lead to no "before" samples in mid-Murray.	Medium	Quick and efficient decision making, timely delivery of previous years evaluation and monitoring plan review.
Delays mean that reporting is unable to be completed prior to the next water planning cycle	Medium	Preliminary analysis and advice to be provided by April, with full evaluation and reporting by December.
Quotes by technical suppliers exceed available budget and not all the priority monitoring can be afforded.	Medium	Clear communication of budget constraints to technical suppliers. Discussion/negotiation with technical suppliers regarding imperative to leverage existing monitoring and options for reducing costs and implications of those options.
Poor or incompatible monitoring methods i.e., methods proposed by service provider are unable to be compared with complementary programs that were anticipated to be leveraged, either due to poor method design by service provider or due to existing programs having a mix of methods that don't lend themselves to robust comparison.	Medium	Robust selection of service providers with right mix of expertise and experience. Active consideration of this risk by technical service provider and discussion with the Steering Committee on options for mitigating the risk prior to annual monitoring design being finalised.
Poor or inadequate integration across space (lower and mid-Murray) and indicators.	Low	Consortium approach for service providers, ensure that this is explicit in requests for quote and proposals.
Inadequate samples / power to detect response to intervention.	Medium	Requirement for service providers to justify the detailed monitoring design and to include an analysis that illustrates the magnitude of change that can be detected with the proposed design.
Complementary data is not available for evaluation.	Low – High (depending on source)	Collaboration, ensure that high risk data is not central to evaluation.
Complementary monitoring ceases.	Low – High (depending on source)	Annual review of monitoring, may require shifting of some sites to fill gaps.
Collected data is incomplete or not to required standard.	Low	Robust selection of service providers with right mix of expertise and experience. Data management standards and system.
KEQs are not addressed and adaptive management messages inadequate.	Low-Medium	Close collaboration between Steering Committee and Service Providers, annual planning of evaluation based on planned and actual flows.
Data QA and storage/management is inadequate	Low-Medium	See Section 6.4
Insufficient finding to complete the program	Medium	SCBEWC is committed to the program and will endeavour to ensure that the program is funded for the five years.
Pandemic restrictions prevent implementation of monitoring	Medium	Service providers to consider the implications of restrictions to field monitoring in their planning. Potential to use regional partners for sample collection.

6.4 Data management

Implementation of the River Murray Channel Monitoring Plan will result in the collection of monitoring data to support evaluation of the KEQ which will inform and support adaptive environmental water management in the River Murray Channel. Data will be shared by multiple organisations and jurisdictions and used in combination with other complementary data sets from a variety of sources. It is imperative that collected data is of high quality, complete, and compatible with the immediate evaluation needs as well as able to be shared with confidence to others to support value adding in other programs.

All field data sheets (to be developed as part of SOPs) and electronic records should be checked for completeness, consistency and potential errors at the completion of each sampling unit prior to moving to the next sampling unit so that data can be re-collected if anomalies are found. This may involve having a second person check the data (on the field sheets and the electronic records) for unusual entries or missing data. Any confirmed errors should be corrected, and a record kept of the correction by the person undertaking the quality assurance check.

All data records must be traceable back to the source data sheets and provider. This is important for auditing purposes, but also for enabling data to be corrected or replaced if found to be problematic during analysis. Consideration of traceability of data begins with the field data sheets, or electronic capture systems which must include the name of the person collecting the data and the person checking for completeness in addition to standard location, time and date fields.

A key consideration when integrating data from various sources is to use an agreed naming convention for identifying data types, locations and sampling occasions. The identifiers used, such as a monitoring site name, must be unique and unambiguous in their definition, so that all related information can be associated with it and they must be adopted and used consistently across the program. These issues surrounding naming extend to valid values for a specific field of data (e.g., valid species names). In all cases, suitable identifiers that are unique and unambiguous are required.

It is expected that the data management systems established for the Plan will follow the principles and technology of that used LTIM and Flow-MER. It focuses on three main components (Figure 13):

- Data providers will be required to submit and manage their data within a central data repository.
- Data must be checked for quality assurance and quality control before data is stored in a repository.
- The data must be accessible and in standard formats with completed metadata to facilitate data sharing.

The most important consideration is the need for a data literate custodian as part of the technical consortium to oversee data submission and quality checking to ensure standards are upheld and data is built upon to be complete and accessible for evaluation.

Data providers will:

- Adopt standard data definitions and data templates to ensure data consistency. These will be developed at the start of the monitoring program during the co-design phase.
- Transcribe field data into data templates. This can be automated if data is collected electronically.
- Submit (upload) the data.
- Examine QA/QC reports on the submitted files to determine if they are accepted.
- Replace rejected data files with corrected versions.
- Provide basic metadata.

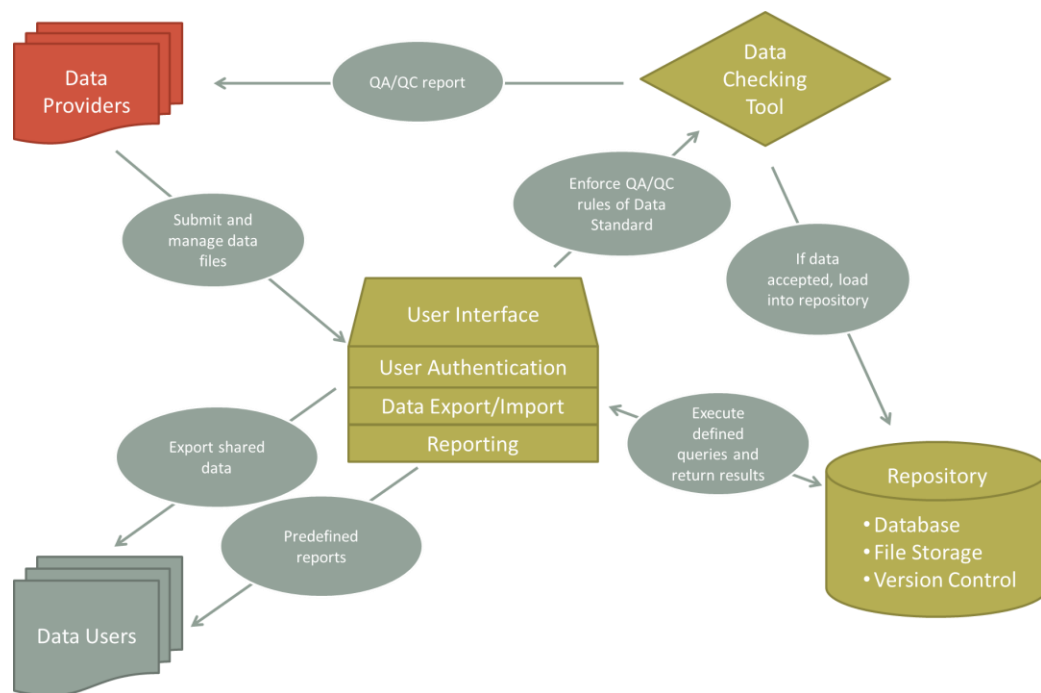


Figure 13. Components of a data management system showing flow of data.

The CEWO data management system is configured with data standards that define attributes such as whether the data is a number or text, the maximum and minimum values, the units, and lookup lists (e.g., species names).

All submitted data are traceable back to the source data file and provider that uploaded it. Submitted data that passes automated QA/QC checking, will be ingested into a database. This database then becomes the single authoritative “master” source for reporting, evaluation and sharing to others. This ensures that any corrections or additions can be tracked and documented and that all users are accessing the same, complete, current and quality checked version of the data. Data can be queried and exported in standard formats (e.g., Comma Separate Value) for analysis and reporting.

7 References

- Aldridge, K., Lorenz, Z., Oliver, R., and Brookes, J. (2012). Changes in water quality and phytoplankton communities in the Lower River Murray in response to a low flow-high flow sequence. Goyder Institute for Water Research Technical Report Series **12**(5).
- Baldwin, D.S., Colloff, M.J., Mitrovic, S.M., Bond, N.R., and Wolfenden, B. (2016). Restoring dissolved organic carbon subsidies from floodplains to lowland river food webs: a role for environmental flows? *Marine and Freshwater Research* **67**(9): 1387–1399. CSIRO.
- Baldwin, D.S. and Mitchell, A.M. (2000). The effects of drying and re-flooding on the sediment and soil nutrient dynamics of lowland river–floodplain systems: a synthesis. *Regulated Rivers: Research & Management* **16**(5): 457–467.
- Baldwin, D.S., Rees, G.N., Wilson, J.S., Colloff, M.J., Whitworth, K.L., Pitman, T.L., and Wallace, T.A. (2013). Provisioning of bioavailable carbon between the wet and dry phases in a semi-arid floodplain. *Oecologia* **172**(2): 539–550. Springer.
- Baumgartner, L.J., Conallin, J., Wooden, I., Campbell, B., Gee, R., Robinson, W.A., and Mallen-Cooper, M. (2013). Using flow guilds of freshwater fish in an adaptive management framework to simplify environmental flow delivery for semi-arid riverine systems. *Fish and Fisheries*: n/a-n/a.
- Bice, C., Zampatti, B., Aldridge, K., Furst, D., Kilsby, N., Nicol, J., Oliver, R., Rogers, D., Turner, R., and Wallace, T. (2014). An assessment of the research requirements to support effective provisions of environmental water in the South Australian Murray–Darling Basin: Part 2 – Development of hydro-ecological conceptual models and identification of knowledge gaps in current understanding of flow–biota relationships. Goyder Institute for Water Research, Adelaide, SA.
- Bloink, C. and Robinson, W. (2016). Gunbower Forest Fish Condition Monitoring. A report to the North Central Catchment Management Authority. Ecology Australia, Fairfield, Victoria.
- Bormans, M. and Webster, I.T. (1999). Modelling the spatial and temporal variability of diatoms in the River Murray. *Journal of Plankton Research* **21**(3).
- Brookes, J., Aldridge, K., Ganf, G., Paton, D.C., Shiel, R., and Wedderburn, S. (2012). Environmental Watering for Food Webs in The Living Murray Icon Sites. Murray-Darling Basin Authority, Canberra, ACT.
- Burns, A. and Ryder, D.S. (2001). Potential for biofilms as biological indicators in Australian riverine systems. *Ecological Management & Restoration* **2**(1): 53–64. Wiley Online Library.
- Burns, A. and Walker, K.F. (2000a). Effects of water level regulation on algal biofilms in the River Murray, South Australia. *Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management* **16**(5): 433–444. Wiley Online Library.
- Burns, A. and Walker, K.F. (2000b). Biofilms as food for decapods (atyidae, Palaemonidae) in the River Murray, South Australia. *Hydrobiologia* **437**(1): 83–90. Springer.
- CEWO. (2017). Blackwater Review: Environmental water used to moderate low dissolved oxygen levels in the southern Murray Darling Basin during 2016/17. Commonwealth of Australia.
- Chee, Y., Webb, J.A., Stewardson, M., and Cottingham, P. (2006). Victorian environmental flows monitoring and assessment program: Monitoring and evaluation of environmental flow releases in the Broken River. eWater Cooperative Research Centre, Canberra.
- Cook, R.A., Gawne, B., Petrie, R., Baldwin, D.S., Rees, G.N., Nielsen, D.L., and Ning, N.S. (2015). River metabolism and carbon dynamics in response to flooding in a lowland river. *Marine and Freshwater Research* **66**(10): 919–927. CSIRO.
- DELWP. (2017). VEFMAP Stage 6 Part A: Program context and rationale. Arthur Rylah Institute for Environmental Research, Heidelberg, Vic.
- Department of Environment, Water and Natural Resources. (2015). Long-Term Environmental Watering Plan for the South Australian River Murray Water Resource Plan Area. Department of Environment, Water and Natural Resources, Adelaide, SA.
- Department of Planning, Industry and Environment. (2020). Murray–Lower Darling Long Term Water Plan. Environment, Energy and Science; Department of Planning, Industry and Environment, Parramatta, NSW.
- Ebner, B.C., Scholz, O., and Gawne, B. (2009). Golden perch *Macquaria ambigua* are flexible spawners in the Darling River, Australia. *New Zealand Journal of Marine and Freshwater Research* **43**(2): 571–578.
- Ecological Associates. (2015). Environmental Water Management Plan for the Murray River at the Lock 15 Weir Pool - System Characterisation. Mallee CMA, Irymple, Victoria.
- Ellis, I., Cheshire, K., Townsend, A., Copeland, C., Danaher, K., and Webb, K. (2016). Fish and Flows in the Murray River Catchment - A review of environmental water requirements for

- native fish in the Murray River Catchment. NSW Department of Primary Industries, Queanbeyan, NSW.
- Fredberg, J., Zampatti, B., and Bice, C. (2020). Chowilla Icon Site Fish Assemblage Condition Monitoring 2019. SARDI, Adelaide, SA.
- Furst, D., Aldridge, K., Bice, C., Zampatti, B., and Ye, Q. (2019). The influence of flow translucency and connectivity on resource availability and lower order food web structure in the Murray River. Commonwealth Environmental Water Office, Canberra, ACT.
- Furst, D., Ye, Q., Bice, C., McInerney, I., Biswas, T., Rees, G.N., and Watts, R. (2020). Zooplankton response to a multi-site environmental watering event during spring 2019 in the River Murray. Commonwealth Environmental Water Office, Canberra, ACT.
- Furst, D.J., Aldridge, K.T., Shiel, R.J., Ganf, G.G., Mills, S., and Brookes, J.D. (2014). Floodplain connectivity facilitates significant export of zooplankton to the main River Murray channel during a flood event. *Inland Waters* **4**(4): 413–424. Taylor & Francis.
- Gawne, B., Merrick, C., Williams, D.G., Rees, G., Oliver, R., Bowen, P.M., Treadwell, S., Beattie, G., Ellis, I., and Frankenberg, J. (2007). Patterns of primary and heterotrophic productivity in an arid lowland river. *River Research and Applications* **23**(10): 1070–1087. Wiley Online Library.
- Gehrig, S. and Nicol, J. (2010). Aquatic and littoral vegetation of the Murray River downstream of Lock 1, the Lower Lakes, Murray Estuary and Coorong. A literature Review. South Australian Research and Development Institute, Adelaide, SA.
- Gibbs, M.S., Bice, C., Brookes, J., Furst, D., Gao, L., Joehnk, K., Marklund, M., Nicol, J., Pethybridge, H., and Szarvas, S. (2020). Ecological connectivity of the River Murray: managing ecological outcomes and water quality risks through integrated river management. Goyder Institute for Water Research Technical Report Series (20/03).
- Grace, M. (2019). 2017–18 Basin scale evaluation of Commonwealth environmental water — Stream Metabolism and Water Quality. Final Report prepared for the Commonwealth Environmental Water Office by La Trobe University. LaTrobe University, Albury, NSW.
- Growns, I., Ryder, D., and Frost, L. (2020a). The basal food sources for Murray cod (*Maccullochella peelii*) in wetland mesocosms. *Journal of Freshwater Ecology* **35**(1): 235–254.
- Growns, I., Ryder, D., McInerney, P., Bond, N., Holt, G., Lester, R., and Thompson, R. (2020b). The use of fatty acids to identify food sources of secondary consumers in wetland mesocosms. *Journal of Freshwater Ecology* **35**(1): 173–189.
- Guo, F., Bunn, S.E., Brett, M.T., and Kainz, M.J. (2017). Polyunsaturated fatty acids in stream food webs—high dissimilarity among producers and consumers. *Freshwater Biology* **62**(8): 1325–1334. Wiley Online Library.
- Hale, J., Bond, N., Brooks, S., Capon, S., Grace, M., Guarino, F., James, C., King, A., McPhan, L., Mynott, J., Stewardson, M., and Thurgate, N. (2020). Murray–Darling Basin Long Term Intervention Monitoring Project — Basin Synthesis Report. Report prepared for the Agriculture, Water and the Environment, Commonwealth Environmental Water Office. Centre for Freshwater Ecosystems, LaTrobe University, Albury, NSW.
- Harris, A., Tonkin, Z., Moloney, P., and Woodhead, J. (2020). Using Otolith Microchemistry to Assign Natal Origin to Juvenile Murray Cod. Arthur Rylah Institute for Environmental Research, Heidelberg, Victoria.
- Hart, B.T., Grace, M.R., Oliver, R.L., and Rees, C. (1995). Nutrient cycling and algal blooms in the Darling River. *In* Researching the Barwon-Darling. Proceedings of the Bourke Conference, NSW. Edited by M.C. Thoms, A. Gordon, and W. Tatnell. CRC for Freshwater Ecology. pp. 63–74.
- Humphries, P. (2005). Spawning time and early life history of Murray cod, *Maccullochella peelii* (Mitchell) in an Australian river. *Environmental Biology of Fishes* **72**(4): 393–407.
- Humphries, P., King, A.J., and Koehn, J.D. (1999). Fish, Flows and Flood Plains: Links between Freshwater Fishes and their Environment in the Murray-Darling River System, Australia. *Environmental Biology of Fishes* **56**(1–2): 129–151.
- James, C.S., Thoms, M.C., and Quinn, G.P. (2008). Zooplankton dynamics from inundation to drying in a complex ephemeral floodplain-wetland. *Aquatic Sciences* **70**(3): 259–271.
- Junk, W.J., Bayley, P.B., and Sparks, R.E. (1989). The flood pulse concept in river-floodplain systems. *In* Proceedings of the International Large River Symposium. Special Publications of Fisheries and Aquatic Sciences. pp. 110–127.
- King, A., Ramsey, D., Baumgartner, L.J., Humphries, P., Jones, M., Koehn, J.D., Lyon, J., Mallen-Cooper, M., Meredith, S., Vilizzi, L., Ye, Q., and Zampatti, B. (2008). Environmental requirements for managing successful fish recruitment in the Murray River valley: review of

- existing knowledge. Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Heidelberg, Vic.
- King, A.J., Tonkin, Z., and Lieshcke, J. (2012a). Short-term effects of a prolonged blackwater event on aquatic fauna in the Murray River, Australia: considerations for future events. *Marine and Freshwater Research* **63**(7): 576–586.
- King, A.J., Tonkin, Z., and Lieshcke, J. (2012b). Short-term effects of a prolonged blackwater event on aquatic fauna in the Murray River, Australia: considerations for future events. *Marine and Freshwater Research* **63**(7): 576–586. CSIRO.
- King, A.J., Tonkin, Z., and Mahoney, J. (2009). Environmental flow enhances native fish spawning and recruitment in the Murray River, Australia. *River Research and Applications* **25**(10): 1205–1218.
- King, A.J., Ward, K.A., O'Connor, P., Green, D., Tonkin, Z., and Mahoney, J. (2010). Adaptive management of an environmental watering event to enhance native fish spawning and recruitment. *Freshwater biology* **55**(1): 17–31.
- Kingsford, R.T. (2000). Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology* **25**(2): 109–127.
- Kobayashi, T. (1997). Associations between environmental variables and zooplankton body masses in a regulated Australian river. *Marine and Freshwater Research* **48**(6): 523–529. CSIRO.
- Koehn, J.D., Balcombe, S.R., and Zampatti, B.P. (2019). Fish and flow management in the Murray–Darling Basin: Directions for research. *Ecological Management & Restoration* **20**(2): 142–150. Wiley Online Library.
- Koehn, J.D., King, A.J., Beesley, L., Copeland, C., Zampatti, B.P., and Mallen-Cooper, M. (2014). Flows for native fish in the Murray–Darling Basin: lessons and considerations for future management. *Ecological Management & Restoration* **15**: 40–50.
- Koehn, J.D., Raymond, S.M., Stuart, I., Todd, C.R., Balcombe, S.R., Zampatti, B.P., Bamford, H., Ingram, B.A., Bice, C.M., Burndred, K., Butler, G., Baumgartner, L., Clunie, P., Ellis, I., Forbes, J.P., Hutchison, M., Koster, W.M., Lintermans, M., Lyon, J.P., Mallen-Cooper, M., McLellan, M., Pearce, L., Ryall, J., Sharpe, C., Stoessel, D.J., Thiem, J.D., Tonkin, Z., Townsend, A., Ye, Q., Koehn, J.D., Raymond, S.M., Stuart, I., Todd, C.R., Balcombe, S.R., Zampatti, B.P., Bamford, H., Ingram, B.A., Bice, C.M., Burndred, K., Butler, G., Baumgartner, L., Clunie, P., Ellis, I., Forbes, J.P., Hutchison, M., Koster, W.M., Lintermans, M., Lyon, J.P., Mallen-Cooper, M., McLellan, M., Pearce, L., Ryall, J., Sharpe, C., Stoessel, D.J., Thiem, J.D., Tonkin, Z., Townsend, A., and Ye, Q. (2020). A compendium of ecological knowledge for restoration of freshwater fishes in Australia's Murray–Darling Basin. *Marine and Freshwater Research* **71**(11): 1391–1463. CSIRO PUBLISHING.
- Kühmayer, T., Guo, F., Ebm, N., Battin, T.J., Brett, M.T., Bunn, S.E., Fry, B., and Kainz, M.J. (2020). Preferential retention of algal carbon in benthic invertebrates: Stable isotope and fatty acid evidence from an outdoor flume experiment. *Freshwater Biology* **65**(7): 1200–1209.
- Maheshwari, B.L., Walker, K.F., and McMahon, T.A. (1995). Effects of regulation on the flow regime of the river Murray, Australia. *Regulated Rivers: Research & Management* **10**(1): 15–38.
- MDBA. (2012). Sustainable Rivers Audit Report 2: The ecological health of rivers in the Murray–Darling Basin at the end of the Millennium Drought (2008–2010), Summary. Murray–Darling Basin Commission, Canberra.
- MDBA. (2013). Constraints Management Strategy 2013 to 2024. Murray–Darling Basin Authority, Canberra, ACT.
- MDBA. (2019). Basin-wide environmental watering strategy. Australian Government, Canberra, ACT.
- Mejia, F.H., Fremier, A.K., Benjamin, J.R., Bellmore, J.R., Grimm, A.Z., Watson, G.A., and Newsom, M. (2019). Stream metabolism increases with drainage area and peaks asynchronously across a stream network. *Aquatic Sciences* **81**(1): 1–17. Springer.
- Moran, N.P., Ganf, G.G., Wallace, T.A., and Brookes, J.D. (2014). Flow variability and longitudinal characteristics of organic carbon in the Lachlan River, Australia. *Marine and Freshwater Research* **65**(1): 50–58. CSIRO.
- Nielsen, D.L., Cook, R.A., Ning, N., Gawne, B., and Petrie, R. (2016). Carbon and nutrient subsidies to a lowland river following floodplain inundation. *Marine and Freshwater Research* **67**(9): 1302–1312. CSIRO.
- Ning, N.S., Gawne, B., Cook, R.A., and Nielsen, D.L. (2013). Zooplankton dynamics in response to the transition from drought to flooding in four Murray–Darling Basin rivers affected by differing levels of flow regulation. *Hydrobiologia* **702**(1): 45–62. Springer.

- Oliver, R.L. and Merrick, C.J. (2006). Partitioning of river metabolism identifies phytoplankton as a major contributor in the regulated Murray River (Australia). *Freshwater Biology* **51**(6): 1131–1148. Blackwell Publishing Ltd Oxford, UK.
- Overton, I.C., Colloff, M., Doody, T.M., Henderson, B., and Cuddy, S. (2009). Ecological outcomes of flow regimes in the Murray-Darling Basin. *Water for a Healthy Country*, [Canberra, A.C.T.].
- Raymond, S., Tonkin, Z., Duncan, M., and Robinson, W. (2019). Barmah-Millewa Fish Condition Monitoring: 2019. Arthur Rylah Institute for Environmental Research, Heidelberg, Victoria.
- Rees, G.N., Biswas, T., McInerney, I., Nielsen, D., Joehnk, K., Pengelly, J., Furst, D., Watts, R., Xiaoying, L., and Ye, Q. (2019). Monitoring productivity outcomes of the 2019 River Murray Channel multi-site water for the environment event – carbon and nutrient loads. CSIRO, Canberra, ACT.
- Rees, G.N., Cook, R.A., Ning, N.S.P., McInerney, P.J., Petrie, R.T., and Nielsen, D.L. (2020). Managed floodplain inundation maintains ecological function in lowland rivers. *Science of The Total Environment* **727**: 138469.
- Reid, M.A. and Ogden, R.W. (2006). Trend, variability or extreme event? The importance of long-term perspectives in river ecology. *River Research and Applications* **22**(2): 167–177. Wiley Online Library.
- Riches, M., Gilligan, D., Danaher, K., and Pursey, J. (2016). Fish Communities and Threatened Species Distributions of NSW. NSW Department of Primary Industries, Sydney, NSW.
- Roach, K.A. (2013). Environmental factors affecting incorporation of terrestrial material into large river food webs. *Freshwater Science* **32**(1): 283–298. The University of Chicago Press.
- Robson, B.J., Lester, R.E., Baldwin, D.S., Bond, N.R., Drouart, R., Rolls, R.J., Ryder, D.S., and Thompson, R.M. (2017). Modelling food-web mediated effects of hydrological variability and environmental flows. *Water research* **124**: 108–128. Elsevier.
- Rohlf, A.-M., Williams, S., Rees, G.N., Lim, R.P., Werry, L., and Mitrovic, S.M. (2018). Experimental dam releases stimulate respiration in an epilithic biofilm community. *Hydrobiologia* **820**(1): 175–187. Springer.
- Rolls, R.J., Baldwin, D.S., Bond, N.R., Lester, R.E., Robson, B.J., Ryder, D.S., Thompson, R.M., and Watson, G.A. (2017). A framework for evaluating food-web responses to hydrological manipulations in riverine systems. *Journal of environmental management* **203**: 136–150. Elsevier.
- Ryder, D.S., Watts, R.J., Nye, E., and Burns, A. (2006). Can flow velocity regulate epixylic biofilm structure in a regulated floodplain river? *Marine and Freshwater Research* **57**(1): 29–36. CSIRO.
- Shams, F., Dyer, F., Thompson, R., Duncan, R.P., Thiem, J.D., Enge, T.G., and Ezaz, T. (2020). Multiple Lines of Evidence Indicate Limited Natural Recruitment of Golden Perch (*Macquaria ambigua*) in the Highly Regulated Lachlan River. *Water* **12**(6): 1636. Multidisciplinary Digital Publishing Institute.
- Shiel, R.J. and Aldridge, K.T. (1949). The response of zooplankton communities in the North Lagoon of the Coorong and Murray Mouth to barrage releases from the Lower Lakes, November 2010–April 2011. Final report prepared for the Department of Environment and Natural ...
- Stuart, I.G. and Sharpe, C.P. (2020). Riverine spawning, long distance larval drift, and floodplain recruitment of a pelagophilic fish: A case study of golden perch (*Macquaria ambigua*) in the arid Darling River, Australia. *Aquatic Conservation: Marine and Freshwater Ecosystems* **30**(4): 675–690.
- Thoms, M., Suter, P., Roberts, J., Koehn, J., Jones, G., Hillman, T., and Close, A. (2000). River Murray-Darling to Wellington and the Lower Darling River. Report for the River Murray Scientific Panel on Environmental Flows. Murray-Darling Basin Commission, Canberra, ACT.
- Thoms, M.C. (2003). Floodplain–river ecosystems: lateral connections and the implications of human interference. *Geomorphology* **56**(3–4): 335–349.
- Tonkin, Z., Jones, C., Clunie, P., Vivian, L., Amtstaetter, F., Jones, M., Koster, W., Mole, B., O'Connor, J., Brooks, J., Caffrey, L., and Lyon, J. (2020). Victorian Environmental Flows Monitoring and Assessment Program. Stage 6 Synthesis Report 2016-2020. Department of Environment, Land, Water and Planning, Heidelberg, Vic.
- Tonkin, Z., Stuart, I., Kitchingman, A., Jones, M., Thiem, J., Zampatti, B., Hackett, G., Koster, W., Koehn, J., Arthur Rylah Institute for Environmental Research, Victoria, and Department of Environment, L., Water and Planning. (2017). The effects of flow on silver perch population dynamics in the Murray River.

- Tonkin, Z., Stuart, I., Kitchingman, A., Thiem, J.D., Zampatti, B., Hackett, G., Koster, W., Koehn, J., Morrongiello, J., and Mallen-Cooper, M. (2019). Hydrology and water temperature influence recruitment dynamics of the threatened silver perch *Bidyanus bidyanus* in a regulated lowland river. *Marine and Freshwater Research* **70**(9): 1333–1344. CSIRO.
- Upadhyay, S. (2017). Responses in Aquatic Ecosystem Metabolism to Managed Inundation of a Regulated Dryland River Floodplain. PhD Thesis, University of Adelaide, Adelaide, SA.
- Wallace, T.A. and Furst, D. (2016). Open water metabolism and dissolved organic carbon in response to environmental watering in a lowland river–floodplain complex. *Marine and Freshwater Research* **67**(9): 1346–1361. CSIRO.
- Watts, R.J., Ryder, D.S., Burns, A., Wilson, A.L., Nye, E.R., Zander, A., and Dehaan, R. (2006). Responses of biofilms to cyclic releases during a low flow period in the Mitta Mitta River, Victoria, Australia. Institute for Land Water and Society Report (24).
- Wright, D.W., Zampatti, B.P., Baumgartner, L.J., Brooks, S., Butler, G.L., Crook, D.A., Fanson, B.G., Koster, W., Lyon, J., Strawbridge, A., Tonkin, Z., Thiem, J.D., Wright, D.W., Zampatti, B.P., Baumgartner, L.J., Brooks, S., Butler, G.L., Crook, D.A., Fanson, B.G., Koster, W., Lyon, J., Strawbridge, A., Tonkin, Z., and Thiem, J.D. (2020). Size, growth and mortality of riverine golden perch (*Macquaria ambigua*) across a latitudinal gradient. *Marine and Freshwater Research* **71**(12): 1651–1661. CSIRO PUBLISHING.
- Ye, Q., Giatas, G., Brookes, J., Furst, D., Gibbs, M., Oliver, R., Shiel, R., Zampatti, B., Aldridge, K., Bucater, L., Busch, B., Hipsey, M., Lorenz, Z., Maas, R., and Woodhead, J. (2020). Commonwealth Environmental Water Office Long-Term Intervention Monitoring Project 2014–2019: Lower Murray River Technical Report. A report prepared for the Commonwealth Environmental Water Office by the South Australian Research and Development Institute, Aquatic Sciences. Commonwealth of Australia, Canberra, ACT.
- Young, R.G. and Huryn, A.D. (1999). Effects of land use on stream metabolism and organic matter turnover. *Ecological Applications* **9**(4): 1359–1376. Wiley Online Library.
- Zampatti, B. and Leigh, S. (2013). Effects of flooding on recruitment and abundance of Golden Perch (*Macquaria ambigua ambigua*) in the lower River Murray. *Ecological Management & Restoration* **14**(2): 135–143. Wiley Online Library.
- Zampatti, B., Wilson, P., Baumgartner, L., Koster, W., Livore, J., McCasker, N., Tonkin, Z., Thiem, J., and Ye, Q. (2015). Reproduction and recruitment of golden perch (*Macquaria ambigua ambigua*) in the southern Murray-Darling basin in 2013-14: an exploration of river-scale response, connectivity and population dynamics. SARDI, Adelaide, SA.

Appendix A: LTWP Objectives and targets and KEQs

Table 10: Cross reference of objectives and targets relevant form Long Term Water Resource Plans for the River Murray Channel (Department of Environment, Water and Natural Resources 2015, Department of Planning, Industry and Environment 2020) to the Program themes of productivity and large-bodied native fish and KEQs.

Ecological objective	Ecological target	Relevant KEQs (from the hierarchy)
Ecosystem processes (South Australia); Priority ecosystem functions (New South Wales)		
<p>NSW: Support instream & floodplain productivity. Support nutrient, carbon & sediment transport along channels, & between channels & floodplains/ wetlands</p> <p>SA: Provide for the mobilisation of carbon and nutrients from the floodplain to the river to reduce the reliance of in-stream foodwebs on autochthonous productivity.</p> <p>Provide diverse hydraulic conditions over the range of velocity classes in the lower third of weir pools so that habitat and processes for dispersal of organic and inorganic material between reaches are maintained.</p> <p>Promote bacterial rather than algal dominance of biofilms and improve food resource quality for consumers.</p>	<p>NSW: Enhance riverine productivity to support increased food availability for aquatic food webs by increasing the supply of autochthonous & allochthonous carbon & nutrients.</p> <p>Maintain nutrient & carbon (DOC) pulses at multiple locations along rivers during freshes, bankfull & overbank events, especially those associated with flows occurring in the River Murray main stem (to SA border)....</p> <p>SA: Open-water productivity shows a temporary shift from near zero or autotrophic dominance (positive Net Daily Metabolism) towards heterotrophy (negative Net Daily Metabolism) when QSA >30,000 ML/day.</p> <p>During inundation periods, record an increase in the abundance and diversity of invertebrate food resources, nutrients and DOC relative to those available during base flow</p> <p>Habitat across the range of velocity classes is present in the lower third of weir pools for at least 60 consecutive days in Sep–Mar, at a maximum interval of 2 years.</p> <p>Annual median biofilm composition is not dominated (>80%) by filamentous algae; Annual median biofilm C:N ratios are <10:1.</p>	<p>How does hydrology (magnitude, timing, water source) influence the quality, quantity and persistence of productivity in the River Murray Channel?</p> <p>How did e-water management over the past five years influence productivity along the length of the River Murray Channel?</p> <p>How did productivity (quality and quantity) in the River Murray Channel vary spatially (along the length of the River) and temporally (over what period of time was productivity enhanced). What were the hydrological conditions associated with this response?</p>
<p>SA: Maintain a diurnally-mixed water column to ensure diverse phytoplankton and avoid negative water quality outcomes.</p> <p>Maintain water quality to support aquatic biota and normal biogeochemical processes.</p> <p>NSW: Provide & protect a diversity of refugia across the landscape.</p>	<p>SA: Thermal stratification does not persist for more than 5 days at any time.</p> <p>Biovolume <4 mm³/L for all Cyanobacteria, where a known toxin producer is dominant; Biovolume <10 mm³/L for all Cyanobacteria, where toxins are not present.</p> <p>Maintain dissolved oxygen above 50% saturation throughout water column at all times.</p> <p>NSW: Very low flows (VFs) & baseflows (BF1) are provided at target magnitudes & durations as specified in PU EWRs.</p> <p>Cease-to-flow (CTF) periods do not exceed maximum durations as specified in PU EWRs.</p>	

Ecological objective	Ecological target	Relevant KEQs (from the hierarchy)
	<p>Adequate water depth is maintained in key refuge pools during dry times.</p> <p>Maintain dissolved oxygen >4 mg/L in surface water & down to 2 m below the surface at key gauges & in key refuge pools for 95% of the time & >2 mg/L for 99% of the time. Monitoring should incorporate overnight data collection between 3am & 6am from November–March each year.</p>	
<p>BWS: The improvements in lateral connectivity that are expected are: a 30 to 60% increase in the frequency of freshes, bank-full and lowland floodplain flows in the Murray...</p> <p>NSW: Provide movement and dispersal opportunities for water dependent biota to complete lifecycles and disperse into new habitats within catchments</p> <p>SA: Maintain habitats and provide for dispersal of organic and inorganic material and organisms between river and wetlands.</p>	<p>NSW: The recommended frequency and duration of flows providing lateral connectivity with anabranches, low-lying wetlands and floodplains are met (see EWRs for large freshes, bankfull and overbank flows.</p> <p>Provide longitudinal connectivity & integrity of flows to end-of-system, including flow pulses (regulated, natural or augmented natural) occurring in the River Murray main stem (including flows originating from the Goulburn & Murrumbidgee & lower Darling rivers) maintained from key source to South Australian (SA) border & including through lower Murray River weir pools.</p> <p>SA: Inundation periods in temporary wetlands have unrestricted lateral connectivity between the river and wetlands in >90% of inundation events.</p>	
Fish (South Australia); Native Fish (New South Wales)		
<p>BSW and NSW: No loss of native fish species</p> <p>SA: Restore the distribution of native fish.</p>	<p>NSW: All known species detected annually</p> <p>SA: Expected species occur in each mesohabitat (channel, anabranch, wetlands) in each weir pool/reach.</p>	
<p>BWS: improved population structure of key species through regular recruitment increased movement of key species expanded distribution of key species and populations in the northern and southern Basin</p> <p>NSW: Increase the distribution & abundance of short to moderate-lived generalist native fish species.</p> <p>Increase the distribution & abundance of short to moderate-lived floodplain specialist native fish species.</p>	<p>NSW: Increased distribution & abundance of short to moderate-lived species compared to 2014 assessment.</p> <p>No more than one year without detection of immature fish (short-lived).</p> <p>No more than two years without detection of immature fish (moderate-lived species).</p> <p>SA:</p> <p>The length-frequency distributions for foraging generalists include size classes showing annual recruitment.</p>	

Ecological objective	Ecological target	Relevant KEQs (from the hierarchy)
<p>SA: Restore and maintain resilient populations of foraging generalists (e.g. Australian smelt, bony herring, Murray rainbowfish, unspotted hardyhead, carp gudgeons, flathead gudgeons).</p>	<p>The length-frequency distributions for wetland/floodplain (native fish) specialists within aquatic zones include size classes showing annual recruitment.</p> <p>Increase range and abundance of wetland/floodplain (native fish) specialists within aquatic zones</p>	
<p>NSW: Improve native fish population structure for moderate to long-lived flow pulse specialist native fish species.</p> <p>SA: Restore resilient populations of golden perch and silver perch (flow-dependent specialists).</p>	<p>NSW: Juvenile & adult fish detected annually.</p> <p>No more than two consecutive years without recruitment in moderate-lived species.</p> <p>No more than four consecutive years without recruitment in long-lived species.</p> <p>SA: Population age structure of golden perch and silver perch includes YOY with sub-adults and adults in 8 years in 10.</p> <p>Population age structure of golden perch and silver perch indicates a large recruitment event 2 years in 5, demonstrated by separate cohorts representing >30% of the population.</p> <p>Abundance (CPUE) of golden perch and silver perch increases by ≥30% over a 5-year period.</p>	<p>Is there a correlation between productivity and recruitment (to YoY) of golden perch and silver perch in the River Murray Channel?</p> <p>How does hydrology (magnitude, timing, water source) influence recruitment (to YoY) of golden perch and silver perch in the River Murray Channel?</p> <p>How did e-water management over the past five years influence recruitment (to YoY) of golden perch and silver perch in the River Murray Channel?</p> <p>How does weir pool raising and lowering impact golden and silver perch larvae survival and recruitment?</p> <p>Are golden perch and silver perch larvae present in each reach? What time of year? What volume / density /biomass?</p> <p>What was the breeding response (eggs, larvae, YoY) of golden perch and silver perch and how did this vary spatially and temporally through the event?</p> <p>What was the survival (to YoY) of golden perch and silver perch larvae?</p>
<p>NSW: Improve native fish population structure for moderate to long-lived riverine specialist native fish species.</p> <p>SA: Restore resilient populations of Murray cod (a long-lived apex predator).</p>	<p>NSW: Minimum of 1 significant recruitment event in 5 years.</p> <p>SA: Population age structure of Murray cod includes recent recruits, subadults and adults in 9 years in 10.</p> <p>Population age structure of Murray cod indicates a large recruitment event 1 year in 5, demonstrated by a cohort representing > 50 % of the population.</p>	<p>What was the relative abundance of age classes of Murray cod?</p> <p>What was the condition of Murray cod (length-weight ratios)?</p>

Ecological objective	Ecological target	Relevant KEQs (from the hierarchy)
Restore resilient populations of freshwater catfish.	<p>Abundance (CPUE) of Murray cod increases by ≥ 50 % over a 10-year period.</p> <p>Population age structure of freshwater catfish includes YOY, with sub-adults and adults in 9 years in 10.</p> <p>Population age structure of freshwater catfish indicates a large recruitment event 2 years in 5, demonstrated by separate cohorts representing > 30 % of the population.</p> <p>Abundance (CPUE) of freshwater catfish increases by ≥ 30 % over a 5-year period.</p>	<p>How does hydrology (variability, magnitude, timing) affect Murray cod recruitment and condition?</p> <p>How does e-water management affect Murray cod recruitment and condition?</p> <p>Is there a correlation between productivity and Murray cod recruitment and condition?</p>

Appendix B: Review of indicators and existing monitoring

Foundational information: gap analysis

Several evaluation questions have been identified at the foundational level. These are largely related to hydrology (the management lever and primary influencing factor of interest), but also include several other indicators that are important co-variables for the biotic indicators of productivity and native fish (e.g., temperature, salinity). The foundational evaluation questions can largely be addressed through existing programs (Table 11).

The exception to this is velocity. There are currently just three active stations directly measuring velocity in the River Murray Channel (all in South Australia); noting that velocity could be modelled at other sites. In addition, the Lower Murray Selected Area as part of LTIM / Flow-MER models hydraulic regimes (discharge, velocity, water level and area inundated for weir pools 1 to 5).

Table 11: Existing monitoring against foundational information requirements.

Evaluation question	Existing sites	Frequency of measurement	Parameters	Custodian
What was the flow at key gauging stations along the entire length of the channel throughout the year?	40 active gauging stations (see Figure 14); larger number measuring water level	Continuous	Discharge	Water NSW, MDBA, SA DEW
What were the weir pool operations throughout the year?	Weir pools 1 -5	Daily	Modelled - velocity, water level, level of inundation	CEWO
What were the velocities in each reach during the watering action?	3 - Loxton, Wilpunda, Morgan	Continuous	Velocity	SA DEW (available from the
What were the sources of water during the watering action?	Operational?			
What was the area and duration of floodplain inundation? ⁷	GeoScience Australia Wetlands Insight Tool – for each ANAE polygon	Various (Landsat record)	Open water, wet vegetation, green vegetation, dry soil	MDBA / GeoScience Australia
What were the relevant water quality responses (temperature, salinity) during the watering action?	>60 stations along the entire channel from Hume to the Mouth	Continuous ⁸	Temperature, electrical conductivity	Water NSW, MDBA, SA DEW

The majority of the metrics available as foundation information are collected (or modelled) at continuous or daily time steps, indicating that frequency of measures is adequate. The distribution of sites includes upstream and downstream of major tributaries and floodplain ecosystems as well as all of the weir pools in the Lower Murray, indicating that spatial coverage is also likely adequate.

⁷ There are also several modelled / measured site-specific tools, such as inundation mapping at Gunbower Forest and Barmah Forest using field measurements and MDBA BIG-MOD modelling).

⁸ There are a number of additional locations that measure periodically (rather than continuous) and several of the telemetered stations also have regular spot / lab samples for other water quality parameters.

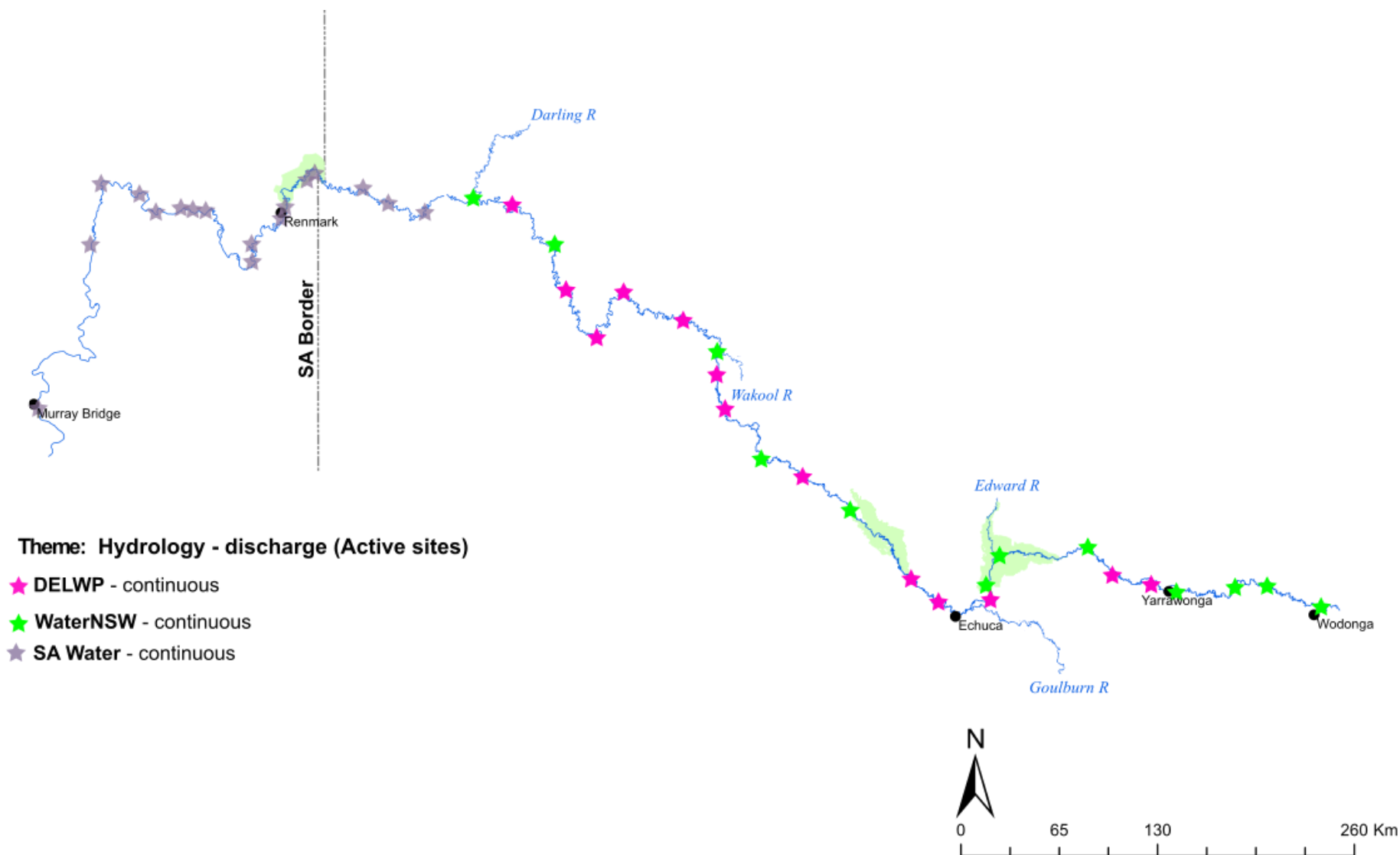


Figure 14: Existing gauge network reporting continuous discharge information (note that where gauges are close together (e.g., upstream and downstream of a weir, they may be represented by a single point).

Productivity: indicators and gap analysis

Evaluation questions

- Long term:
 - How does environmental water contribute to the quality and quantity of food resources and their transfer through food webs in the River Murray Channel to support native fish recruitment?
- Intermediate:
 - How did e-water management over the past five years influence productivity along the length of the River Murray Channel?
 - Is there a correlation between productivity and recruitment (to YoY) of golden perch and silver perch in the River Murray Channel?
 - Is there a correlation between productivity and Murray cod recruitment and condition?
- Immediate:
 - How did productivity (quality and quantity) in the River Murray Channel vary spatially (along the length of the River) and temporally (over what period of time was productivity enhanced). What were the hydrological conditions associated with this response?

Conceptual understanding

Riverine productivity is the flow of energy and essential nutrients through food webs from basal food resources such as organic carbon, through trophic levels to apex predators such as fish and waterbirds (Robson et al. 2017). Hydrology is a driver of aquatic food webs in terms of production of food resources and transport of those resources between floodplains and rivers and along river systems (Junk et al. 1989, Brookes et al. 2012). The reduction in floodplain-river connectivity as a result of water resource use and land management practices, together with the decrease in flow variability in channels has disrupted carbon and nutrient cycling. The effect has been periods of low productivity in river systems, interspersed with large productivity events such as algal blooms and mass movement of floodplain carbon causing deoxygenation of the water column following large, but infrequent floods (Hart et al. 1995, Kingsford 2000, Thoms 2003, King et al. 2012a, CEWO 2017).

While the effect of hydrology on basal food resources in riverine and floodplain ecosystems is relatively well understood (Roach 2013), there are a large number of factors that affect that response, including (Ryder et al. 2006, Baldwin et al. 2016, Robson et al. 2017, Rolls et al. 2017):

- seasonal timing (and hence temperature)
- frequency of inundation of floodplains and in channel substrates (and hence the accumulation and bioavailability of terrestrial carbon and nutrients)
- the magnitude of inundation, physical-chemical conditions such as turbidity (which can affect primary production) and
- salinity (which affects biotic responses and the frequency of hydrological disturbances).

There is evidence that managed flows both instream and through floodplain inundation can influence riverine productivity outcomes through the mobilisation of carbon and nutrients, but also through the transfer of biota such as phytoplankton and microcrustaceans (Baldwin and Mitchell 2000, Gawne et al. 2007, Nielsen et al. 2016). Productivity outcomes are targeted by environmental water in the River Murray Channel and the Basin Plan contains two environmental objectives specifically targeting productivity:

- *8.04 (2) An objective is to protect and restore a subset of all water-dependent ecosystems of the Murray-Darling Basin, including by ensuring that:...(c) water-dependent ecosystems are able to support episodically high ecological productivity and its ecological dispersal.*
- *8.07 (7) An objective is to protect and restore ecological community structure, species interactions and food webs that sustain water-dependent ecosystems, including by protecting and restoring energy, carbon and nutrient dynamics, primary production and respiration.*

Previous monitoring of productivity in the River Murray Channel and comparable systems have shown that while responses to individual hydrological events are highly variable, there is a body of evidence that indicates:

- Large flood events, particularly those following a dry period, result in significant increases in dissolved organic carbon and nutrients on floodplains, which is mobilised to the river channel with return flood waters (Nielsen et al. 2016). These large events also result in

stimulation of primary and secondary production on the floodplain, with the transport of phytoplankton and zooplankton back to the river (Gawne et al. 2007, Nielsen et al. 2016).

- Return waters from managed floodplain inundation in the mid-Murray (Hume to Euston) and lower Murray (Euston to Wellington) also result in measurable productivity responses in the river channel downstream (Wallace and Furst 2016, Furst et al. 2019, Rees et al. 2019); but these are smaller in magnitude, influence a smaller extent of river channel and persist for less time than that of large floods.
- Rises in in-channel flows that inundate benches, backwaters and areas of bank that were previously dry can also result in productivity responses in the River Murray Channel (Furst et al. 2019).
- Floodplain return waters and modest rises in in-channel flows can result in improved food quality in the River Murray Channel, by increasing diatoms over less nutritious blue-green algae (Aldridge et al. 2012, Furst et al. 2019) and increasing diatom grazing zooplankton over the poor nutritional value introduced rotifer *Keratella americana* (Furst et al. 2019).
- Temperature is an important factor, with little productivity response to winter flows (Gawne et al. 2007).
- While return waters from inundation of Chowilla can stimulate productivity in the River Murray Channel (Wallace and Furst 2016, Upadhyay 2017), and small increases in channel flows can inundate littoral vegetation stimulating zooplankton production (Furst et al. 2020); the effects of managed flows experienced during LTIM (2014 to 2019) on stream metabolism in the South Australian weir pools is generally < 1% (Ye et al. 2020).

Dissolved organic carbon and nutrients

Rationale: The ecological effect of floodplain inundation on organic carbon and nutrients in rivers, including the River Murray is well established (Baldwin et al. 2013, 2016, Moran et al. 2014, Nielsen et al. 2016, Rees et al. 2019). There is also a growing body of evidence that small rises in in-channel flows can liberate stored carbon (Hale et al. 2020). The use of organic carbon concentrations provides a direct measure of the primary pathway for the link between hydrology and productivity as illustrated in Figure 15. It does not, however, provide any information about the fate of that increased carbon concentrations and if that resulted in increased productivity or food resources through the food chain.

Expected responses from flows in the Murray: Previous investigations in the River Murray Channel have found that the response of dissolved organic carbon and nutrients from floodplain inundation is highly influenced by the magnitude and timing of inundation. A small flood of Barmah Forest (15,000 ML/day) in July 2010 did not result in any significant release of dissolved organic carbon to the river, which a large flood in October 2020 (100,000 ML/day) resulted in the mobilisation of 300 tonnes of carbon (Nielsen et al. 2016). Conversely recent monitoring suggested carbon loads of around 40 tonnes per day downstream of Barmah Forest following modest (15,000 ML/day) inundation (Rees et al. 2019), illustrating that the response from the same flow can vary depending on season, the parts of the forest that are inundated and duration of inundation. The increase in carbon and nutrient concentrations was not detected 100 kilometres downstream and responses in the mid-Murray from in-channel inundation were small and short-lived (Rees et al. 2019).

The results in the Lower Murray have been more variable. There have been some reports of the movement of dissolved organic carbon and nutrients to the river following floodplain inundation at Chowilla (Wallace and Furst 2016, Upadhyay 2017). The increases in dissolved organic carbon were realised at least 40 kilometres downstream. While the increase in concentrations (30 to 40 %) was moderate, the additional load may have been substantial (loads were not calculated, and volumes not reported). Dissolved organic carbon concentrations for the five years of the LTIM program in the Lower Murray remained relatively low throughout the period, which was attributed to the relatively stable water levels in weir pools in this section of the Murray (Ye et al. 2020). This is consistent with recent short-term intervention monitoring that showed no increase in carbon or nutrients as a result of a small and short-duration spring flow (Rees et al. 2019).

Existing monitoring: Dissolved organic carbon (as well as nutrient and chlorophyll concentrations) is measured under a number of existing programs within the River Murray Channel (Figure 5). The MDBA, and WaterNSW programs collect samples weekly; the former having a data set that began in 1990. The MDBA water quality monitoring program also monitors in several tributaries including the Ovens, Goulburn, Campaspe, Loddon, Edward/Kolety-Wakool and Murrumbidgee Rivers and Broken Creek). In addition, the Flow-MER stream metabolism program collects water quality samples every six weeks in spring and summer. The existing sites are located at or near to existing gauging stations which would allow for load calculations.

Gaps: The existing programs provide adequate coverage for many locations in the River Murray Channel, with the current network covering most of the sites and recommendations of the 2019 short term monitoring (Rees et al. 2019; Table 12). The program would better meet the recommendation of Rees et al. 2019 with a small number of additional sites:

- Murray River between Barmah Forest and the Goulburn River
- Edward/Kolety River upstream of Barmah
- Locks in SA – noting that the 2019 monitoring did not detect any changes in carbon and nutrient concentrations in the Lower Murray and recommended an alternative approach in the Weir Pools of the Lower Murray involving loggers for stream metabolism, and fatty acid analysis.

Pros and cons

- Foundational information with a direct causal link to hydrology
- Existing monitoring program that can be leveraged off
- Large long-term data set would allow for retrospective analysis for trends and causal relationships to flow
- System scalable
- Established methods and protocols
- Low cost
- *Does not tell us if the carbon mobilised translates to outcomes for biota*

- *Maybe a limited response in the Lower Murray Weir Pools*
- *Effect size in years where there is little return water from floodplain inundation maybe poor.*

Table 12: Existing monitoring against sites proposed in Baldwin (unpublished) and Rees et al. (2019).

Recommended sites	Response	Existing sites	Custodian
Murray R @ Tocumwal	U/s of Barmah-Millewa	Murray River d/s Yarrawonga (too far upstream?)	MDBA
Edward R @ 4 Posts	Barmah-Millewa input		
Broken C d/s Casseys Weir	Tributary input	Broken Creek at Rice's Weir	MDBA
Murray R @ Barmah	Barmah-Millewa flooding		
Goulburn R u/s Murray R	Tributary input	Goulburn R @ McCoys Bridge	MDBA
Murray R u/s Echuca	Goulburn R. e-flow impacts	Murray River u/s of Echuca	Water NSW
Campaspe R u/s Echuca	Tributary input	Campaspe River at Rochester	MDBA
Murray R @ Barham	Main channel processing	Murray River at Barham	Water NSW
Loddon R u/s Swan Hill	Tributary input	Loddon River at Kerang	MDBA
Murray R @ Swan Hill	Main channel processing	Murray River at Swan Hill	MDBA
Edward-Wakool @ Kyalite	Anabranh input	Edward-Wakool @ Kyalite	MDBA
Murrumbidgee R u/s Boundary Bend	Tributary input	Murrumbidgee @ Balranald	MDBA
Murray R @ Boundary Bend	Main channel processing		
Murray R u/s Euston Weir	Influence of Locks	Murray R u/s Euston Weir	MDBA
Murray R d/s Euston Weir	Influence of Locks		
Darling R @ Burtundy	Main channel processing	Darling River @ Burtundy	MDBA
Murray R d/s Lock 9	Tributary input	Murray R u/s Lock 9	MDBA
Rufus River	Main channel processing		
Murray R d/s L. Victoria	Lake Victoria inputs		
Murray R u/s Lock 5	Main channel processing	Murray R u/s Lock 5	MDBA
Murray River @ Mannum	Influence of locks	Murray River at Morgan	MDBA

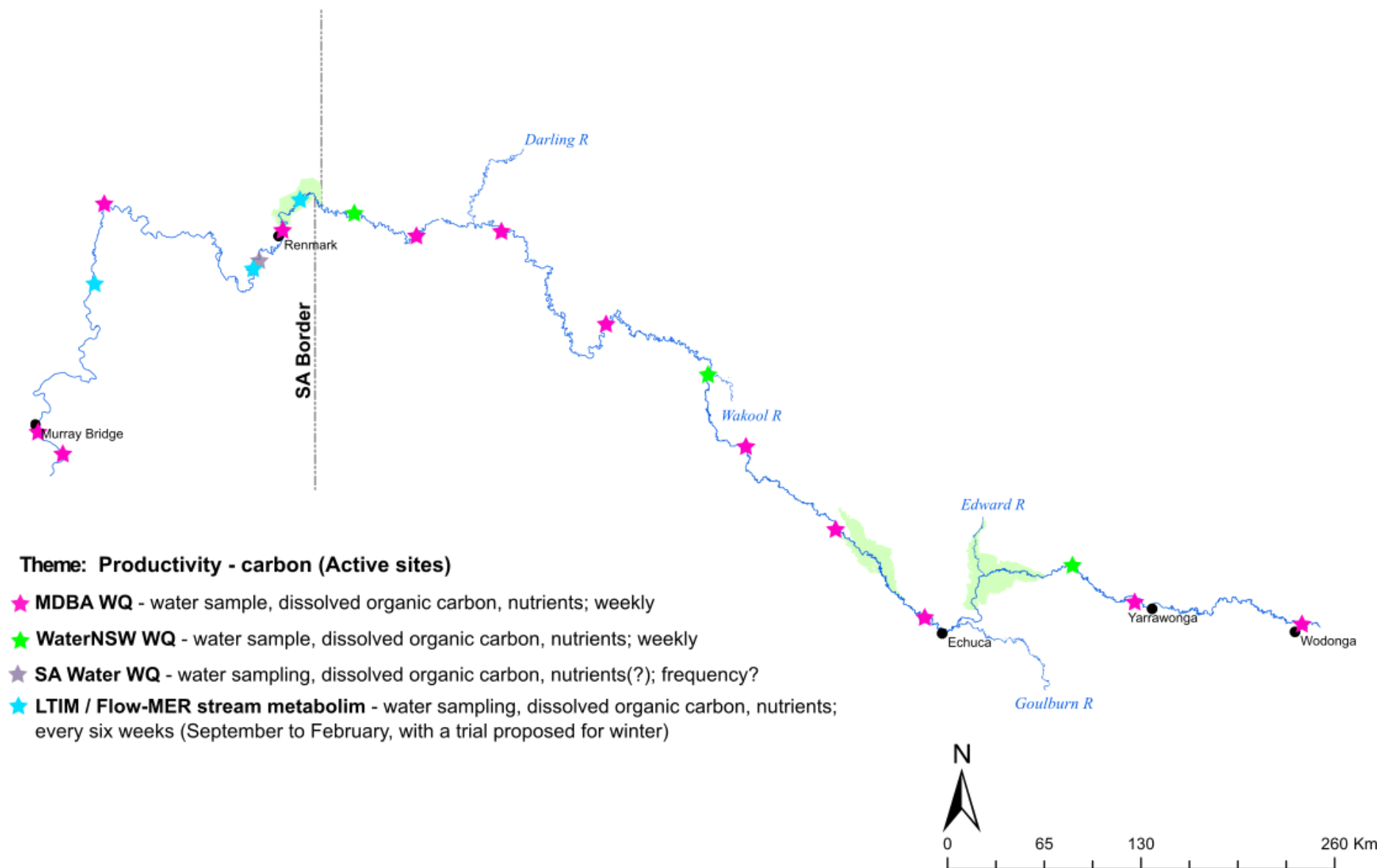


Figure 16: Existing monitoring locations for DOC and nutrients (tributary sites not shown).

Stream metabolism

Rationale: Stream metabolism is the estimation gross primary production and ecosystem respiration from measurements of changes in dissolved oxygen, temperature and light in open water. It represents an intermediate step in the primary productivity cycle illustrated in Figure 7. Changes in lateral connectivity (inundation of floodplains, wetlands and backwaters) as well as rises in in-channel flows that inundate new areas of banks and benches, are known to illicit a response in stream metabolism both in the Murray River and elsewhere (Young and Huryn 1999, Cook et al. 2015, Grace 2019, Mejia et al. 2019).

Expected responses from flows in the Murray: There are limited investigations related to the effect of managed flows in the mid-Murray on stream metabolism. A study of the rates of gross primary production (GPP) and Ecosystem respiration (EP) at relatively low flow rates (average of 12,000 ML/day at Albury to an average of 7500 ML/day at Hattah) indicated moderate productivity. At these low flows and in the absence of floodplain return waters, primary productivity was dominated by phytoplankton and allochthonous organic carbon played a minor role in food webs (Oliver and Merrick 2006). A study of the 2010 spring flood in Barmah Forest indicated that stream metabolism increased over 100% from winter to spring at both up and downstream sites, illustrating the effect of temperature (Cook et al. 2015). Results indicated that the return waters of the large floodplain inundation (peaking at over 100,000 ML/day at Tocumwal) resulted in a 10% increase in annual GPP and a 32% increase in ER (Cook et al. 2015). By contrast a small managed floodplain inundation in 2020-21 resulted in small increases in stream metabolism immediately downstream of the forest, but also further downstream (immediately downstream of the Murrumbidgee confluence) indicating that in-channel flows may be having an effect on stream metabolism (Rees et al. in prep.). Similarly, there were increases in stream metabolism in sites downstream of Chowilla following a managed inundation event in 2014 (Wallace and Furst 2016, Upadhyay 2017). Evidence from the Lower Murray monitoring 2014-19, however, has indicated that the effects of managed flows during these years on stream metabolism in the South Australian weir pools is generally < 1% (Ye et al. 2020).

Existing monitoring: Stream metabolism estimations require continuous measures of dissolved oxygen, temperature and light (photosynthetically active radiation). While there a number of gauging stations in NSW (Edward River at Deniliquin, Murray River at Barham, below Wakool Junction, at Boundary Bend and at Coligan) and South Australia (upstream of old Customs House and downstream of Lyrup); where dissolved oxygen and temperature are measured continuously; there is no corresponding measure of light.

LTIM and Flow-MER in the Lower Murray Selected Area measure stream metabolism between September and February each year at six locations (Figure 6). The Edward-Wakool, Murrumbidgee and Goulburn Selected Areas also measure stream metabolism over this period, providing a complimentary data set from major tributaries.

Gaps: There is no stream metabolism monitoring in the River Murray Channel above the South Australian border. Dissolved organic carbon, chlorophyll-a and nutrients are important co-variates and there is the possibility to leverage off existing MDBA sites where this information is being collected. As well as to tap into existing logging of dissolved oxygen and temperature at several sites in the main Murray Channel, by adding a light logger to each.

Pros and cons:

- Provides a direct measure of the basics of productivity.
- Has been shown to be responsive to both floodplain inundation (return waters) and in channel flows (Grace 2019).
- Methods are well established
- Provides an opportunity to leverage off existing monitoring, if sites are located at Water NSW and MDBA long term sites.
- Lower Murray is currently covered by Flow-MER, noting that these sites would need to be funded under the River Murray Channel Monitoring Plan if the Flow-MER program changes.
- Moderate costs – especially if it can be integrated with a higher trophic order sampling regime.
- *Does not provide any indicator of the fate of energy produced.*
- *Loggers and probes can fail.*
- *It is unknown whether the types of flows delivered in the River Murray would illicit an ecologically meaningful response.*

- *Utility for informing adaptive management may be low.*

Table 13: Existing monitoring against sites proposed in in February workshop.

Recommended sites	Existing sites	Parameters	Custodian	Gaps
Downstream of Hume dam	Murray River at Albury	DOC, nutrients, chl-a – weekly DO, temperature, continuous	MDBA Water NSW	Light
Upstream of Barmah	Murray River d/s Yarrawonga	DOC, nutrients, chl-a – weekly	MDBA	Light
Downstream of Barmah				All
Downstream of Goulburn	Murray River u/s Echuca	DOC, nutrients, chl-a – weekly	MDBA	DO, temp light
Downstream of Gunbower	Murray River at Barham	DOC, nutrients, chl-a – weekly DO, temperature, continuous	Water NSW	Light
Downstream of the Wakool	Murray River below Wakool	DO, temperature, continuous	DELWP	Light
Downstream of Murrumbidgee	Murray River u/s Euston Weir	DOC, nutrients, chl-a – weekly	MDBA	
Upstream of the Darling	Murray River at Boundary Bend	DO, temperature, continuous	DELWP	Light
Downstream of the Darling	Murray River d/s Lock 9	DOC, nutrients, chl-a – weekly	MDBA	DO, temp light
Upstream of Chowilla	Murray River d/s Lock 6	Stream metabolism	CEWO	None
Downstream of Chowilla	Murray River d/s Lock 4	Stream metabolism	CEWO	None
SA Weir pools	Murray River d/s Lock 1	Stream metabolism	CEWO	None

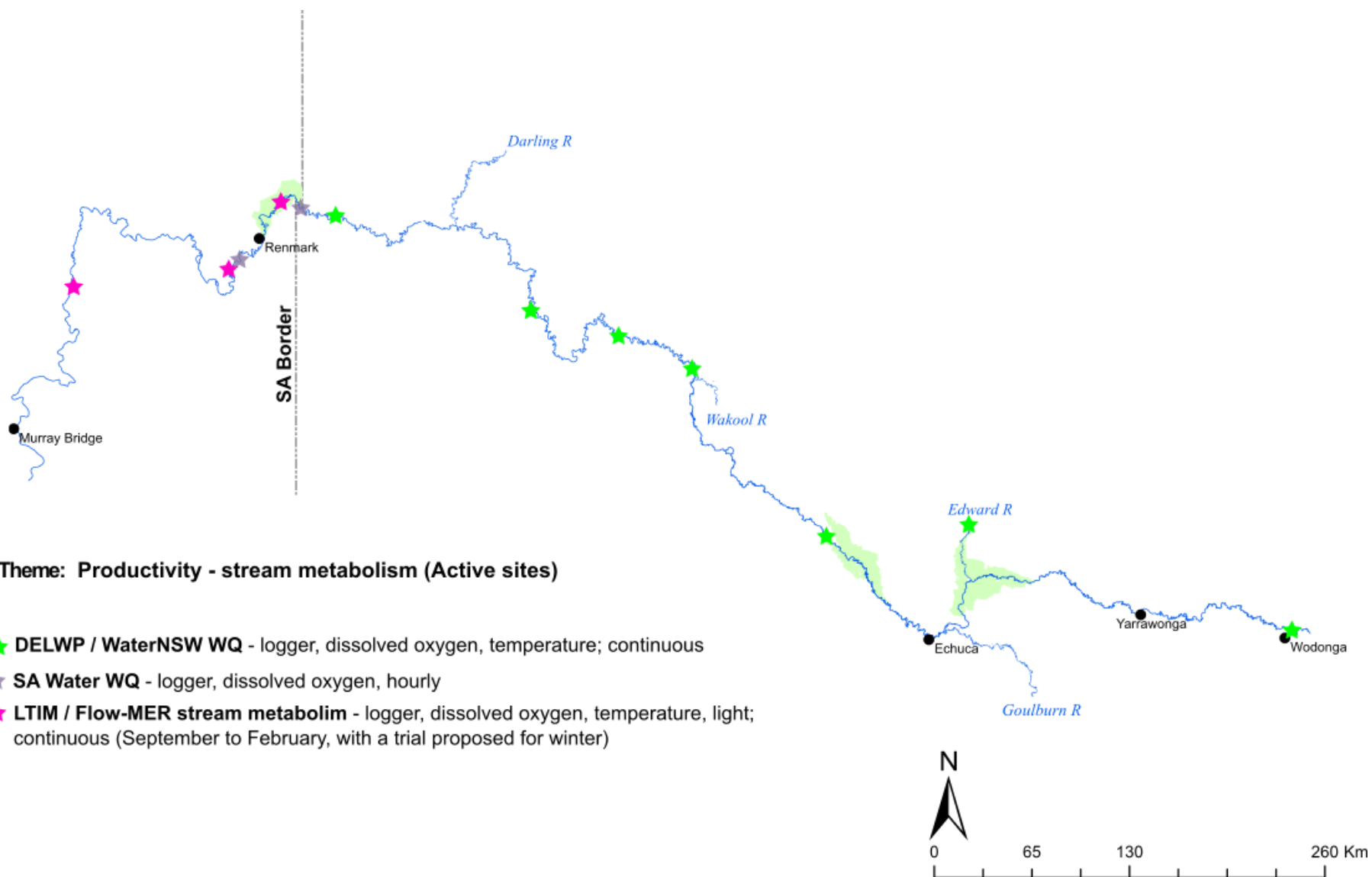


Figure 17: Existing monitoring locations for dissolved oxygen, and stream metabolism.

Biofilms

Rationale: Biofilms are a mix of algae, fungi and bacteria. They are known to respond to increasing nutrients and dissolved organic carbon in river systems, both by increasing in biomass and altered community composition, and hence basal food quality (Burns and Walker 2000a, Burns and Ryder 2001, Ryder et al. 2006, Rohlfs et al. 2018). In addition, hydrological disturbance (increasing flows) is known to scour biofilms, which increases the nutritional quality during initial regrowth (Robson et al. 2017). They represent an intermediate step in the River Murray chain of consequence model (Figure 7).

Expected responses from flows in the Murray: Cook et al. (2015) measured the effect of large floodplain inundation in Barmah Forest in October 2010 (maximum flows > 100,000 ML/day) on biofilms in the River Murray Channel downstream. They found a 4 to 7% decrease in autotrophic carbon in downstream sites following the flood and a rapid incorporation of allochthonous carbon into the biofilm. There are few other studies on biofilms from the Murray River Channel, although Ryder et al. (2006) found that flow velocities of 0.55 metres / second were sufficient in the Murrumbidgee to scour biofilms. There are currently several research projects looking at the relationships between flow and biofilms in the Basin, including the MMCP Collaboration Project at Latrobe University (<https://www.latrobe.edu.au/freshwater-ecosystems/research/projects/mmcp>).

Existing monitoring: While there have been several short term monitoring and research projects assessing biofilms in the River Murray (Cook et al. 2015, Rees et al. 2020) and tributaries (Ryder et al. 2006, Watts et al. 2006); there is no ongoing biofilm monitoring in the main channel.

Gaps: With no existing monitoring, a program would have to be developed and fully funded under the River Murray Channel Monitoring Plan. There are several methods / sub-indicators that could be collected including: biomass, community composition, stable isotope analysis, polyunsaturated fatty acid (PUFA) content, for example. Previous reviews have indicated that include both structural (e.g. biomass) and functional (e.g. PUFA as an indicator of food quality) would provide the best information (Burns and Ryder 2001). Biofilms can be collected from natural substrates or artificial substrates can be deployed; the latter providing a more controlled monitoring with a defined start point.

By way of example, a previous program proposed was to measure biofilms at 10 sites from upstream of Barmah to downstream of Lock 3 in South Australia. Samples were to be collected every two weeks over a 14-week period from early spring to summer. Analysis of biomass, chlorophyll a concentration, protein analysis and fatty acid composition or stable isotope analysis.

Pros and cons:

- Provides a more direct measure of the quality of food produced than stream metabolism and water quality measurements.
- Represents a short food chain pathway from allochthonous carbon to shrimp and other macroinvertebrates.
- Some flow-ecology relationships established.
- Moderate costs
- *Does not offer any direct leveraging opportunities on existing monitoring.*
- *It is unknown whether the types of flows delivered in the River Murray would illicit a detectable response.*
- *There are a large number of covariates (nutrients, temperature, grazing pressure) that may make linking back to hydrological regimes difficult.*

Phytoplankton

Rationale: Phytoplankton are important primary producers in the River Murray Channel and traditionally, the phytoplankton community of the River Murray has been dominated by diatoms (Reid and Ogden 2006). Diatoms represent a high nutritional value food source for grazers, and have a direct link to river flow, requiring sustained flow to keep them in suspension (Gibbs et al. 2020). They represent an intermediate step in the River Murray chain of consequence model (Figure 7).

Existing monitoring: There has been a long-standing MDBA phytoplankton program in the River Murray that has collected data weekly since 1980 (with some modifications to sites in 2013). The program identifies and counts phytoplankton to species or genus. There are also phytoplankton programs conducted by Water NSW and SA Water, but these may be limited to nuisance species only (Figure 7).

Expected responses from flows in the Murray: Modelling (validated against monitoring data) indicated that flow has an effect on phytoplankton abundance and community composition through several mechanisms: the movement of silica from upper catchments and floodplains increases diatom growth, as does sufficient flow velocities (e.g. > 10,000 ML/day at Merbein) to maintain well mixed conditions and keep diatoms from sinking below the photic zone; and increasing temperatures in spring increase primary production (Bormans and Webster 1999). A longitudinal study of the River Murray (and tributaries) in 2016 found that phytoplankton during high flows (peaks of 72,000; 113,000 and 180,000 ML/day in the lower, mid and upper Murray respectively) resulted in a phytoplankton community dominated by diatoms. Conversely low flows (5000 to 8000 ML/day) resulted in high proportions of blue-green algae (Furst et al. 2019). This is consistent with the study of phytoplankton dynamics in the lower Murray comparing low flow periods (June 2008 to August 2009) and high flow periods (June 2010 to August 2011). Effects of managed floodplain discharge on phytoplankton communities were studied in the River Murray near Hattah Lakes, with results indicating a localised increase in phytoplankton biomass downstream of the return waters (Furst et al. 2019). Phytoplankton in low flow conditions in the lower Murray was dominated by cyanobacteria, this switched to diatoms in the high flow period, there was also a 7-fold increase in algal biomass as indicated by chlorophyll-a (Aldridge et al. 2012).

Gaps: Existing monitoring by the MDBA adequately covers much of the River Murray Channel. The main gaps, comprise the Murray Channel downstream of Barmah and upstream of the Goulburn River, and the Edward/Kooley.

Table 14: Existing monitoring against sites proposed in Baldwin (unpublished) for biological monitoring.

Recommended sites	Response	Existing sites	Custodian
Murray R @ Tocumwal	U/s of Barmah-Millewa	Murray River d/s Yarrawonga	MDBA
Edward R @ 4 Posts	Barmah-Millewa input		
Murray R @ Barmah	Barmah-Millewa flooding	Murray River at Barmah*	GMW
Goulburn R u/s Murray R	Tributary input	Goulburn River at McCoys	GMW
Murray R u/s Echuca	Goulburn R. e-flow impacts	Murray River at Torrumbarry	MDBA
Murray R @ Barham	Main channel processing	Murray River at Barham*	Water NSW
Murray R @ Swan Hill	Main channel processing	Murray River at Swan Hill	MDBA
Murrumbidgee R u/s Boundary Bend	Tributary input	Murrumbidgee at Balranald	MDBA
		Murray River at Euston	MDBA
		Murray River at Merbein	MDBA
		Darling River at Burtundy	MDBA
Murray R u/s Lock 5	Main channel processing		
Murray R d/s Lock 5	Influence of locks		
Murray R u/s Lock 3	Influence of locks		
Murray R d/s Lock 3	Influence of locks	Murray River at Morgan	MDBA
		Murray River at Tailem Bend	MDBA

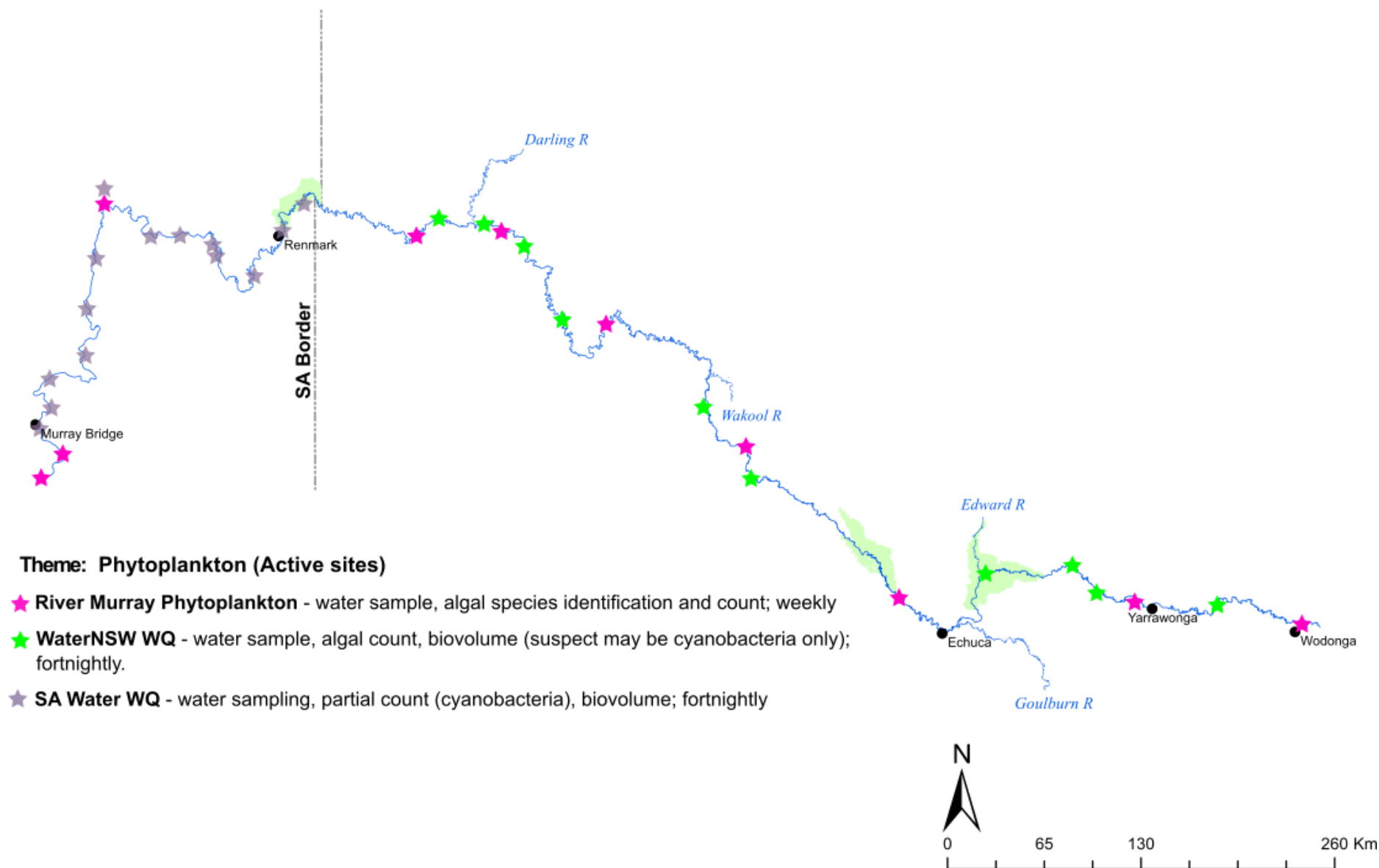


Figure 18: Existing monitoring locations for phytoplankton (note that tributary sites are not shown).

Pros and cons:

- Provides a more direct measure of the quality of food produced than stream metabolism and water quality measurements.
- Has been shown to be responsive to flows.
- Methods are well established
- Potentially low cost
- Can be directly leveraged off existing programs.
- *It is unknown whether the types of flows delivered in the River Murray would illicit a detectable response.*
- *There are a large number of covariates (nutrients, temperature, grazing pressure) that may make linking back to hydrological regimes difficult.*

Zooplankton / microinvertebrates

Rationale: Zooplankton are part of the food web of the River Murray, consuming phytoplankton, bacteria, detritus) and acting as food source for higher organisms such as fish. They are known to respond to changes in the flow regime, particularly where dry sediments are inundated resulting in hatching of eggs banks (Shiel and Aldridge 1949, James et al. 2008). Flows can influence zooplankton quantity and quality. Increases in zooplankton biomass in rivers can come from stimulating productivity in the river channel and growth/reproduction of zooplankton within the river, or from the movement of zooplankton from inundated floodplains to river systems with return waters.

Expected responses from flows in the Murray: Previous investigations in the River Murray Channel have found that the response of zooplankton from floodplain inundation is highly influenced by the magnitude and timing of inundation. A small flood of Barmah Forest (15,000 ML/day) in July 2010 did not result in any significant change in zooplankton abundance in the river, while a large flood in October 2020 (100,000 ML/day) resulted in the mobilisation of seven tonnes of zooplankton (Nielsen et al. 2016). This is consistent with the results of small-scale inundation of Hattah, which resulted in modest and localised increases in zooplankton in the River downstream (Furst et al. 2019) and a large-scale (flow peaks of 93,000 ML day) inundation of Chowilla that resulted in the mobilisation of 6 tonnes of zooplankton to the river per day (Furst et al. 2014). The effects of the 2019 spring pulse and Barmah inundation resulted in increases in zooplankton abundance in downstream sites and the flows in the Lower Murray inundated littoral vegetation stimulating zooplankton production (Furst et al. 2020). A longitudinal study of the River Murray (and tributaries) in 2016 found that during high flows (peaks of 72,000; 113,000 and 180,000 ML/day in the lower, mid and upper Murray respectively) the zooplankton community was dominated by diatom consumers, which present a high food quality for predators. Conversely low flows (5000 to 8000 ML/day) resulted in high numbers of the poor nutritional value introduced rotifer *Keratella americana* (Furst et al. 2019).

Existing monitoring: There have been several short-term monitoring and research programs for zooplankton in the River Murray (Kobayashi 1997, Ning et al. 2013, Furst et al. 2014, 2020). It is also included in the Flow-MER program in the Lower Murray Selected Area (Figure 19); but is not monitored upstream of the SA border or in the tributaries.

Gaps: Baldwin (unpublished) recommended 10 sites for zooplankton in the River Murray system; while Furst et al. (2020) undertook sampling at just six sites; but recommended dividing the river into regions (e.g., upstream of the Goulburn, Goulburn to the Darling, downstream of the Darling) and having a minimum of three replicate sites in each region. In both designs, the sampling under Flow-MER would adequately cover the Lower Murray, with the upstream regions requiring additional monitoring.

Pros and cons:

- Provides a more direct measure of the quantity of food produced than stream metabolism and water quality measurements.
- Has been shown to be responsive to flows.
- Methods are well established
- Moderate cost
- Can be directly leveraged off existing programs.
- *It is unknown whether the types of flows delivered in the River Murray would illicit an ecologically meaningful response in the absence of significant floodplain inundation.*
- *There are a large number of covariates (nutrients, temperature, grazing pressure) that may make linking back to hydrological regimes difficult.*
- *Zooplankton abundance potentially does not provide an indication of the nutritional value of the food resource. This would require analysis of fatty acid content (for which sample volumes required may be large).*

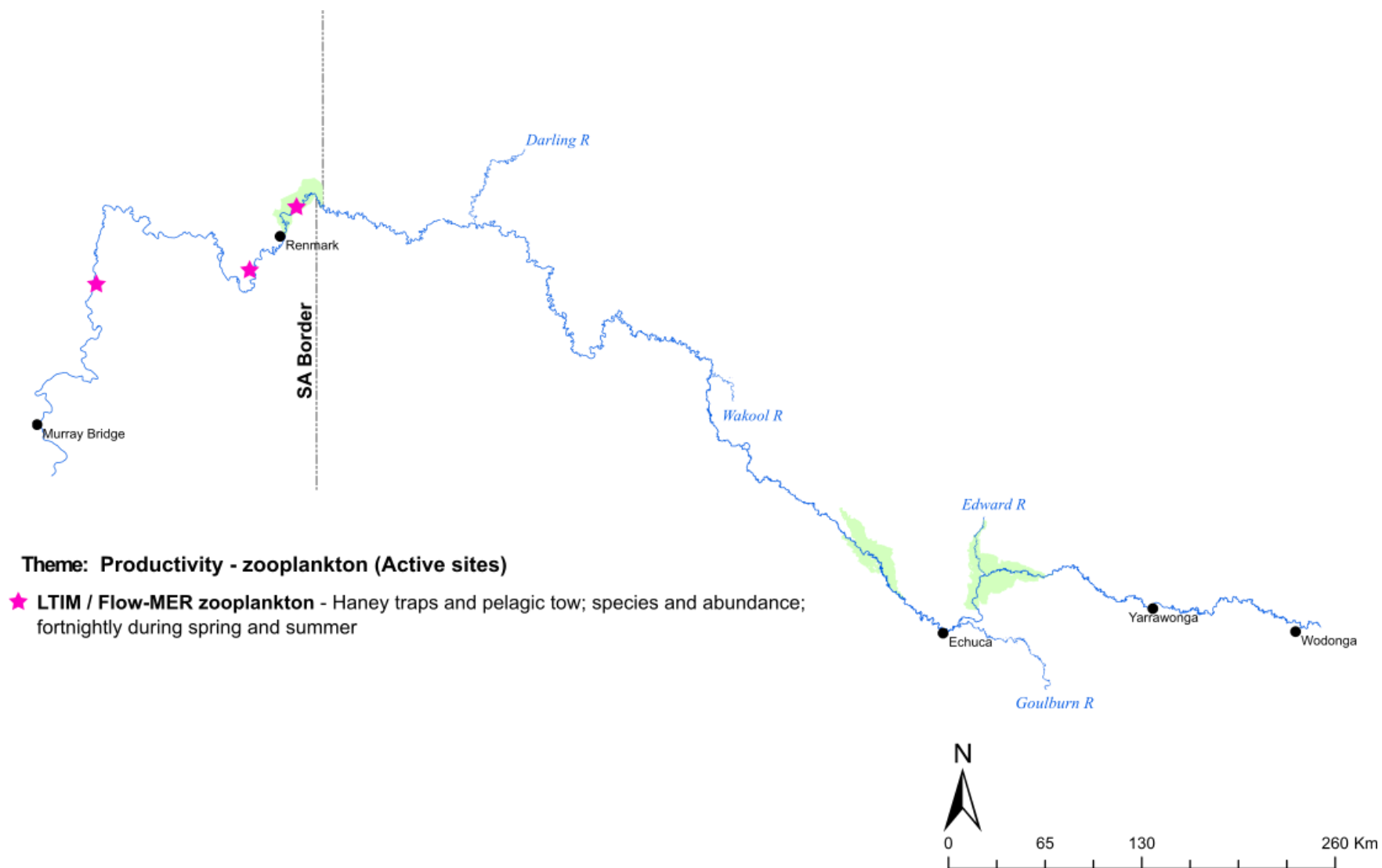


Figure 19: Existing monitoring locations for zooplankton.

Higher trophic levels (e.g., decapods, Murray cod)

Rationale: Decapods (freshwater shrimp) act as both mid-trophic order consumers as well as provide an important food resource to fish; Murray cod represent the highest level of the obligate aquatic food chain. They represent a higher level of the productivity chain of consequence in Figure 7.

Expected responses from flows in the Murray: To date, there have been several experimental research projects that have explored the quality of food resources in the Basin (Guo et al. 2017, Growns et al. 2020a, 2020b, Kühmayer et al. 2020) and some preliminary experiments looking at the quality of food from biofilms to decapods (Burns and Walker 2000b). The Flow-MER program in the Lower Murray has an integrated research project looking at productivity that includes shrimp and Murray cod. No completed reports or articles that used the abundance, diversity or fatty acid content of freshwater decapods or Murray cod to monitor the effects of environmental flows could be sourced.

Existing monitoring: There is no existing monitoring of these higher trophic levels, but the research component of the Flow-MER program in South Australia is trialling methods.

Gaps: Would require a novel project to be developed, until the methods used in South Australia have been trialled.

Pros and cons:

- Provides a direct measure of the quantity of food produced at a higher level in the food chain.
- *Methods need to be tested*
- *No guarantee that it would be responsive within the timeframe of monitoring to e-flows or changes in hydrology throughout the system.*
- *Potentially high cost and high risk.*

Fish: indicators and gap analysis

Evaluation questions

- Long term:
 - How does environmental water contribute to the quality and quantity of food resources and their transfer through food webs in the River Murray Channel to support native fish recruitment?
 - How could environmental water management be improved to enhance golden perch and silver perch populations in the River Murray Channel?
 - What are the flow related limiting factors to recruitment of golden perch and silver perch in the River Murray Channel and southern basin?
 - How could environmental water management be improved to enhance Murray cod populations in the River Murray Channel?
- Intermediate:
 - Is there a correlation between productivity and recruitment (to YoY) of golden perch and silver perch in the River Murray Channel?
 - How does hydrology (magnitude, timing, water source) and e-water management influence recruitment (to YoY) of golden perch and silver perch in the River Murray Channel?
 - How does weir pool raising and lowering impact golden and silver perch larvae survival and recruitment?
 - How does hydrology (variability, magnitude, timing) affect Murray cod recruitment and condition?
 - How does e-water management affect Murray cod recruitment and condition?
 - Is there a correlation between productivity and Murray cod recruitment and condition?
- Immediate:
 - Are golden perch and silver perch larvae present in each reach? What time of year? What volume / density /biomass?
 - What was the breeding response (eggs, larvae, YoY) of golden perch and silver perch and how did this vary spatially and temporally through the event?
 - What was the survival (to YoY) of golden perch and silver perch larvae?
 - What was the relative abundance of age classes of Murray cod?
 - What was the condition of Murray cod (length-weight ratios)?

Conceptual understanding

Hydrological influences on large-bodied native fish populations in the Basin have been studied for several decades (Humphries et al. 1999, King et al. 2009, Koehn et al. 2014, Ellis et al. 2016). As research and monitoring have progressed, our conceptual understanding and models of flow-fish relationships have been updated (e.g. Chee et al. 2006, DELWP 2017) and a generalised conceptual model illustrates the links between drivers (flow regime, habitat, water quality and connectivity); modifiers (altered flow and habitat; introduced species and barriers to connectivity) with fish life-history processes and population outcomes (Figure 8). In particular, a reduction in the frequency and magnitude of spring flow pulses and overbank flows and a reduction in flow variability in the River Murray Channel has impacted large-bodied native fish populations (Zampatti and Leigh 2013, Tonkin et al. 2019).

Three species of large-bodied fish are targeted by coordinated large-scale environmental water releases in the River Murray Channel⁹, two of which are listed threatened species under the EPBC Act (Murray cod and silver perch) while golden perch has experienced low recruitment in recent years, including in several tributaries of the mid-Murray (Shams et al. 2020, Stuart and Sharpe 2020). The Basin Plan has several objectives that are relevant to these three species including:

- *8.05 (3) An objective is to protect and restore biodiversity that is dependent on Basin water resources by ensuring that:...(a) water-dependent ecosystems that support the life cycles of a listed threatened species or listed threatened ecological community, or species treated as threatened or endangered (however described) in State law, are protected and, if necessary, restored so that they continue to support those life cycles.*

⁹ While freshwater catfish are targeted in the Lower Murray, they are not the focus of water management across the entire system.

- 8.06 (6) *An objective is to protect and restore ecosystem functions of water-dependent ecosystems that maintain populations (for example recruitment, regeneration, dispersal, immigration and emigration).*

Golden perch and silver perch are considered flow recruitment specialists (Baumgartner et al. 2013, Tonkin et al. 2019) and it is generally thought that a spring flow pulse is required to generate a spawning response (King et al. 2009). Higher flows (greater than baseflows) are also required for adult movement, larval drift, recruitment and dispersal. The two species are also known to take advantage of inundated wetland and floodplain habitat and spawning movements and recruitment occurs over relatively large spatial scales (100s of kilometres). Golden perch in particular may require high flows or floods for successful recruitment and to maintain good population structure (Zampatti and Leigh 2013), although this may vary with location and other non-flow factors (Ebner et al. 2009). For example, flows > 20,000 ML day at the South Australian border are recommended to provide the extensive flowing habitat to support golden perch and silver perch spawning and recruitment (Ye et al. 2020) and while exact thresholds in the mid-Murray are not known, there is evidence that silver perch spawn in most years (Tonkin et al. 2017). An example of a hydrograph that illustrates the flow – response for golden perch and silver perch is provided in Figure 21.

Murray cod are apex predators and spawning generally occurs in most years in lotic habitats, and not in response to changes in the flow regime (Koehn et al. 2020). Increased flows in late winter, however, can benefit Murray cod by inundating additional spawning habitat. While increased summer flows decrease recruitment success (Tonkin et al. 2020). Management of flow variability and food resources can also affect Murray cod condition and recruitment success (Figure 22).

Despite several decades of study, significant knowledge gaps remain. In particular the influence of flow on survival rates between life stages is largely unknown as is the importance of flow on the rate of movement of eggs, larvae and adults (Koehn et al. 2019).

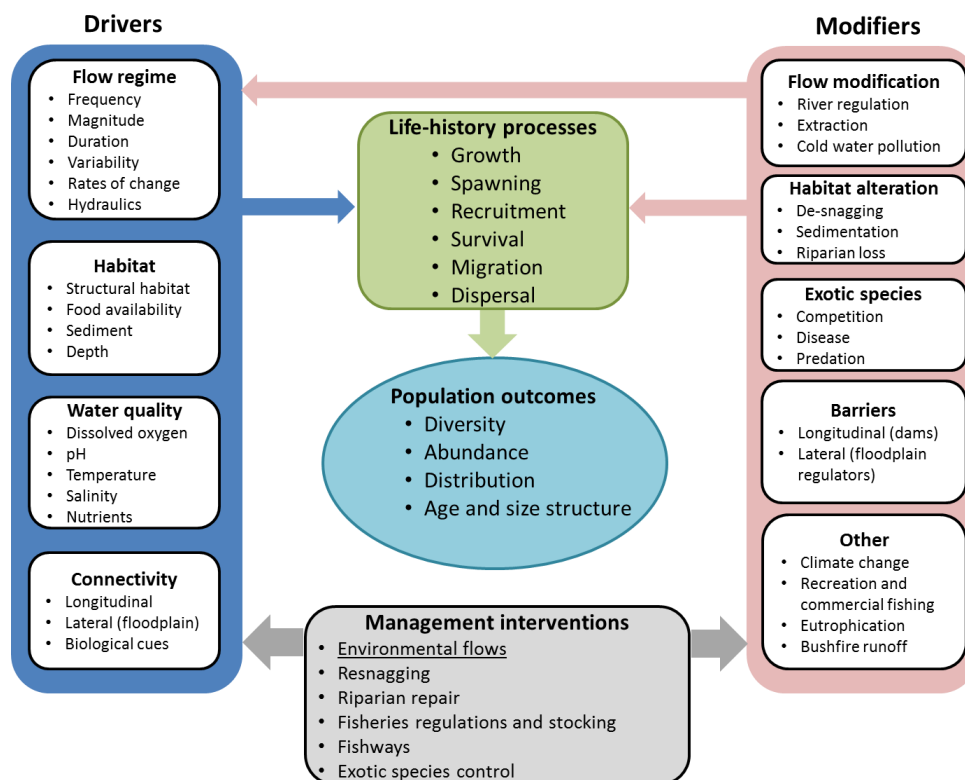


Figure 20: Overarching conceptual model of native fish population outcomes to drivers, modifiers and management interventions (DELWP 2017).

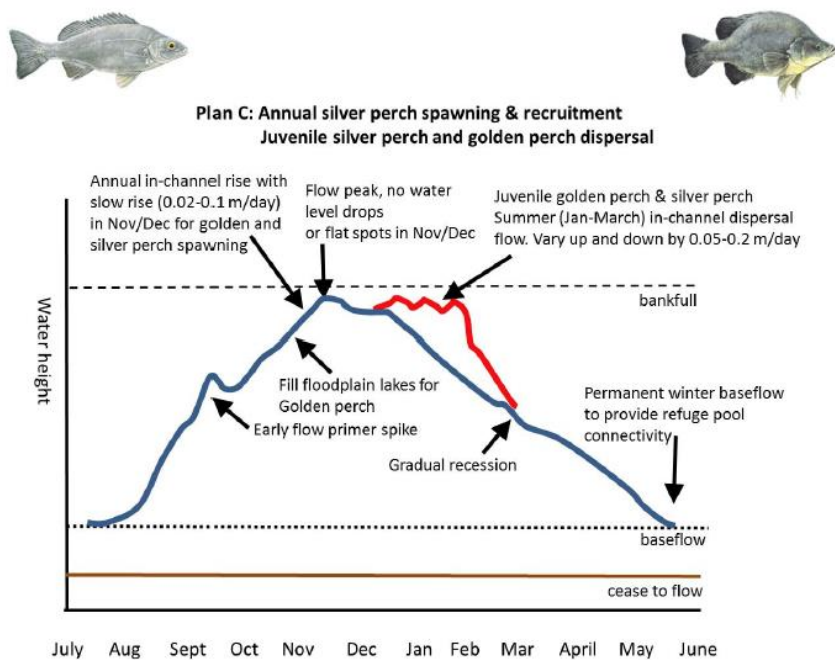


Figure 21: Fish hydrograph for silver and golden perch spawning, recruitment and dispersal (Stuart and Sharpe 2017).

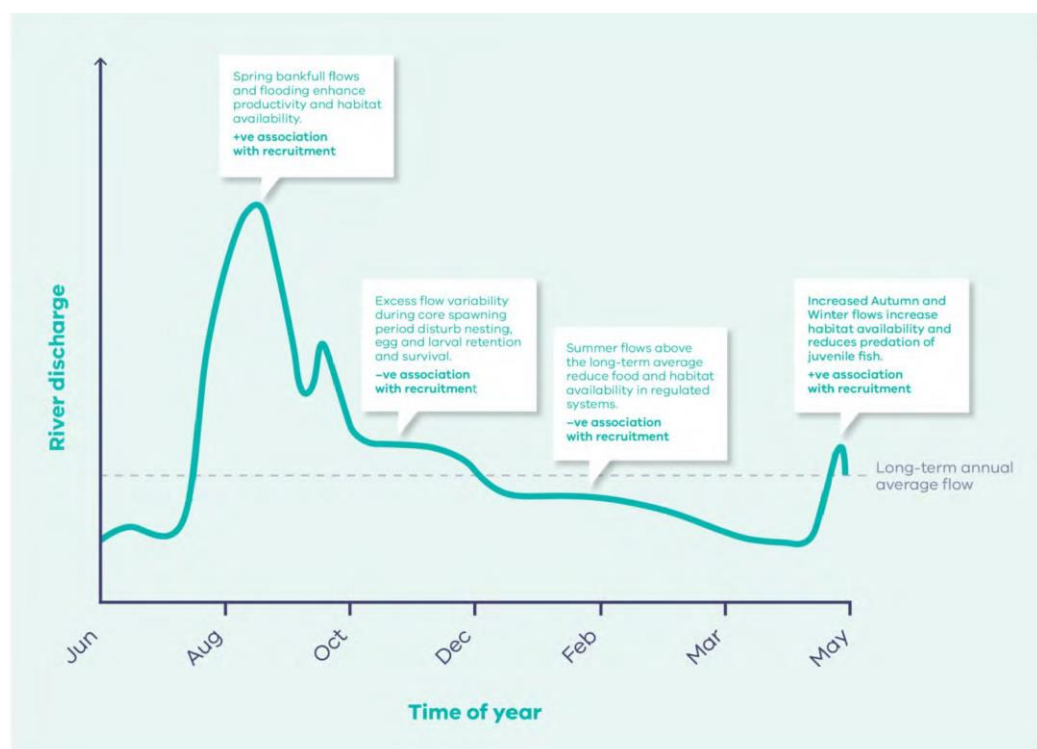


Figure 22: Fish hydrograph for Murray cod outcomes (DELWP 2017). Unlike the productivity KEQs, which could be answered through the measurement of a number of different indicators, in many respects the KEQs for fish, define the indicator to be measured:

- Golden perch and silver perch:
 - Abundance of eggs, larvae, YoY
 - Population structure and recruitment
- Murray cod
 - Condition (length: weight)
 - Population structure and recruitment

Expected responses

There are a large number of studies for native fish in the River Murray Channel (e.g. Humphries 2005, King et al. 2008, 2010, 2012b, Zampatti and Leigh 2013, Zampatti et al. 2015, Bloink and Robinson 2016, Raymond et al. 2019, Fredberg et al. 2020, Tonkin et al. 2020, Ye et al. 2020). There is a large body of evidence that natural flows (in channel and floodplain inundation) do result in improved spawning and sometimes recruitment outcomes for golden perch and silver perch (see summaries in Ellis et al. 2016, Koehn et al. 2020). There is also evidence of fish responding to managed flows. For example, in the mid-Murray Channel, moderate natural flooding (flows of around 25,000 ML/day at Tocumwal) extended with environmental water, resulted in significant (5 fold to an order of magnitude) increases in golden perch and silver perch eggs and larvae in the River Murray Channel adjacent to the Forest and several kilometres downstream (King et al. 2009). While there was no increase in eggs of Murray cod, there was an increase in YOY and larvae that the authors suggested could have been from increased habitat and food resources as a result of floodplain inundation. Similarly, in 2013-14 golden perch spawning was identified in the mid Murray at Barmah and Hattah and in the Lower Murray River, after flows of around 24,000 ML/day at Torrumbarry and 27,000 ML/day at the South Australia border in late spring 2013. Recruitment of golden perch, was only observed in the lower Murray, however, and these fish originated in either the lower Murray or Darling Rivers (Zampatti et al. 2015).

Data collected from 2014 to 2019 in the lower Murray concluded that (Ye et al. 2020, p102):

“...increased spawning [golden and silver perch], as indicated by the abundance of eggs and larvae, was associated with elevated in-channel (>20,000 ML/d) and overbank (>45,000 ML/d) flows in concert with water temperatures $\geq 20^{\circ}\text{C}$ during spring–summer.”

The results of multi-year monitoring and modelling of fish populations in the mid Murray River indicated that for Murray cod (Tonkin et al. 2020):

- An increase in spring discharge by 10,000 ML/day resulted in an associated 25% increase in recruitment strength.
- An increase in summer discharge (double the long-term annual median) would result in a 34% decrease in recruitment strength.
- Increases in spawning season flow variability (double the long-term annual median for three days) would result in a 94% decrease in recruitment strength.

Existing monitoring

There are several programs that currently measure fish metrics in the River Murray Channel (Figure 23). In addition, Flow-MER measures larval fish in the Edward-Wakool and Goulburn Selected Areas, providing a complementary data set for tributaries.

Gaps

There are a number of gaps, depending on the number of locations that fish monitoring is desirable. For example, the entire mid-section of the River Murray Channel has just two sites that are captured by the Murray-Darling Basin Fish Strategy (MDBFS) annual monitoring. Much of the existing monitoring is annual, which may be appropriate for abundance, condition, recruitment, but will not show spawning and larval fish development and movement over the course of an event.

Additional sampling of spawning and larval fish will be required in the NSW River Murray. If spawning is detected, then additional population census data that includes YoY will be required at a number of locations in the NSW River Murray.

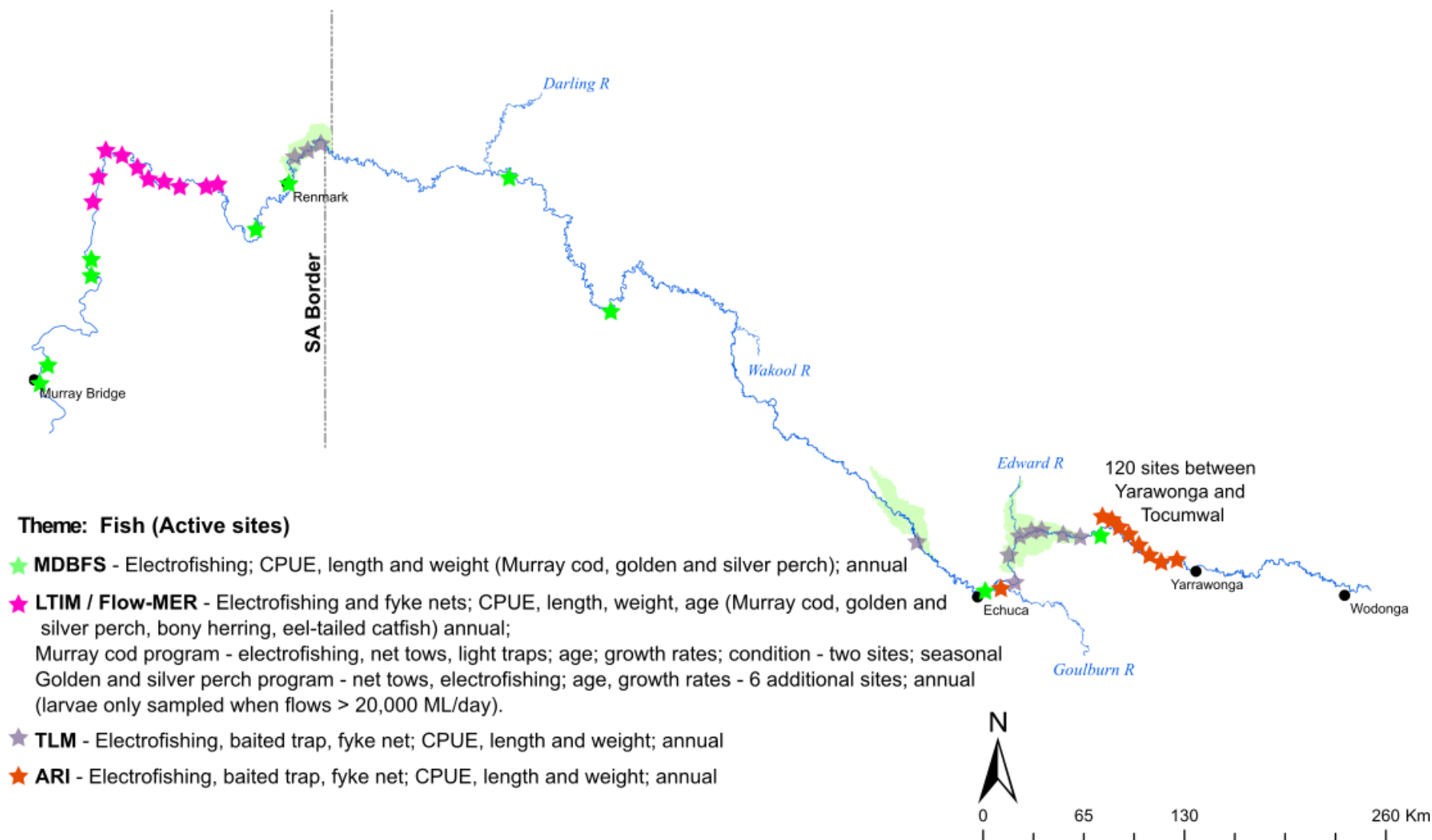


Figure 23: Existing fish monitoring on the main channel of the River Murray.

