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Murrumbidgee Environmental Benefits and Risks Analysis Synthesis Report

Reconnecting River Country Program

March 2023

Acknowledgement of Country

The Department of Planning and Environment acknowledges that it stands on Aboriginal land. We acknowledge the Traditional Custodians of the land and we show our respect for Elders past, present and emerging through thoughtful and collaborative approaches to our work, seeking to demonstrate our ongoing commitment to providing places in which Aboriginal people are included socially, culturally and economically.

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Murrumbidgee Environmental Benefits and Risks Analysis Synthesis Reports

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Cover image: River Red Gum and herbaceous wetland on the Murrumbidgee floodplain, Amelia Walcott DPE

Preamble

The Reconnecting River Country Program is investigating options to reduce or remove some of the barriers, or constraints, impacting environmental water delivery in the Murray and Murrumbidgee valleys (Figure 1). These options would enable environmental flows to connect more wetlands and low-level floodplains more frequently than is currently possible, improving ecological outcomes for the Murray and Murrumbidgee rivers and their associated floodplains.

The environmental benefits and risks resulting from potential changes to flow limits and flow regimes have been explored using a range of ecohydrological models (fish, vegetation, waterbirds, and ecosystem production themes) and qualitative/ semi-quantitative assessments (water quality (including hypoxic blackwater), weeds and geomorphology themes) developed in partnership with independent experts.

Each model or semi-quantitative assessment uses modelled river discharge time series to represent potential changes to the flow regime associated with the relaxation of flow constraints to levels associated with the flow limit options being investigated by the program. These modelled discharge time series have been developed by the NSW Department of Planning and Environment (the department) to represent the potential changes in flows with currently available environmental water entitlements.

This report synthesises the expected environmental benefits and risks associated with the flow regimes enabled by the flow limit options being investigated, drawing on a series of more detailed reports outlined below. These reports include contributions from a range of experts. We acknowledge and thank them for their considerable intellectual input.

	Native fish population modelling: Murray cod and golden perch Todd, C., Wootton, H., Koehn, J., Stuart, I., Hale, R., Fanson, B., Sharpe, C., Thiem, J. (2022). *Population modelling of native fish outcomes for the Reconnecting River Country Program: Golden perch and Murray cod: Final Report for the NSW Department of Planning and Environment*. Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, Heidelberg.
	Waterbirds Bino, G., Spencer, J., Brandis, K., Thomas, R. (2022). *Environmental benefits assessment – Waterbirds. Phase 2 – Project area – Murrumbidgee River*. Final report. June 2022. Prepared by University of New South Wales and NSW Department of Planning and Environment for the NSW Reconnecting River Country Program.

Vegetation

McPhan L.M., Capon S., Bond N.R., (2022) *Reconnecting River Country – Floodplain Vegetation Condition Predictive Modelling; Draft Final Part 2: Murrumbidgee River floodplain*, CFE Publication #27, Prepared for the NSW Department of Planning and Environment, Centre for Freshwater Ecosystems, School of Life Sciences, La Trobe University

Ecosystem production condition predictive modelling

Siebers, A., Crook, D., Silvester, E., Bond, N.R. (2022) *Production Condition Predictive Modelling – Part 2: Murrumbidgee River*. Report prepared by the Centre of freshwater Ecosystems, School of Life Sciences, La Trobe University (in collaboration with the NSW Department of Planning and Environment).

Water quality risk

McInerney P., Rees G., Wahid S., Chen Y., Cuddy S.M. (2022) *A qualitative assessment of the risks and benefits to in-channel water quality from changes in flow related to the Reconnecting River Country Program*. CSIRO, Australia.

Wolfenden, B and Baldwin, D. (2022) *Hypoxic blackwater time series assessment for the Reconnecting River Country Program*. Prepared by the NSW Department of Planning and Environment and Rivers and Wetlands for the NSW Reconnecting River Country Program.

Invasive species (weeds)

Capon, S., Grieger, R., Chauvenet, A., Johnston-Bates, J., Franklin, H., Burgoyne, H. (2022) *Reconnecting River Country: Weed risks and benefits assessment – Technical Report*. Griffith University. Report prepared for the NSW Department of Planning and Environment.

Geomorphology risk

Lauchlan Arrowsmith, C.S., Vietz, G., Wakelin-King, G., Grove, J., Rutherfurd, I., Cheetham, M., Martin, J., Gower, T.G., Al Baky, A., Woods, K., Lam, D., (2022). *Geomorphic assessment for the NSW Reconnecting River Country Program in the Murray and Murrumbidgee Rivers*, report prepared for the NSW Department of Planning and Environment.

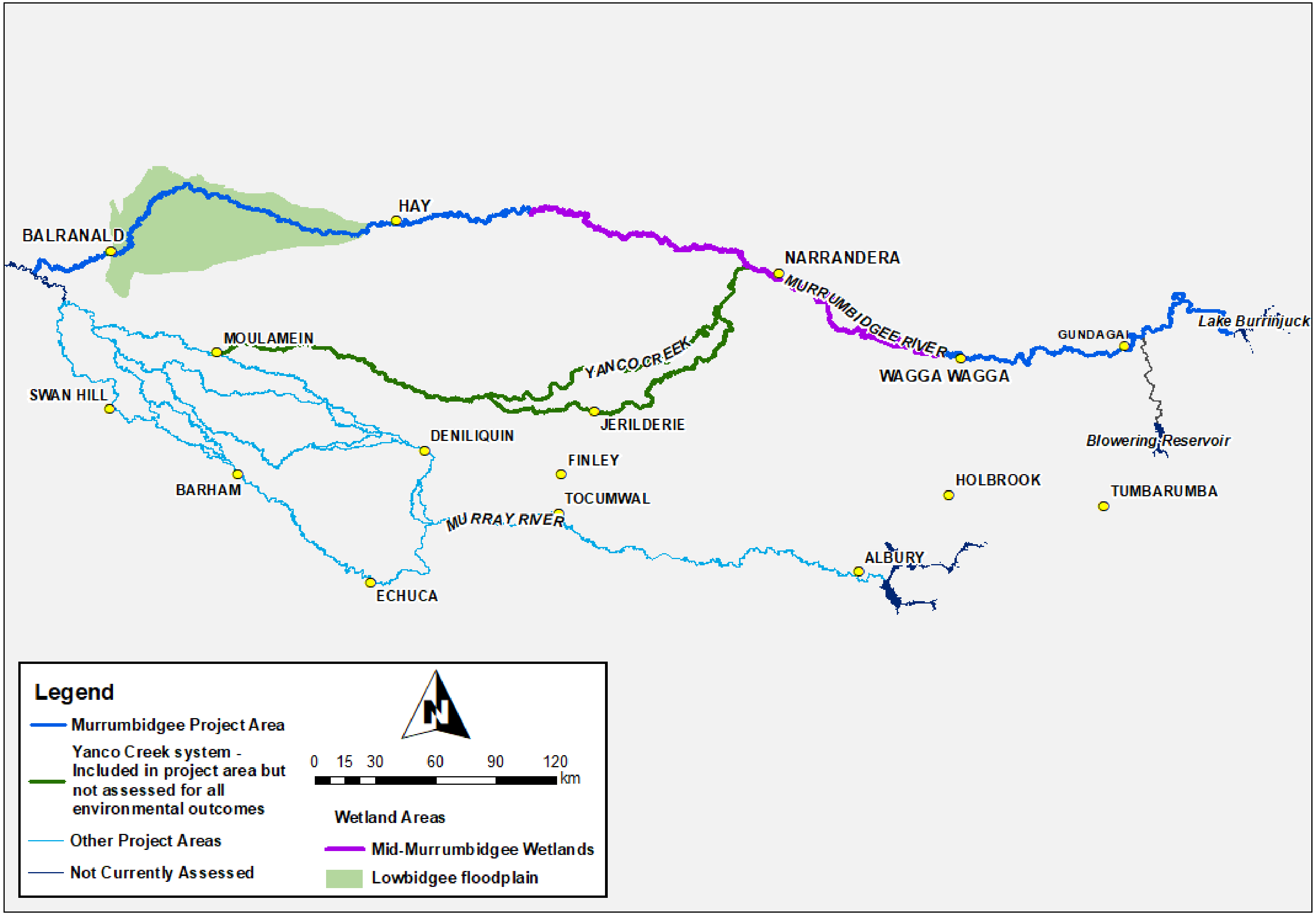

Figure 1: Project Areas for the program EBRA in the Murray and Murrumbidgee catchments

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1 Executive summary

The natural flow regime of the Murrumbidgee River has been significantly changed by river regulation and the consumptive use of water, resulting in fewer flows connecting wetland and floodplain environments. Wetlands, floodplains, and adjacent riverine environments along the Murrumbidgee River depend on these flows for their health and viability. This reduction in overbank flows has meant the floodplains have declined in condition and the health of adjacent river systems have suffered as the wetlands and floodplains now provide fewer resources such as food and habitat for aquatic flora and fauna.

The program is investigating options to relax or remove some of the constraints limiting the delivery of water for the environment in the Murray and Murrumbidgee valleys. A constraint is any physical, policy or operational barrier limiting the delivery of water for the environment. These options allow for more frequent environmental flows connecting wetlands and low-level floodplains than are currently possible, improving ecological outcomes for the Murray and Murrumbidgee rivers (Figure 1).

This Environmental Benefit and Risk Analysis (EBRA; Figure 3) is a major component of the options investigation and evaluation process being undertaken by the program, providing an assessment of the potential positive and negative environmental outcomes of the flow limit options being investigated. The EBRA assesses potential outcomes within the following themes:

- native fish – population response
- waterbirds – abundance and species richness response
- wetland and floodplain vegetation communities – condition response
- ecosystem production
- water quality risks
- invasive weed risks
- geomorphology risks.

The flow limit options being investigated by the program and assessed in the EBRA are listed in Table 1.

Table 1: Flow limit options being investigated in the Murrumbidgee system

Flow limit option	Flow limits at Wagga Wagga (ML/d)
Base case (W22)	22,000[1]
Option 1 (W32)	32,000[2]
Option 2 (W36)	36,000
Option 3 (W40)	40,000

(1 Current temporary flow limit applied by WaterNSW recognising local impacts

(2 Current water sharing plan limit

The EBRA has been informed by two key inputs:

- hydrological modelling representing system-wide flow regimes that may be possible using currently available volumes of water for the environment and the different flow limit options being investigated
- inundation mapping that provides an understanding of the spatial areas that may be inundated under the flow limit options being investigated.

This synthesis report describes outcomes at multiple spatial scales according to the nature of the theme assessments and with respect to the program project areas. Typically, results are presented at the following scales depending on theme (Figure 1):

- system scale – Burrinjuck to the Murray River Junction
- Burrinjuck to Hay Weir
- Hay Weir to the Murray River Junction

Summary of outcomes

System scale outcomes

- The relaxation of flow constraints has the potential to deliver substantial environmental benefits across the Murrumbidgee River system, for example:
  - an increase from less than half to nearly two thirds of floodplain habitats (creeks, wetlands, forests, woodlands and grasslands) that can be reached by environmental water, including doubling the area of river red gum, compared to the base case
  - increased river-wetland connections and greater ability to water the Mid-Murrumbidgee wetlands, with predicted improvement to a range of ecological outcomes
  - up to 34 per cent increase in the long-term average abundance of golden perch in the Murrumbidgee system
  - up to 23 per cent increase in the area of river red gum forests and woodlands remaining healthy during dry periods in the Mid-Murrumbidgee.
- The higher flow limit options enable much greater wetland and floodplain connectivity and would provide the most substantial benefits.
- Fish, vegetation and waterbird theme assessments all predict benefits during drier times when the relative contribution of water for the environment to river flows is greatest. During wet periods, dam spills and tributary flows dominate flows along our rivers and water for the environment is either not needed to create these elevated flows or provides a supplementary role alongside existing flows. During extreme dry periods there is insufficient water for the environment to deliver flows up to the flow limits assessed.

Note, for some themes there is currently limited scope to report on potential benefits in the Lowbidgee due to difficulty in modelling the complex flow paths and water management infrastructure, and gaps in inundation mapping. Subject to next phase funding for the program, the department intends to make refinements to the flow and inundation modelling to enable modelling of environmental benefits in this area and better reflect what may be achievable.

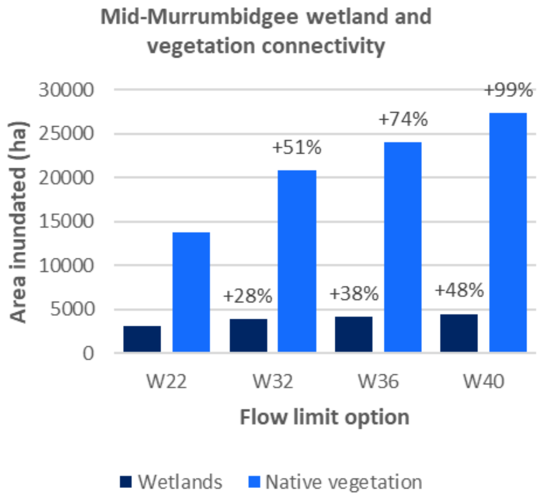
Outcomes by theme

Outcomes are described relative to the base case. Titles also denote whether the area assessed was the Mid-Murrumbidgee (Burrinjuck Dam wall to Hay) or the whole Murrumbidgee, including the Lowbidgee Floodplain.

Lateral connectivity; Mid-Murrumbidgee

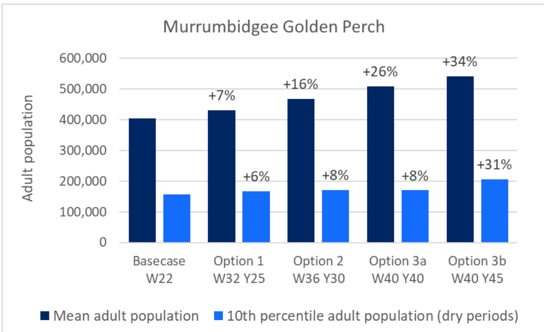
- Up to 48% increase in the area of wetlands that can be reached by water for the environment (between Burrinjuck Dam and Hay Weir).
- Up to 99% increase in the area of native vegetation that can be reached by water for the environment.

Up to 27% increase in frequency of wetland and floodplain reconnection flows in the Mid-Murrumbidgee wetlands (measured at Darlington Point).



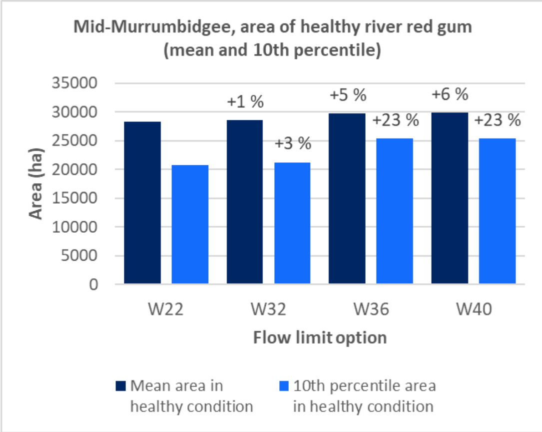
Native fish; whole Murrumbidgee

- Up to 34% increase in the long-term average abundance of golden perch in the Murrumbidgee River (47% increase in the Gundagai to Hay reach and 32% increase in the Hay Weir to Murray junction reach).
- Up to 31% increase in the abundance of golden perch during dry periods.
- Negligible change in Murray cod populations expected as life histories are less related to flow cues and floodplain inundation.
- Increased breeding and recruitment opportunities for floodplain and wetland specialist fish species, including locally extinct southern pygmy perch, southern purple spotted gudgeon, flat-headed galaxias and Murray hardyhead which are targeted for re-establishment in the Murrumbidgee. Also support for more common species such as Australian smelt and bony bream through delivery of more frequent wetland-connecting flows.



Wetland and floodplain vegetation; Mid-Murrumbidgee

- Up to 1,600 ha (6%) increase in healthy (good or moderate condition) river red gum forest over the long-term, with greatest benefits under the higher flow limit options.
- Increased resilience of river red gum communities, with up to a 4,700 ha (23%) increase in river red gum forest remaining healthy during dry periods.

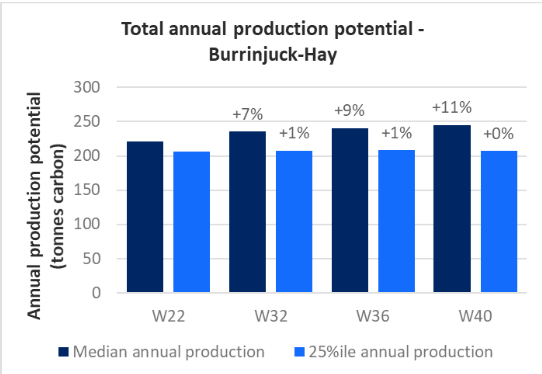


Waterbirds; Mid-Murrumbidgee

- Modelling predicted neutral outcomes for waterbirds, with model predictions of small increases in the number of species (2-3%) and waterbird abundance (1-2%) in the Mid-Murrumbidgee region.
- Waterbird predictive modelling was limited by the observational data on which models were developed, and these results are potentially reflective of that limitation.
- Despite the neutral modelling outcome, the relaxation of constraints is expected to have benefits for the availability and condition of waterbird habitat for breeding and foraging, and also for supporting breeding opportunities for some species.
- Benefits to habitat along the Murrumbidgee River are also expected to compliment and support outcomes at a broader scale in combination with outcomes in the Murray system.

Ecosystem production; Mid-Murrumbidgee

- Up to 11% increase in median production potential for the Burrinjuck to Hay Weir project area with the greatest benefit predicted for the highest flow limit option.
- Consistent production relative to base case in dry years.
- Increased energy and food availability for native fish and other biota, with small increases in production across multiple years.



Water quality; whole Murrumbidgee

- No significant increase to the risk of adverse water quality events.
- Benefits to water quality are likely, due to the potential to bring forward the timing of some high flow events from the warmer months (late spring/summer) to cooler months earlier in the season (winter/early spring), reducing the risk of hypoxic blackwater events and blue green algae blooms.

Invasive species – weeds; whole Murrumbidgee

- The predicted distribution of suitable habitat for invasive weeds decreases for amphibious species and increases for terrestrial species.

- Decrease in weed hot spots (areas of suitable habitat for 4 or more assessed weed species)
- When considering the predicted changes in habitat suitable for weeds and weed hot spots together with the potential impact of weeds and existing weed control methods, there is a slight benefit (reduction in weed impact) for the two higher flow scenarios (W36 and W40) and a slight increase in risk (increase in weed impact due to willows) in the lowest flow scenario (W32).

Geomorphology; whole Murrumbidgee

- It is unlikely that relaxed flow constraints will impact geomorphic processes in any Murrumbidgee sub-reaches.
- For most sub-reaches upstream of the branching of Yanco Creek potential geomorphic changes under the W40 flow limit option were assessed to be of *moderate* level consequence. These potential geomorphic changes primarily relate to the lateral migration of the river channel, billabong formation (meander cutoffs), and anabranching (further development of channels and flood runners).
- Due to the *moderate* level consequence rating, most sub-reaches in this area were assessed to have a *medium* risk rating (although impact remains unlikely). A range of options were identified that could reduce the risk to *low* in all reaches (including flow regime management, ongoing monitoring, and physical intervention).
- Murrumbidgee sub-reaches near Old Man and Beavers Creeks received a *medium* benefit rating, with the potential for increased deposition of sediment on banks. This supports natural levee formation — important for stabilising the riverbank crests against anabranching or flood runner development, and flow and flood routing.

2 Introduction

2.1 The Reconnecting River Country Program

The Murray–Darling Basin Plan aims to protect water-dependent ecosystems on the floodplain by setting out ecological objectives and targets to help guide their management and setting limits on the amount of water that can be taken. Water for the environment (recovered from consumptive use by the Australian and State Governments) is used to meet some of these outcomes. However, to date, environmental water managers in the Murrumbidgee Valley have only been able to deliver water to wetland and floodplain ecosystems in a limited number of locations, for example by pumping into individual wetlands adjacent to rivers (e.g. Yarradda Lagoon in the Mid-Murrumbidgee) or by providing river flows to a limited area of low-lying floodplain and wetlands within regulated areas, such as the Gayini-Nimmie-Caira floodplain.

While these actions have contributed to the protection of a small portion of wetlands, current operational limits within the system prevent delivery of water for the environment to most wetlands and low-lying floodplains. Operational limits (i.e. the height managed flows can reach in the river channel) exist to protect public infrastructure and third-parties, including floodplain landholders, from potential damage caused by inundation. However, these limits restrict the effectiveness of the recovered environmental water, with many water-dependent floodplain and wetland ecosystems at heights above the current operational limits.

The program is investigating ways to reinstate flow events that inundate wetlands and low-lying floodplains using existing water entitlements held by the Australian and State governments. Relaxing flow limits will enable environmental flows to be delivered high enough, and long enough, for water to flow through connector channels into wetlands, anabranches and low-lying floodplains, inundating wetland and floodplain vegetation and providing habitat and food resources for native fish and other animals. During moderate to wet years, this will provide opportunities to improve or expand the existing extent of populations while in drier years it will provide a critical safety net by protecting more wetland habitat.

This Environmental Benefit and Risk Analysis (EBRA) is a major component of an investigation and evaluation of options being undertaken by the program, providing an assessment of the potential positive and negative environmental outcomes of the flow limit options being investigated. The EBRA assesses potential outcomes within the following themes:

- native fish – population response
- waterbirds – abundance and species richness response
- wetland and floodplain vegetation communities – condition response
- ecosystem productivity
- water quality risks
- invasive weed risks
- geomorphology (e.g. erosion) risks.

2.2 Why is the program needed?

Floodplain rivers are among the world's most abundant and diverse ecosystems, supporting a wide range of aquatic and semi-aquatic organisms that are adapted to a highly variable regime of flooding and drying (Opperman et al. 2010; Figure 2). However, their dependence on hydrological events that connect the river and floodplain means they are also highly vulnerable to human-induced change. In the Murray–Darling Basin, dams and other water resource infrastructure have allowed for the capture and regulation of water, altering the amount and timing of river flows, including those that connect the river and floodplain. These alterations, coupled with changing land use, have impacted on the number and type of plants, animals and ecosystem processes that regulated floodplain river ecosystems can support (Thompson et al. 2019; Appendix A: Table 20). For example:

- by 2003, an estimated 76 per cent of Murrumbidgee River floodplain ecosystems were destroyed or degraded as a result of altered flow regimes, with remaining wetlands altered (Kingsford, 2003)
- over 19 years (1983–2001) on the Lowbidgee floodplain, waterbird numbers estimated during annual aerial surveys collapsed by 90 per cent (Kingsford & Thomas, 2004). There is a positive relationship between waterbird abundance and water availability on the floodplain (Wen et al. 2011)
- by 2004, the Murrumbidgee fish community was severely degraded. Eight of the 21 native species which previously existed in the catchment were either locally extinct or survive at very low abundances. In addition, high numbers of exotic fish species were present: 33 per cent of the species richness, 71 per cent of the total population and nearly 90 per cent of the total biomass (Gilligan, 2005)
- during droughts, degraded water quality originates mostly from return flows from irrigation and other diversions, with higher water quality dilution flows primarily from regulated dam releases. This suggests a need for water for the environment to support increased river flows during dry periods in the lower Murrumbidgee (Lowbidgee; Watson, 2020).

Without intervention these declines are expected to continue, limiting services these ecosystems provide for future generations.

Flow regulation in the Murrumbidgee River system has reduced the frequency of flows that inundate wetlands and low-lying floodplains (Page et al. 2005; see also Rolls & Bond, 2017). The loss of these flows can be especially damaging during dry years, where the persistence of species is highly dependent upon the relatively few events that occur and are easily intercepted and re-regulated by dams.

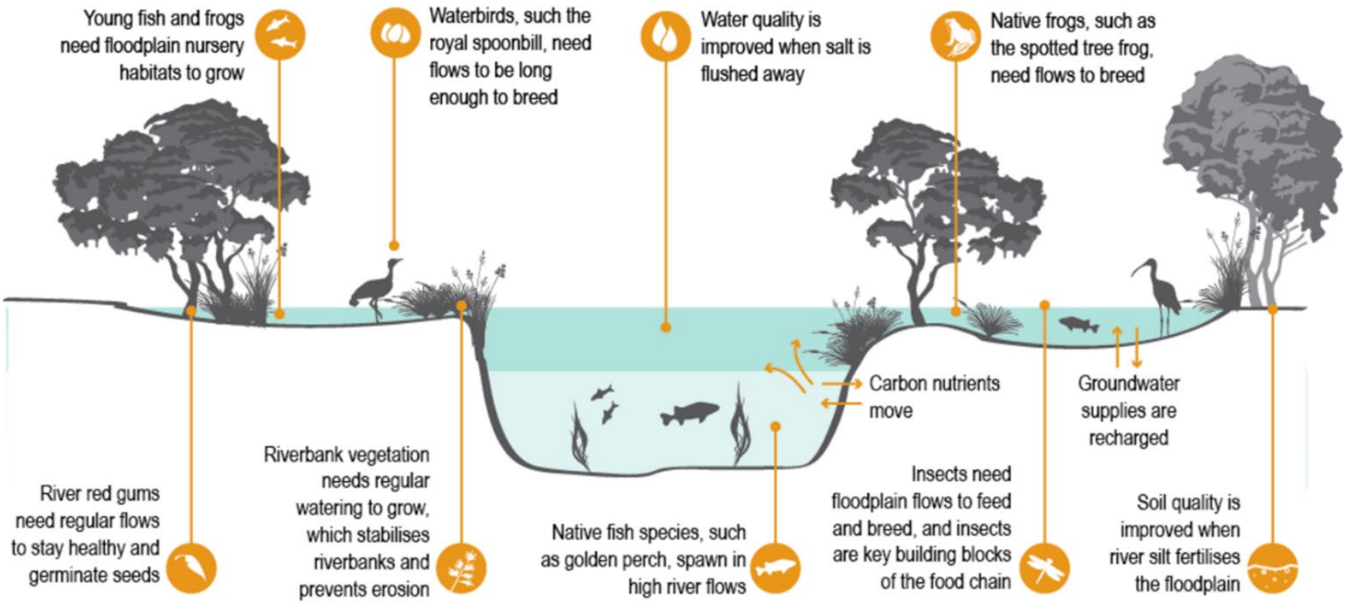


Figure 2: The importance of river floodplain connection (MDBA, 2015)

2.3 The Murrumbidgee catchment

The Murrumbidgee is a diverse catchment with both the Mid-Murrumbidgee River Wetlands and Lowbidgee Floodplain Wetlands listed in the *Directory of important wetlands of Australia* (DAWE, 2005) and partly protected through reserve networks. The Mid-Murrumbidgee area upstream of Hay is characterised by river red gum forests interspersed with permanent to semi-permanent shallow lagoons and swamps dominated by sedgelands (MDBA, 2012a). The Murrumbidgee below Hay includes the Lowbidgee Floodplain Wetlands, comprised of a mosaic of aquatic habitats including in-channel habitat, swamps, lakes, lagoons and floodplains where a diverse range of plant species are found (MDBA, 2012b). Across the complex system of interconnected creeks and channels of the Redbank region there are extensive stands of river red gum forests and river red gum and/or black box woodlands. The Gayini-Nimmie-Caira system is characterised by extensive lignum shrubland distributed along the channels and floodways providing important breeding waterbird habitat (Kingsford & Thomas, 2004).

2.3.1 Mid-Murrumbidgee wetlands

For the purposes of the EBRA projects, we classify the Mid-Murrumbidgee wetlands as those occurring between Burrinjuck Dam and Hay. Approximately 1,600 wetlands have been identified between Gundagai and Hay, with most between Carrathool and Hay (Frazier, 2001). Encompassing a range of habitats, the lagoons and swamps of the Mid-Murrumbidgee are dominated by non-woody vegetation, such as sedges. These semi-permanent to permanently inundated low-growing vegetation communities provide critical habitat for fauna, for instance native fish and frogs (Wassens et al. 2011). Yet in these wetlands, persistence and condition of non-woody vegetation has declined markedly, with river red gum saplings now encroaching upon some areas (MDBA, 2015). This is attributed to the longer durations between inundation events, with negative environmental outcomes for these wetlands.

Many Mid-Murrumbidgee wetlands are connected to the river through flood runners or small connector channels, meaning inundation in these wetlands occurs without Murrumbidgee flows overbanking. However, environmental flows cannot reach these flood runners as they are above the current flow limit of 22,000ML per day at Wagga Wagga. In some cases it is possible to pump water into these wetlands from the river, but this can only be done in a very few wetlands (e.g. Yarradda Lagoon) at great cost and with limited benefit to the adjacent river. Increasing the flow limit will increase our ability to effectively deliver environmental flows to many of the Mid-Murrumbidgee wetlands.

2.4 Flow limit options and EBRA

The flow limit options being investigated by the program for the strategic business case and assessed in the EBRA are listed in Table 2 and gauged at Wagga Wagga on the Murrumbidgee River. Water-dependent plants and animals that occupy higher parts of the floodplain, above the flow limits being investigated, will continue to rely upon large unregulated flow events.

Table 2: Flow limit options being investigated in the Murrumbidgee system

Flow limit option	Flows at Wagga Wagga (ML/d)
Base case (W22)	22,000[1]
Option 1 (W32)	32,000[2]
Option 2 (W36)	36,000
Option 3 (W40)	40,000

([1] current temporary flow limit applied by WaterNSW recognising local impacts

([2] current water sharing plan limit

For each EBRA theme, potential environmental outcomes were quantified using purpose-built ecohydrological models, or assessed using semi-quantitative / qualitative methods. The scale and scope of the assessments were dependent on the data and modelling techniques available. In most instances outcomes were estimated for only the Mid-Murrumbidgee, where hydrological modelling is most reliable (see Section 2.5).

Environmental outcomes were compared between the base case (current flow limit) and three relaxed constraint flow limit options (see Table 2), using modelled flow scenarios (modelled daily time series of flow at Wagga Wagga) described in Section 3.1. The flow scenarios integrate a range of river operations decision-making and risk management practices. The modelling does not represent historical delivery of water for the environment, but instead uses the known historical climate as a canvas for demonstrating how flows might be delivered across a long period of time with current levels of water use, infrastructure and system operations. Relaxed flow constraints does not increase the environmental water allocations, but instead allows existing allocations to be used more effectively. The flow scenarios were a key input to each environmental assessment.

In addition to the flow scenarios, some themes also used inundation modelling, representing the extent of potential wetland and floodplain inundation based on the amount of flow passing an indicator gauge. The Computer Aided River Management System for the Murrumbidgee River (CARM; DPI, 2015) 1D hydraulic model was used to represent the Mid-Murrumbidgee (Burrinjuck Dam wall to Hay). It was considered the most appropriate currently available product for representing long-term inundation patterns with the modelled flow time series.

Where EBRA themes included the Lowbidgee, a combination of Murrumbidgee-FIM (Sims et al. 2014) and an in-house inundation model (DPE-EHG, 2022) was used to model floodplain inundation. More information on the inundation modelling used can be found within the technical report prepared for each theme.

A quality assessment of CARM model inundation outputs with respect to satellite imagery of past events and expert opinion identified that the modelling provided a suitable representation of inundation extent from 22,000 ML/d at Wagga Wagga and above, but overstated inundation for flows below 22,000 ML/day at Wagga Wagga. To address this limitation, we attributed flows of 16,000 ML/day at Wagga Wagga as in channel and then removed all inundated areas attributed to flows between 16,000 ML/d and 22,000 ML/d at Wagga Wagga. For assessments that use the CARM model this means floodplains begin to inundate from 22,000 ML/day at Wagga Wagga.

The exception is the invasive species theme, where modelling had already been undertaken and could not be redone within the time constraints of this project. The inundation modelling used by the invasive species theme will therefore overestimate inundation at flows below 22,000 ML/day. As this overestimation effects relatively small areas of inundation and is consistent across the base case and all the flow limit options assessed, relative differences between scenarios are not expected to be substantially affected. Options to enhance the inundation modelling for environmental benefits and risk assessment, potentially using hydraulic models developed by the program in 2021-22, will be considered in future phases of the program.

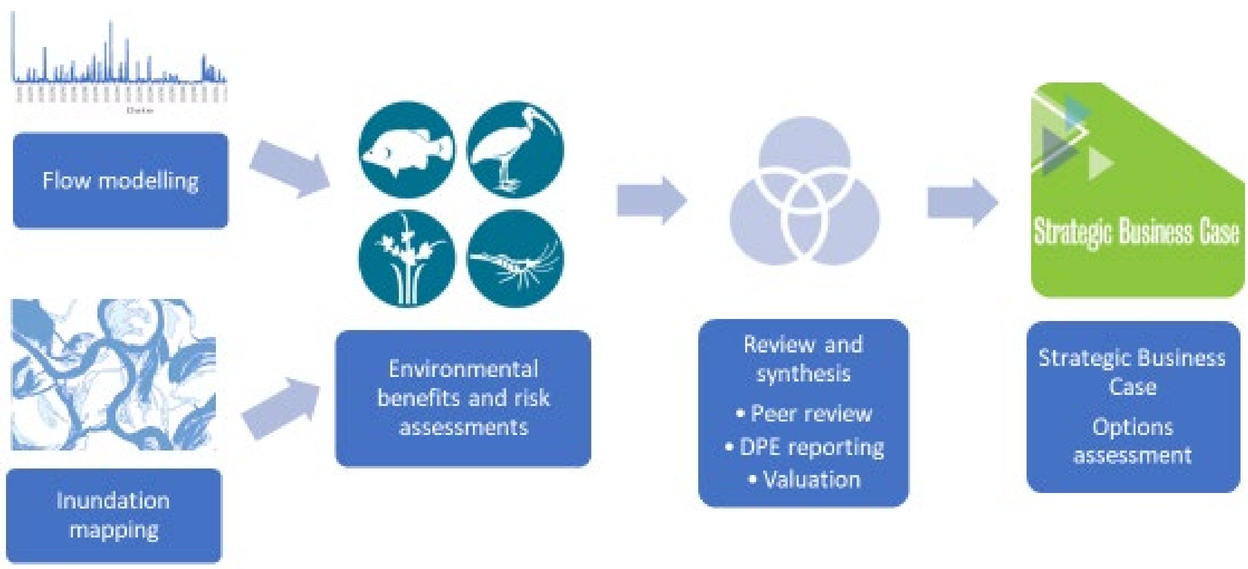


Figure 3: The EBRA process to inform the strategic business case

2.5 Modelling complexity in the Lowbidgee

Following construction of the original Burrinjuck Dam from 1907 to 1928, overbank flows on the Lowbidgee floodplain reduced significantly. Landholders lobbied for the construction of weirs and infrastructure to allow some inundation to still be provided to the Lowbidgee Floodplain, even under low river flows. Inundation was, and still is, critically important for supporting grazing enterprises on the floodplain. Two weirs were constructed in the 1940s: Maude Weir, which enables the inundation of the Gayini-Nimmie-Caira area, and Redbank Weir, which enables the inundation of South Redbank (Yanga National Park) and the North Redbank area.

In most years, the area inundated in these sections is mostly dependant on when water deliveries are made via infrastructure and is largely independent of river flows. This provides a challenge for inundation modelling, and we were not able to produce reliable predictions of inundation extent based on river flows - a key driver for many measures of environmental health. There are, however, large areas of the floodplain below Hay that are not able to be watered by infrastructure, and here the area inundated is still related to river flow levels. These areas include:

- The floodplain from Hay to Maude
- The floodplain downstream of Maude through to Redbank Weir pool that is adjacent to the River. On the northern bank this area is large and includes a section of Juanbung/the Great Cumbung Swamp.
- The floodplain below Balranald, including the Junction Wetlands.

For some EBRA themes, it is not possible to analyse the effect of river flows for these areas separately. For example, waterbird breeding events, species richness, and abundances in the region will be heavily influenced by the effects of inundation in the large Gayini-Nimmie-Caira and Redbank sections of the Lowbidgee where inundation may be due to infrastructure delivery, not river flows.

Similarly, there are challenges in modelling flow regimes in the Lowbidgee, given the complexity of the landscape and flow paths, and the influence of infrastructure if it is operated. The Source Murrumbidgee Model is currently not configured to represent this complexity and is therefore unable to represent aspects of the flow regime.

Given the above limitations, we are unable to obtain reliable results for the Lowbidgee for several EBRA themes. Where these limitations would have affected EBRA outcomes Lowbidgee results were excised from models, except in the case of Invasive species (see below). The native vegetation, ecosystem production and waterbird themes only present data from the Mid-Murrumbidgee. Remaining themes were able to include Lowbidgee results for the following reasons:

- Native fish; as models are based on river flow analysis and the model is largely within the Murrumbidgee River channel, so not subject to the issues surrounding floodplain inundation.

- Water quality & Geomorphology; while results do use the modelled flow data, this is only as an event counter at Hay and therefore not as affected by the issues detailed above. Further, rather than a predictive model based on the modelled flow, risk matrices were produced using multiple lines of independent evidence, of which the modelled flow is just one dataset. This limits the effect of Source issues on the final outcome.
- Invasive species; the Murrumbidgee Species Distribution Model was run with the both the Mid-Murrumbidgee and Lowbidgee flow data having their own contributing sub-models. There was insufficient time to decompose these sub-models and re-run the SDMs, however, there is the standalone expert elicitation dataset, which concurs with model results. Future modelling can address the Lowbidgee component of this model.

3 Hydrological modelling of potential environmental flow outcomes

River system hydrological modelling has been used to obtain a realistic indication of the potential environmental flow outcomes from the program over the long-term under the varying climate conditions experienced in the Murrumbidgee valley. Outcomes of the hydrological modelling have been used as direct inputs to environmental benefit and risk assessments, so that these assessments reflect likely environmental flow outcomes from the program and river flow regimes over extended time periods.

River system modelling has been undertaken using the Source Murrumbidgee Model, a hydrological model of the Murrumbidgee River system developed by the NSW Department of Planning and Environment. The model version used for this work represents current system operations, current environmental water recovery, and historical climate over the period 1 May 1890 to 28 March 2021 (130 years). This version of the model was further developed by the department to include the program flow scenarios and water delivery strategies described in this report.

3.1 Flow limit options modelled

Table 2 shows the flow limit options represented in the modelling. For all flow limit options the constraint on flow releases on the Tumut River was maintained at 9,000 ML/d at Oddy's Bridge and 9,250 ML/d downstream of the Adjungbilly Creek junction.

3.2 Environmental water recovery represented in the modelling

The modelling assumes that the following environmental water is available for use in delivering environmental flows associated with the flow limit options investigated:

- held environmental water available as December 2019:
  - Commonwealth Environmental Water Office (CEWO; approximately 373 GL of high security, general security, conveyance and supplementary entitlements)
  - NSW Government holdings (approximately 186 GL of general security and supplementary entitlements)
  - the Living Murray holdings (approximately 85 GL of general security entitlements)
- Environmental Water Allowances 1, 2 and 3 as specified in the Water Sharing Plan for the Murrumbidgee Regulated Water Source 2016

The model calculates environmental water account balances daily including entitlement allocations, carryover, and use consistent with water sharing plan provisions. The model limits the use of the environmental water to the account balance available.

3.3 Environmental water delivery strategy

The modelling assumes that environmental flows that would be delivered under the flow limit options are ordered at Wagga Wagga. The environmental flow actions are based on the Environmental Water Requirements (EWRs) specified in the Murrumbidgee Long T erm Water Plan (LTWP; DPIE, 2020a&b) at Wagga Wagga (Planning Unit 4). The model achieves these actions through releases of environmental water from Burrinjuck and Blowering Dams, in combination with other releases from those storages and unregulated flows from tributary valleys. The EWRs at Wagga Wagga are the basis of the environmental flow actions, however, this approach has been adopted with the understanding that provision of these flows at Wagga Wagga would provide environmental outcomes along the Murrumbidgee River, both upstream and downstream of Wagga Wagga.

The EWRs in the LTWP are not intended as a fixed set of environmental water actions for environmental water managers to deliver. It is intended that variability in flow rate and duration will be a feature of future environmental water deliveries. Accordingly, a number of actions were established in the model reflecting a range of flows from the current constraint limit of 22,000 ML/d at Wagga Wagga up to 40,000 ML/d for the highest flow limit option.

Table 3 shows the actions included in each of the flow limit options. For all actions the rate of rise and fall in flow was set to 15 per cent increase in flow rate per day reflecting guidelines in the LTWP based on analysis of modelled natural flows.

Table 3: Environmental flow actions included as environmental orders at Wagga Wagga for each flow limit option modelled

Peak flow (ML/d)	Duration at peak flow (days)	Flow limit option			
		Base case 22,000	Option 1 32,000	Option 2 36,000	Option 3 40,000
22,000	5	✓	✓	✓	✓
28,000	5	✗	✓	✓	✓
32,000	5	✗	✓	✓	✓
36,000	5	✗	✗	✓	✓
40,000	5	✗	✗	✗	✓

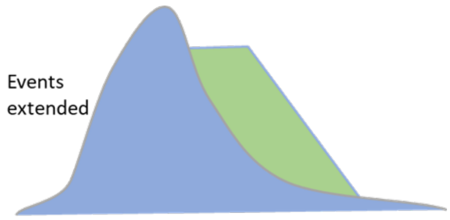
The modelling has adopted a delivery strategy (i.e. a strategy that determines when environmental flow actions should be ordered) with three nested delivery types that respond to climate and water availability conditions in a way that makes efficient use of environmental water and adopts more significant interventions as the duration since the last flow event increases, indicating higher ecological priority for delivering these events. The three delivery types are described in below.

All orders are timed so that flows return to in-channel levels before the end of November.

Delivery types used to schedule environmental flow orders

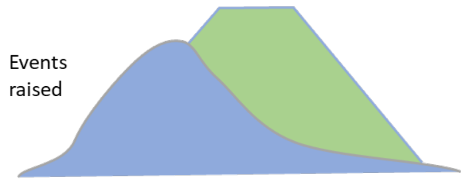
1. Extending and/or raising an existing 'high' flow event

This is a highly efficient method of achieving environmental flow outcomes, building on existing high flows that don't meet the required flow rate and duration. This delivery type is given the greatest timing window (May to November), and the model will seek to implement this delivery type each water year if the opportunity arises.



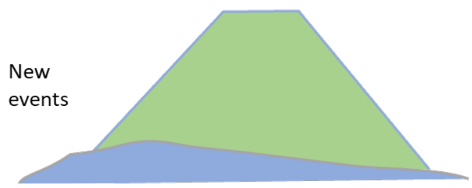
2. Raising and extending and existing 'medium' flow event

This delivery type requires the use of larger volumes of environmental water, and so it is expected that environmental water managers would wait for increased environmental demand before adopting this type of delivery. The model waits a year since the last flow event before incorporating this approach, and the timing window is also pushed back later in the season (July to November) to give first opportunity for higher flows triggering the first delivery approach.



3. Delivering a 'new' event under low flow conditions

This delivery type utilises the most environmental water, and so it is expected that environmental water managers would wait for increased environmental demand before adopting this type of delivery. The model waits for two years since the last flow event before adopting this approach and the timing window is also pushed back further (September) to give first opportunity for higher flows triggering the other delivery approaches. Where conditions have been relatively dry over the last 5 years this action can also trigger in early June, if sufficient water is available.



The model estimates the volume of environmental water required to deliver the actions and only orders those actions that are considered feasible given the amount of environmental water available at that time. Where the criteria for multiple actions occur concurrently the model is configured to prioritise the highest flow action (based on peak flow rate), as these actions are typically hardest to achieve from a water availability perspective and opportunities need to be taken when they arise.

In addition to the environmental actions described above, the Source Murrumbidgee Model includes a range of environmental actions reflecting existing environmental watering priorities, including (as examples) deliveries to Gayini-Nimmie-Caira and Yanga National Park. These have been retained in the model, however, the delivery of higher flows in the model through the relaxation of constraints will impact on the pattern of deliveries to these sites.

3.3.1 Managing the risk of above target flows

The modelling adopts some simple strategies to reduce the likelihood of exceeding target flows:

- commencing orders on the receding limb of existing flow events (for delivery types 1 and 2), reflecting that river operators would have a higher degree of confidence in flows once inflows have peaked
- cancelling orders when tributary flows rise significantly, to reduce the risk of exceeding target flows

The model also considers antecedent conditions and prevents orders for RRCP flows from occurring when one or more of the following criteria are met:

- the target flow magnitude and duration has been achieved within the last 90 days
- a flow of greater than 90,000 ML/d has occurred at Wagga Wagga in the last 90 days
- a flow of greater than 50,000 ML/d has occurred at Wagga Wagga in the last 7 days

These criteria would act to reduce the likelihood of above target flows downstream of Wagga Wagga, preventing orders during wet periods when losses and attenuation downstream of Wagga Wagga may be reduced, and higher flow outcomes achieved further downstream.

These strategies are provisional and will be reviewed and potentially expanded in modelling for the final business case to incorporate outcomes from concurrent work investigating mechanisms to manage river operations risks.

3.4 Modelled environmental flow outcomes

Modelled flow time series for the program base case and flow limit options were provided directly to the teams that have undertaken the environmental benefit and risk assessments for incorporation into those assessments in the most appropriate manner. Summary flow outcomes are presented and discussed here.

Key observations from the modelling are:

- there is sufficient water for the environment to deliver the environmental flow actions enabled by the relaxation of flow constraints and significantly increase the frequency of associated flows (Table 4, Figure 4)
- the frequency of flows up to the relaxed constraint limit increases relative to the base case with upstream areas experiencing the greatest change, and progressively less change in the downstream direction (Figure 5)
  - up to 15 per cent increase in frequency of wetland and low-level floodplain connecting flows between Gundagai and Wagga Wagga
  - up to 10-12 per cent increase in frequency of wetland and low-level floodplain connecting flows between Wagga Wagga and Darlington Point, and in the upper Yanco Creek system
  - 5-10 per cent increase in frequency of wetland and low-level floodplain connecting flows downstream of Darlington Point to Balranald, and in the mid to lower Yanco-Billabong Creek system
- the achievement of EWRs (both proportion of years EWRs achieved and duration of dry spells) show significant improvement in the Murrumbidgee River upstream of Gogeldrie Weir, and smaller changes in other areas
- the model shows the potential for significant improvements in environmental flows during prolonged dry periods such as the late 1890s/early 1900s (Federation Drought), 1940s (World War II Drought) and 2000s (Millennium Drought) (Figure 4).
- there are no modelled high flow deliveries in the very dry years (e.g. 2006 to 2009) owing to reduced environmental water availability and no existing flow events to extend or raise (Figure 4)
- there are no modelled high flows delivered in the very wet years (e.g. 1956, 1974, 1993) owing to environmental water requirements already being met (together with potential adverse flooding impacts) and no orders placed in the model
- the frequency of flows above the relaxed constraint limit reduces slightly relative to the base case as greater environmental flow releases enable greater dam air space creation and the potential for flood mitigation benefits (Table 5)
- Table 5This effect is greatest for the higher flow limit options and reduces for the lower flow limit options (Figure 4)

Table 4: The number of years with flow orders for each model scenario, for each environmental flow action (total length of modelled flow record is 130 years)

Many orders augment an existing flow event, so these numbers do not equate to additional events

Flow action (ML/d)	Base case W22	Option 1 W32	Option 2 W36	Option 3 W40
22,000	36	15	15	15
28,000	NA	18	6	3
32,000	NA	43	5	3
36,000	NA	NA	65	31
40,000	NA	NA	NA	36

Table 5: The number of years with flows of at least 5-days duration at Wagga Wagga (total length of modelled flow record is 130 years)

Flow threshold (ML/d)	Base case W22	Option 1 W32	Option 2 W36	Option 3 W40
22,000	82	86 (+4)	86 (+4)	85 (+3)
28,000	69	80 (+11)	80 (+11)	80 (+11)
32,000	60	71 (+11)	80 (+20)	80 (+20)
36,000	56	57 (+1)	66 (+10)	72 (+16)
40,000	52	51 (-1)	53 (+1)	57 (+5)

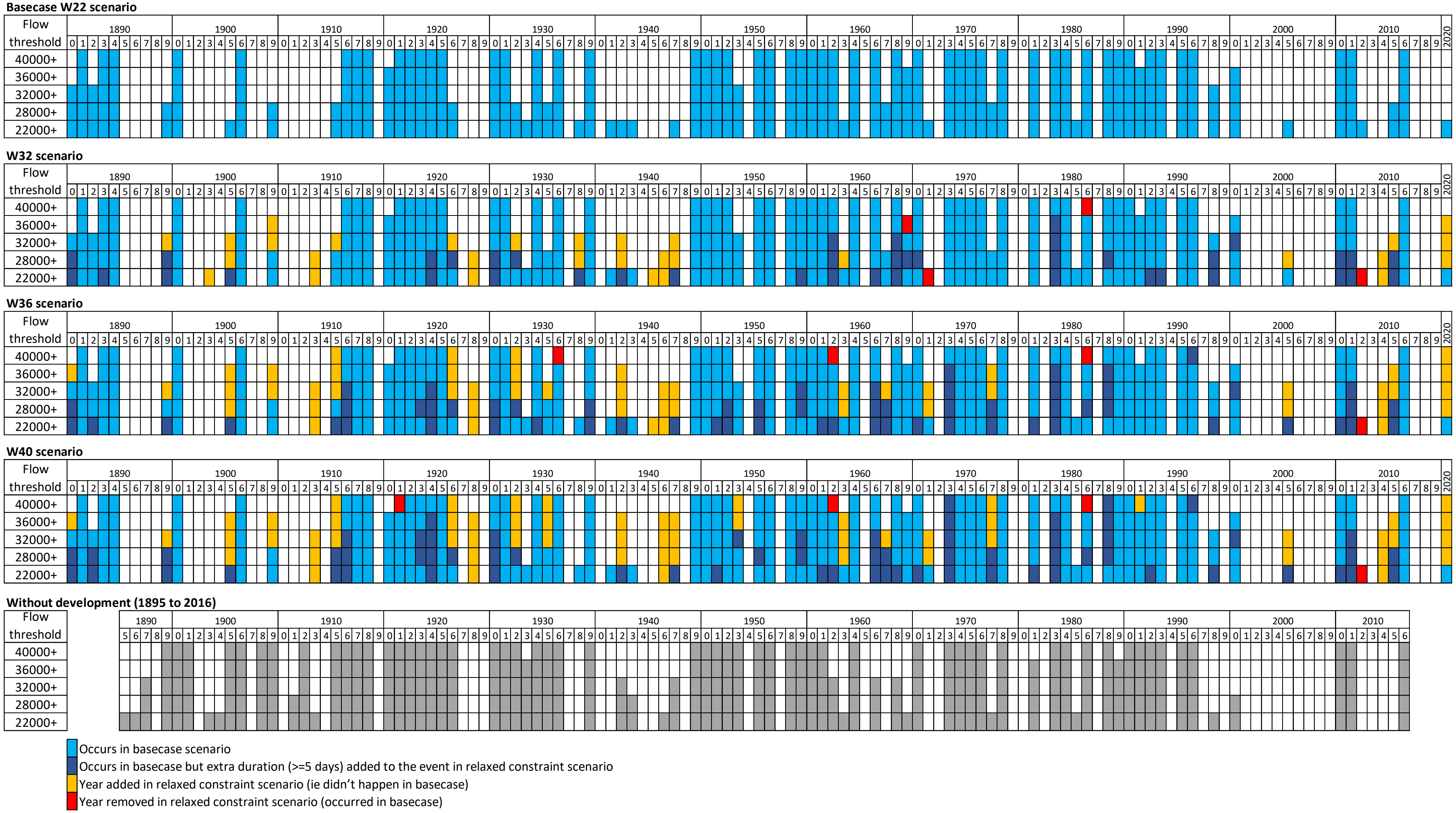


Figure 4: Years when flows exceed selected thresholds for a total duration of 5 days or more at Wagga Wagga for program flow limit option scenarios

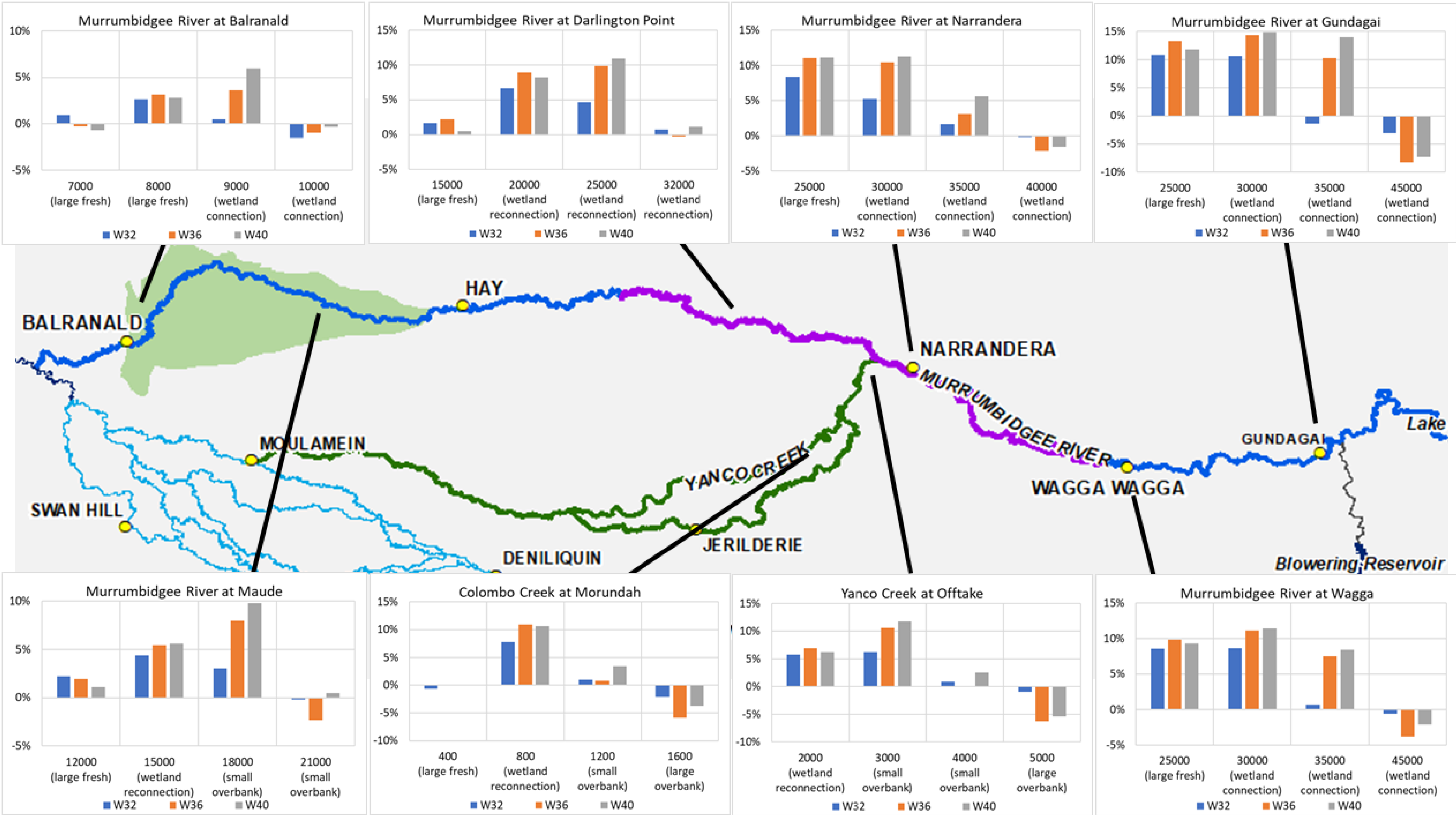


Figure 5: Change in proportion of time flows experienced at sites through the Murrumbidgee system for program flow limit option scenarios

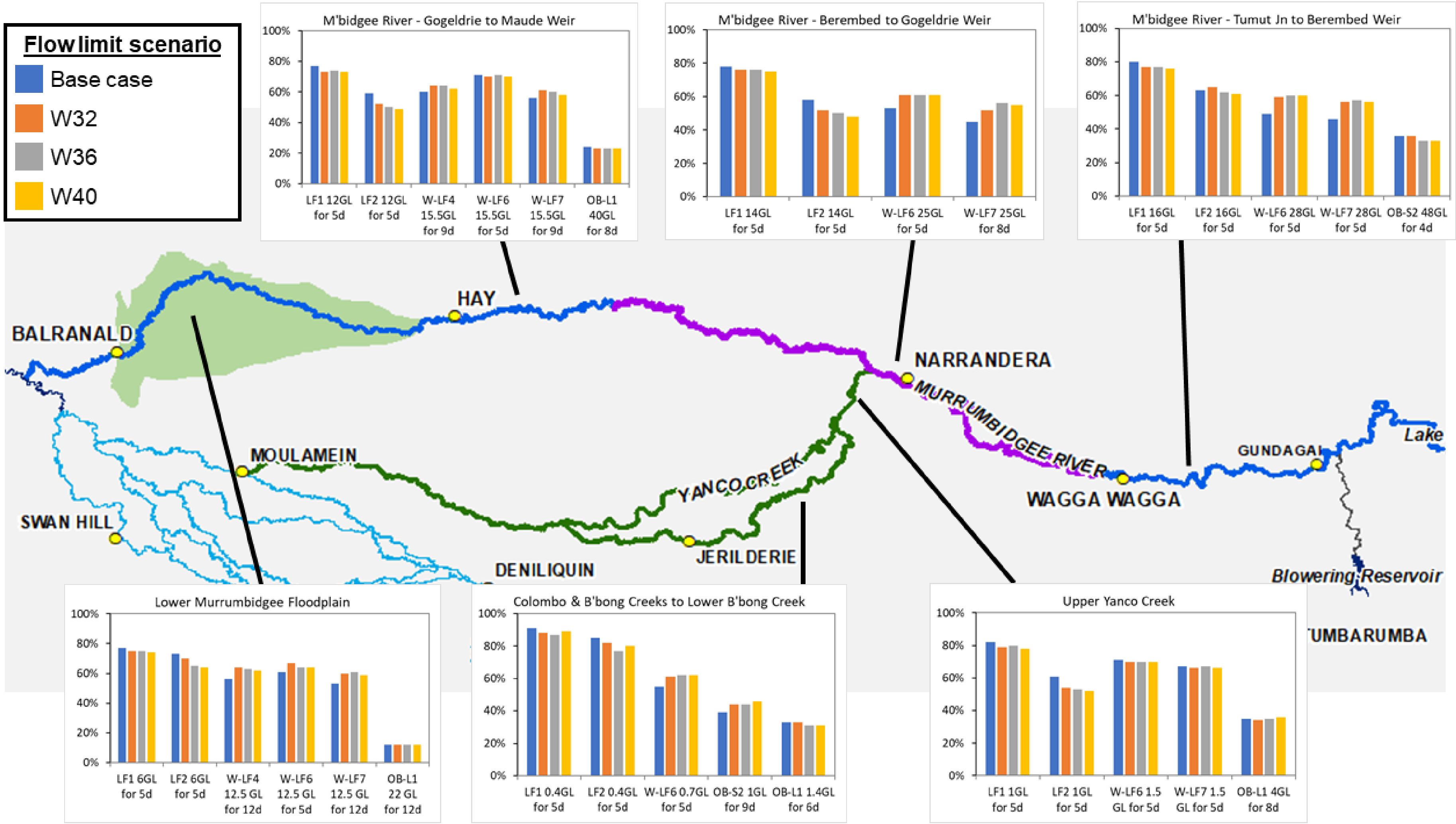


Figure 6: EWRs – proportion of years EWRs are achieved. These charts present selected EWRs within the flow range potentially affected and show the proportion of years they are achieved under different flow limit scenarios at different locations

Each EWR is given a specific code that abbreviates the EWR name (e.g. LF1 for large fresh 1). W-LF and OB are *wetland connection flows* and *overbank flows* respectively. EWR codes are detailed further in the Murrumbidgee LTWP (DPIE, 2020b).

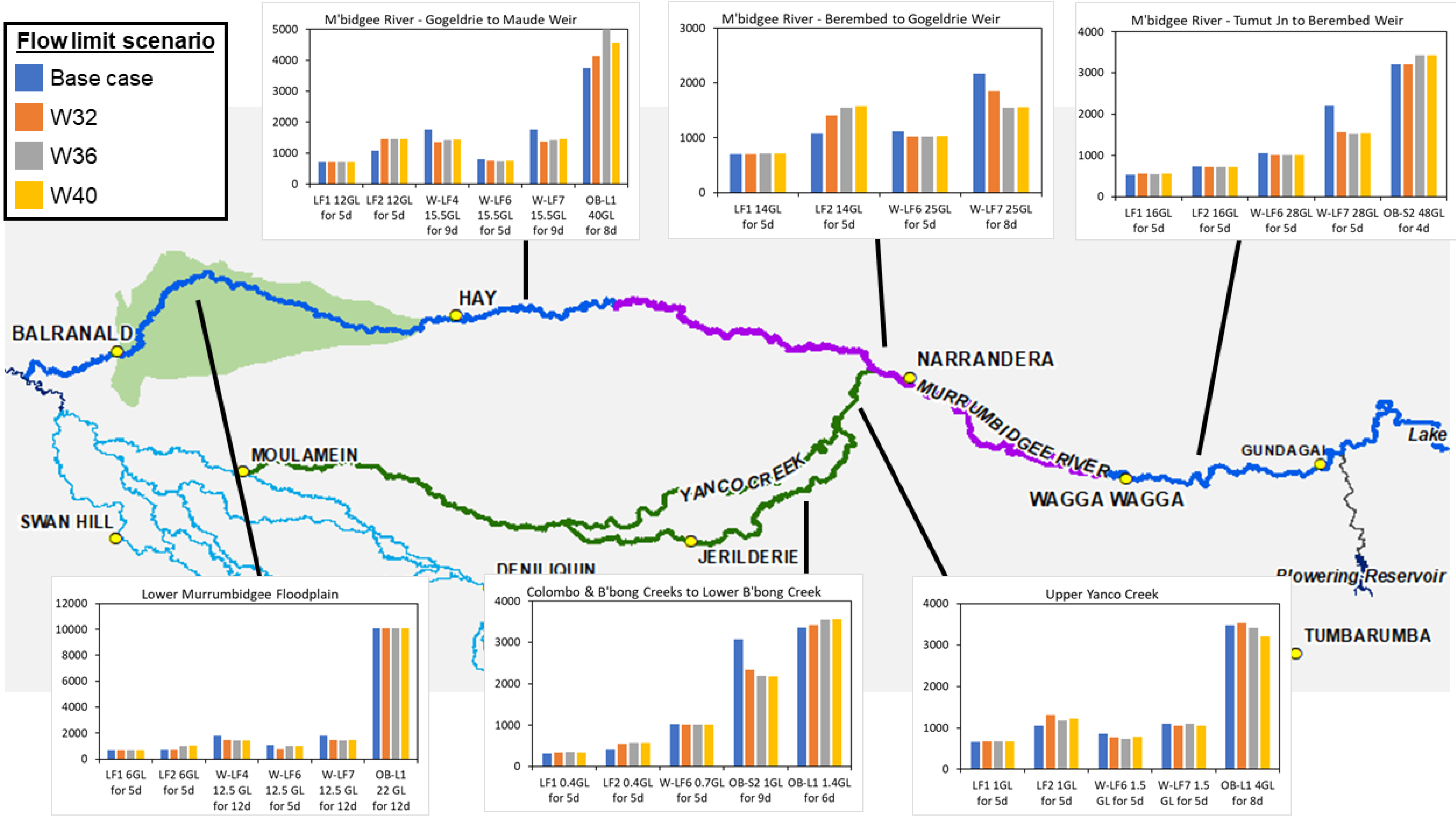


Figure 7: EWRs – 95th percentile duration of dry spells (in days) between EWRs (selected EWRs within the flow range potentially affected)

These charts present selected EWRs within the flow range potentially affected and show the 95th percentile duration of dry spells (in days) between EWRs being achieved under different flow limit scenarios at different locations. Each EWR is given a specific code that abbreviates the EWR name (e.g. LF1 for large fresh 1). W-LF and OB are *wetland connection flows* and *overbank flows* respectively. EWR codes are detailed further in the Murrumbidgee LTWP (DPIE, 2020b).

4 Environmental benefit assessments

4.1 Lateral connectivity

Relaxed flow constraints will significantly increase the area of wetland environments (up to +48 per cent), and native vegetation communities (up to +260 per cent) that can be inundated by deliveries of water for the environment. As a result, the frequency at which these environments can be inundated is greatly increased - a key requirement for sustaining native floodplain vegetation types, stimulating in-stream productivity, and providing habitat and food resources for native fish, waterbirds, and other animals.

Flow regulation in the Murrumbidgee River has reduced lateral (floodplain) connectivity by reducing the frequency of flows that inundate wetlands, anabranches, and low-lying floodplain areas (Page et al. 2005, MDBA 2012a). This reduction can be seen in Table 6 where only 44 per cent of total floodplain wetland areas across the Mid-Murrumbidgee can be connected by regulated flows under current constraints. This reduction in lateral connectivity is associated with negative ecological outcomes for floodplain ecosystems, especially during drier years. Raising flow limits will allow environmental water to reconnect wetlands, anabranches, and low-lying floodplain areas, thus partially mitigating the effects of regulation.

Table 6: Percentage of the total area of wetlands that can be inundated by an environmental flow delivery at investigated flow limits (Murrumbidgee River, Burrinjuck Dam to Hay Weir)

Flow limit option	Percentage of the total area of wetlands inundated (%)
Base case (W22)	44
Option 1 (W32)	57
Option 2 (W36)	61
Option 3 (W40)	65

The impact of relaxed flow constraints on lateral connectivity was investigated through a combination of geospatial and hydrological analyses. Firstly, the spatial extent of potential inundation for each flow limit option was derived using an inundation model developed using hydraulic model outputs of inundation extent from CARM. Vector maps of wetlands (Brooks, 2021; Crossman & Li, 2015) and vegetation types (OEH, 2016) on the floodplain were cross-tabulated with the predicted extents to determine the area of said environments inundated. Cross tabulation was performed in Python (version 2.7) using the tabulate area tool from the ArcPy library.

Approximately 3,900 ha (Option 1) to 4,500 ha (Option 3) of wetlands would be inundated in the Mid-Murrumbidgee under the flow limit options being considered (Figure 8). This is 900 - 1,500 ha more than the ~3,000 ha of wetlands that can be inundated under the current operational flow limit of 22,000 ML/d. This corresponds to a +28 to +48 per cent increase in area of wetlands potentially inundated. With ~6,900 ha of wetland areas mapped across the total Mid-Murrumbidgee floodplain, raising flow limits increases the proportion of total areas that can be reached from 44 per cent (base case) to 57, 61, or 65 per cent (Options 1 to 3 respectively). In other words, an increase from less than half to nearly two thirds of wetland areas could be inundated by raising the flow limit to 40,000 ML/day. While this is a significant improvement it highlights that (at a minimum) 35 per cent of wetland areas would still be out-of-reach from environmental flow deliveries under relaxed constraints.

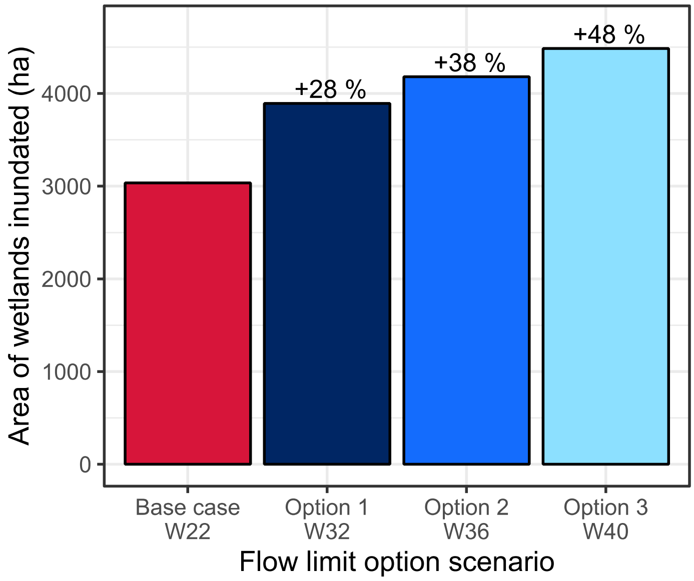


Figure 8: Maximum potential area of wetlands inundated under different flow limit options in the Murrumbidgee catchment (Burrinjuck Dam to Hay Weir)

Labels above columns represent the percentage increase in area relative to the base case. Here inundated area was determined using the CARM inundation model.

Relaxed flow constraints largely increase the area of native vegetation that can be inundated by environmental water (Figure 9 and Appendix C). For example, under current constraints ~10,400 ha of river red gum can be watered using environmental water in the Mid-Murrumbidgee. Under relaxed flow constraints between 15,800 ha (+52 per cent; Option 1) and 20,600 ha (+98 per cent; Option 3) of river red gum forest can be watered — increases of 4,400 ha and 10,200 ha respectively. While areas of river red gum forests and woodlands experience the greatest increases to inundated area, large proportional increases occur for multiple native vegetation types. For example, approximately three and a half times more black box woodland (+260 per cent) could be watered by a 40,000 ML/day flow at Wagga Wagga compared to a delivery at the current limit (Figure 9).

As detailed in Section 4.4 below, this substantial increase in lateral connectivity significantly increases the potential for water for the environment to sustain healthy native vegetation conditions, particularly during periods of drier climate.

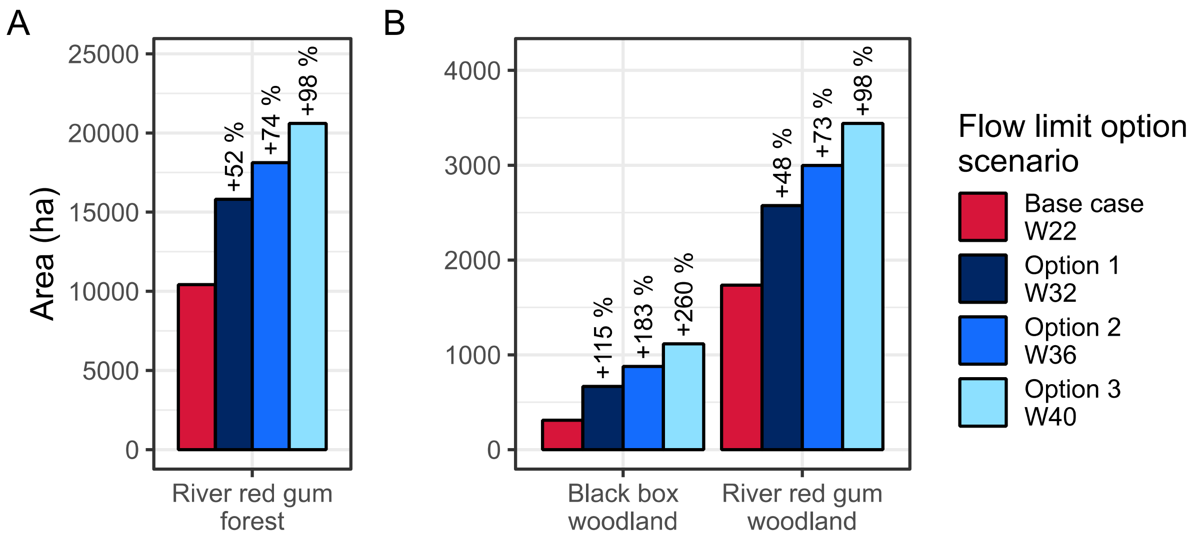


Figure 9: Maximum potential area of vegetation type inundated under different flow limit option scenarios in the Murrumbidgee catchment (Burrinjuck Dam to Hay Weir)

Labels above columns present the percentage increase in area relative to the base-case flow limit option scenario. Note that sub-figures (A and B) are presented on different y-axis scales for readability. Here inundation area was determined using the CARM inundation model.

Figure 10 shows the predicted areas of inundation under different flow limits for the Yanco Weir to Darlington Point sub-reach of the Murrumbidgee; a reach that possesses many ecologically significant off-channel wetlands (Mid-Murrumbidgee Wetlands; Section 2.3.1). Here we see the spatial patterns of increased lateral connectivity, with lower-lying wetlands and flood runners/ anabranches increasingly filling and eventually larger areas of floodplain becoming inundated as wetland-connection thresholds are exceeded. We also see that environmental water deliveries under relaxed flow constraints do not uniformly inundate the floodplain, but specifically target the filling of low-lying wetlands. While some wetlands are connected under a current maximum delivery (22,000 ML/day at Wagga Wagga), the majority are not.

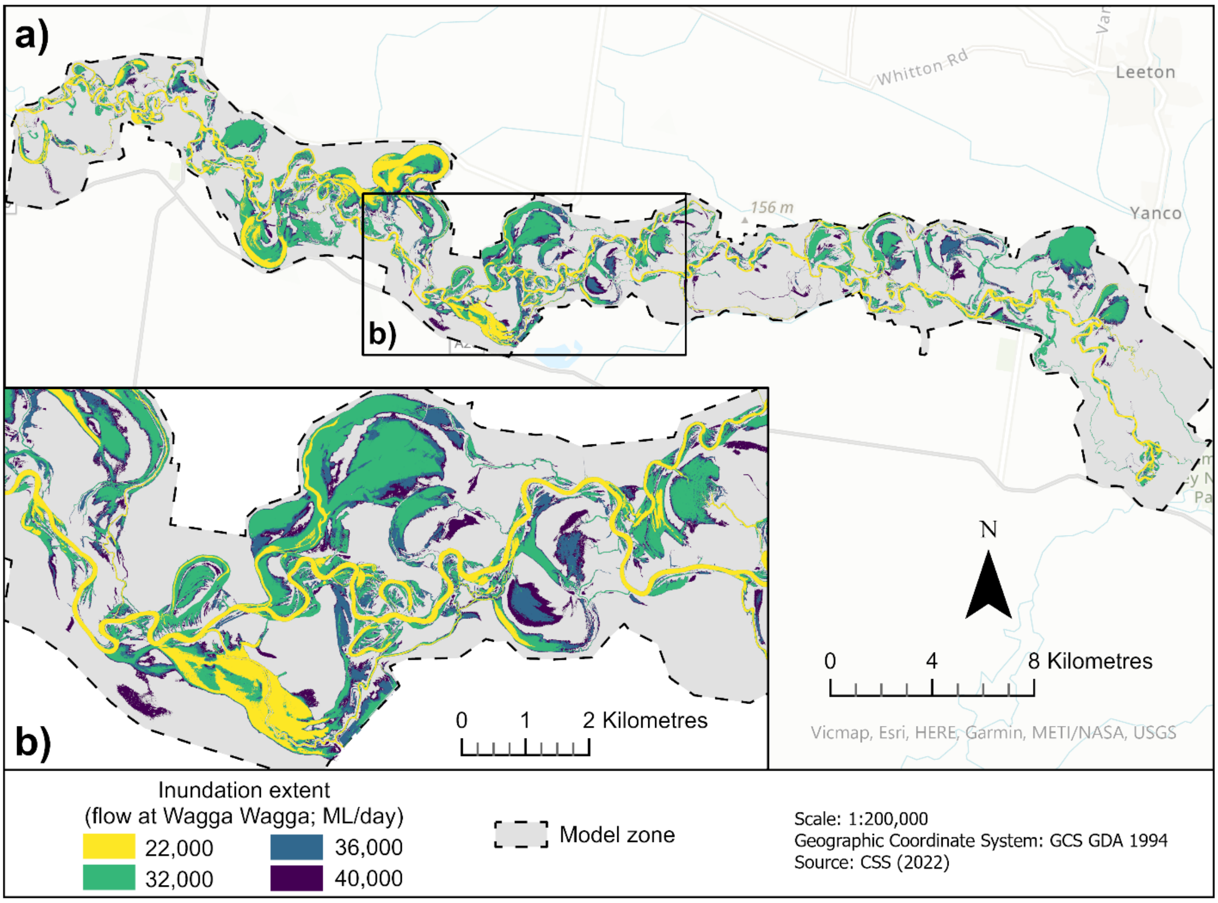


Figure 10: Map of inundation extent under each flow limit option for a Mid-Murrumbidgee sub-reach (Yanco Weir to Darlington Point; Work Package 7)
Facet a) presents the full modelled extent, and b) highlights finer-scale detail. Inundation extents were generated from recently developed hydraulic models for the Murrumbidgee River (CSS, 2022)

4.1.1 Expected outcomes of increased wetland connection

The Mid-Murrumbidgee includes many wetlands along the river corridor, such as natural lagoons, anabranches and swamps in former river channels. These wetlands support diverse flora and fauna in semi-permanent to temporary waterbodies and are recognised in the *Directory of important wetlands of Australia* (DAWE, 2005). However, many of these wetlands are unable to be filled with regulated flows due to current constraint limits on the Murrumbidgee channel. The relaxation of constraints is expected to increase lateral connectivity and therefore the number of these wetlands that can be reached through environmental water delivery (Figure 8, Figure 10).

There is also an increase in the number of times that the LTWP flow thresholds for wetland connection at Darlington Point are met for some selected durations. The Darlington Point gauge (410021) is a good location for representing connection of the Murrumbidgee River with the Mid-Murrumbidgee Wetlands. The gauge represents river flows between Gogeldrie Weir and Maude Weir (DPIE, 2020b). The number of events for flow meeting (exceeding) the LTWP flow thresholds was calculated for each flow scenario with event durations of greater than 5, 10 and 20 days between May and November. Large fresh wetland connections and small overbank flows are defined in the LTWP as durations ranging from 5-10 days.

An increase in the number of events of at least 10 days duration can be seen for the large freshes (15,500 ML/d) and overbank flows (28,000 ML/d) for each flow scenario (Figure 11; DPIE, 2020b). In this analysis, we also included a threshold of 21,000 ML/d at Darlington Point (410021). Although this is not a threshold outlined in the Murrumbidgee LTWP, it provides a middle ground between large fresh wetland connection and small overbank thresholds that achieves significant wetland connection in the Gogeldrie Weir to Maude Weir planning unit. An increase in the number of events is predicted for the majority of the duration events at this threshold, with an increase of +27per cent for the highest scenario with a greater than 10-day duration (Figure 11).

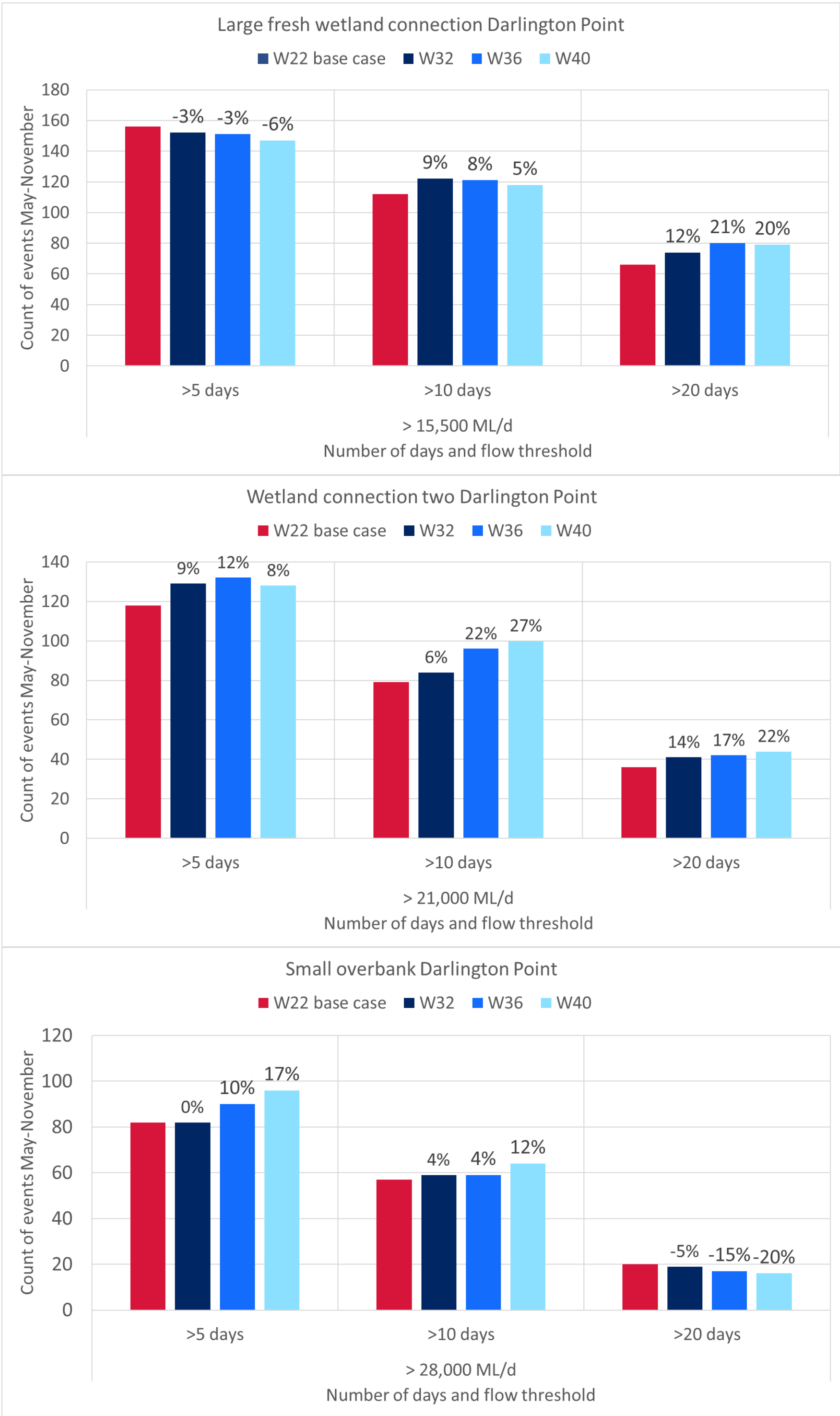


Figure 11: Count of events between May – November at Darlington Point (410021) for more than 5, 10 and 20 days at flow thresholds top: large fresh (wetland connection one, 15,500 ML/d), middle: wetland connection two (21,000 ML/d), bottom: small overbank (28,000 ML/d)

Several ecological outcomes can be expected across themes from increases in wetland connections. These benefits, although often assessed individually, can complement each other, and increase overall benefits for a wetland system. Some of the benefits that may occur are summarised below (Table 7).

Table 7: Expected benefits from increase in connection with Mid-Murrumbidgee wetlands

Theme	Expected benefits
Native vegetation	Support improvements in the condition of large areas of river red gum forest and woodlands. Maintain or restore non-woody vegetation communities in wetlands located along river corridors and in large floodplain forests, providing food and habitat for native fish, frogs and other water-dependant biota and driving riverine productivity.
Waterbirds	Improved breeding outcomes from increased areas of floodplain wetland habitat (including breeding and foraging habitat). Greater food resources available for waterbirds from increased extent and duration of inundation of foraging areas. Improved condition of colonial waterbird breeding sites so that they are in event-ready condition. Increased opportunities for non-colonial waterbirds to breed.
Fish	Increased floodplain and wetland conditions support population abundance and distribution of floodplain specialists such as the endangered/locally extinct small-bodied flathead galaxias and southern pygmy perch (should they be re-introduced) and more common species such as the Australian smelt and bony bream. Providing in channel habitat and productivity to support instream specialists such as trout cod, Murray cod and catfish. Restore the function, productivity and condition of floodplain wetland habitats for wetland/floodplain specialist and generalist native fish. Improved spawning and recruitment opportunities for flow-pulse specialist species including golden perch and silver perch and movement of all native fish. Supporting condition, growth and recruitment of all native fish in project areas and across the broader southern connected basin through improved floodplain productivity and the subsequent transfer of carbon and nutrients to river reaches to drive food webs. Supporting recovery of threatened species
Productivity	It is expected that increased connectivity with the floodplain will improve the quality and quantity of food available for aquatic animals, with flow on effects to the health, size and composition of ecological communities. This is through an increased extent of inundated floodplain habitat, affecting the amount and diversity of food sources available to aquatic consumers.

This benefit in wetland recovery and condition from more frequent inundation can be seen when looking at the recovery of two Mid-Murrumbidgee wetlands post the millennium drought, McKennas and Yarradda lagoons. Both wetlands were in similar condition pre drought (Figure 12) and experienced declines in aquatic vegetation response in the years following the end of this dry period (Figure 13). They experienced different connections throughout the millennium drought with McKennas Lagoon remaining dry between 2002-2010 and Yarradda Lagoon also drying in 2002 but partially filling in 2005 (Wassens et al. 2017). The inundation regime at Yarradda Lagoon was restored to close to natural largely through pumping and river connections with environmental water after drought breaking flows in 2010. This flow regime restoration was not an option at McKennas Lagoon and it consequently was inundated less frequently.

McKennas Lagoon 2000, pre millennium drought
(photo: James Maguire, DPE)

Yarradda Lagoon 1998, pre millennium drought
(photo: Lorraine Hardwick, DPE)

Figure 12: Images of McKennas and Yarradda lagoons pre–Millennium Drought

The increased frequency of inundation at Yarradda Lagoon, as well as the connection during the millennium drought, has allowed faster recovery following the drought with an increase in aquatic vegetation species, waterbirds and frog species detected. The threatened southern bell frog has been detected at Yarradda Lagoon since 2015 and the lagoon is considered a refuge site for other species of frogs and turtles (Figure 13) (Wassens et al. 2015; 2021). The number of water dependant plant species recorded at Yarradda Lagoon in 2019-2020 was comparable to surveys pre-millennium drought (Wassens et al. 2021). In comparison, McKennas Lagoon was consistently less similar to its pre drought state even up to two years after more regular inundation regimes were introduced (Wassens et al. 2017). Although there has been an increase in the number of aquatic vegetation species, McKennas Lagoon has also experienced river red gum encroachment and the rate of increase in the number of aquatic vegetation species is much lower than Yarradda Lagoon (Wassens et al. 2017). Species recovery of frogs and waterbirds has also been lower (Figure 13).

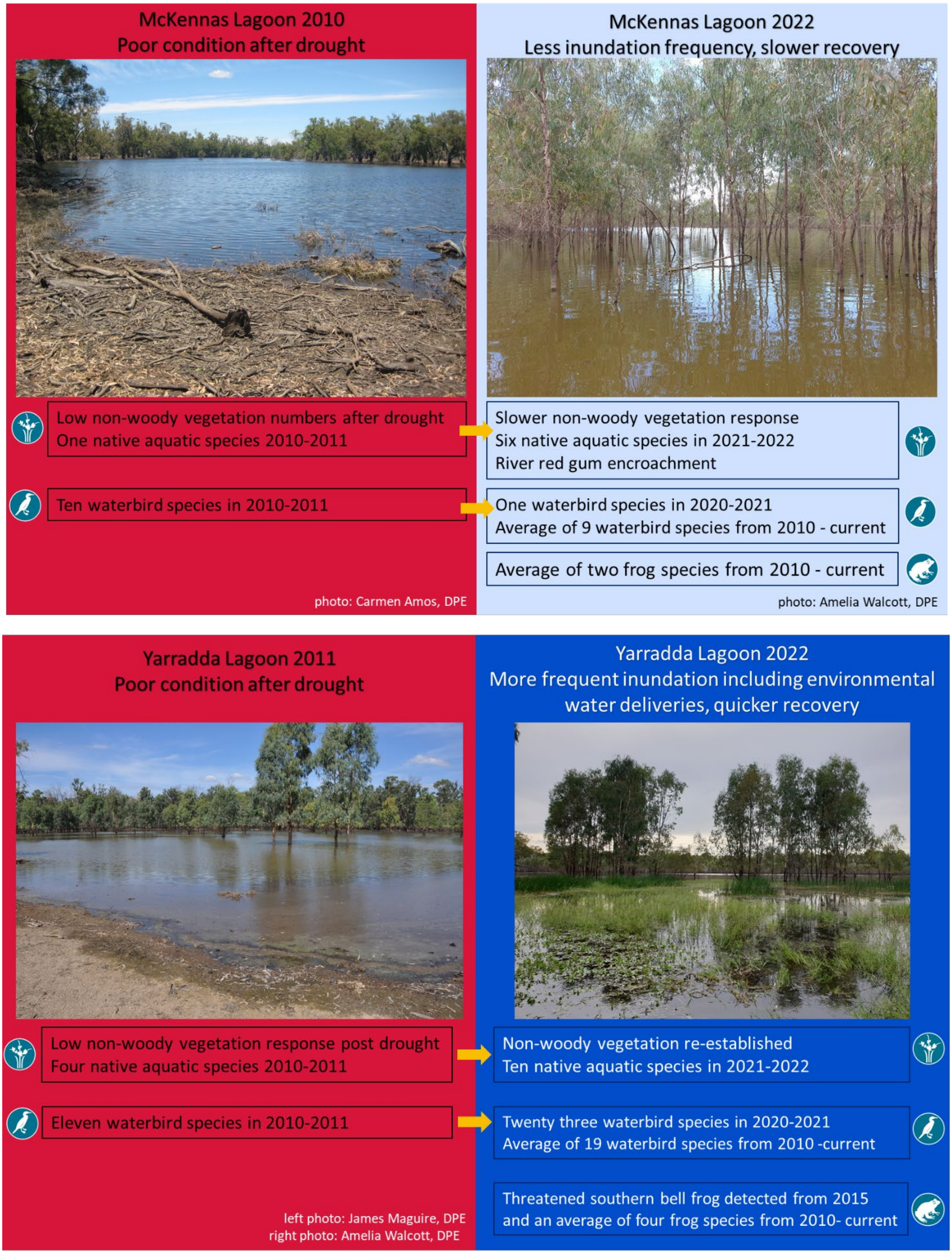


Figure 13: Report cards for *top* McKennas Lagoon and bottom - Yarradda Lagoon in the Mid-Murrumbidgee wetlands

Information and data from (Amos, 2011; Wassens, 2006; Wassens et al. 2011; Wassens et al. 2012; Wassens et al. 2013; Wassens et al. 2017; Wassens et al. 2021; DPE, 2022)

4.2 Native Fish

Up to a 34 per cent increase in golden perch numbers is expected in the Murrumbidgee River as a result of relaxing constraints, with up to a 47 per cent increase in the Gundagai to Hay reach and up to 32 per cent in the Hay Weir to Murray confluence.

In dry years, golden perch are expected to increase overall by up to 31 per cent, with increases in the Gundagai-Hay reach up to eight-fold from a very low base as a result primarily of upstream migration during higher program flows. In the Hay Weir to Murray junction, golden perch numbers are expected to increase by up to 24 per cent.

Modelling predicted negligible change in Murray cod populations. This is likely related to the life history of Murray cod being less dependent on cues from flows.

Increased breeding and recruitment opportunities are expected for generalist and floodplain specialist fish species through delivery of more frequent wetland-connecting flows.

Historically, the program area in the Murrumbidgee, from Gundagai to the Murray River confluence, would have supported 21 native fish species across four functional groups (Ellis et al., 2022). This included nine Commonwealth and NSW threatened species: flat-headed galaxias, Murray hardyhead, southern pygmy perch, olive perchlet (considered locally extinct), southern purple-spotted gudgeon, trout cod, Macquarie perch, freshwater catfish, and Murray crayfish. (DPIE, 2020a; DPI, 2016). A full species list is provided in Appendix C.

Native fish populations in the program area are in poor to very poor condition based on species complexity, proportion of native fish remaining and their level of recruitment (DPI, 2016; Ellis et al. 2022). River regulation and extraction for consumption has resulted in multiple stresses for native fish populations including:

- reduced magnitude, frequency, and duration of flows to connect wetlands and floodplains in winter and spring limits habitat for breeding and recruitment opportunities for native fish. For example, vulnerable and endangered floodplain specialist native fish that require regular wetland connection for breeding and recruitment have not been detected in the reach since 1995 (Gilligan, 2005)
- reduced frequency and duration of floodplain inundation also limits productivity of the river system (mobilisation of floodplain nutrient inputs)
- rapid fluctuations in flow that can strand or expose nests of fish species like Murray cod and trout cod, leading to nest abandonment by adults
- cold water pollution during development of eggs and larval stages reduces survival and recruitment, and can impact growth and development
- barriers to fish passage including weirs, levees, culverts, road crossings and other human made structures
- reduced available spawning habitat due to fast-flowing instream habitat being restricted to the main channel, except during natural unregulated higher flows, limiting opportunities for flow cued spawning species like golden and silver perch

- weir pool creation resulting in lentic (slow flowing) sections of habitat over long stretches of river that were naturally lentic (flowing) and hydrodynamically complex. This has resulted in a reduction in the suitable faster flowing hydraulically complex habitat for many species of fish adapted to lentic environments. Regulated weir pools also reduce the length or connections between remaining lentic reaches (outside of regulated weir pools) contributing to reduced dispersal and survival of drifting eggs and larvae.

Existing flow limit constraints mean that environmental water managers are unable to deliver flows that connect wetlands at the scale required to support large-scale breeding, dispersal, and recruitment of native fish species. Nor can they support the recovery of wetland vegetation that provides food and shelter for native fish. This reduced frequency and duration of wetland-connecting flows isolates floodplain habitat and may result in stranding of native fish and eventual death through exposure to predation (e.g. birds) or loss of suitable surface water habitat (Cornell et al. 2021). The isolation of native fish in wetlands also means they cannot contribute to maintaining and building the broader native fish community in the Murrumbidgee River and southern connected basin more broadly.

Methods

The program's fish modelling project targeted two iconic native fish species: the Murray cod (*Maccullochella peelii*) and golden perch (*Macquaria ambigua*) and the invasive, non-native, European carp (*Cyprinus carpio*). European carp has not been presented in this synthesis as the modelling is still in progress. These three species inhabit much of the Murray Darling Basin riverine landscape. Murray cod and golden perch are totemic to First Nations peoples and are highly valued by anglers. Both species have experienced population declines (Koehn & Todd, 2012; Koehn et al. 2020a) despite extensive restocking programs.

Golden perch and Murray cod were selected for modelling due to their significance to communities and differing expected responses to relaxed flow constraints. Golden perch generally rely on flow events to cue spawning, movement and migration; and their growth and recruitment success are expected to be enhanced by increased river productivity and access to off-channel floodplain habitat (Ellis et al. 2016; Stuart & Sharpe 2022). Murray cod prefer deep and fast-flowing habitat with submerged structure (woody debris) and natural rates of water level increase/decrease during breeding season in October/November. Murray cod recruitment can potentially be enhanced through improved river productivity and connectivity with floodplain habitats (Ellis et al. 2016).

European carp (carp) abundance and impacts generally increase with high river flows and these need to be considered when identifying the benefits of flows to native fish species and other aspects of the ecosystem (Conallin et al. 2012; Stuart & Jones, 2006a&b).

The modelling process used expert knowledge and the outcomes of research and monitoring to:

- develop contemporary conceptual models of the life-cycle processes of the fish species
- identify ecologically sound population extents from the Murrumbidgee River at Gundagai to the Murray confluence below Balranald (Figure 15, Figure 16)

- develop further models for the Murray River downstream of Hume Dam to Wentworth and the lower Darling River (Figure 14)
- set project areas for analysis in the Murrumbidgee are Gundagai to Hay and Hay to the Murray confluence (Todd et al. 2022)
- set parameterization and management units for each of the sub-populations, including local context; such as fishway passage, flow rates, physical structure, and fish movement
- run models and evaluate outcomes of modelled program flow scenarios (Table 7), followed by validation of model predictions using existing empirical data. Model validation for this theme used data from NSW e-fishing (1994-2021), NSW Commercial Fisheries (1948-1984) and Victorian ARI (2000-2019) These were all performed by Todd et al. (2022)
- compile carp modelling results at a later date and add when available.

The model integrated 124 years of modelled hydrological data from 1896-2019. Daily flow and temperature data were used to inform the model which also included information on anoxic blackwater, productivity and commercial and recreational fishing, providing a powerful tool to predict the effects of environmental water and other interventions on fish population dynamics. Stocking data were not included in the model. More information is available from Todd et al. (2022). The potential influence of hypoxic blackwater (i.e. low oxygen caused by high concentrations of carbon that can be lethal to fish and other aquatic animals) has been included in the Murray Cod population model. A hypoxic blackwater risk assessment of the program’s flow limit options found no increased risk of hypoxia associated with the use of environmental water (McInerney et al. 2022). A time series of likely hypoxic blackwater events was used to inform fish population modelling, developed using historical carbon and oxygen observations in consultation with experts (Wolfenden & Baldwin, 2022). The occurrence and severity of predicted events was used to represent the extent and lethality of hypoxic blackwater events on Murray cod populations.

The population models for each species were run in a series of river reaches, Gundagai to Berembed Weir, Berembed Weir to Gogeldrie Weir, Yanco Ck, Gogeldrie Weir to Hay Weir and Hay Weir to Murray (Murray cod); and Gundagai to Hay Weir and Hay Weir to Murray confluence (golden perch). A range of flow scenarios (Table 8) associated with the program flow limit options were modelled for all program reaches to explore which flows are predicted to provide the most benefit for fish. The modelled flows were linked through to equivalent Murray River flow scenarios for golden perch only to account for movement between the rivers in the model.

Table 8: Flow scenarios for fish population modelling with linked Murray flows, used for the golden perch population model

Modelled flow scenario for fish population modelling	Flow limit option in the Murrumbidgee River[1] at Wagga Wagga ML/d (linked to flow limit option in the Murray River downstream of Yarrawonga Weir).
Base case (W22)	22,000
Option 1 (W32 Y25))	32,000 (linked to Yarrawonga flows of 25,000)
Option 2 (W36 Y30)	36,000 (linked to Yarrawonga flows of 30,000)
Option 3a (W40 Y40)	40,000 (linked to Yarrawonga flows of 40,000)
Option 3b (W40 Y45)	40,000 (linked to Yarrawonga flows of 45,000)

[1] Murrumbidgee flow limit options were matched with Murray flow limit options for the purpose of the golden perch model, which is a meta-population (linked model) that incorporates movement between golden perch population spatial units.

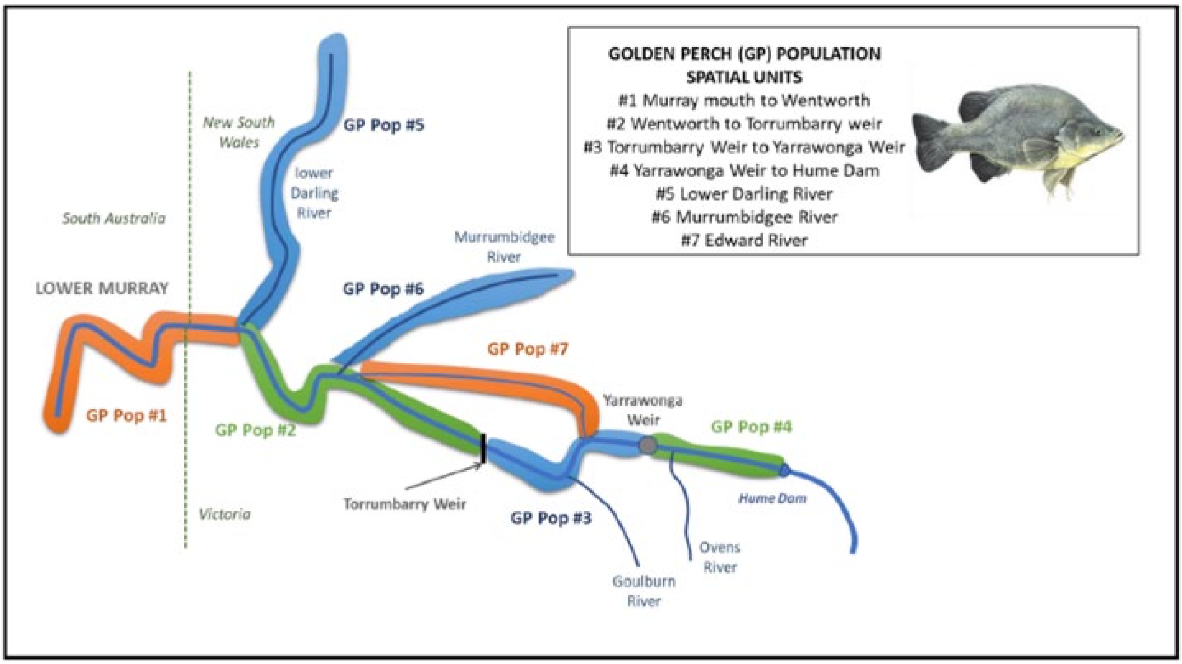


Figure 14: Spatial structure of golden perch populations modelled for the program in the lower Murray Darling Basin

Includes all of the modelled area; Murray, lower Darling and Murrumbidgee, as populations may be linked (from Todd et al. 2022)

Fish population model outputs were generated for total adult and juvenile population size (abundance) for each species for all spatial units under the base case and the program flow limit options. In this synthesis report we present results for long-term average (mean) and minimum adult population size as well as trajectories of adult population over the 124-year modelled time period. Other outputs including results for juvenile populations can be found in full technical report (Todd et al. 2022).

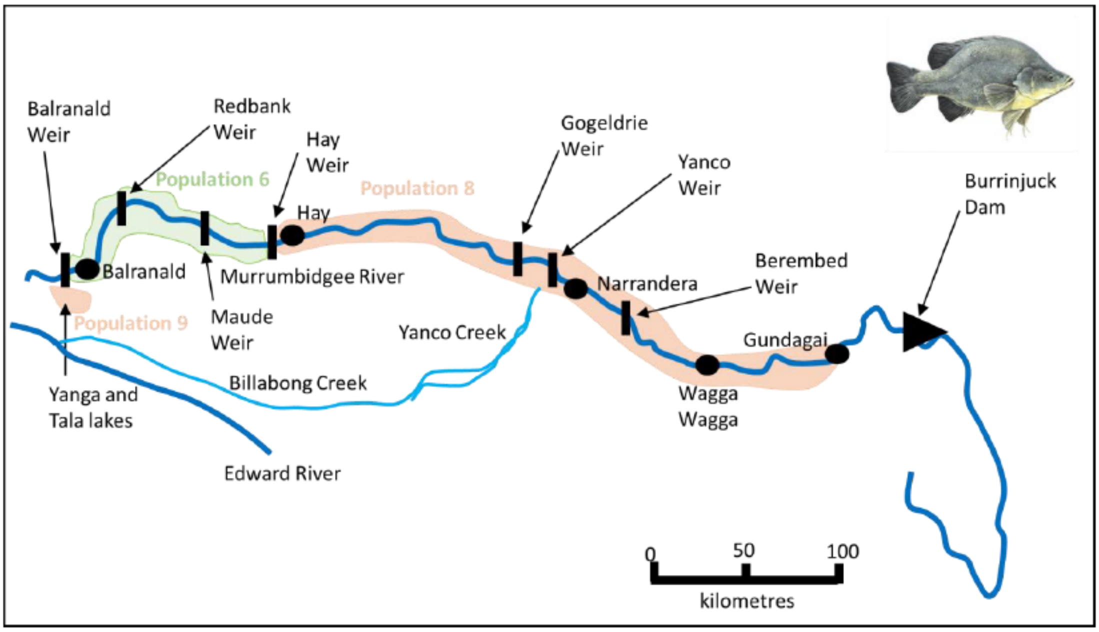


Figure 15: Spatial structure of golden perch populations in the Murrumbidgee modelled for the program (from Todd et al. 2022)

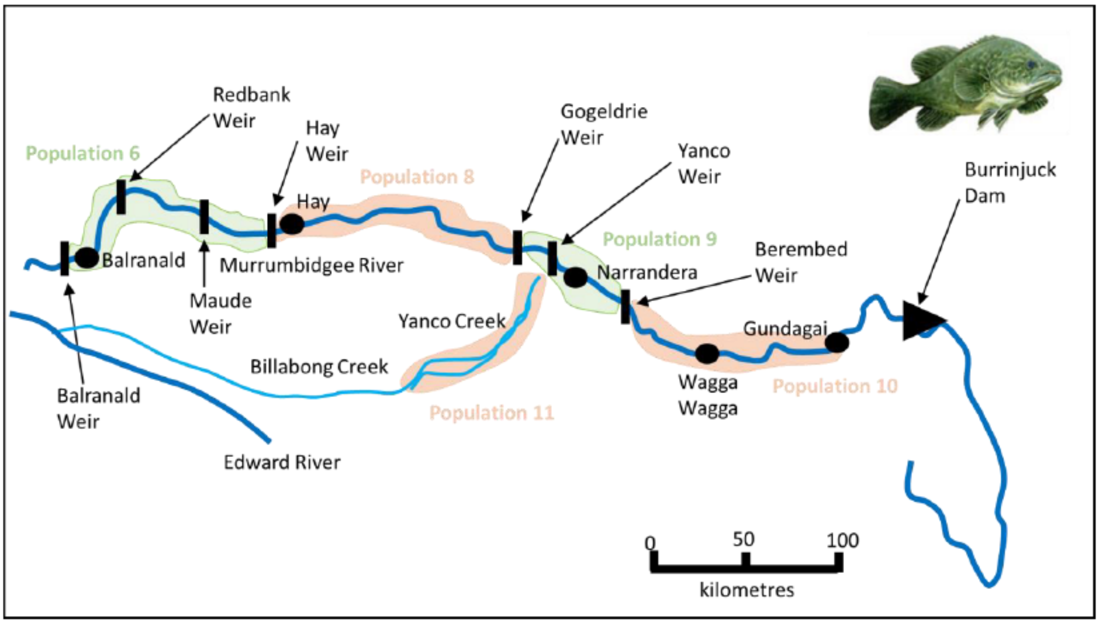


Figure 16: Spatial structure of Murray cod populations in the Murrumbidgee modelled for the program (from Todd et al. 2022)

Key outcomes

Fish population modelling predicts that relaxing flow constraints will provide substantial benefits to golden perch populations in the Murrumbidgee system and the whole southern-connected basin, with the benefits increasing with the higher flow limit options in both project areas. These findings are in line with our understanding of golden perch life history in which flow has a strong influence on spawning, movement and dispersal and recruitment of young fish into the adult population.

For Murray cod, the model predicts neutral outcomes, that is, negligible change to Murray cod populations over the long-term under higher flow limits compared to the base case in most modelled reaches of the Murrumbidgee. This result aligns with our understanding of Murray cod life history, which spawn seasonally as a response to increasing water temperature, as long as the in-river habitat such as snags are covered.

Golden perch outcomes

Golden perch population modelling predicts that relaxed flow limits will increase long-term average golden perch abundance (population size) in the Murrumbidgee system by up to 34 per cent compared to the base case. The benefits increase substantially with increasing flow limit, from a 7 per cent increase for the lowest flow limit option of 32,000 ML/d at Wagga Wagga to a 16 per cent increase for 36,000 ML/d, 26 per cent increase for 40,000 ML/d (Option 3a-W40Y40) and 34 per cent increase for the highest flow limit option of 40,000 ML/d (Option 3b-W40Y45; Figure 17).

The significant benefits, especially at higher flow limit options, are predicted for all modelled river reaches, including the program areas:

- Gundagai to Hay Weir - up to 40 per cent increase in mean abundance (Figure 18)
- Hay to Murrumbidgee/Murray confluence - up to 32 per cent increase (Figure 18)

Population increases are also predicted for reaches downstream of the program area in the Southern connected basin in the Murray and Darling rivers (Appendix C, Table 23):

- Torrumbarry Weir to Wentworth - up to 27 per cent increase in mean abundance
- Lower Murray below Wentworth, including South Australia - up to 43 per cent increase
- Lower Darling River – up to 19 per cent increase.

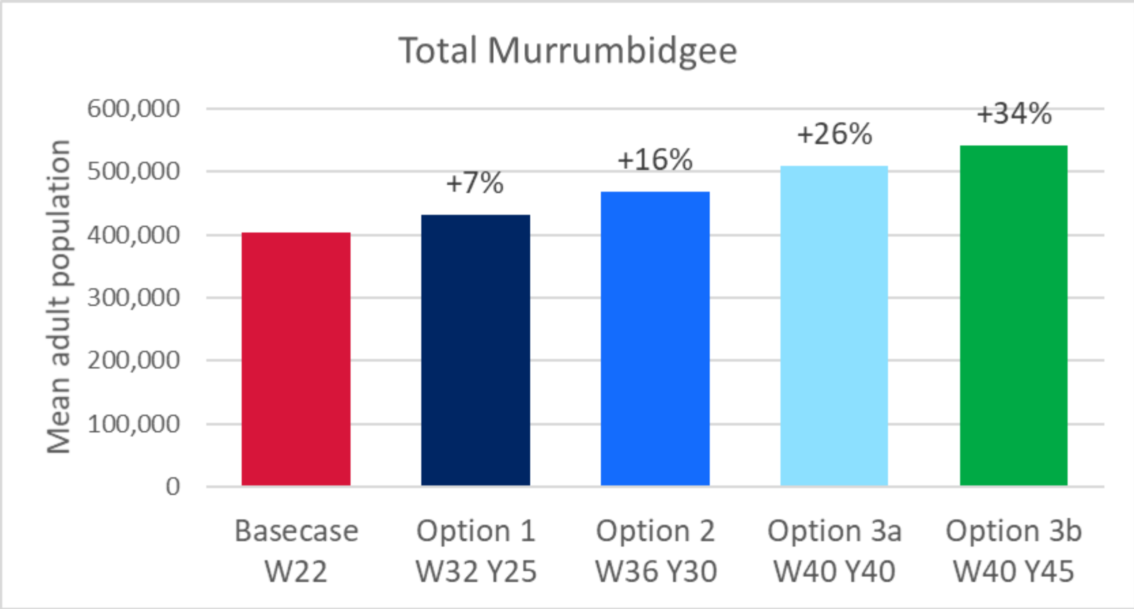


Figure 17: Predicted long-term average adult golden perch population size (abundance) in the Murrumbidgee River under the base case and relaxed flow limit option scenarios

Labels above columns present the percentage increase in populations relative to the base case (redrawn from Todd et al. 2022)

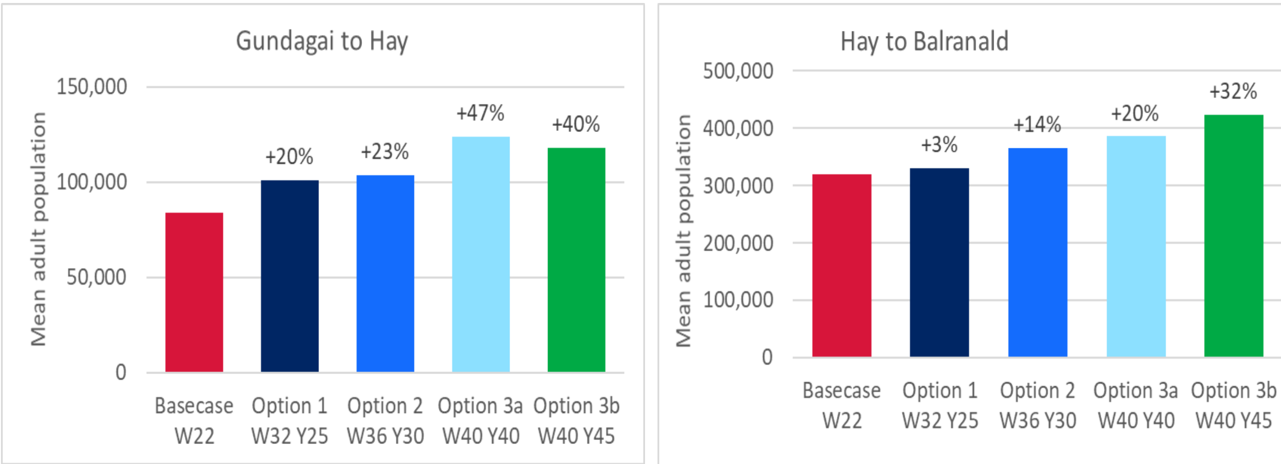


Figure 18: Predicted long-term average adult golden perch population size (abundance) for the Gundagai to Hay (left) and the Hay to Balranald (right) reaches of the Murrumbidgee River under base case and relaxed flow limit option scenarios

Labels above columns present the percentage increase in populations relative to base case (redrawn from Todd et al. 2022)

Modelled estimates of minimum golden perch abundance over time (how low the population drops during dry periods and droughts – assessed as the 10th percentile of adult populations) provide further evidence of improved outcomes for golden perch under relaxed constraints during drier periods. For the Murrumbidgee system (Hay Weir to the Murray Junction), the minimum golden perch population under the highest flow limit option is predicted to be 24 per cent higher than the base case (Figure 18). In the Gundagai to Hay Weir reach, the minimum population size is predicted to be much higher under relaxed constraints, with an almost 8-fold increase over the base case during dry periods (Figure 20). The large predicted increase in population for dry periods can be explained by several factors. Golden perch are flow responders; that is, they breed in response to flow events (King et al. 2016). Due to river regulation, many of the breeding cues in the past have reduced breeding capacity. Previous commercial and recreational fishing have also impacted populations (Reid et al. 1997). So current conditions are not optimal for golden perch populations. The dry period results represent the difference between a relatively small modelled base case population of 2,547 adult fish and almost 20,000 (19,655) under the highest relaxed flow limit option scenario.

Modelling results acknowledge that the Murrumbidgee River upstream of Hay appears as a ‘sink’ reach, relying on immigration from downstream. Golden perch are a highly mobile species, migrating long distances after breeding (Koehn & Nicol, 2016; Zampatti et al. 2019). With fish passage enabled through weirs such as Hay Weir during flow events under relaxed constraints, upstream migration would be expected during drier years.

Overall, fish population modelling indicates that raising flow limits in the Murrumbidgee River is likely to have benefits for golden perch abundance at the reach, project, and Murrumbidgee-system scale. These findings are in line with our understanding of golden perch life history in which flow strongly influences spawning, movement, and dispersal (including egg and larval drift and long- range migrations by juveniles and adult fish), and connectivity with off-channel habitats, which is important for recruitment outcomes (survival of young fish and growth into adults).

Golden perch population trajectories over the modelled period show broad population fluctuations in response to dry and wet periods under all flow limit options. For example, modelled golden perch abundance drops significantly during the Millennium Drought in the 2000s, in the mid 1950’s and is also generally low in first three decades of the modelled time series between 1890s and 1915 around the time of the Federation Drought (Figure 21). Note the modelling is based on current river regulation and extraction conditions and so predicted Federation Drought population numbers reflect the hypothetical case that current river regulation and extraction were in place during the Federation Drought. Nevertheless, the results indicate considerably larger golden perch populations for relaxed flow limit options compared to the base case for a range of climate conditions throughout the flow time series (Figure 21).

This suggests that relaxing constraints has the potential to boost population increases during average and wetter climate conditions, while protecting populations during drier times to build greater resilience.

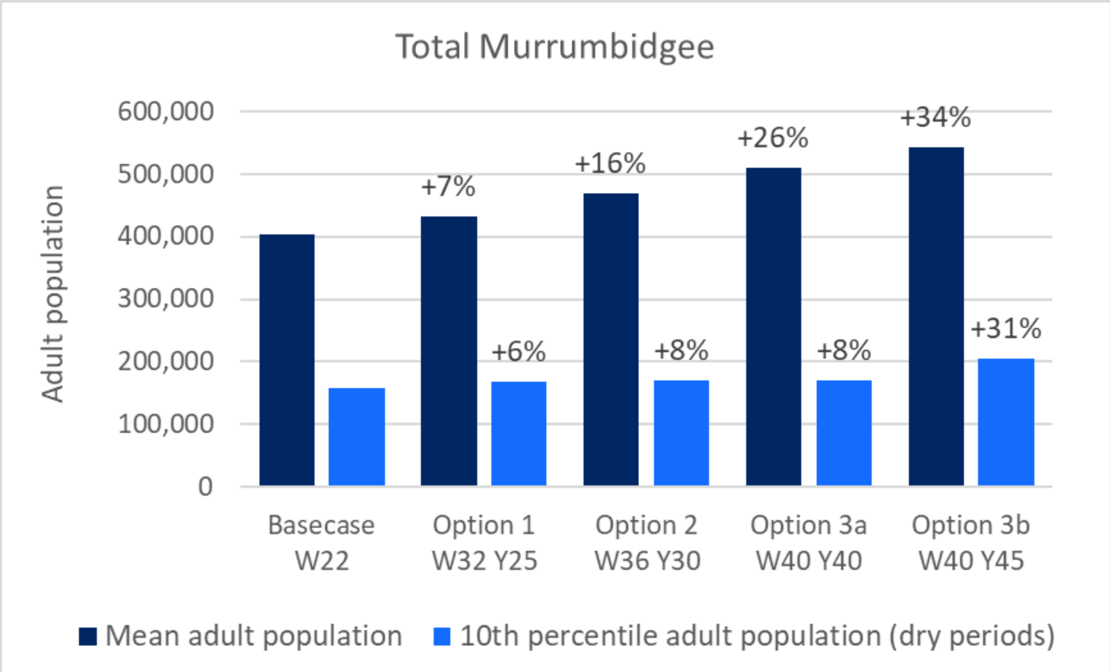


Figure 19: Long-term average and minimum total adult golden perch population size under base case and relaxed flow limit option scenarios for the Murrumbidgee River

Labels above columns present the percentage increase in populations relative to base case (redrawn from Todd et al. 2022)

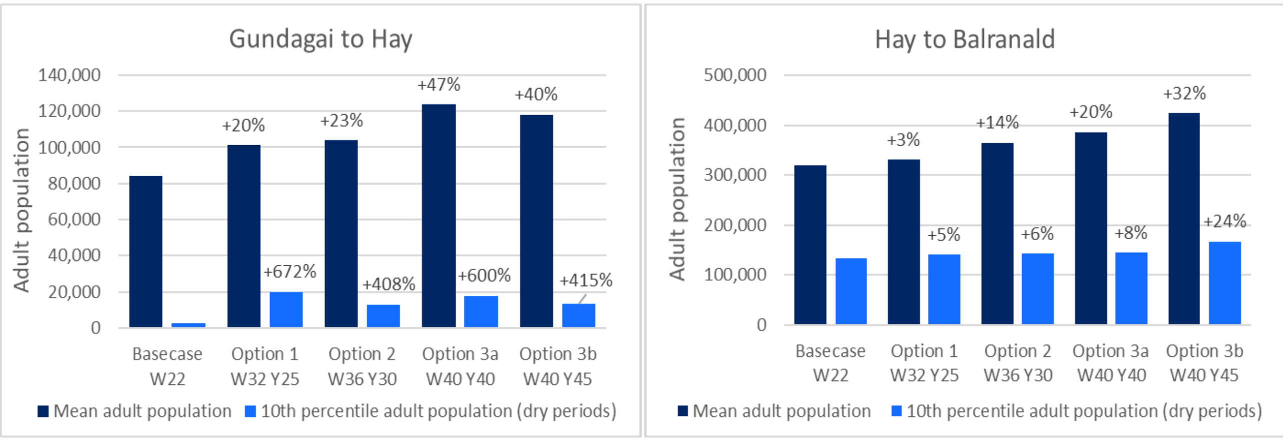


Figure 20: Long-term average and minimum total adult golden perch population size under base case and relaxed flow limit option scenarios for the Gundagai to Hay (left panel) and the Hay to Balranald (right panel) reaches of the Murrumbidgee River

Labels above columns present the percentage increase in area relative to base case (redrawn from Todd et al. 2022)

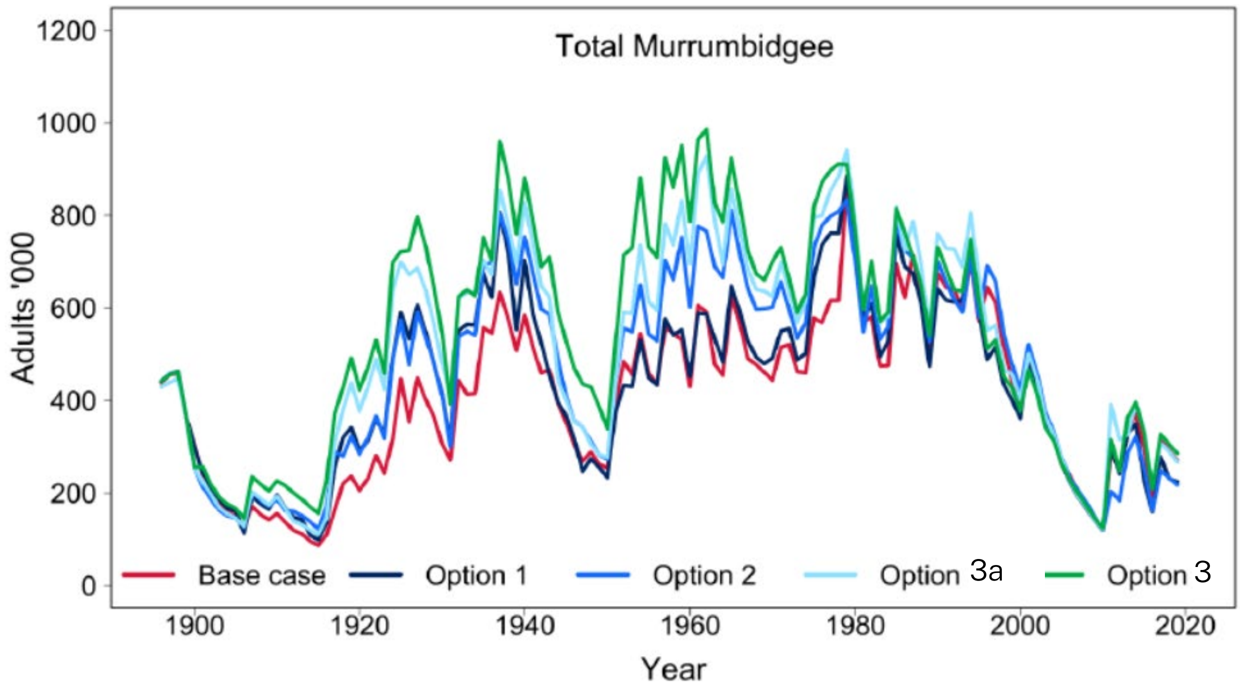


Figure 21: Modelled 124-year time series of the mean golden perch population in the Murrumbidgee River (from Todd et al. 2022)

Murray cod outcomes

For Murray cod, the model predicts neutral outcomes, that is, negligible change to Murray cod populations over the long-term under higher flow limits compared to the base case in most modelled reaches of the Murrumbidgee for any of the flow scenarios (Figure 22). While improvements in abundance were expected in the Murrumbidgee River under higher flow limits, the results likely reflect that Murray cod spawning and recruitment is less dependent on flow than it is for golden perch (Figure 23).

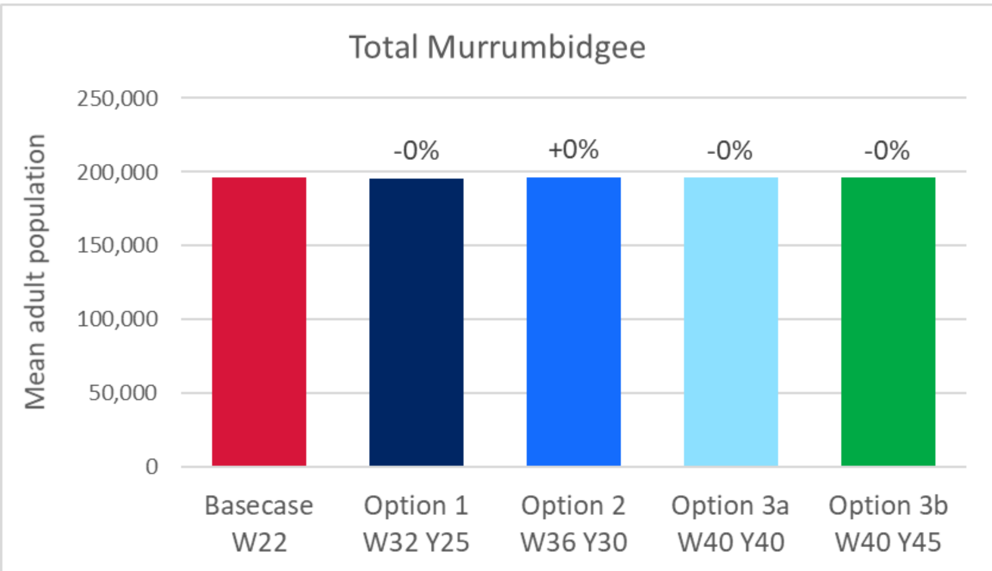


Figure 22: Total adult Murray cod population size (abundance) under base case and relaxed constraint flow limit option scenarios for the Murrumbidgee River
Labels above columns present the percentage increase in area relative to base case (redrawn from Todd et al. 2022)

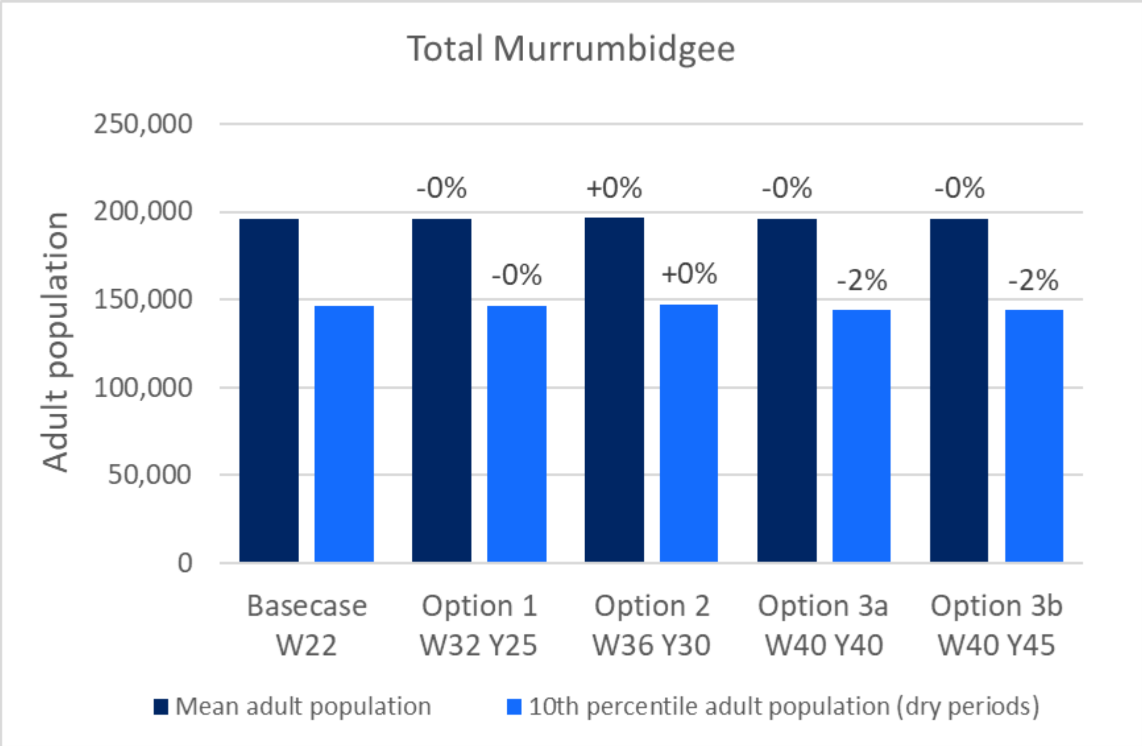


Figure 23: Long-term average and minimum Murray cod populations for the Murrumbidgee system
Gundagai to Balranald – Murray confluence; redrawn from Todd et al. 2022)

Explanation of results and expected benefits for other native fish species

The different responses of Murray cod and golden perch can be explained by their dependence on different aspect of the flow regime. Magnitude (both the height and volume) as well as duration of flow events, when and how often they occur, are important triggers for fish breeding (Figure 24). The flows anticipated by the program are expected to reinstate some of the small and large pulses, particularly in spring. This will assist flood pulse and floodplain specialist fish. One example is the predicted growth in population for golden perch in dry years under raised flow limit options, which can be explained largely by migration upstream from the Murray during flow events and by low modelled populations in the Gundagai to Hay project area under the base case. Golden perch populations are expected to grow from a very low base through both improved migration and breeding under relaxed constraints. River specialists and generalists such as Murray cod respond to flows more generally but require spawning sites to remain inundated and temperatures to be above key trigger thresholds.

Relaxed flow constraints in the Murrumbidgee River are also expected to benefit other native fish species that have not been modelled as part of the program. These include generalist and floodplain (wetland) specialists that require regular wetland connection and permanent off-channel aquatic habitat to complete their life cycles. Silver perch, like golden perch, rely on flow cues for spawning and movement and benefit from wetland and floodplain connectivity to promote recruitment (Ellis et al. 2022). Other river specialists in the same functional group as Murray cod, such as freshwater catfish may benefit as well.

Examples of how relaxed flow constraints might benefit these species and functional groups:

Floodplain specialists – like the critically endangered and locally extinct flathead galaxias and endangered southern pygmy perch, are short to medium-lived species that require regular (every 1-2 years) wetland connection for breeding and recruitment (Ellis et al. 2022; Pearce et al. 2018). More common generalist species such as Australian smelt and carp gudgeon, which provide food for waterbirds will also be assisted (see Appendix C, Table 22). Current flow limits mean only limited areas of wetland habitat can be connected at the required frequency to sustain populations of floodplain specialists. Relaxed flow constraints would double the area of wetland habitat that can be supported with water for the environment (Section 4.1). This is expected to substantially increase breeding and recruitment opportunities for floodplain specialist native fish in off-channel wetlands and floodplains and promote recovery and increase range of these threatened species populations (Figure 24). While several of these species are currently locally extinct and critically endangered elsewhere, a number are targeted for reestablishment.

Other River and flow pulse specialists – River specialist species including Macquarie perch, trout cod and freshwater catfish, which are vulnerable or endangered in the Murrumbidgee (Appendix C, Table 22), are severely depleted in the Murrumbidgee as a result of flow regulation (Burndred et al. 2017) and require more natural instream flows and anabranch connections to improve their population potential. Silver perch are flow pulse specialists, similar to golden perch in their requirement for flow pulses or faster flow velocities to cue movements and spawning. Regular floodplain inundations are also expected to improve recruitment outcomes for this species. Flow variability and more regular floodplain connectivity experienced in the Murrumbidgee under the program would be expected to improve enhance habitat availability and improve recruitment success through increased river productivity for these functional groups of fish (Figure 24).

A conceptual model showing current conditions and the benefits of relaxed constraints to non-modelled fish species in shown in Figure 25 and Figure 26. The conceptual models include a limited selection of beneficiaries only and other generalist and river specialist species within the program areas are also expected to benefit from increased floodplain inundation and flow variability.

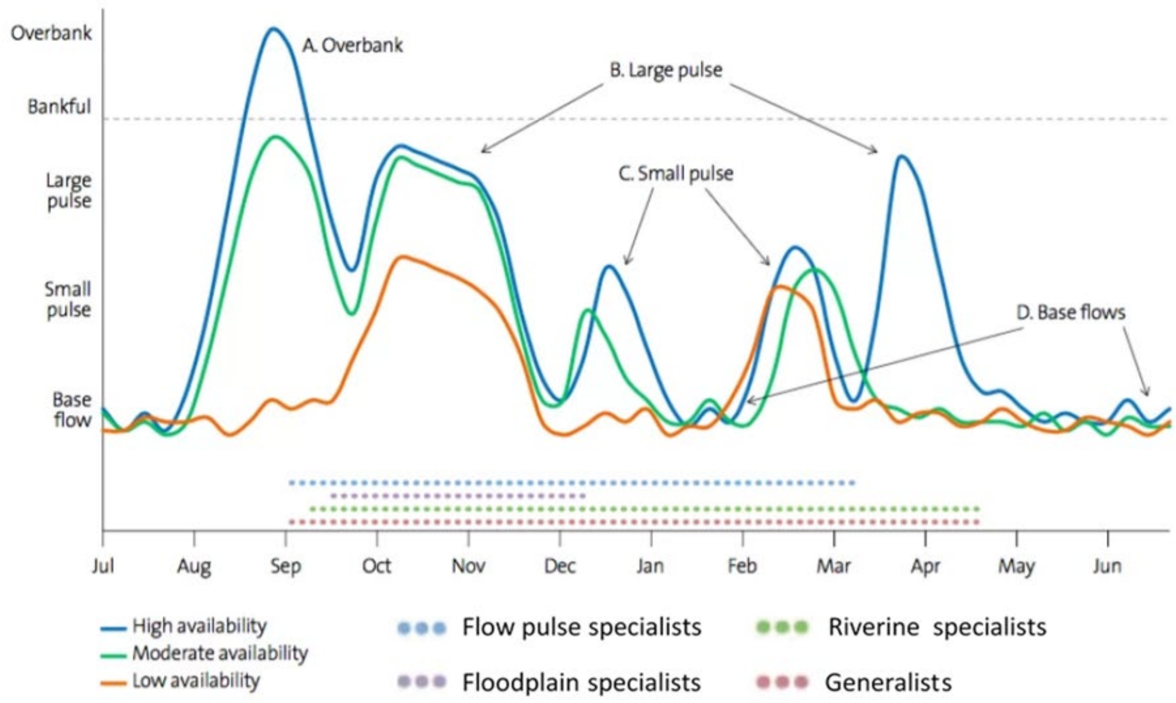


Figure 24: Conceptual flow and southern MDB fish breeding season windows for each fish functional group (redrawn from Ellis et al. 2016)

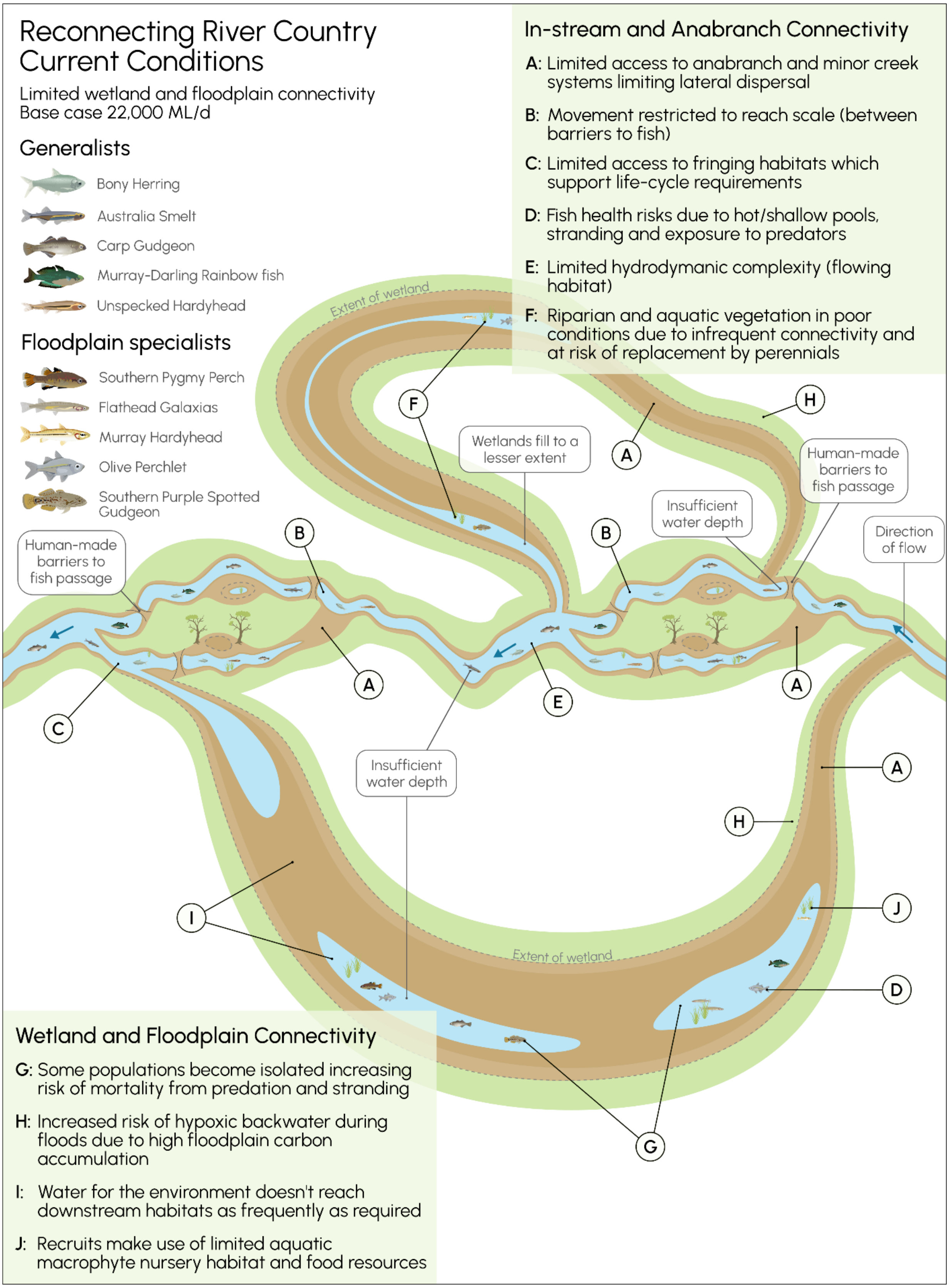


Figure 25: A conceptual model showing current conditions that limit outcomes for generalist and floodplain (wetland) specialist native fish species

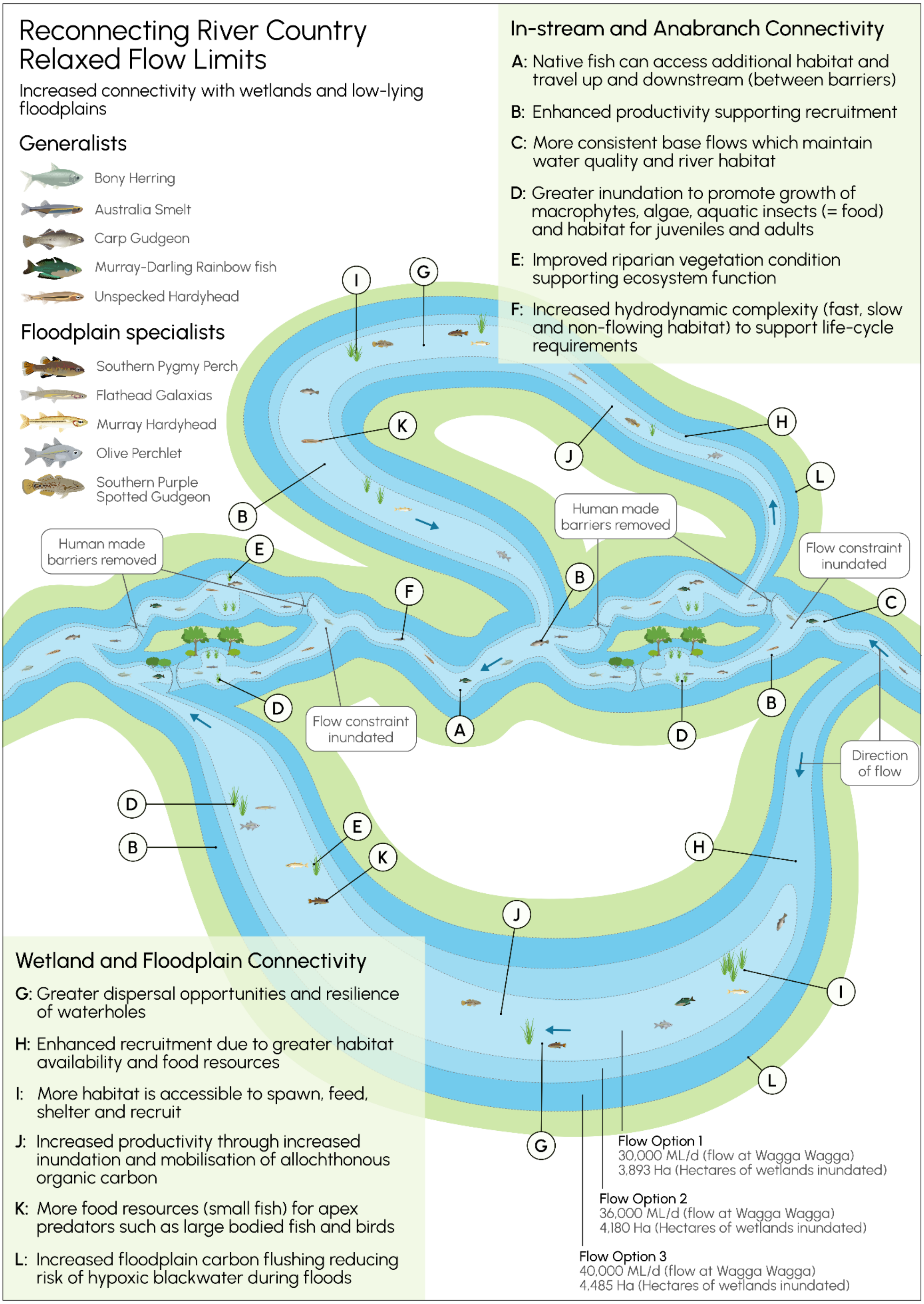


Figure 26: A conceptual model showing the benefits of the program and relaxed flow limits for generalist and floodplain (wetland) specialist native fish species

Other factors important for fish

There are several other factors related to flow that increase or decrease the ability to recover population health. They include

- Cold water pollution (CWP): The major irrigation dams in the Murrumbidgee mostly release water from the bottom of the dams (hypolimnetic releases). During summer, these releases may be up to 15°C colder than surrounding natural stream temperatures. The effect on Murrumbidgee water temperatures from releases from Burrinjuck and Blowering dams attenuates but is felt as far downstream as Narrandera. The low water temperatures affect fish breeding and recruitment, particularly of temperature sensitive species such as trout cod and Murray cod (Lugg & Copeland, 2014). The fish modelling undertaken for this current report (Todd et al. 2022) included CWP as a spawning factor for Murray cod but not golden perch. Cold water shock is instrumental in high mortality of spawn of Murray cod, silver perch and golden perch (Michie et al. 2020), However, as population predictions for golden perch derive largely from upstream migration from recruitment sites, it wasn't included in recruitment modelling for golden perch
- Fish stocking: Stocking of native and non-native fish as a management tool for providing ecological and recreational fishing improvements
- Pest fish species: While European carp are being investigated in future assessments, other pest species, such as red fin (*Perca fluviatilis*) and mosquito fish (*Gambusia holbrooki*) will not. Both have an ability to disrupt improved benefit to native fish (Macdonald, 2008; NSW DPI 2022c)
- Productivity growth associated with relaxing constraints: Fish breeding is closely related to instream ecological productivity (Figure 34). Results from the Ecosystem Production theme (Section 4.5; Siebers et al. 2022) predicts median increases in total annual potential production of energy available for large bodied native fish of up to 24 tonnes of carbon annually in the Burrinjuck to Hay project area. Potential production benefits have been included for aspects of fish population modelling, however, the effects of food limitation on fish populations is not well understood
- Hypoxic blackwater: the potential impact of hypoxic blackwater has been included for Murray cod but not for other species. Golden perch can quickly move long distances when faced with declining water quality whereas Murray cod tend to remain within particular reaches. Hypoxia can affect golden perch, however, the impact on populations is affected by multiple drivers that cannot yet be modelled.

Risks of not proceeding with program

Populations of both the iconic and protected Murray cod and the flow event responder golden perch species are declining in the Murrumbidgee River system. At present, populations are maintained by restocking by Fisheries agencies. This is a sub-optimal management scenario, leading to long-term depletion of genetic variability and thus viability. Risks from not proceeding with the program include:

- fish population modelling suggests that golden perch populations would be 10–29 per cent smaller than current over the long-term if the program does not proceed

- we could continue to observe sharp declines in golden perch populations in response to natural disturbance events including droughts and, in the case of Murray cod, hypoxic blackwater events associated with large natural unregulated flood events if they occur in the warmer months. Recovery of fish populations would be slower following these disturbance events
- pressures on existing small-bodied floodplain specialist native fish species, currently at risk due to long-term reduction of wetland spawning habitat would continue, leading to expected loss and in some cases more local extinctions.

4.3 Waterbirds

Modelling predicted small benefits or neutral outcomes for waterbirds, with model predictions of small increases in the number of species (2-3 per cent) and waterbird abundance (1-2 per cent) in the Mid-Murrumbidgee wetlands. Waterbird predictive modelling was limited by the observational data on which they were developed, and these results are potentially reflective of that limitation.

Despite the subtle modelling outcome, the relaxation of constraints is expected to have significant benefits for the availability and condition of waterbird habitat for breeding and foraging, and also for supporting breeding opportunities for some species. Benefits to habitat along the Murrumbidgee River are also expected to complement and support outcomes at a broader scale in combination with outcomes in the Murray.

Waterbirds rely on floodplain wetlands for breeding and foraging habitat. Regulation has impacted waterbird habitat and populations across the Murray–Darling Basin are currently in poor condition, with recent declines seen across all guilds (Kingsford et al. 2017; Porter et al. 2021). The Murrumbidgee environmental benefit analysis for waterbirds in the program investigated the benefits that might occur from relaxed constraints and specifically focused on the Mid-Murrumbidgee wetlands between Narrandera and Hay. These wetlands are listed as nationally important (DAWE, 2005). Wetlands in the Mid-Murrumbidgee waterbird project area are located on both private land or within the NSW National Park estate and are subject to periodic grazing by cattle. The majority of land surrounding the Mid-Murrumbidgee wetlands is cleared for grazing and cropping and the hydrology of some of the wetlands is influenced by water extraction and storage (DPIE 2020a&b) .

Relaxing constraints would potentially allow more of the Mid-Murrumbidgee wetlands to be inundated at a greater frequency and provide habitat for up to 52 waterbird species. It is important to note that the number of species and total abundance of waterbirds observed in Mid-Murrumbidgee wetlands was typically low in observed survey from 2010 onwards, and the waterbird community is dominated by ducks and fish-eating waterbirds. The relaxation of constraints may lead to an increase in species richness and waterbird abundance, but the relationship is expected to be complex and intricately linked with patterns in the availability of different wetland habitat types in the Murrumbidgee and other nearby catchments (Bino et al. 2022).

Methods

The waterbird environmental benefits assessment used observed waterbird and hydrological data to model predictive relationships between key predictor flow variables and waterbird responses (number of species and waterbird density: number of waterbirds). The observed data consisted of ground waterbird survey data and historical inundation mapping for the Mid-Murrumbidgee wetlands, clipped from Berembed Weir to the Hay Weir, and river flow data from the nearest river gauges. Ground survey data from 2010 onwards was used to develop predictions of waterbird species richness and waterbird abundance (represented as waterbird density) in the Mid-Murrumbidgee. Colonial waterbird breeding outcomes were not considered due to insufficient records for the analysis.

Expected benefits for waterbirds were assessed for each of the flow scenarios based on the best flow predictor variable determined from the observed data. These were compared to both the base case (or current flow limits) and without development scenarios to determine the relative benefits of the four relaxed constraint flow scenarios.

Key Outcomes for the Mid-Murrumbidgee wetlands

- Cumulative river flows in the 180 days prior to spring ground surveys was the best predictor for waterbird species richness and waterbird abundance in the Mid-Murrumbidgee wetlands
- However, the relationships used to predict the waterbird outcomes were not strong and based on recent ground survey data from 2010-2020. This period included dry conditions, low waterbird numbers and represented poor condition at some wetlands. Some wetlands are also inundated by pumping in this period (not high river flows) which may have influenced the observed relationships between waterbird communities and river flows. This may have influenced the strength of the predicted relationships and the ability to predict potential improvements from the relaxation of constraints
- A small increase relative to base case was predicted for both the number of species, +2-3 per cent, and waterbird density (number of waterbirds), +1-2 per cent, and a small decrease in the 25th percentile which represents dry periods over the flow time series (Figure 27, Figure 28). Overall, these results are viewed as neutral due to their small percentage and uncertainties in model data sets.
- In the most recent decades (2000-2019), which include the Millennium Drought, an increase in benefit was predicted under the highest constraint scenarios W36 and W40. This predicted benefit, relative to the base case, ranged from +6-10 per cent increase for median species richness and +4-7 per cent increase for median waterbird density (birds/ha; Figure 29). This small increase in the 2000-2019 period is a positive outcome for this period given many of these years were dry and low numbers of waterbirds were observed in the most recent decade
- These subtle benefits predicted from the modelling potentially do not fully realise the outcomes the relaxation of constraints may have on waterbird populations in the Mid-Murrumbidgee wetlands. The relaxation of constraints will increase the opportunities to deliver flows to low-lying wetlands, including lagoons and billabongs in the Mid-Murrumbidgee wetlands which will increase habitat for waterbirds in the project area and potentially create opportunities for initiating small-scale colonial waterbird breeding and maintaining required water depth and habitat condition. Colonial waterbirds are reliant on inundation and maintenance of water depth in their breeding locations for young chicks to successfully reach the fledging stage which would be easier to achieve in a constraints relaxed scenario
- Many waterbird species move easily between wetland systems if habitat conditions are suitable. The Mid-Murrumbidgee wetlands were considered in isolation for the purposes

of this assessment; however, there are likely to be cumulative benefits not just in other areas of the Murrumbidgee that may benefit from the relaxation of constraints, but also neighbouring systems like the Murray River. The relaxation of constraints in both systems would increase options for water delivery to support waterbirds with benefits across the systems, complementing each other with outcomes that are likely to support overall improvements in waterbird populations in the Murray–Darling Basin

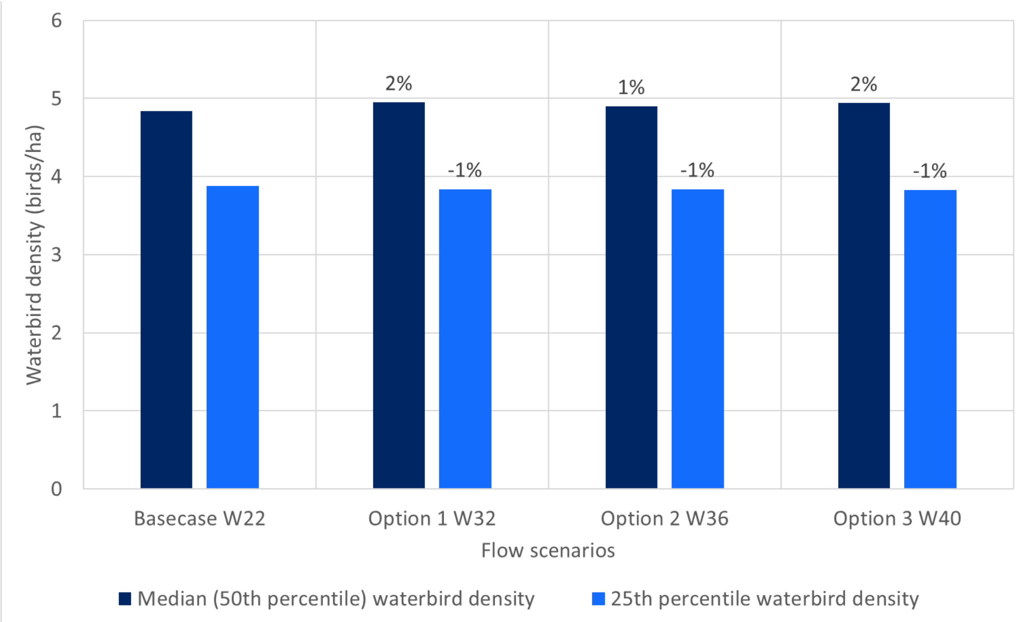


Figure 27: Predicted waterbird density (waterbirds/ ha) and percent change from base case for 25th percentile and median for each flow scenario based on 180 days cumulative river flows prior to surveys (1896-2019) at Darlington Point

Note that modelled responses are based on ground survey data for the Mid-Murrumbidgee wetlands

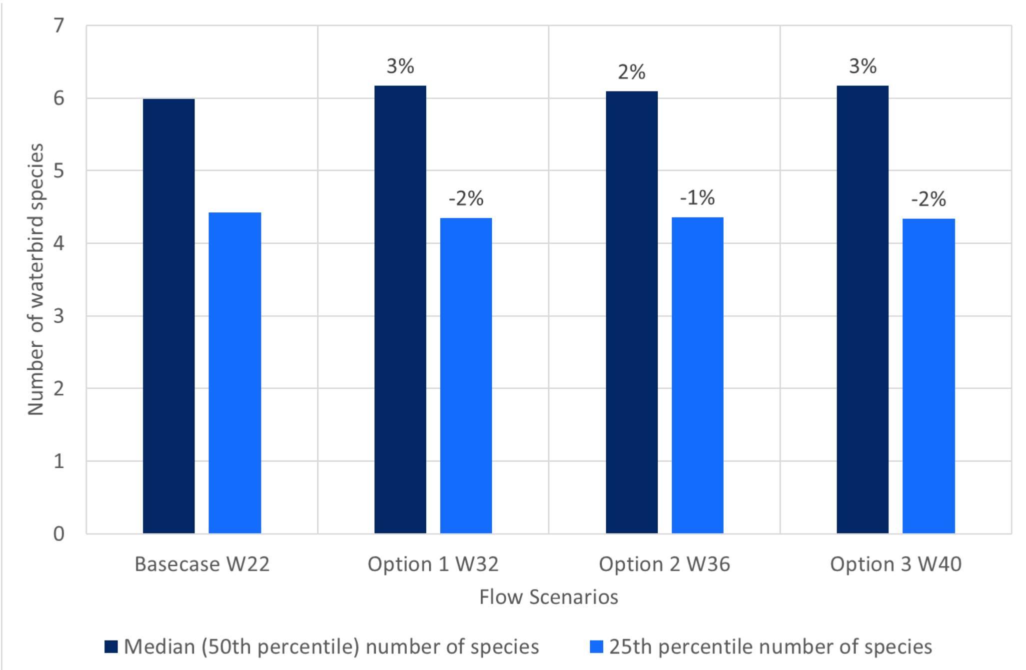
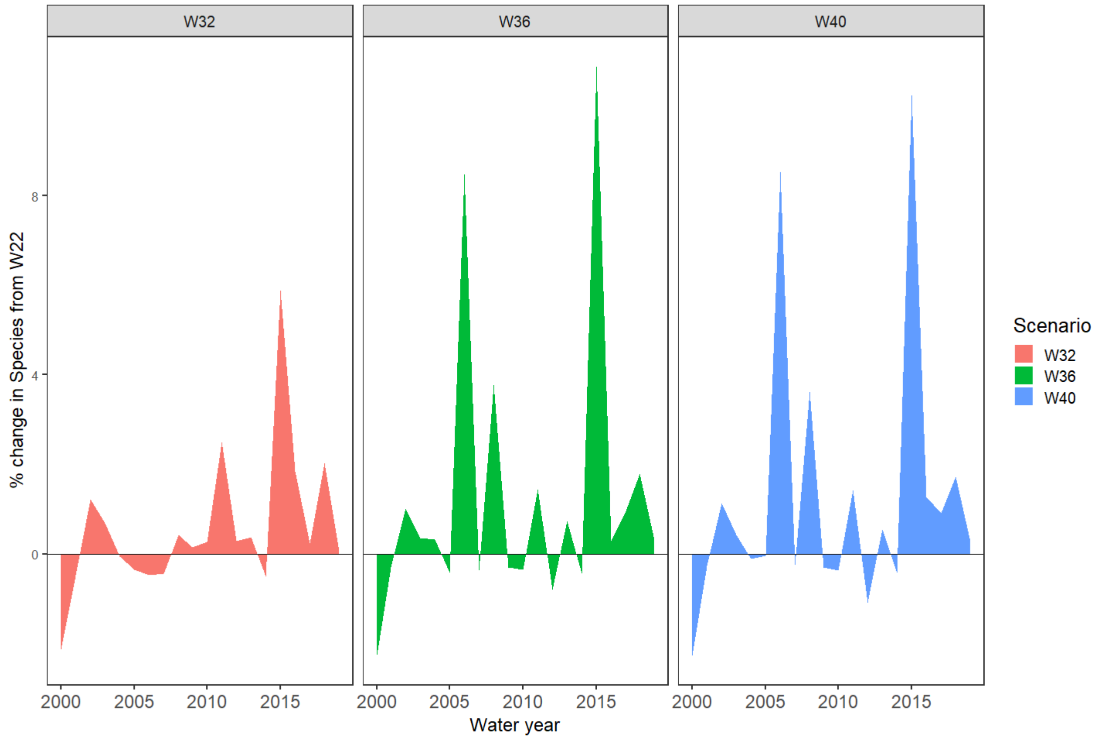


Figure 28: Predicted number of waterbird species and percent change from base case for 25th percentile and median for each flow scenario based on 180 days cumulative river flows prior to surveys (1896-2019) at Darlington Point

Note that modelled responses are based on ground survey data for the Mid-Murrumbidgee wetlands



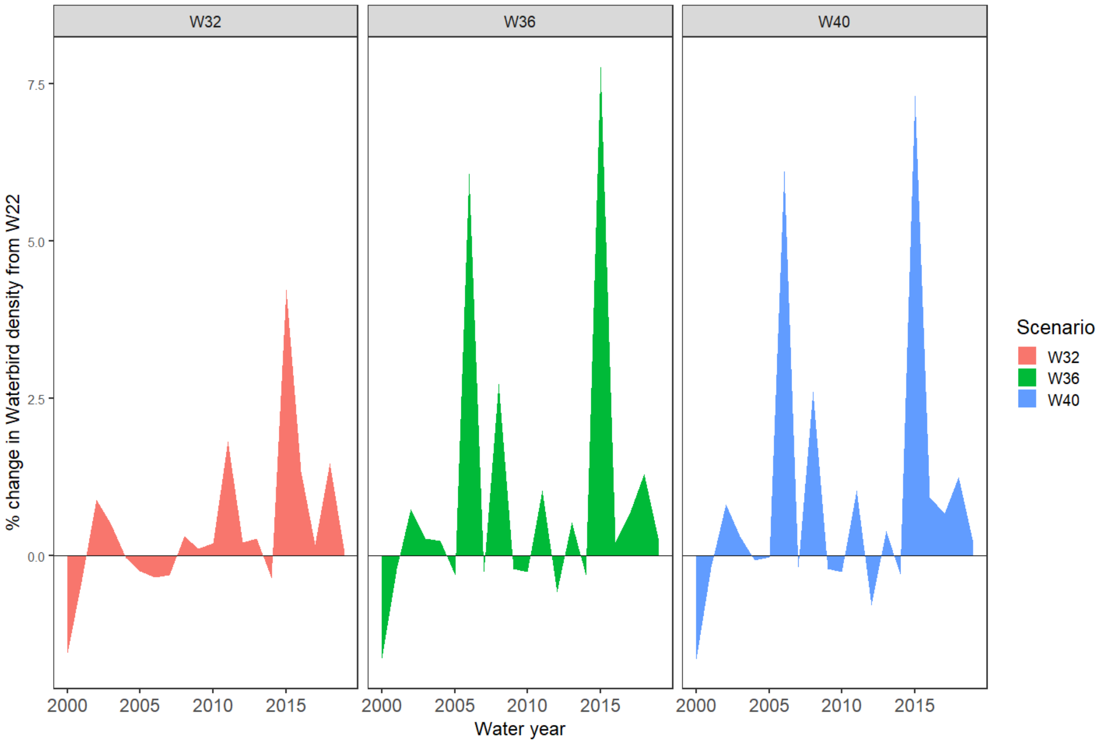


Figure 29: Time series of species richness across (upper) and waterbird density (birds/ha) (lower) 2000-2019 period only. Values above zero represent increase in responses compared to W22 (base case). Values below zero represent decrease from W22 (base case)

Predicted change in number of waterbird species and waterbird density (birds/ha) under each scenario compared to base case is based on cumulative rivers flows 180 days preceding spring surveys as main predictor variable. Note that the modelled time series assumes current levels of river regulation and water extraction throughout the whole period. Therefore, the base case (W22) trajectory does not represent actual waterbird populations under observed historical flows (from Bino et al. 2022)

Risks of not proceeding with program

Given waterbird dependence on floodplain wetlands for food resources and breeding habitat there are several risks of not progressing with the relaxation of constraints including:

- flows to wetlands will not be frequent enough to provide waterbirds with opportunities for both breeding and feeding
- habitat will decline in condition and sites will not be “event-ready” for breeding events initiated by natural high river flows
- breeding events initiated by natural high river flows will not be able to be supported successfully due to declines in habitat quality and food resources (insufficient food for chicks to be fully fledged).

4.4 Native vegetation

Higher flow limit options are predicted to increase the resilience of river red gum communities, with an increase of up to ~4,700 ha (23 per cent) in Mid-Murrumbidgee river red gum forest remaining healthy during drier years. These benefits are likely to be reflected for low-lying vegetation communities in areas that could not be modelled at this point (i.e. Lowbidgee).

Over the long-term, river red gum is predicted to benefit from relaxed flow constraints with up to a 1,600 ha (6 per cent) increase in average area of healthy (good or moderate condition) forests and woodlands when compared with the base case.

Floodplain vegetation communities within the Murray and Murrumbidgee catchments have been impacted by changes to the rivers' hydrological regimes; a result of increased regulation and water extraction following European colonisation, and climate variability and change (Roberts and Marston, 2011; Whetton and Chiew, 2021). Effective environmental watering can be used as mitigation against these changes, leading to an improvement in the health of floodplain vegetation communities.

The Murray and Murrumbidgee catchments are home to a diversity of native vegetation types, including river red gum (*Eucalyptus camaldulensis*), black box (*Eucalyptus largiflorens*), lignum (*Muehlenbeckia florulenta*), and various wetland herbland species (moira grass; *Pseudoraphis spinescens)*, giant rush (*Juncus ingens*), and common reed (*Phragmites australis*). Several sites within the catchments have been recognised as areas of international significance (Australian Ramsar sites: 14, 15, 16, 17, 62, 64) possessing expansive tracts of native vegetation types and supporting diverse and threatened species. Also, expansive wetland environments within the Murrumbidgee catchment are recognised as nationally important within the Directory of Important Wetlands in Australia, including the Lowbidgee Floodplain, Tuckerbil Swamp, and the Mid-Murrumbidgee Wetlands. Typically, riparian fringes are dominated by river red gum forests, with higher elevated areas supporting black box, and lower lying, regularly inundated, areas featuring shrub or herb-lands (Harrington and Hale, 2011).

Presently, the potential area of water-dependent vegetation that can benefit from environmental water is limited by operational constraints on flow delivery. Relaxing constraints would substantially increase this area, particularly in the Mid-Murrumbidgee Wetlands (McPhan et al. 2022a). For example, nearly double the area of river red gum forest can be inundated under the Option 3 (W40) scenario limit relative to the current operational limit (W22; Section 4.1).

Methods

The potential benefits to floodplain vegetation condition under relaxed constraints flow regimes (flow scenarios in Table 2) were assessed by researchers at La Trobe University using a Floodplain Vegetation Condition Model developed specifically for this project (FVCM; McPhan et al. 2022b). The FVCM uses spatial vegetation and inundation data and simulated flow data to provide a dynamic time-series of vegetation condition in response to different inundation sequences (defined in terms of frequency and duration; spells analysis). These results are temporally and spatially explicit; meaning the condition of a specific vegetation type, at a particular location, each year, can be simulated. For the Murrumbidgee catchment the FVCM used the Source-modelled flow data (Section 3.1), the CARM inundation model (DPIW, 2015) and a modified NSW vegetation spatial dataset built using the *Plant Community Type* (OEH, 2016) datasets, as key inputs.

The FVCM used the Source-modelled flow data and CARM inundation maps in a step-wise iteration to simulate change in vegetation health over the modelled time series. Each 125 m^2 area represented one vegetation community and was projected across the time series, with past inundation controlling the condition responses of vegetation at any given point in the time series. Inundation was modelled using a hydrological spells analysis to take the flow-at-gauge from the Source model and translate that into a time series of inundation for every pixel of the CARM dataset. Due to the differences in flow regime and inundation duration between the Murrumbidgee and the Murray rivers, preliminary Murrumbidgee vegetation models using flow responses determined for the Murray were not representative for the Murrumbidgee system. Vegetation inundation responses were discussed with Murrumbidgee vegetation experts and reset for the system. All vegetation was started in a good condition, so changes in vegetation health are the direct result of the inundation regime. The model also allowed for the vegetation type to change if there were substantial changes in flooding. For example, a pixel denoting river-red gum could decline in health during drought times (e.g. Federation Drought), recover in times of higher inundation (e.g. 1950s) and could change to a different vegetation type, after perishing from desiccation or becoming water logged, if it received too much or too little flooding under a scenario. The different flow scenarios caused unique inundation conditions on the floodplain leading to differences in the projected states of vegetation condition. One limitation of the current vegetation extents is inaccurate mapping of lignum to areas of herbaceous wetland vegetation in the Mid-Murrumbidgee. Given the small area lignum shrublands occupy in this landscape, we have removed them from results presented here. Future models using updated vegetation mapping would address this issue.

Key outcomes

The vegetation condition modelling predicts that relaxing flow constraints will provide modest benefits to the average condition of native vegetation communities. More substantial benefits are evident during drier climate periods, with the benefits increasing with the higher flow limit options (Table 9). Note that we use the 10^{th} percentile of the annual modelled area in good or moderate condition as reflective of conditions during drier climate periods.

River red gum forests showed the largest improvement in good/moderate condition area with relaxed constraints generating an increase of up to ~1,600 ha (+6 per cent) in the average area of river red gum in good or moderate condition across the Murrumbidgee catchment (Burrinjuck to Hay Weir). During drier climate periods less river red gum experienced condition decline with ~4,700 ha (+23 per cent) more red gum persisting in a healthy condition under the W36 and W40 scenarios relative to base case. The projected large areas of river red gum benefitting from relaxed constraints is consistent with its geographical location on the floodplain; approximately half of the total mapped area within the floodplain

(24,000 ha) resides at elevations that can be inundated by a 40,000 ML/day at Wagga Wagga delivery (Appendix B).

For black box woodland relaxed flow constraints caused small declines in the average area experiencing good or moderate conditions (~200 ha). Predicted declines are likely due to relaxed flow constraints leading to reductions in the magnitude of unregulated flows (discussed in more detail below).

Table 9: Average area (ha; and percentage change from base case) of vegetation types in 'good' or 'moderate' condition across the entire modelled time-series (Burrinjuck Dam to Hay Weir)
The 10th percentile area of river red gum in 'good' or 'moderate' condition in each flow limit scenario is included as it is reflective of condition during drier climate periods.

Flow limit option scenario	River red gum forest	River red gum forest (10th percentile)
Base case (W22)	28,206	20,686
Option 1 (W32)	28,547 (+1 %)	21,217 (+3 %)
Option 2 (W36)	29,703 (+5 %)	25,373 (+23 %)
Option 3 (W40)	29,837 (+6 %)	25,377 (+23 %)

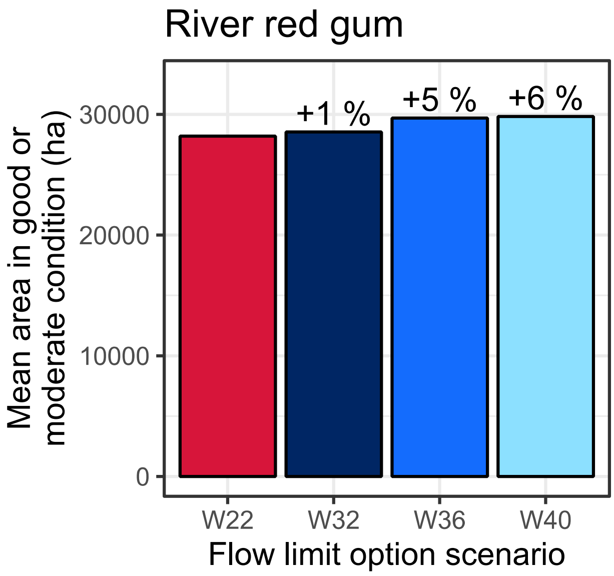


Figure 30: Mean area of river red gum in good or medium condition in each flow limit option scenario for the Murrumbidgee River, Burrinjuck Dam to Hay Weir

The magnitude of benefit achieved by relaxed flow constraints varies over time (Figure 31, Figure 32). When the climate is highly wet (e.g. late 1950s and 1960s; Figure 31 and Figure 32), the benefit of relaxed flow constraints for vegetation condition is reduced, with little to no difference between the flow limit option scenarios and the base case evident. Conversely, greater differentiation is apparent during relatively moderate or dry climates (Figure 32, Figure 33). At such times environmental deliveries can provide watering event frequencies more in-line with species requirements.

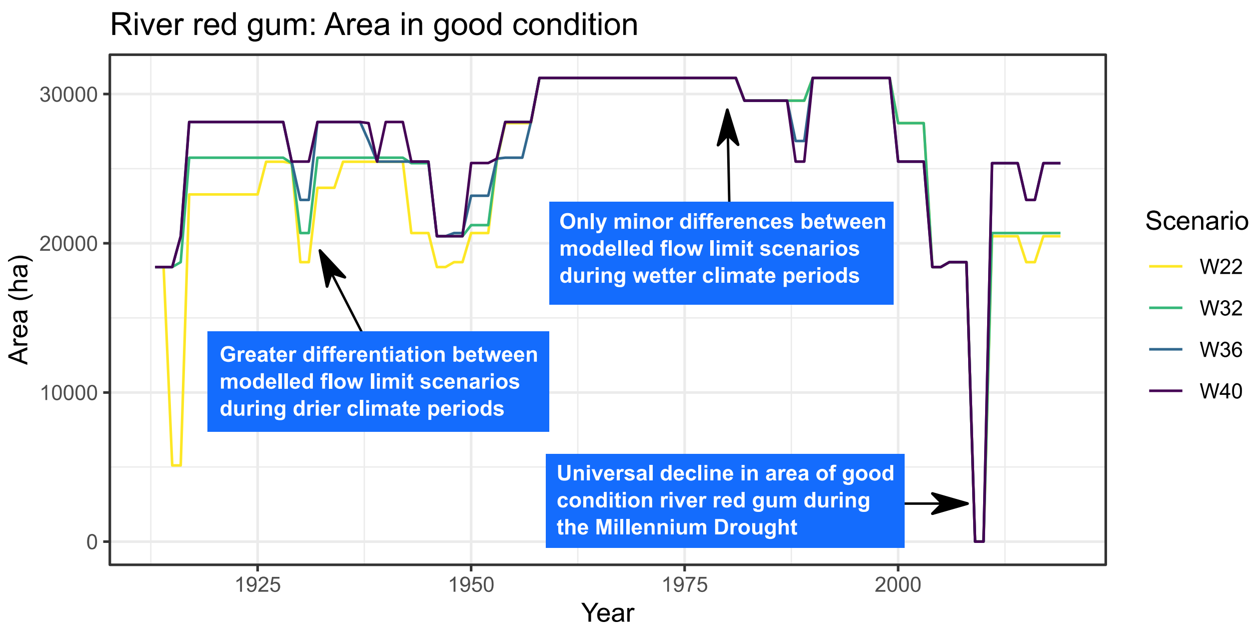


Figure 31: Area of river red gum in 'good' condition over the modelled time period (1911 to 2019) for the base case and three flow limit option scenarios

Model assumes all river red gum start in good condition at start of modelling period in 1895, so figure is truncated to post-1911 to showcase changes following initial, assumption driven, patterns

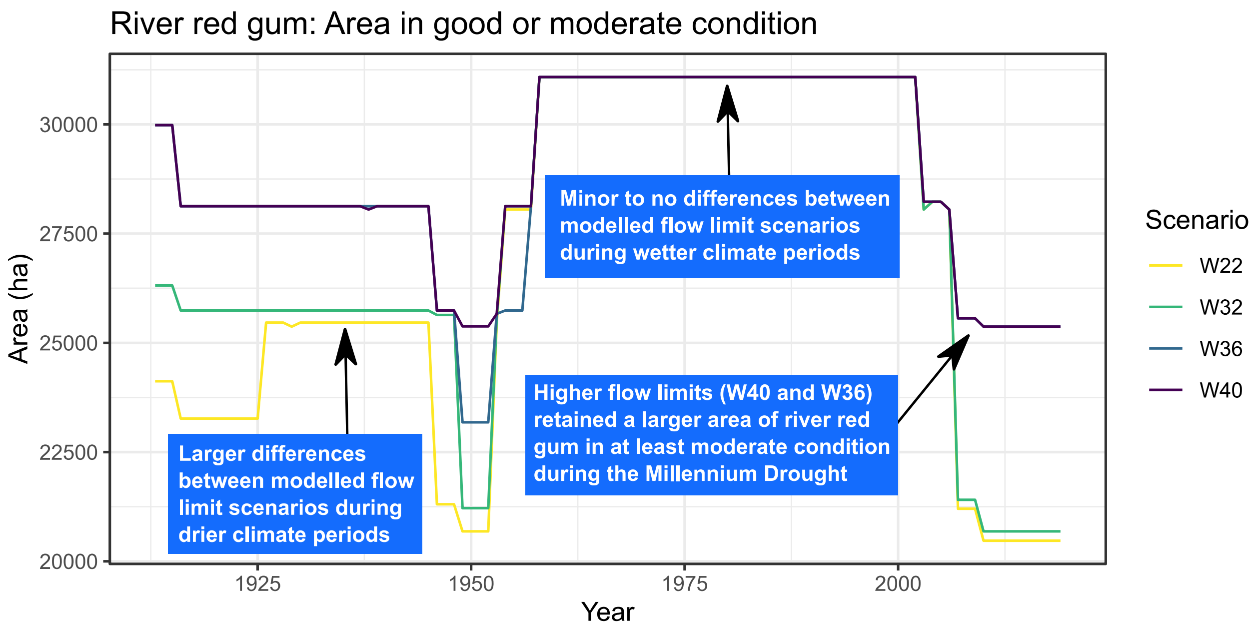


Figure 32: Area of river red gum in 'good' or 'moderate' condition over time (1911 to 2019) for the base case and three flow limit option scenarios

Model assumes all river red gum start in good condition at start of modelling period in 1895, so figure is truncated to post-1911 to showcase changes following the initial, assumption driven, patterns

These time-series results suggest that raising flow limits can reduce the negative impact of meteorological drought on vegetation condition. During dry periods across the time series (10th percentile) the higher flow limits (W36 and W40) provided a 23 per cent increase in the area of river red gum in good or moderate condition (Figure 33). Universal declines in 'good' condition river red gum for all flow limit option scenarios during the Millennium Drought highlight that low water availability during extreme droughts may limit the potential to prevent declines in native vegetation during these periods. Despite reductions in 'good' condition, the W36 and W40 scenario sustained approximately 24 per cent more area of river red gum in at least 'moderate' condition following the Millennium Drought, relative to all other flow limit option scenarios.

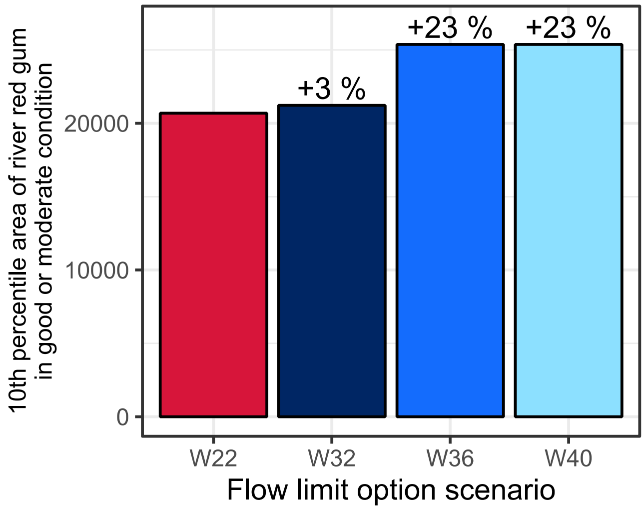


Figure 33: 10th percentile area of river red gum in good or medium condition in each flow limit option scenario, for the Murrumbidgee River, Burrinjuck Dam to Hay Weir

This 10th percentile area data gives us an idea of the area in good or moderate condition during drier climate periods. We can see that relaxed flow constraints substantially improve river red gum condition during dry climate periods, and more so than during average climates (Figure 30).

In this phase of the project, results presented are largely focused on river red gum, despite other vegetation being modelled. This is due either to lack of accuracy in input datasets to the model (vegetation mapping) or constraint relaxation being more relevant to lower floodplain areas. For instance, current results indicate that areas of black box at higher elevations may experience negative outcomes from relaxed flow constraints; however, this is a relatively small area (~200 ha). This negative result is likely due to larger deliveries of water for the environment, as modelled within the higher flow limit option scenarios, creating air-space within storages that can lower the magnitude of subsequent spills. This results in smaller unregulated flows and consequently the area inundated during large unregulated flows is reduced. Which in turn results in vegetation decline in areas that lie 'outside-the-reach' of water deliveries at the proposed flow limits. However, vegetation at higher elevations (e.g. black box) are also possibly sustained by water sources that would complement large floods (e.g. soil pore- and groundwater) to a greater degree, while the FVCM used here currently only models the influence of inundation from river flows. Of the ~4,100 ha of black box in the model, only ~800 ha can be reached by relaxed constraint flow limit options above a maximum current delivery. These areas can be compared with the ~1,600 ha of river red gum that improve in condition over the whole time series and the ~4,700 ha that improve during drought. Yet, the potential reduction in volume of unregulated flows should be considered as the program proceeds.

Risks of not proceeding with program

There are clear risks of not proceeding with the program with regards to native vegetation condition outcomes. Outside wetter climate periods, raising flow limits will achieve significant benefits for the large areas of native vegetation accessible by program flows within the Murrumbidgee catchment for extended durations of time — benefits unattainable by other measures. These benefits are very likely to be substantial during periods of meteorological drought, where maintaining up to +23 per cent more river red gum in good-to-moderate condition would be critical to more efficient recovery post-drought and providing crucial habitat refugia for native fauna. Further, there are likely to be benefits to other low-lying vegetation, such as wetland herblands, which were not considered in current models, but will be in the future. Such benefits will be more pronounced and important in a drier future climate, where currently inundated areas may dry out and therefore not proceeding with the program risks losing a potential strategy for mitigating predicted climate change effects.

4.5 Ecosystem Production

'Production' or *energetic carrying capacity* modelling predicts that relaxed flow constraints will lead to a consistent increase in the availability of food with median total annual production increasing by up to 11 per cent (relative to the base-case) in the Burrinjuck to Hay study area for the maximum flow limit option. Findings indicate that large, unregulated flows are an important source of production through time.

Ecosystem 'production' describes the growth and transfer of photosynthetic energy from plants and algae into the body mass of animals in the aquatic food web. During photosynthesis, energy from the sun is captured and used to create plant material ('organic matter') – providing the basic food resource that ultimately supports all animals in an ecosystem. Although populations of aquatic animals change in response to a range of drivers, the number and biomass of organisms is fundamentally limited by the amount and timing of available energy. Food-based energy is passed among organisms in the aquatic food web, with different energy sources making their way to various groups of organisms depending on the amount and quality of different sources of organic matter (Figure 34).

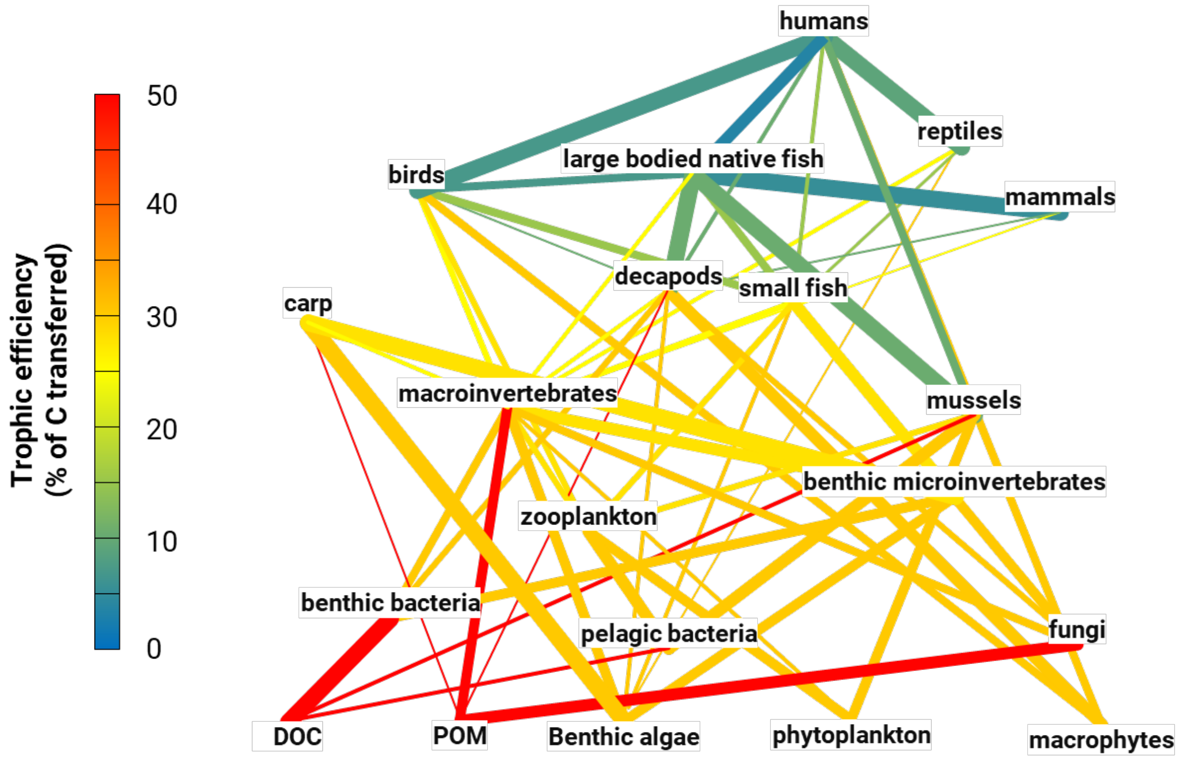


Figure 34: Modelled food web including carp (Siebers et al. 2022). Lines between different organism groups and basal resources (a.k.a. nodes) indicate trophic connections (higher nodes consume lower nodes)
Colour of lines indicates proportion of carbon at lower node that contributes to production at upper, linked node (a.k.a. trophic transfer efficiency). Relative width of lines indicates relative proportion of lower node energy transferred along each line.

Floodplain river ecosystems are unique in the way they acquire energy from both the river and the floodplain. Terrestrial plants grow on dry floodplains, accumulating organic matter in the form of leaves, bark and twigs that can be consumed by aquatic organisms when the floodplain is inundated. Inundation also expands the area of aquatic habitat, increasing the amount of inundated surface area upon which aquatic plants and algae can grow. The combination of increased area of aquatic habitat and hydrologically connecting the products of terrestrial primary production with aquatic ecosystems, creates periods of increased food availability that are highly beneficial to aquatic ecosystems. By relaxing constraints, environmental flows can contribute to improved food availability for aquatic organisms via more frequent and/or extensive hydrological connectivity with low-lying floodplains.

Methods

Ecosystem production was modelled for the program using an 'energetics model' developed to track the availability, quality and movement of energy through aquatic food webs (Siebers et al. 2022). The approach uses the relationship between flow and habitat inundation to account for changes in production through time, with the amount of energy produced dependent upon the amount, duration, and type of area that has been inundated. For each day in the flow time series, the expected inundation extent was estimated using the CARM model. These floodplain extents were further classified into one of four different habitat classes, each with a different production rate informed by an analysis of literature. Production rates were used to estimate the total amount of energy supplied to a model food web where the supply of energy to different groups of organisms could be further explored. Monthly production estimates were added together to yield results for each year.

Production modelling results provide insights into the potential amount of energy (food) that could be supplied to different organisms under ideal conditions and are summarised at an annual scale. Rather than present the full results of energy flowing throughout different parts of the food web, the results for energy supplied to "large bodied native fish" (i.e. potential food available to native fish) are presented. The data were examined to understand how relaxing constraints might contribute to changes in annual ecosystem production. Production outcomes for flow limit options were compared by calculating the difference in total annual production between each flow limit option and the base case scenario (W22) for each year in the time series.

Key outcomes

Production modelling predicts that relaxing constraints will contribute a moderate but consistent increase to the overall amount of energy in the Murrumbidgee River between Burrinjuck Dam and Hay Weir, with benefits increasing with higher flow limit options (Table 10, Figure 35). Over time, the pattern of total annual production potential is dominated by production during large, unregulated flow events (Figure 36), underscoring the importance of large flows as drivers of enhanced production in river ecosystems. Constraints relaxation does not mean more flows are added to the river, but will allow for more water for the environment to be contributed towards flow pulses. Modelling suggests relaxed flow constraints could increase the median total amount of production by between 7 and 11 per cent. This is achieved by adding small amounts to floodplain inundation, increasing production across multiple years.

The impact of constraints relaxation on production estimates was also analysed for low-production years (i.e. the 25th percentile production rates). The model also predicts no improvement upon base case for dry years (Table 10, Figure 35).

Table 10: Total annual production potential for large bodied native fish (tonnes of carbon) for the Burrinjuck to Hay area. Data are the median and 25th percentile production potential calculated using all water years (n= 124 years)

Flow limit option scenario	Median total annual production (% change from base case)	25th percentile total annual production (% change from base case)
Base case (W22)	221	206
Option 1 (W32)	235 (+7%)	208 (+1%)
Option 2 (W36)	240 (+9%)	208 (+1%)
Option 3 (W40)	245 (+11%)	207 (+1%)

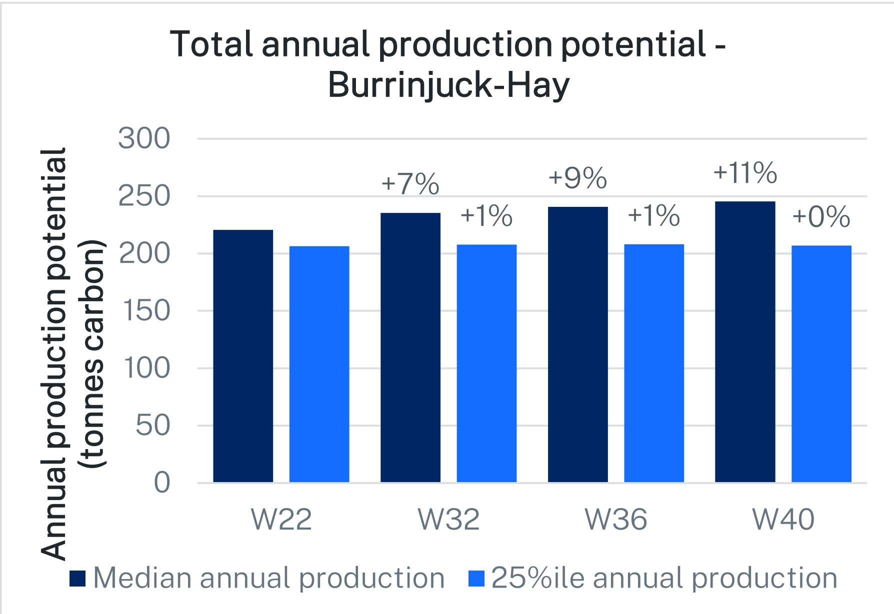


Figure 35: Median total annual production potential for large bodied native fish (tonnes carbon) for the Burrinjuck to Hay project area
Data are the median and 25th percentile production potential calculated using all water years (n= 124 years). Labels are the per cent change from the base-case scenario

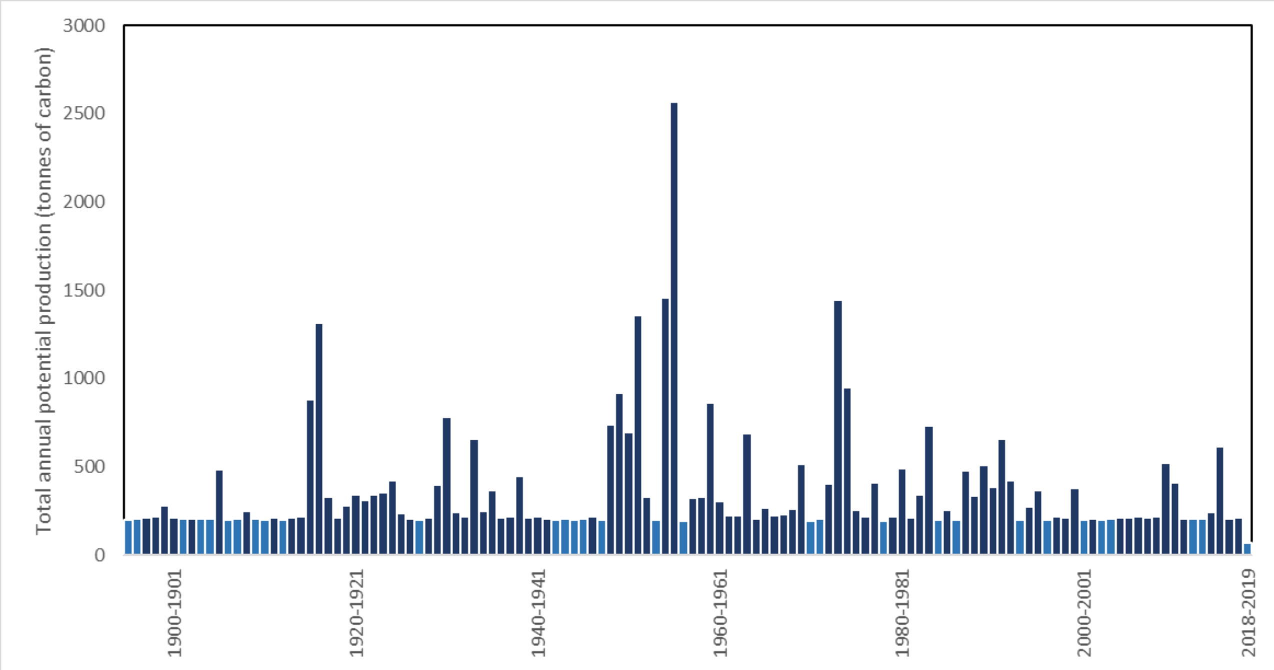


Figure 36: Modelled total annual production for large bodied native fish (tonnes of carbon) for the Burrinjuck to Hay project area

Results are shown for the base case (W22). Light blue lines indicate low-production years (i.e. where total annual production potential is less than the 25th percentile)

Risks of not proceeding with the program

The program's production modelling demonstrates how relaxing constraints influences a key limitation on ecological communities caused by regulation. Energy limitation is not expected to always influence aquatic communities, rather it will become limiting at key moments in time. Because production is so closely related to river flows, it is anticipated that energy limitation would occur because of the flow environment. The challenge for water management is to identify these critical moments and to provide flows that augment production, thereby increasing the capacity of aquatic ecosystems. If constraints are not relaxed, the amount of energy available to aquatic ecosystems will be lower overall. In the context of a changing climate, this may result in longer periods of resource limitation.

5 Risk and benefit assessments

5.1 Water Quality

Raising flow limits does not increase the risk of adverse water quality events.

Benefits to water quality are likely, due to the potential to bring forward the timing of some high flow events from the warmer months (late spring/summer) to cooler months earlier in the season (winter/early spring; Table 11)

Table 11: Overarching risk/benefit assessment of constraint relaxation scenarios for the Murrumbidgee River (from McInerney et al. 2022)

CONSTRAINT RELAXATION SCENARIO	CHANGE IN RISK RATING FROM CURRENT	RISK RATING	CHANGE IN BENEFIT RATING FROM CURRENT	BENEFIT RATING
W32	No change	Moderate	Moderate -> High	High
W36	No change	Moderate	Moderate -> High	High
W40	No change	Moderate	Moderate -> High	High

Adverse water quality events occur intermittently within the program areas and can be affected by regulated flows. These events can impact native species, agriculture and domestic and recreational users. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) completed a qualitative assessment to consider the benefits and risks of relaxed flow constraints on adverse water quality events for the program.

Methods and key findings

Eight adverse water quality issues affecting the Murrumbidgee River were identified by the department (Table 12) and considered in the assessment. Firstly, a decision matrix was developed to target water quality issues that are directly impacted by flow and that are potentially affected by the raising of flow limits.

Three water quality issues — hypoxic blackwater, blue green algae and salinity — were selected for further assessment as increased flow magnitude under relaxed flow constraints was identified to potentially cause increased risk or benefit (Table 12). For the rationale and justification for these decisions, please refer to the technical report for this project "*A qualitative assessment of the risks and benefits to in-channel water quality from changes in flow related to the Reconnecting River Country program*" (McInerney et al. 2022).

Table 12: Summary of links to changes in flow magnitude for the water quality parameters being assessed (N/A indicates that a link has not been established; from McInerney et al. 2022)

WATER QUALITY PARAMETER	MECHANISTIC LINK TO INCREASED FLOW MAGNITUDE	POSITIVE, NEGATIVE OR BOTH	INCREASED RISK / BENEFIT WITH INCREASED FLOW MAGNITUDES
Blackwater	Yes	Both	Yes
Eutrophication	No	N/A	N/A
Blue-green algal blooms	Yes	Both	Yes
Salinity	Yes	Both	Yes
Turbidity	Yes	Negative	Not increased above current risk
Weir pool stratification / destratification	Yes	Both	Not increased above current risk
Acid sulfate soils	Yes	N/A	N/A
Thermal pollution	Yes	Negative	Not increased above current risk

The relationship between higher flows and water quality risks and benefits was then established:

- *Blue-green algae* – Blue-green algal blooms are common within the surface waters of storages within the Murrumbidgee River system, and the passage of water via these storages will occur regardless of flow magnitude. One potential risk presented by higher magnitude flows is the larger geographical distribution of blue-green algae from the seed location. Conversely, larger flows can also break up downstream blue-green algal bloom events, thus improving water quality.
- *Salinity* – Increased flow magnitude has both a positive and negative relationship with salinity. Potential risks include the mobilisation of salt from the floodplain (leading to increased river salinity), as well as the raising of saline groundwaters. Large flushing flows, however, are critical to the export of salt from the system and lead to net decreases in basin salinity.
- *Hypoxic blackwater* - Hypoxic blackwater events occur rarely in the Murrumbidgee River and are caused by high river flows that contribute high concentrations of dissolved organic carbon during periods of warm water temperature. The amount of dissolved organic carbon mobilised from inundated floodplain and wetland areas will vary with the amount of accumulated organic matter and the extent of inundation. Organic matter accumulation is both positively and negatively affected by inundation. Details on the relationship between hypoxic blackwater likelihood and flow magnitude used for this assessment were partly informed by the hypoxic blackwater time series assessment (Wolfenden and Baldwin 2022).

For blue-green algae and hypoxic blackwater the timing of a high flow event (season) was more significant than the magnitude of flow with regards to water quality risk/benefit (Table 13; Table 14). Blue-green algae and hypoxic blackwater are water quality events that are driven by metabolic processes which increase in rate with higher water temperature — hence why the identified potential benefit and risk ratings are higher in warmer months (November to April). Understanding this relationship, particularly for hypoxic blackwater, is key for risk mitigation where flows are planned to be delivered before November and this was incorporated into the environmental water delivery strategy in the hydrological modelling (Section 3.3). For hypoxic blackwater, summer flows greater than 40,000 and 36,000 ML/day in the Burrinjuck to Hay and downstream of Hay areas respectively lead to an increase in risk rating ('high' to 'very high').

For salinity, risk and benefit ratings are independent of timing, and are constant ('moderate' and 'high' respectively) across all flow thresholds in both reaches in the Murrumbidgee project area. In the Burrinjuck to Hay reach, the risk and benefit ratings for salinity are consistently 'moderate' across flow categories, whilst potential benefits remain 'high' across all evaluated flow thresholds (Table 13). Similarly, for downstream of Hay the risk and benefit ratings for salinity are consistently 'low' across flow categories, whilst potential benefits remain 'high' across all evaluated flow thresholds (Table 14).

Table 13: Collation of water quality event risk/benefit assessment by flow category for events of >7 days duration, Burrinjuck Dam to Hay

Note that the summer and winter periods were expanded to November to April, and May to October respectively (reproduced from McInerney et al. 2022)

FLOW CATEGORY	FLOW EVENT	RISK OF A WATER QUALITY EVENT			BENEFIT OF A WATER QUALITY EVENT		
Upstream of Hay (ML/day)	TIMING	BLACKWATER	BLUE-GREEN ALGAL BLOOM	SALINITY	BLACKWATER	BLUE-GREEN ALGAL BLOOM	SALINITY
>22,000	Summer	High	High	Moderate	High	High	High
	Winter	Moderate	Moderate	Moderate	High	Moderate	High
>32,000	Summer	High	High	Moderate	High	High	High
	Winter	Moderate	Moderate	Moderate	High	Moderate	High
>36,000	Summer	Very high	High	Moderate	High	High	High
	Winter	Moderate	Moderate	Moderate	High	Moderate	High
>40,000	Summer	Very high	High	Moderate	High	High	High
	Winter	Moderate	Moderate	Moderate	High	Moderate	High

Table 14: Collation of water quality event risk/benefit assessment by flow category for events of >7 days duration, downstream of Hay

Flow categories relate to large fresh, bankfull and overbank flows in the Murrumbidgee River downstream of Wagga Wagga (reproduced from McInerney et al. 2022)

FLOW CATEGORY	FLOW EVENT	RISK OF A WATER QUALITY EVENT			BENEFIT OF A WATER QUALITY EVENT		
D/S Hay (ML/day)	TIMING	BLACKWATER	BLUE-GREEN ALGAL BLOOM	SALINITY	BLACKWATER	BLUE-GREEN ALGAL BLOOM	SALINITY
>22,000	Summer	High	High	Low	High	High	High
	Winter	Moderate	Moderate	Low	High	Moderate	High
>32,000	Summer	High	High	Low	High	High	High
	Winter	Moderate	Moderate	Low	High	Moderate	High
>36,000	Summer	Very high	High	Low	High	High	High
	Winter	Moderate	Moderate	Low	High	Moderate	High
>40,000	Summer	Very high	High	Low	High	High	High
	Winter	Moderate	Moderate	Low	High	Moderate	High

The impact of relaxed flow constraints on the risk or benefit of a water quality event was then determined by evaluating how relaxed flow constraints would change the frequency of high flows relative to the base case using the modelled ‘flow limit options’ scenario data (Table 11).

Overall outcomes

Relaxed flow constraints do not increase the risk of negative water quality outcomes in the Murrumbidgee project area which was split into Burrinjuck to Hay and downstream of Hay for the purpose of this assessment. For these reaches, relaxed flow constraints will likely benefit water quality outcomes with a raised overall benefit rating from ‘moderate’ to ‘high’ (Table 14). The increased benefit rating is primarily due to the potential to shift flows from the higher risk summer period to winter.

5.2 Invasive Species – Weeds

The predicted change in distribution of suitable habitat for invasive weeds decreases for amphibious species and increases for terrestrial species. There is a small decrease in weed hot spots with the greatest decreases for higher flow limits.

When considering the changes in habitat suitable for weeds and weed hot spots with the impact of weed species and existing mitigation, there is a slight benefit (reduction in weed impact) for the two higher flow scenarios (W36 and W40) and a slight increase in risk (increase in weed impact) in the lowest flow scenario (W32) for the assessed priority weed taxa.

Altering hydrological conditions can make rivers and their floodplains susceptible to invasion from exotic weeds, particularly in systems like the Murrumbidgee River, where regulation has led to a decline in water-dependent plants in favour of terrestrial species (Catford et al. 2011; Haby et al. 2019). Although environmental flows benefit native vegetation, they have also been associated with increased risk of spreading exotic weeds (Haby et al. 2019; Stokes et al. 2010). Weed invasion can reduce the biodiversity value and ecosystem functioning of native wetland vegetation communities. Re-instating flow regimes more similar to historic/natural conditions, however, can also mitigate weed expansion (Catford et al. 2011; Haby et al. 2019). Weeds can impact biodiversity, industry and infrastructure. A review of weed impacts found that in the Murrumbidgee catchment management area, 67 species were directly impacting biodiversity (DPI & OEH, 2011; Riverina LLS, 2017). The program invasive weeds assessment therefore considers both the potential risk and benefits from the three Murrumbidgee raised flow limit options on invasive weed outcomes.

Methods and key findings

Species Distribution Models (SDMs) were used to predict areas providing suitable habitat for each weed species/functional group under the Source-modelled flow scenarios and associated inundation patterns determined from RiMFIM/EW-FIM. Inundated areas were classified into criteria (e.g. 30-60 days of inundation) for each year in each of the flow time series. In addition to inundation, other environmental factors affecting weeds were considered: climatic indicators (including rainfall), land use, wetland and vegetation types. Seven weed species and two functional groups were modelled in this project (listed in Table 16). Weed species were those with sufficient data and identified as of concern by expert elicitation and were sourced from data and literature including the strategic weed management plans for Riverina Local Land Services area (Capon et al. 2022; Murray LLS, 2017). Functional groups consist of many weed species that have similar habitat requirements and so were able to be modelled together: terrestrial damp (germinate on saturated/damp ground but do not tolerate flooding) and terrestrial dry (do not require flooding) groups (Brock & Casanova, 1997). Species occurrences were extracted from the Atlas of Living Australia and the department's vegetation surveys. SDMs take the environmental data from where existing species occur and use this to predict where a species may occur under changing environmental conditions. Here SDMs were used more broadly to predict where suitable habitat for weeds could occur under altered changed inundation regimes. An SDM was built for every species/functional group and flow limit option scenario for all the program's areas in the Murrumbidgee, including the Lowbidgee (see Section 2.5).

Weed hotspots, areas of suitable habitat for several weed species or functional groups, were also identified. Based on the outputs a risk assessment was undertaken using a scoring system with criteria that included risks/benefits and associated consequence and severity. An overall risk score was calculated by summing the relevant risk scores and then standardising this value to give a proportional risk value. These values can be used to compare the risks and consequences of different flow limit options in regard to the change in habitat for weed species.

Overall, when considering the likelihood of change in suitable habitat and also the consequence of potential distribution change, there is a slight benefit for flow limit option scenarios W36 and W40 in the Murrumbidgee, with a slight disbenefit from flow scenario W32 (Table 15, Table 16). There is very little difference between the scenarios with the benefits and disbenefits being slight either way.

Table 15: Summary of overall standardised risk scores for the Murrumbidgee (scale: benefit -100 to100 risk) (modified from Capon et al. 2022)

Flow Scenario	W32	W36	W40
Standardised score (-100-100)	*1.2*	*-1.5*	*-2.3*
Overall risk	*Likely overall slight risk*	*Likely overall slight benefit*	*Likely overall slight benefit*

- Drivers for change among weed taxa tended to be climatic rather than flow driven with annual rainfall being the most important predictor in five of seven models. However, changes were observed under the different flow limit option scenarios and the extent and distribution of priority weed species were moderately associated with inundation and drying metrics.
- The SDMs consider the change in suitable habitat, not actual dispersal of species, and both increase and decreases in suitable habitat were seen in the Murrumbidgee for priority weed species. Therefore, in the final risk scores the consequence and current mitigation methods are considered as well as the likelihood of change in suitable habitat as these will also have a strong influence on potential species distribution.
- Species distribution modelling showed that under the raised flow limit option scenarios amphibious species (i.e. *Phyla scandens* – lippia and Tdr – terrestrial damp species) have a reduction in suitable habitat area. This is most likely driven by areas with interrupted flow regimes with reduced flows under current conditions, which provide ideal invasion habitat under the base case, being restored to areas of longer inundation periods, which help reduce the extent of species such as lippia (Figure 37). There was no suitable habitat predicted for *Sagittaria platyphylla* – arrowheads in the Murrumbidgee. There was also an increase in highly suitable habitat for lippia, but this is at a much smaller scale than the suitable habitat area (Figure 38).
- Terrestrial species were seen to have an increase in suitable habitat area (i.e. *Lycium ferocissimum* – African boxthorn and *Marrubium vulga*re - horehound). This change is most likely due to the increase in fringing areas with increased moisture availability but

no extended inundation and a potential increase in dispersal. The primary flow driver for this change was periods of dry between flows. However, there was no highly suitable habitat at all for horehound in the Murrumbidgee and suitable habitat area declined slightly for *Xanthium* – Bathurst burr. Notably suitable habitat area for Tdr – terrestrial dry species disappeared completely under the raised flow limit options (Figure 37, Figure 38).

- Weed hot spots (four or more weed species), represent ~ 0.4 per cent (1286 ha) of the project area in the base case for the Murrumbidgee and are largely close to major town centres as well as along the Murrumbidgee Rivers south of Griffith. Declines from the base case between 0.78 per cent-7.0 per cent where observed across the three scenarios, with the decline increasing with increasing flow limit. These declines reflect the general decline in suitable habitat area for each taxa, particularly for amphibious species.

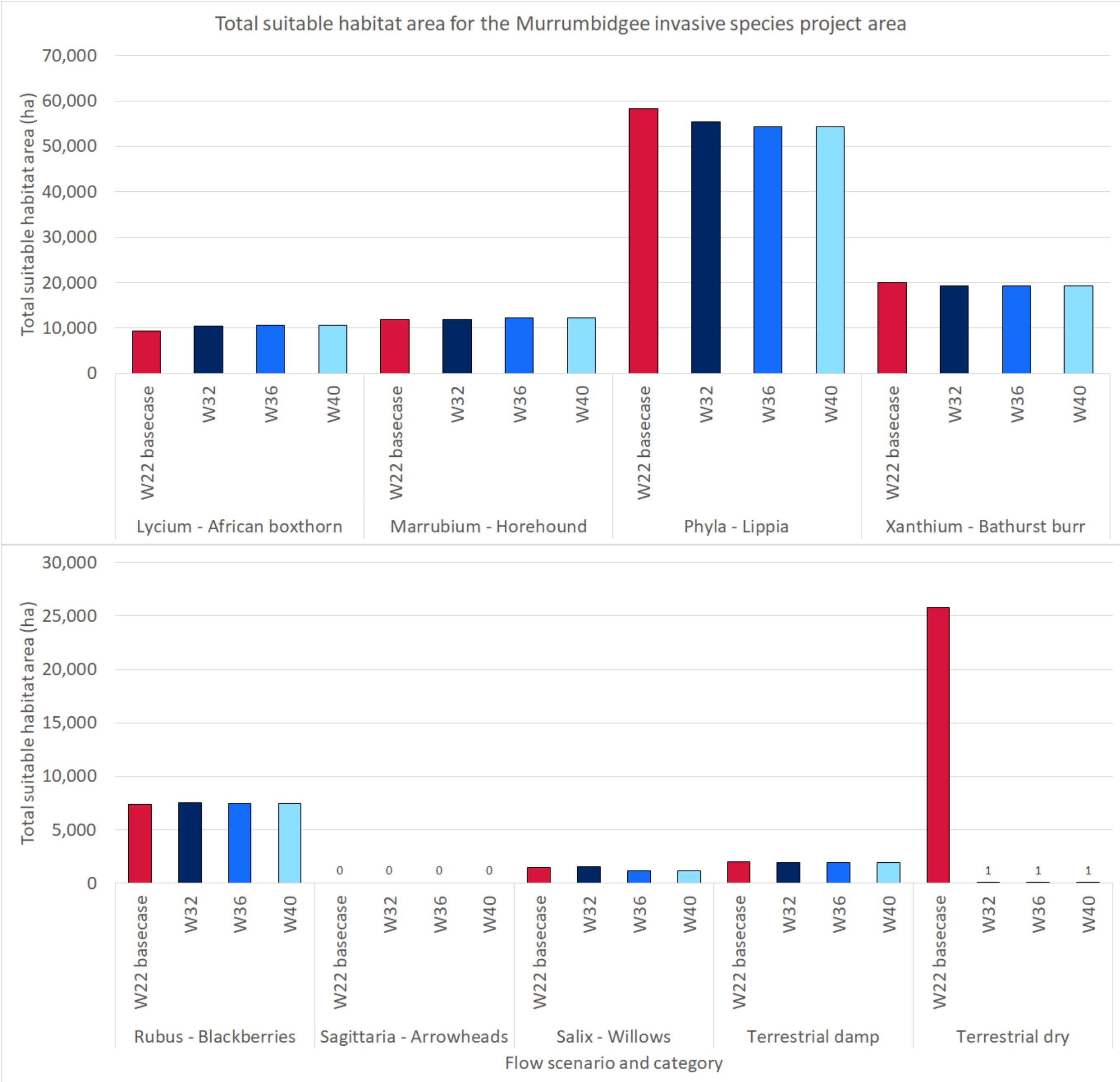


Figure 37: Total area (ha) of suitable habitat predicted by SDMs for all modelled taxa the Murrumbidgee under the base case and each flow limit option
(from Capon et al. 2022)

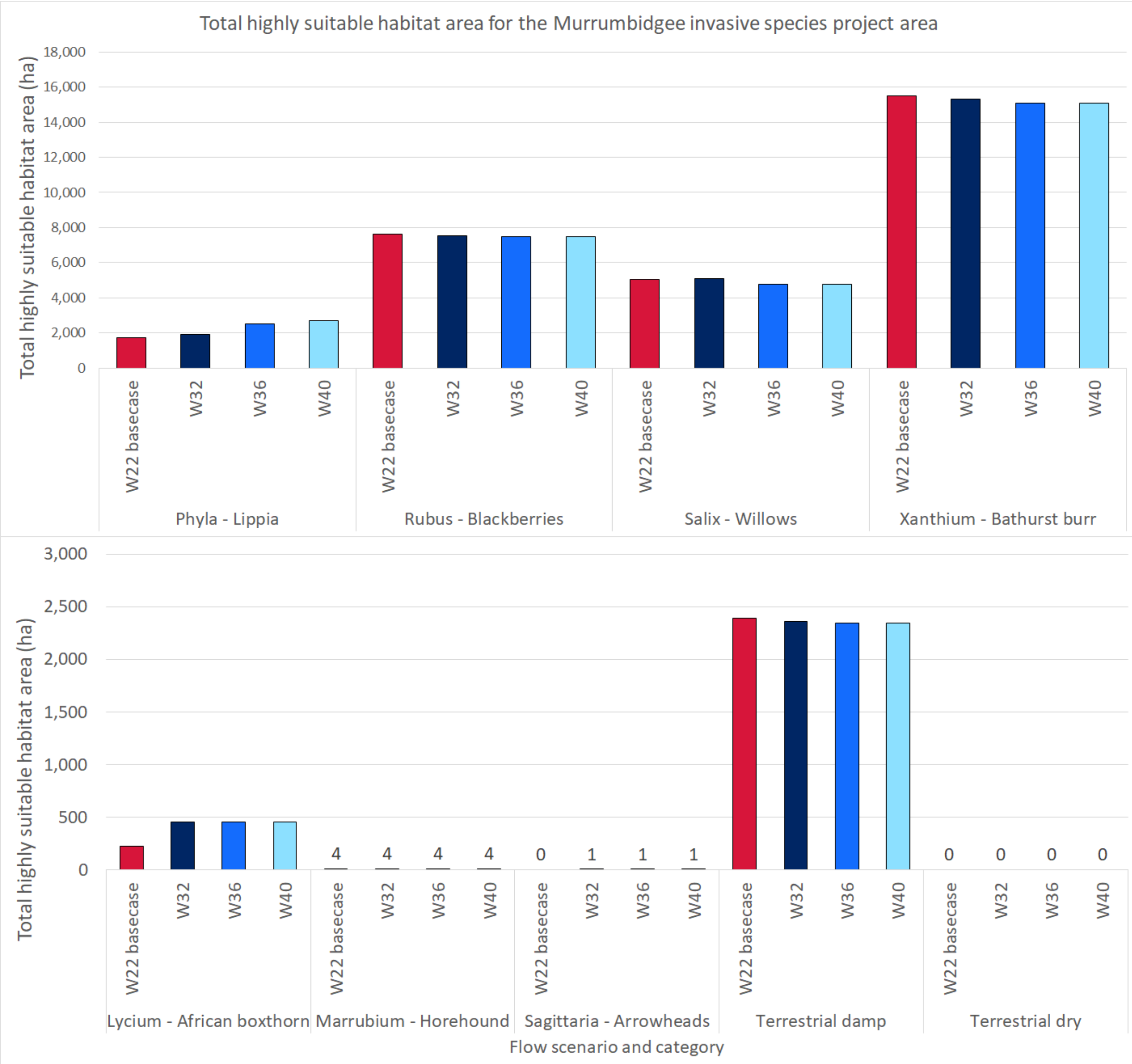


Figure 38: Total area (ha) of highly suitable habitat predicted by SDMs for all modelled taxa the Murrumbidgee under the base case and each flow limit option
(from Capon et al. 2022)

Limitations

There are several limitations that have been recognised in this approach and outlined in more detail in Capon et al. (2022). One of these includes the relatively small number of species records in the program area (particularly for lippia), reducing the number of data points that could be included within the modelling. This leads to lower confidence in modelled distribution for some of the species considered; however, the approach taken used the best knowledge, and best data available within the time frame of the project. Future projects could address this shortcoming through refining the model input datasets and potentially sourcing alternative species records.

Overall outcomes

When taking into account the consequences from the change in distribution (this considers if the priority species is a weed of national significance, the current mitigation measures in place based on its regional weed priority and impacts to fauna, vegetation, humans and agriculture as well as other impacts) with the increase and decrease of suitable habitat for each species and functional group, there is a slight benefit across flow limit option scenarios W36 and W40 and a slight disbenefit from flow limit option scenario W32 (Table 16). This difference is largely attributed to the change in suitable habitat for salix across the scenarios.

Expert elicitation from nine vegetation experts in the Murray and Murrumbidgee supports the expectation that there is little to no change with over half the respondents expecting no to a slight decrease under increased inundation scenarios (Capon et al. 2022). However, there is uncertainty in the outcomes of changes to flow and their importance relative to other drivers of weed distribution, impacts and management.

Table 16: Total risk scores for each weed taxa and weed hotspots under each flow limit option and overall total and standardised scores

Incorporates the overall likelihood (–132 to 132) and consequence scores (0–24) multiplied together for each taxon. These account for the risk of change in distribution and the impact of distribution change if it occurs. A negative risk score relates to a reduced weed risk and a positive risk score relates to an increased weed risk (represented by colours yellow: increased risk, blue: reduced risk, white: no change). Scale for standardised final scores is –100 to 100 (from Capon et al. 2022)

Taxa	Murrumbidgee		
	Option 1 (W32)	Option 2 (W36)	Option 3 (W40)
Sagittaria (Arp)	0	0	0
Phyla (Atl)	-414	-405	-414
Salix (Tda)	324	-576	-576
Rubus (Tdr)	-323	-374	-374
Marrubium (Tdr)	45	145	130
Lycium (Tdr)	1,020	1,190	1,071
Xanthium (Tdr)	-324	-270	-270
Species sub-total	*328*	*-290*	*-433*
Tda species	-21	-2	-11
Tdr species	-44	-45	-71
Weed hotspots	-2	-2	-2
Total	*261*	*-339*	*-517*
Standardised score (-100-100)	*1.2*	*-1.5*	*-2.3*
Overall risk	*likely overall slight risk*	*likely overall slight benefit*	*likely overall slight benefit*

5.3 Geomorphology

The assessment identified *low* to *medium* risks and benefits across the study area. There is *low* risk of negative geomorphic outcomes for Murrumbidgee River reaches downstream of the Yanco bifurcation.

If unmanaged, there is a *medium* risk of geomorphic changes with relaxed flow constraints for the Murrumbidgee River reaches upstream of the Yanco Creek bifurcation and in the upper Yanco system. While these changes are assessed to be *unlikely,* the *medium* risk captures the *moderate* level consequences of potential changes (primarily meander migration, cutoffs, and avulsion). The implementation of identified mitigation strategies, and ongoing monitoring, reduces the risk to *low* for the entire system.

Medium level benefits are predicted in the Mid-Murrumbidgee sub-reaches near the Old Man Creek and Beavers Creek anabranches. These benefits relate to aggraded and stabilised riverbank crests through increased deposition of sediment.

Increased flow limits being assessed in the program have the potential to affect active or dormant geomorphic processes within the system, and thus impact on various cultural, social, economic, or ecological values and assets. One perceived risk regularly expressed by stakeholders is the potential impact of relaxed flow constraints on rates of bank erosion, which is an identified issue in some reaches of the catchment (ABC, 2015; Olley & Scott, 2002; Rutherfurd et al. 2020).

Methods

To undertake a risk and benefit assessment at the large project scale, a hierarchical approach was applied to evaluate the likelihood and consequences of geomorphic processes and outcomes under the program flow limit options. The assessment considered both potential risks (dis-benefits) and benefits.

Firstly, a river classification system was developed that defined morphologically similar reaches across the broader project area (Figure 39). Sub-reaches that were characteristic of the broader reach type and contained at least one of the dominant geomorphic features or processes were then identified and selected for detailed assessment (Figure 40). These detailed assessments were then used to inform the broader reach and study area risk and benefit assessment.

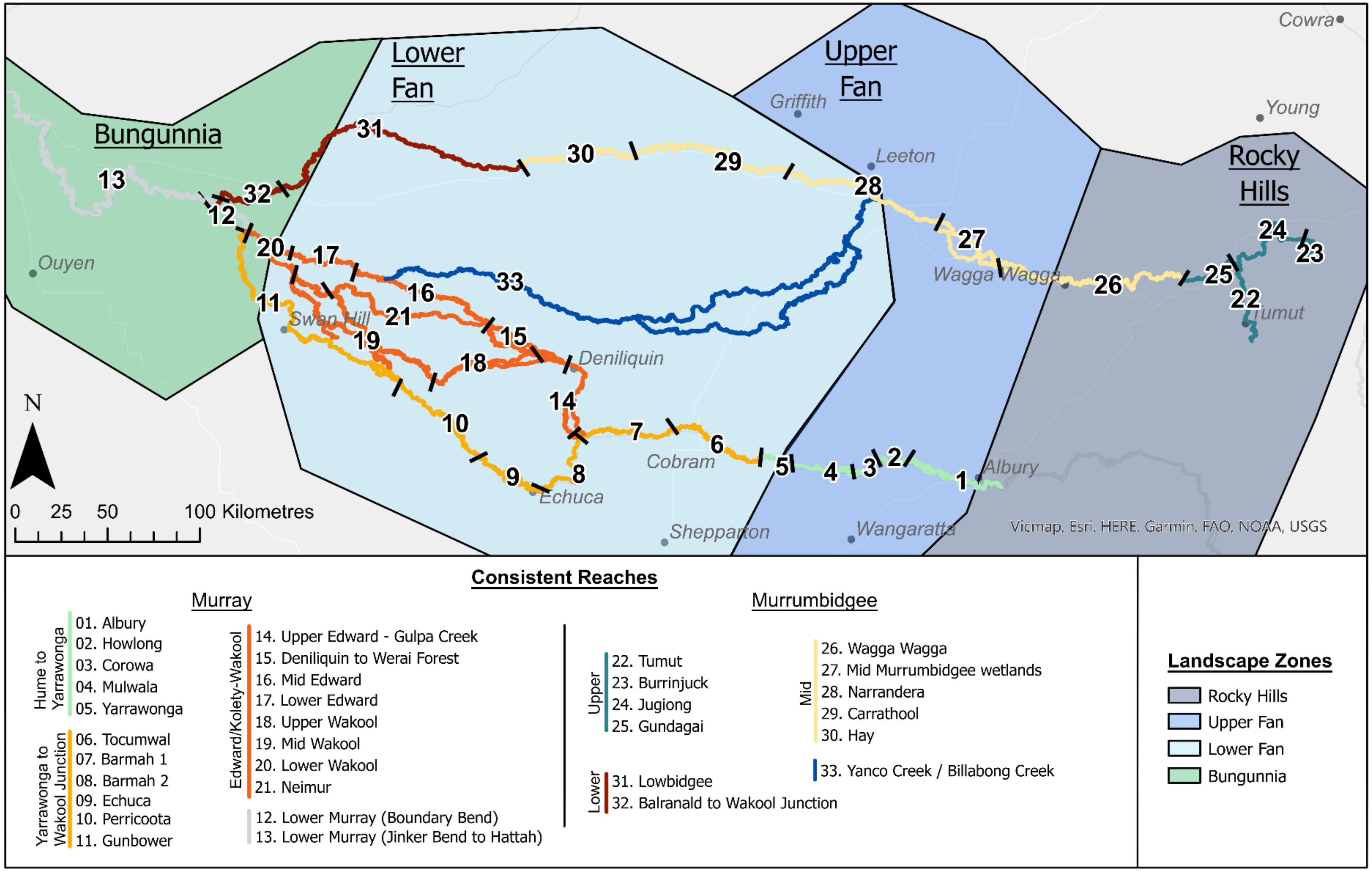


Figure 39: Functionally and morphologically similar reaches in the Murrumbidgee and upper-mid Murray catchments as established by Streamology using information on landscape zones, the level of confinement of the river, and the dominant geomorphic features present.

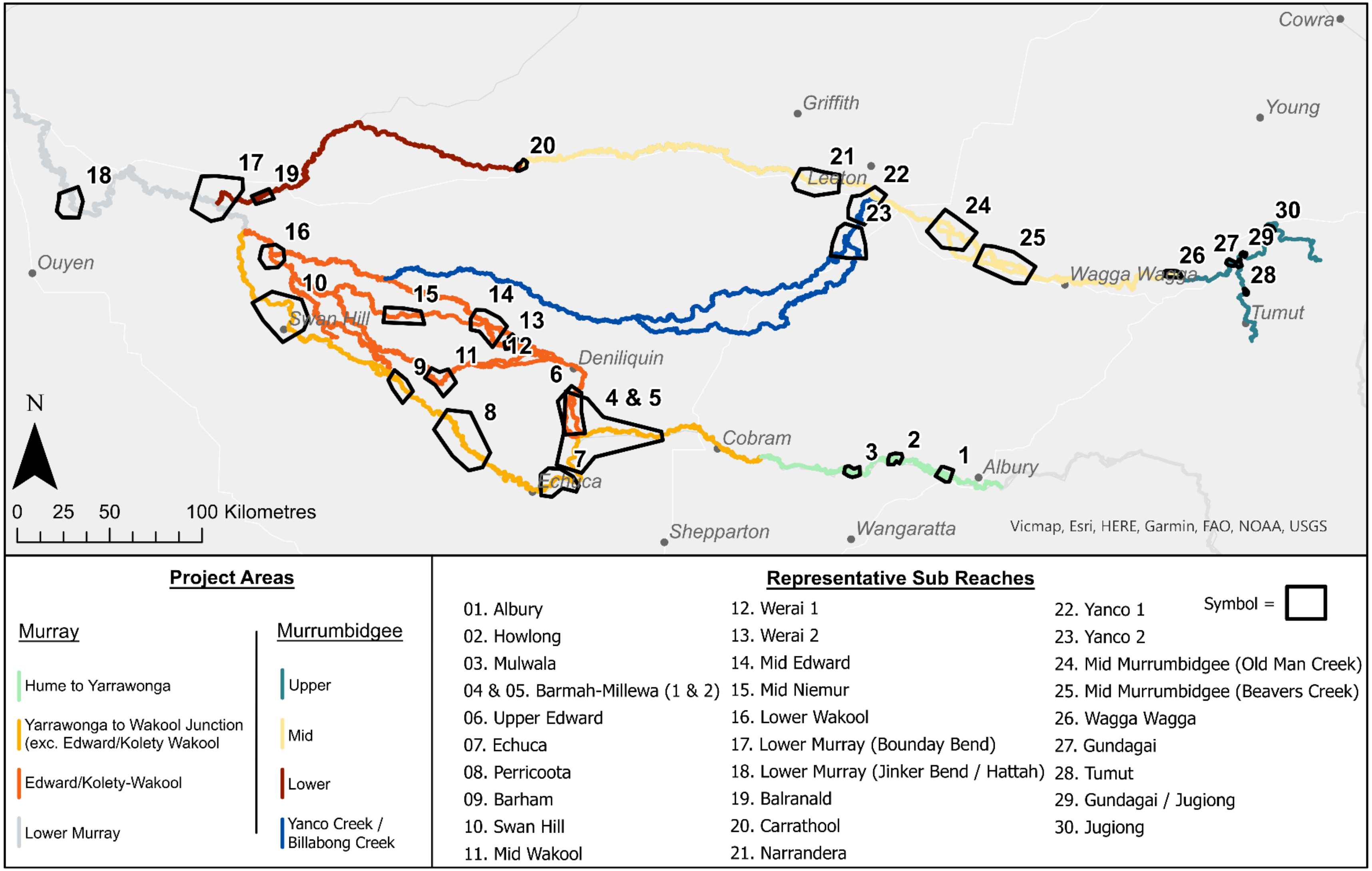


Figure 40: Sub-reaches selected for detailed assessment, which inform the broader reach and study area risk and benefit assessment.

To assess the risk and benefit of relaxed flow constraints on geomorphic features and processes within the Murrumbidgee, two questions needed to be answered:

- What is the *likelihood* that relaxed flow constraints will materialise change (both positive or negative) to existing geomorphic features and processes, or change their current trajectory?
- What are the *consequences* of any changes?

To answer the first question, an *impact score* was calculated (Figure 41). This impact score quantified the mechanistic relationship between geomorphic features or processes and the frequency of different flow conditions. The percentage change in *impact score* was evaluated for each flow limit option scenario to provide an indication of how likely an alternative flow regime is to affect geomorphic features and processes within the project areas, thus determining a *likelihood rating*.

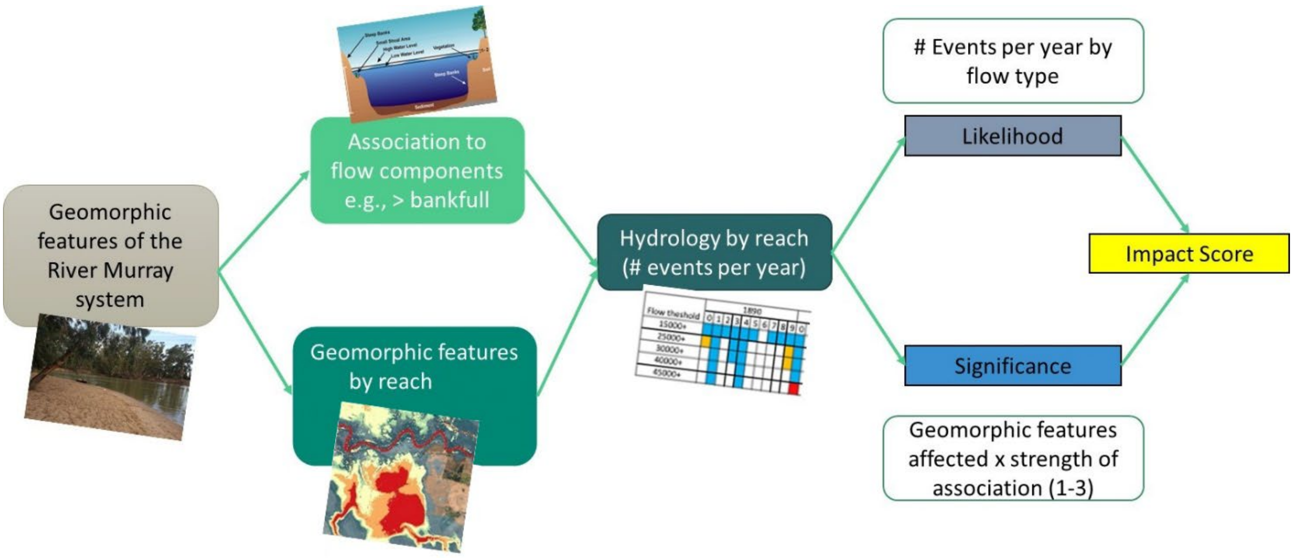


Figure 41: Overview of the method to derive the *impact score* that evaluates geomorphic features and processes within a sub-reach to different flow conditions
(figure reproduced from Lauchlan Arrowsmith et al. 2022)

The second question was answered by establishing a *consequence rating,* which was determined by considering the spatial scale and temporal persistence of a change, and if said change impacted upon any identifiable assets. The *likelihood rating* was combined with the *consequence rating* using the assessment matrix (Table 17) to assign a risk and benefit rating to each flow limit option for each sub-reach and project area.

The W40 and W32 flow limit options were assessed, and their results discussed below. The other proposed flow limit option (W36) was not explicitly assessed, as the precision of the semi-quantitative assessment could not reliably discriminate outcomes at the finer resolution. As evident below, the investigation of the W40 and W32 scenarios provides a range of assessments useful for evaluating the risks and benefits of relaxed flow constraints on geomorphic features and processes.

Table 17: Geomorphology risk and benefit assessment matrix
(taken from Lauchlan Arrowsmith et al. 2022)

Likelihood	Consequence				
	Very Low	Low	Moderate	High	Very High
Rare	Low	Low	Low	Medium	Medium
Unlikely	Low	Low	Medium	Medium	Medium
Possible	Low	Medium	Medium	Medium	High
Likely	Medium	Medium	Medium	High	High
Almost Certain	Medium	Medium	High	High	High

Lastly, the assessment reviewed any *medium* or high-level risks identified to determine if they are adequately addressed by existing mitigation strategies or whether new strategies or mitigation may be required. If existing strategies and ongoing monitoring were assessed to reduce the consequence rating, the revised risk (with mitigation measures considered) may have been downgraded (Table 18).

Key findings

There is a *medium* risk of geomorphic change under relaxed flow constraints for some reaches of the Murrumbidgee River, if potential risks are unmanaged. Spatially, the pattern of risk decreases in the downstream direction, with most reaches in the upper to Mid-Murrumbidgee River (Burrinjuck to the Yanco bifurcation, including the upper Yanco Creek system) having a *medium* risk under the W40 option, and *low* from the Yanco bifurcation to the Murrumbidgee/Murray confluence (Table 18). All *medium* risk ratings were defined by *moderate* level consequences, and an unlikely likelihood. One exception to this pattern is the Tumut River where relaxed flow constraints are of *low* risk because minimal change to the frequency of larger flows is predicted. Under the W32 flow limit option, the risk of geomorphic change is *low* for all Murrumbidgee reaches.

For all Murrumbidgee reaches assessed to have a *medium* risk, this risk can be reduced to *low* through the implementation of existing and potential mitigation measures and ongoing monitoring. This includes the active management of the flow regime (e.g. suitable rates of rise and fall), use rules, and physical intervention (e.g. riparian revegetation, revetments, pile-fields). It is current practice that environmental water deliveries are adaptively managed meaning any potential risks are considered before water is delivered (including the scheduling of *low*-risk rates of fall), and that events are actively monitored. While no formal works programs are established within the Murrumbidgee River, successful precedent exists in the form of the ongoing River Works Program in the Tumut River and Upper Murray River (Hume to Yarrawonga; MDBA, 2017).

Geomorphic processes that may be affected by relaxed flow constraints the Murrumbidgee are primarily already existing, negatively valued, geomorphic processes, rather than new issues. For example, the Burrinjuck to Yanco Creek bifurcation reach of the Murrumbidgee is currently (and has been historically) an actively meandering and anabranching (avulsion developing) system – active processes that more frequent higher flows may enhance. Issues regarding these ongoing processes already exist, for example, bank erosion has been identified in the Mid-Murrumbidgee near the Old Man Creek and Beavers Creek anabranches (see sub-reaches 24 and 25 in Figure 40; local stakeholder; personal communication, Feb 2022) due to ongoing lateral migration of meanders and rapid flow changes around regulating structures.

Potential geomorphic benefits from relaxed flow constraints typically involve the redistribution of sediment across the system, including deposition on benches, bars, and banks. Such changes can increase nutrient and carbon transfer into the riparian zone and enhance geomorphic diversity – creating and sustaining in-channel and riparian zone habitat structures. For sub-reaches 24 and 25 (Murrumbidgee River near the Old Man Creek and Beavers Creek anabranches), relaxed flow constraints were identified to provide *medium* level benefits, specifically the increased deposition of sediment on banks, supporting natural levee aggradation – features important for stabilising banks against avulsion, and flow and flood routing.

Table 18: Risk and benefit assessment ratings for the Murrumbidgee River. Sub-reaches 22, 23, and 28 are outside of the program areas

Sub-reach	**Reach**	**Risk**		**Risk (with mitigation measures considered)**		**Benefit**	
		W40	W32	W40	W32	W40	W32
30	Jugiong	Medium	Low	Low	Low	Low	Low
29	Gundagai / Jugiong	Medium	Low	Low	Low	Low	Low
28	Tumut	Low	Low	Low	Low	Low	Low
27	Gundagai	Medium	Low	Low	Low	Low	Low
26	Wagga Wagga	Medium	Low	Low	Low	Low	Low
25	Mid-Murrumbidgee (Beavers Creek)	Medium	Low	Low	Low	Medium	Low
24	Mid-Murrumbidgee (Old Man Creek)	Medium	Low	Low	Low	Medium	Low
23	Yanco (upper)	Medium	Low	Low	Low	Low	Low
22	Yanco (upper)	Medium	Low	Low	Low	Low	Low
21	Narrandera	Low	Low	Low	Low	Low	Low
20	Carrathool (Hay)	Low	Low	Low	Low	Low	Low
19	Balranald	Low	Low	Low	Low	Low	Low

Overall outcomes

It is unlikely that relaxed flow constraints will cause any geomorphic changes in the Murrumbidgee that are greater than those expected under the base case. For sites that possess a medium risk due to moderate level consequences of any change, identified mitigation measures, ongoing monitoring, and/or adaptive management can be implemented to reduce the risk to low. Expected benefits are typically low, however medium level benefits are expected for some Mid-Murrumbidgee reaches (24 and 25) where increased sediment deposition on banks will support the building and stabilisation of riverbank crests.

6 Discussion

The EBRA for the program demonstrates how relaxing constraints could contribute substantial improvements to water-dependent ecosystems in the Murrumbidgee River catchment (Table 19). Models predict either no change or benefits across the environmental themes assessed. The long-term average abundance of native golden perch is expected to increase by up to 34 per cent due to increased spawning, movement and recruitment opportunities, while river red gum shows improvement of up to 6 per cent on the base case scenario. Overall, results predict improvements for all three raised flow limit options, with the greatest outcomes predicted for Option 3 (W40), particularly for native fish and production (+11 per cent). This trend is unsurprising given that all indicators benefit from increased floodplain inundation, and that predicted inundation extents increase with increasing constraints relaxation. The exception is waterbirds, where waterbird density and number of species remain consistent with the base case scenario. These relationships may have been influenced by the observed data used to inform them.

Although some of the predicted benefits may appear modest overall, modelling results show that constraints relaxation has the potential to contribute significantly to the health and resilience of aquatic ecosystems despite the overarching influence of much larger unregulated flow events. Moreover, these improvements are achieved by using water for the environment to reconnect and inundate low-lying floodplains and wetlands without reallocating more water to the environment. Therefore, relaxing constraints provides for more effective use of existing volumes of water for the environment.

Environmental flows deliver the greatest benefit when they can reach ecologically important wetlands, lagoons, swamps and floodplains. In the Mid-Murrumbidgee current constraints have limited ability to inundate wetlands, reaching only 44 per cent of the total floodplain wetland area. By relaxing constraints it is possible to inundate many Mid-Murrumbidgee wetlands through flood runners and floodplain channels, increasing the total floodplain wetland area that can be inundated to 57-65 per cent (48 per cent increase under Option 3). This is an increase from less than half under base case to nearly two thirds of wetland areas being reached under the highest flow limit option. The area of native vegetation that can be reached by inundation also doubles. Ecosystem production reflects this increased area, with an increase of up to 11 per cent over the base case. In addition to increasing inundated areas of floodplain wetlands, there are also predicted increases in inundation frequencies. For wetland and low-level floodplain connecting flows, this includes up to a 15 per cent increase between Gundagai and Wagga Wagga, up to a 10-12 per cent increase between Wagga Wagga and Darlington Point and in the Upper Yanco Creek system and a 5-10 per cent increase from Darlington Point to Balranald and in the mid-lower Yanco Creek system. There is also an expected increase in the number of times across the modelled, relaxed constraints flow time series that LTWP EWR flow thresholds are met: up to 27 per cent increase in frequency for large freshes of a 10-day duration (DPIE 2020a;b). The comparison of Yarradda and McKennas lagoons (Section 4.1.1) demonstrates the ecological outcomes that can be achieved when their flow regime can be restored. Through relaxing constraints, we expect to achieve greater lateral connectivity between rivers and wetlands, which has associated benefits across the range of themes.

Environmental flows play a crucial role in ecosystem resilience by supporting environmental outcomes during dry periods when water-dependent ecological communities are at risk of collapse. Environmental benefits modelling shows that even with reduced inflow volumes during drier times, relaxing constraints can allow for water for the environment to be used to deliver small overbank flows to low-lying wetlands that do not occur under the base case scenario. If flows of 32,000 ML/day for 5 days at Wagga Wagga are used as a point where many Mid-Murrumbidgee wetlands could be reached, then relaxing constraints will support these wetlands in an additional 20 years over the base case modelled time series (130 years). By providing these crucial events, relaxed constraints can lead to substantial improvements across many ecological themes, helping ecological communities to persist through prolonged drought and to recover afterwards. Waterbird species richness and abundance are slightly increased (6-10 per cent and 4-7 per cent respectively) for the higher two option scenarios (W36 & W40) relative to the base case in the last two decades of the flow time series (2000-2019), which includes the Millennium and other droughts. Further, these waterbird benefits are potentially underestimated, due to poor condition of many of the wetlands and the low number of waterbirds across the recent observed data used to predict these outcomes.

Models also predict relaxed constraints prevents large areas of river red gum forest from declining into poor condition during drought; with an up to 23 per cent increase in the extent of healthy river red gum condition during the driest years across the time series (10th percentile). The minimum population size of native golden perch is predicted to increase by up to 31 per cent in dry years (10th percentile), with an up to 8 fold increase in the Gundagai to Hay reach alone. The exception is production, which did not have such a strong response between the base case and scenarios in the 25th percentile. Overall, these findings suggest a much greater capacity for aquatic communities to survive dry conditions if constraints are relaxed.

The program will enable environmental water deliveries to target small overbank flows that are heavily impacted by river regulation (MDBA, 2015). While the modelling for the EBRA focusses on a range of indicators and attributes that can be feasibly modelled, there are many other water dependent plants and animals and important ecosystem functions that are not modelled. These ecological outcomes are broadly captured by the Murrumbidgee LTWP (DPIE, 2020a), which specifies a range of flow event types that are necessary to provide ongoing support to the overall ecosystem.

The program is not expected to increase the risk of adverse outcomes for the water quality and invasive weeds risk assessments, and in some cases, an increased benefit (i.e. reduced risk) is predicted. For water quality, operational decision frameworks prevent environmental flow releases during warmer months or when there is increased risk of hypoxic blackwater. This means that the risk of negative water quality events, such as hypoxic blackwater, is the same for relaxed constraints as the base case, but under relaxed constraints there is a benefit due to shifting flows to cooler months. Similarly, although modelling predicts a mix of increases and decreases in suitable habitat of priority weed species and functional groups, when taking into consideration the consequences, impacts and current mitigation (i.e. complementary measures such as weed management) there is slight overall benefit for the W36 and W40 scenarios in the Murrumbidgee. There is, however, a slight increased risk of salix species spreading under the W32 scenario. Environmental water deliveries are adaptively managed, meaning multiple risks are considered before water is delivered while the capability to identify and mitigate risks improves over time.

The geomorphic risk assessment rated the constraints options as low risk for the entire system. While a medium risk for geomorphic processes was found in the Murrumbidgee reaches upstream of the Yanco Creek bifurcation and the upper Yanco system, this moves to a low risk with identified mitigation measures and monitoring. Potential risks are primarily related to the restoration of geomorphic processes previously active in the system prior to river regulation, such as meander migration, cut-offs and avulsion.

The modelling for the EBRA integrates hydrological and spatial modelling with ecohydrological models to evaluate potential changes in ecological condition resulting from changes to river flows. The models do not perfectly represent the complex ecological systems they attempt to replicate but use the current state of knowledge in each field to explore potential responses. The ecohydrological models also inherit uncertainties from underlying hydrological and spatial models as well as any datasets they use to define flow-ecology relationships. The CARM model has limitations (discussed in Section 2.4) that could be improved upon by using the newly available hydrological models. Further, the CARM models are all linked to the Wagga Wagga gauge, which may not fully characterise flows in more distant reaches. By spatially breaking up the area and relating inundation to a wider range of gauges it is possible to address this concern in the future. Additionally, there are uncertainties in modelling the flow in the Murrumbidgee due to its complex flow regime (Section 2.5 & 3) meaning we were unable to report results from the Lowbidgee in several models. Combined these limitations yield a degree of uncertainty in model predictions, some of which can be more fully understood by reading the relevant technical reports. There are also a range of assumptions implicit in each model that need to be considered. For example, fish and vegetation models make assumptions about the extent and condition of the initial population and track relative changes to this initial population through time. The hydrological model uses historical inflows to provide a canvas for testing the interacting effects of climate, environmental deliveries, and ecosystem responses. The ecological models use the outputs of the hydrological model and therefore assume a fixed configuration of the floodplain environment, represented by present-day conditions (or a recent fixed point in time). Models presented here are run at a whole of system scale and there may be finer-scale patterns of increasing or decreasing benefit. Future investigations could consider finer scales or small areas of high interest to more fully tease apart some of the issues identified here.

Although the models in the EBRA represent historical climate patterns as a driver of change, the influence of future climate change has not yet been included. Climate modelling lists an overall reduction in inflows, and increase in the extent and severity of droughts, and an increase in the length and severity of heatwaves as some key changes that are expected in the near future (CSIRO, 2022). This adds a large degree of uncertainty in how constraints relaxation will impact on aquatic communities of the Murrumbidgee River. The outcomes of the current modelling suggest environmental flows may become disproportionately important for river and wetland health if climate change results in a net reduction in the frequency of floodplain inundation. However, the influence of climate change on the effectiveness of constraints relaxation needs to be further examined for the final business case.

The EBRA for the program demonstrates a range of expected improvements to the health and extent of ecological communities resulting from the relaxation of constraints along the Murrumbidgee River. It also raises a relatively small number of risks of localised geomorphic risks. There is an inevitable trade-off between potential negative outcomes and environmental benefits;

however, careful planning of environmental water delivery and complementary measures means the balance sits largely in favour of environmental benefits.

Table 19: A summary of environmental benefits and risks for the program flow limit options scenarios (Murrumbidgee program area)

Theme	Predicted Outcome	Description of outcomes
Native vegetation	Overall improvement	Up to 6% increase in healthy (good or moderate condition) river red gum forest over the long-term in the Mid-Murrumbidgee. Increased resilience of river red gum communities, with up to 23% increase in river red gum forest remaining healthy during extreme drought in the Mid-Murrumbidgee.
	Improvements during specific periods	During dry periods, an increase of up to 23% in the area of healthy river red gum in the Mid-Murrumbidgee.
Native fish	Overall improvement	Golden perch numbers are predicted to increase up to 34% with relaxed constraints for the Murrumbidgee as a whole. Negligible change in Murray cod populations expected as life histories are less related to changes in flow level instream.
	Improvements during specific periods	In dry years, golden perch numbers are expected to increase overall by 31% for relaxed flow constraints, with increases in the Gundagai-Hay reach of up to 8-fold and in the Hay Weir to Murray confluence by 24%.
	Improvements seen for specific spatial areas	Predicted increases in golden perch populations by up to 47% in the Hay-Gundagai reach and up to 32% in the Hay-Murray junction reach.
Waterbirds	Overall improvement	Modelling predicted small benefit / neutral outcomes for waterbirds, with model predictions of small increases in the number of species (2-3%) and waterbird abundance (1-2%). Waterbird predictive modelling was limited by the observational data on which they were developed, which was ground survey data collected during a recent period when many of the wetlands are in poor condition. The relatively small/neutral predicted results of the modelling are potentially reflective of these limitations. Despite a subtle outcome the modelling, site-based data has shown that increases frequency and duration of inundation, which could be enhanced by relaxation of constraints, can provide significant benefits for waterbirds by increasing the availability and condition of waterbird habitat for breeding and foraging. These types of flows can also potentially provide breeding opportunities for some waterbird species. Benefits to waterbird habitat along the Murrumbidgee River are also expected to complement and support outcomes at a broader scale in combination with outcomes in the Murray.
	Improvements during specific periods	A slight increase during the period 2000-2019 of +6-10% for median waterbird species richness and +4-7% increase in median waterbird density (birds/ha) in the Mid-Murrumbidgee. This period includes the Millennium Drought.

Theme	Predicted Outcome	Description of outcomes
Production	Overall improvement	Increase in production due to increased floodplain inundation with benefits increasing consistently with the level of constraints relaxation up to 11% increase with production for Option 3 (W40).
	Improvements during specific periods	Increased production during flow events which are increased under relaxed constraints.
Water Quality	No increased risk	Relaxed flow constraints do not increase the risk of adverse water quality events relative to the base case.
	Benefits are likely	Benefits to water quality are likely, due to the potential to bring forward the timing of some high flow events from the warmer months (late spring/summer) to cooler months earlier in the season (winter/early spring).
	All flow limit options provide benefit	All flow limit options shift the benefit rating from *moderate* to *high.*
Invasive Species	Minimal change from base case overall with slight benefit	The predicted change in distribution of suitable habitat for invasive weeds decreases for amphibious species and increases for terrestrial species. There is a small decrease in weed hot spots with the decline increasing with increasing flow limit. When considering the changes in habitat suitable for weeds and weed hot spots with the impact of weed species and existing mitigation, there is a slight benefit (reduction in weed impact) for the two higher flow limit options (W36 and W40) and a slight increase in risk (increase in weed impact) in the lowest flow limit option (W32) for the assessed priority weed taxa.
	Benefits for specific functional groups	A decrease in the suitable habitat area for amphibious weeds was observed from the species distribution modelling. Decrease in weed hot spots.
	Risk for specific functional groups	An increase in the suitable habitat for terrestrial species was seen from the species distribution modelling.
Geomorphology	Low risk of negative outcomes for specific areas	The risk assessment identified *low* to *medium* risks and benefits across the study area. There is low risk of negative geomorphic changes with relaxed flow constraints for Murrumbidgee River reaches downstream of the Yanco bifurcation.
	Medium risk of negative outcomes for specific areas	If unmanaged, there is a *medium* risk of geomorphic changes with relaxed flow constraints for the Murrumbidgee River reaches upstream of the Yanco Creek bifurcation and in the upper Yanco system. These changes are assessed to be *unlikely* and the implementation of identified mitigation strategies, and ongoing monitoring, reduces the risk to *low* for the entire system.

Theme	Predicted Outcome	Description of outcomes
	Benefits for specific areas	*Medium* level benefits are predicted in the Mid-Murrumbidgee sub-reaches near the Old Man Creek and Beavers Creek anabranches. These benefits relate to aggraded and stabilised riverbank crests through increased deposition of sediment.

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8 Appendices

Appendix A

Table 20: The Environmental Benefits Assessment Themes, including current conditions and references

Theme	Current Condition	References
Flow regime changes	River regulation has reduced the frequency and duration of wetland and floodplain inundation along the Murrumbidgee River. Mid-Murrumbidgee flows that inundate low level wetlands and floodplain have reduced in frequency by about 50%. For the Lowbidgee floodplain, the reduction in frequency of these flows is even greater at 60 to 70% reduction.	MDBA (2012a), MDBA (2012b)
Waterbirds	Waterbirds are in decline across the Murray–Darling Basin Long-term aerial surveys show that water bird populations are severely degraded Recent surveys in 2021 show this decline continuing across all guilds The Murrumbidgee Catchment has scored as very poor in catchment conditions required for waterbirds and significant declines have been seen, particularly in the Lowbidgee floodplain.	Kingsford et al. (2017), Kingsford & Thomas, (2004), Porter et al. (2021), Reid et al. (2013)
Native vegetation	At least 76% of the floodplain of the Murrumbidgee River in South-Eastern Australia destroyed or degraded over past 140 years	Kingsford (2003)
Fish	Golden perch populations have declined following alienation of floodplains, reduced river flow pulses and loss of flowing water habitats. Murray cod have experienced population declines despite extensive restocking. European carp are a major pest species whose abundance and impacts generally increase with high river flows and floodplain inundation. Carp numbers need to be considered alongside the benefits of flow events to native fish.	Koehn et al. (2020a&b), Todd et al. (2005), Todd et al. (2018). Koehn & Todd (2012), DPI (2022a&b) Stuart & Jones (2006a&b) Conallin et al. (2012) Brown et al. (2020) Forsyth et al. (2013), Koehn et al. (2018),

Theme	Current Condition	References
Productivity	River regulation has reduced connectivity between the river and floodplain, thus limiting inputs of allochthonous material that fuels productivity. Dam releases are usually low in sediments and turbidity. In the Murrumbidgee, irrigation releases lead to significant phytoplankton contribution to gross primary production, with little zooplankton grazing, some biofilm contribution and low P/R (production to respiration) ratios. This has implications for instream productivity that drives food webs	Vink et al. (2005)

Appendix B

Table 21: Area of vegetation types inundated during a delivery at different flow limits – Burrinjuck Dam to Hay Weir

	Area inundated (ha) and *(% of total area of species on floodplain)*			
Vegetation type	W22 (Base case)	W32 (Option 1)	W36 (Option 2)	W40 (Option 3)
River red gum woodland	1,734 *(20 %)*	2,574 *(29 %)*	2,998 *(34 %)*	3,441 *(39 %)*
River red gum forest	10,428 *(25 %)*	15,810 *(38 %)*	18,129 *(44 %)*	20,606 *(50 %)*
Black box woodland	310 *(7 %)*	666 *(16 %)*	878 *(21 %)*	1,115 *(27 %)*

Appendix C

Table 22: Native fish observed or predicted (P) to occur in the Murrumbidgee program area by functional group (Ellis et al. 2015, 2022; Gehrke, 1997; Gilligan, 2005; Lintermans, 2007; DPI, 2016). Commonwealth or NSW threatened species are indicated as V = Vulnerable, E = Endangered or CE = Critically Endangered

Generalist (Short to moderate-lived)	Floodplain Specialist (Short to moderate-lived)	River Specialist (moderate to long-lived)	Flood pulse specialist (moderate to long-lived)
- Australian smelt - Carp gudgeon - Dwarf flathead gudgeon - Flat-headed gudgeon - Mountain galaxias - Murray–Darling rainbowfish - Obscure galaxias - Unspecked hardyhead - Bony herring	- Flathead galaxias (CE,P) - Southern pygmy perch (E,P) - Spangled perch - Murray hardyhead (CE) - Olive perchlet (E) - Purple-spotted gudgeon (E)	- Murray cod (V) - River blackfish - Murray crayfish (V) - Trout cod (E) - Freshwater catfish (eel-tailed catfish; E)	- Golden perch - Macquarie Perch (E) - Silver perch (V)

Table 23: Modelled long-term mean golden perch and Murray cod abundance by model spatial unit and for Murrumbidgee

Golden perch model spatial unit	Mean populations				
	Base case W22	Option 1 W32Y35	Option 2 W36Y30	Option 3a W40Y40	Option 3b W40Y45
Gundagai to Hay	84,060	101,117	103,760	123,582	118,033
Hay to Balranald	320,229	330,788	364,992	385,672	424,051
Total Murrumbidgee	404,288	431,905	468,752	509,254	542,083
	Percent change from base case				
% Gundagai to Hay	na	20.29	23.44	47.02	40.42
% Hay to Balranald	na	3.3	13.98	20.44	32.42
% Total Murrumbidgee	na	6.83	15.94	25.96	34.08
Murray cod model spatial unit	**Mean populations**				
	Base case W22	Option 1 W32Y35	Option 2 W36Y30	Option 3a W40Y40	Option 3b W40Y45
Gundagai to Berembed	32,373	32,128	32,564	32,323	32,323
Berembed to Gogeldrie	42,319	42,033	42,211	42,210	42,210
Gogeldrie to Hay	48,496	48,430	48,434	48,336	48,336
Hay to Balranald	49,144	49,128	49,181	48,945	48,945
Yanco Creek	23,914	24,058	23,933	24,067	24,067
Total Murrumbidgee	196,246	195,778	196,324	195,881	195,881
	Percent change from base case				
% Gundagai to Berembed	na	-0.76	0.59	-0.15	-0.15
% Berembed to Gogeldrie	na	-0.68	-0.25	-0.26	-0.26
% Gogeldrie to Hay	na	-0.13	-0.13	-0.33	-0.33
% Hay to Balranald	na	-0.03	0.08	-0.41	-0.41
% Yanco Creek	na	0.6	0.08	0.64	0.64
% Total Murrumbidgee	na	-0.24	0.04	-0.19	-0.19