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Murray Environmental Benefits and Risks Analysis Synthesis Report

Reconnecting River Country Program

November 2022

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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Preamble

The Reconnecting River Country Program is investigating options to relax or remove some of the constraints or physical barriers impacting the delivery of water for the environment in the Murray and Murrumbidgee valleys (Figure 1). These options would enable environmental flows to connect 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 the flow limits and flow regimes have been explored using a range of ecohydrological models (for fish, vegetation, waterbird, production, and hypoxic blackwater themes) and qualitative/ semi-quantitative assessments (broader water quality and geomorphology themes) developed in partnership with expert external contractors.

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

This report synthesises the expected environmental benefits and risks associated with the flow regimes that would be 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.

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

Vegetation

McPhan LM, Capon S and Bond NR (2022) *Reconnecting River Country – Floodplain Vegetation Condition Predictive Modelling; Part 1: Murray River floodplain*, CFE Publication #27, prepared for the Department of Planning, Industry and Environment NSW, Centre for Freshwater Ecosystems, School of Life Sciences, La Trobe University.

Production condition predictive modelling

Siebers A, Crook D, Silvester E and Bond N (2022) *Production Condition Predictive Modelling – Part 1: River Murray, Hume to Wakool junction*, Centre for 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, Cuddy SM, Wahid S and Chen Y (2022) *Qualitative ecological assessment of 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 timeseries 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 and Burgoyne H (2022) *Reconnecting River Country: Weed Risks and Benefits Assessment – Technical Report*, report prepared for the Department of Planning and Environment, Griffith University.

Geomorphology risk

Lauchlan Arrowsmith CS, Vietz G, Wakelin-King G, Cheetham M, Martin J, Grove J and Rutherfurd I (2022) *Geomorphic Assessment for the NSW Reconnecting River Country Program in the Murray and Murrumbidgee Rivers*, report prepared for Water Infrastructure NSW, Department of Planning and Environment.

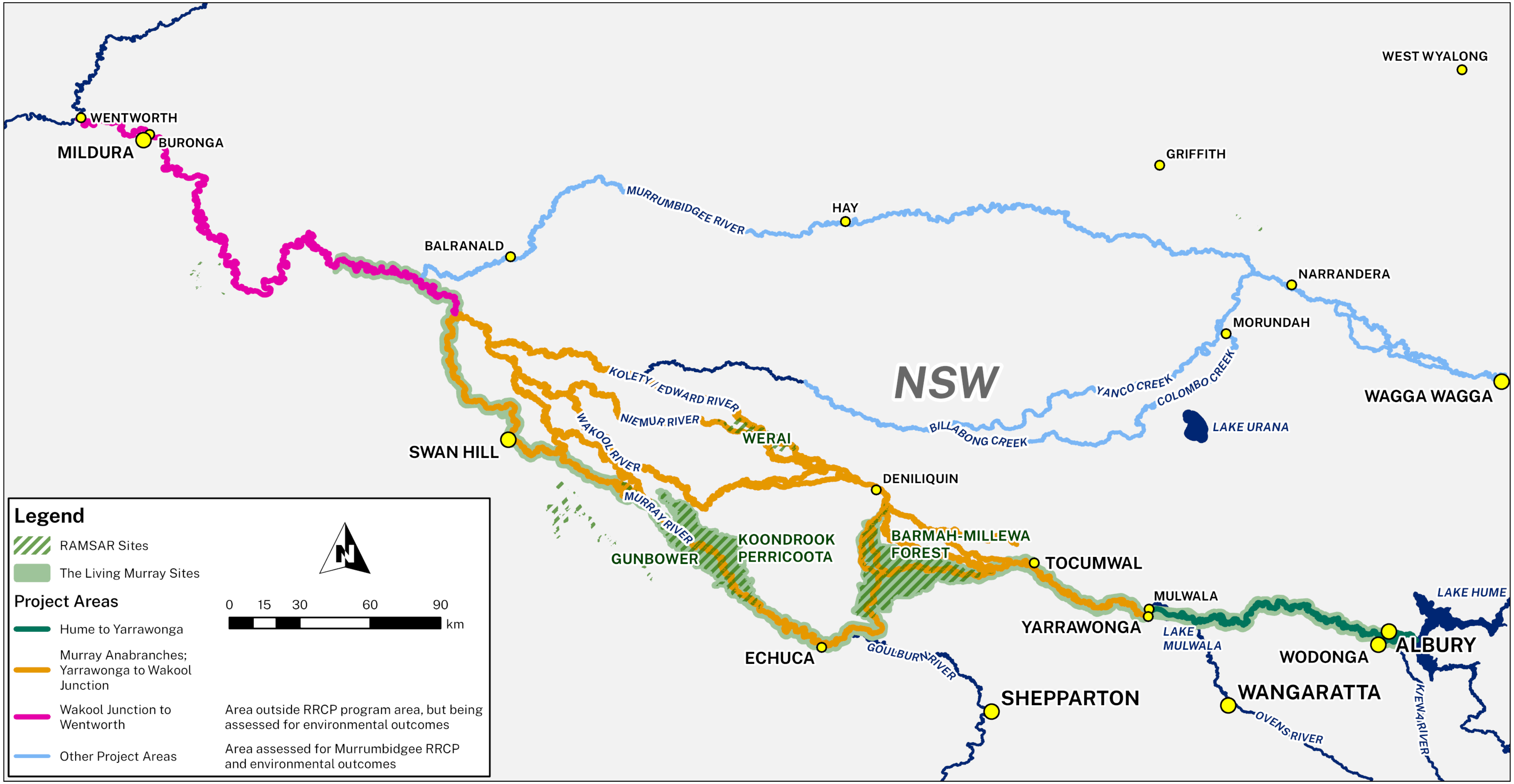

Figure 1: Project areas for the Reconnecting River Country Program Environmental Benefits and Risks Analysis (EBRA) in the Murray and Murrumbidgee catchments

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Executive summary

The natural flow regime of the Murray River has been significantly altered by river regulation and the consumptive use of water, with the result being fewer flows that connect wetland and floodplain environments. Wetlands, floodplains and adjacent riverine environments along the Murray River depend on these flows for their health and viability. Reduced occurrence of these flows has meant that 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 Reconnecting River Country Program is investigating options to relax or remove some of the constraints or barriers limiting the delivery of water for the environment in the Murray and Murrumbidgee valleys. These options allow for more frequent environmental flows that connect wetlands and low-level floodplains than are currently possible, improving ecological outcomes for the Murray and Murrumbidgee rivers (Figure 1).

This Environmental Benefits and Risks Analysis (EBRA) (Figure 3) is a major component of the options investigation and evaluation process being undertaken by the program. It is 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, species richness and breeding 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. The flow limit options comprise linked flow limits at both the Doctors Point and downstream of Yarrawonga Weir gauges on the Murray River.

The EBRA has been informed by two key inputs:

- hydrological modelling that represents system-wide flow regimes that may be possible using currently available volumes of environmental water 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.

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

Flow limit option	Hume to Yarrawonga Flow measured at Doctors Point (D) (ML/d)	Yarrawonga to Wakool Junction Flow measured below Yarrawonga Weir (Y) (ML/d)
Base case (Y15D25)	25,000 [1]	15,000 [2]
Option 1 (Y25D25)	25,000	25,000
Option 2 (Y30D30)	30,000	30,000
Option 3 (Y40D40)	40,000	40,000
Option 4 (Y45D40)	40,000	45,000

[1] current water sharing plan limit
[2] current temporary operational limit

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 (Figure 1):

- system scale – Hume Dam to Wentworth
- Hume to Yarrawonga project area
- Yarrawonga to Wakool Junction project area.

Summary of outcomes

System scale outcomes

- The relaxation of flow constraints has the potential to deliver substantial environmental benefits across the River Murray system, for example:
  - nearly three times the area of floodplain habitats (creeks, wetlands, forests, woodlands and grasslands) that can be reached by environmental water, compared to the base case
  - up to 29 per cent increase in the long-term average abundance of golden perch in the Murray system, and 45 per cent increase in abundance during dry periods
  - up to 15 per cent increase in healthy river red gum forest and woodland over the long term, and up to 50 per cent increase during dry periods.
- The higher flow limit options enable much greater wetland and floodplain connectivity and would provide the most substantial environmental benefits across all of the themes assessed. The higher flow limit options also provide the greatest environmental benefits across all of the spatial areas assessed (including Hume to Yarrawonga).

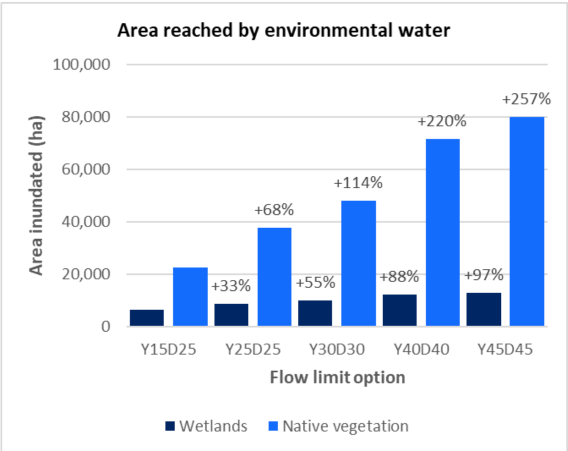
- The benefits are greatest during moderate to dry periods, when the relative contribution that environmental water can make to river flows is greatest. During wet periods, dam spills and tributary flows dominate flows along our rivers and environmental water is either not needed to create these elevated flows or supplements existing flows. During extreme dry periods there is insufficient environmental water to deliver flows up to the flow limits assessed.
- The predicted environmental benefits are greatest in the Hume to Yarrawonga and Yarrawonga to Wakool project areas and reduce in scale downstream (with the exception of golden perch population increases, which are of similar scale in all reaches of the Murray from Hume Dam to the sea). The smaller benefits downstream of the project areas for themes like native vegetation may be due, in part, to limitations in the coordination of flows across the Murray, Goulburn and Murrumbidgee valleys, as represented in the hydrological modelling. If the program proceeds, it is intended that refinements to the modelling be undertaken to improve the coordination of flows and better reflect what may be achievable in reality.

Outcomes by theme

Outcomes are described relative to the base case and at the Murray system scale (Hume Dam to Wentworth), unless otherwise specified.

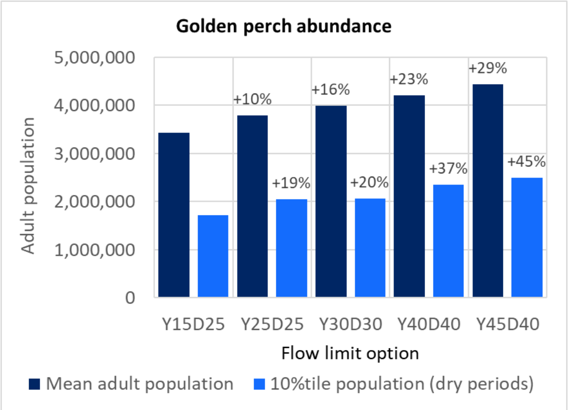
Lateral connectivity

- Up to 97 per cent increase in the area of wetlands that can be reached by environmental water (between Hume Dam and Wentworth)
- Up to 257 per cent increase in the area of native vegetation that can be reached by environmental flows
- Up to 40 per cent increase in frequency of wetland and floodplain reconnection flows between Hume and Yarrawonga
- Up to 20 per cent increase in the frequency of wetland and floodplain reconnecting flows between Yarrawonga and Wakool Junction



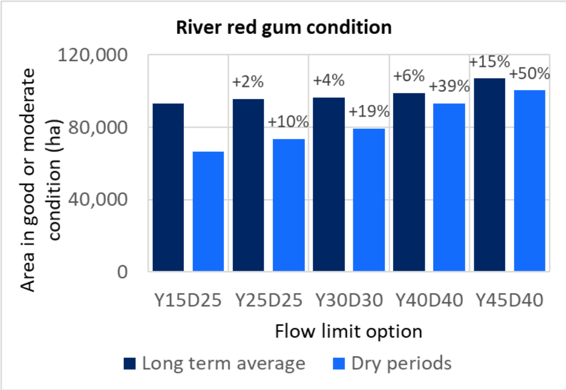
Native fish

- Up to 29 per cent increase in the long-term average abundance of golden perch in the Murray system
- Up to 45 per cent increase in the abundance of golden perch in the Murray system during dry periods
- Neutral outcomes for Murray cod populations in the Murray and Edward/Kolety rivers
- Increased breeding and recruitment opportunities for floodplain specialist fish species through delivery of more frequent wetland-connecting flows



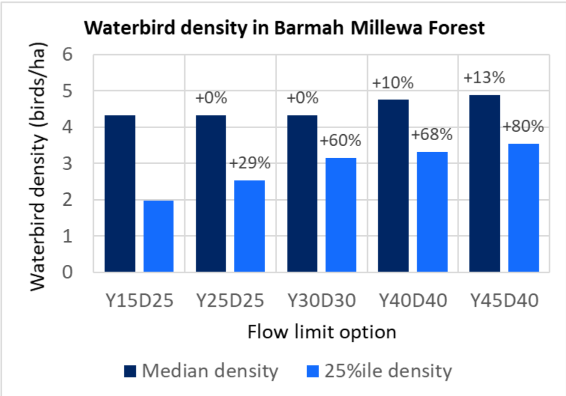
Wetland and floodplain vegetation

- Up to 15 per cent increase in healthy (good or moderate condition) river red gum forest and woodland over the long term
- Up to 50 per cent increase in healthy river red gum forest and woodland during dry periods
- Increased resilience of river red gum communities, with up to 75 per cent less decline in condition during extreme drought
- Moderate increases of healthy black box woodland (up to +5 per cent), lignum shrubland (up to +11 per cent), and perennial wetland grass, sedge, and rush species (up to +10 per cent)
- Possible declines in vegetation condition for some higher-elevation areas due to reduced peak discharge rates during unregulated flood events



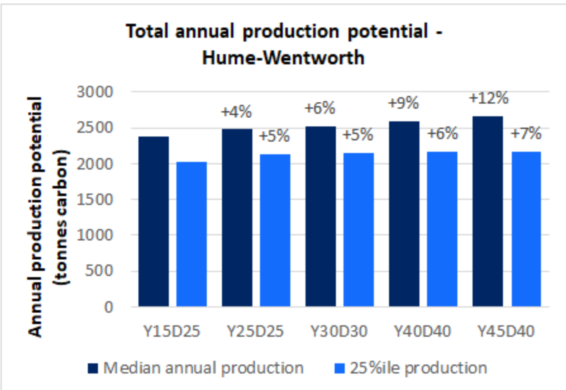
Waterbirds

- In moderate years, up to 13 per cent increase in median waterbird density in Barmah–Millewa Forest and 48 per cent increase in abundance in Gunbower–Koondrook–Perricoota Forest
- In dry years (25th percentile), up to 80 per cent increase in waterbird density in Barmah–Millewa Forest and 34 per cent increase in abundance in Gunbower–Koondrook–Perricoota Forest
- Increased probability of colonial waterbird breeding and increased number of waterbird species in Barmah–Millewa Forest
- Benefits for waterbirds are likely to accumulate with improved wetland condition in Gunbower–Koondrook–Perricoota Forest area providing benefits to waterbirds breeding in the nearby Barmah–Millewa Forest and vice-versa



Ecosystem production

- Up to 12 per cent increase in production potential overall, with greater benefits in the Yarrawonga to Wakool project area
- Up to 7 per cent increase in production during dry years
- Increased energy and food availability for native fish and other biota during critical times of breeding and recruitment



Water quality

- No 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 algal blooms

Invasive species – weeds

- The likelihood of change in distribution of suitable habitat decreases for amphibious species and increases for terrestrial species
- Decrease in weed hotspots
- When considering changes in habitat suitability and weed hotspots in conjunction with the impacts on humans, agriculture and natural environments with existing mitigation measures, there is a slight increase in benefit for each flow scenario in the Murray for assessed priority weed taxa (i.e. slightly reduced impact of weeds across the Murray project area)

Geomorphology

- Low to medium risk that existing geomorphic processes (e.g. bank erosion and anabranch development) would be accelerated. The risk is reduced to low in most sub-reaches with existing mitigation measures
- The risk of reinstating previously active geomorphic processes in some reaches of the Edward/Kolety–Wakool system remains medium after risk mitigation options are considered – processes including enhanced anabranch development and meander migration. This medium risk is defined by low level consequence, but possible likelihood
- Risks are accompanied by predicted benefits, including nutrient and carbon transfer into the riparian zone and enhance geomorphic diversity (creating and sustaining in-channel and riparian zone habitat structures)
- Risk ratings are similar for all flow limit options

1 Introduction

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 resources 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, has impacted on the number and types of plants and animals and ecosystem processes that regulated floodplain river ecosystems can support (Thompson et al. 2019), Appendix A. For example:

- By 2010, an estimated 70 per cent of river red gums along the Murray River were affected by dieback as a result of altered flow regimes (Mac Nally et al. 2011).
- Numerous native fish populations, including Murray cod, silver perch, golden perch, trout cod, freshwater catfish and numerous floodplain specialist fish are in decline in the Murray River system (Koehn and Todd 2012; Koehn et al. 2020a, 2020b).
- Long-term aerial surveys show waterbird populations are in decline across the Murray–Darling Basin (Porter et al. 2021). Barmah–Millewa and Koondrook–Perricoota forests support less colonial waterbird breeding than historically (Hutton 2017).

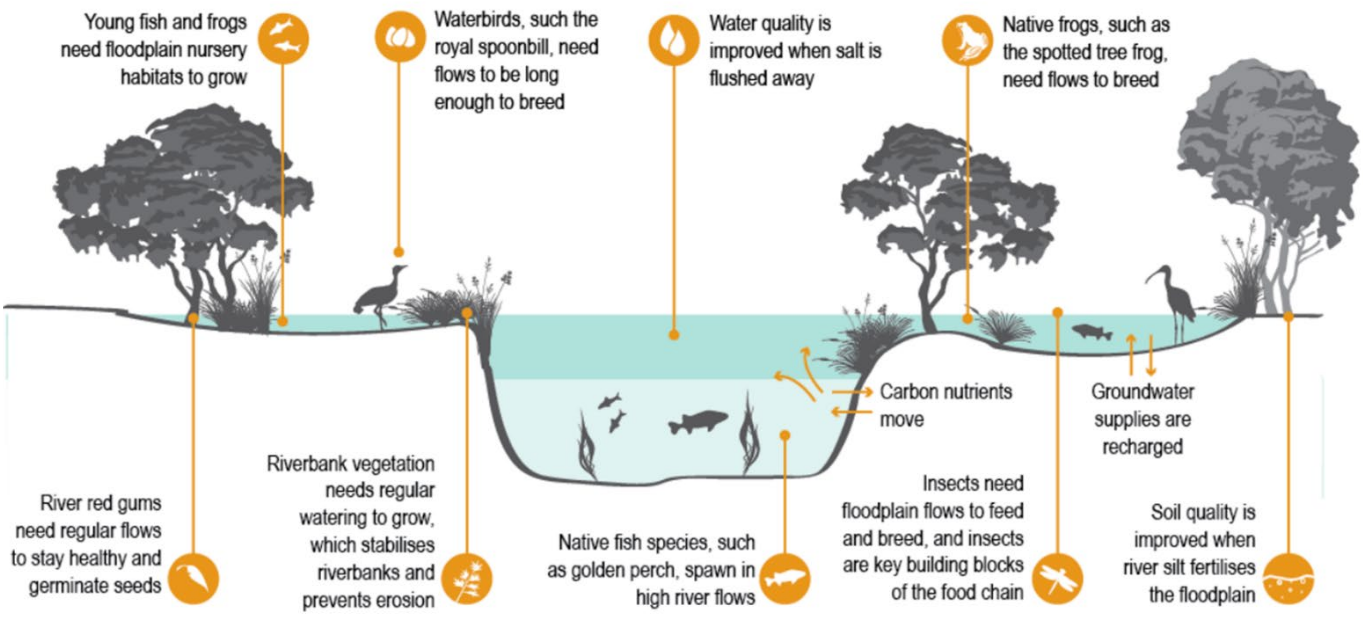


Figure 2: The importance of river floodplain connection (MDBA 2015)

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

Flow regulation in the Murray and Murrumbidgee River systems has increased the permanence of in-channel river flows while reducing the frequency of flows that inundate wetlands and low-lying floodplain (Gippel and Blackham 2002; Rolls and Bond 2017). The loss of these flows can be especially damaging during dry years, where the persistence of species is highly dependent upon relatively few events that are easily intercepted and regulated by dams.

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 Commonwealth and state governments) is used to meet some of these outcomes. However, to date, environmental water managers 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 or by providing river flows to a limited area of low-lying floodplain and wetlands within areas like parts of Barmah–Millewa Forest.

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 Reconnecting River Country Program is investigating ways to reinstate flow events that inundated wetlands and low-lying floodplain areas, using existing water entitlements held by the Australian and state governments. Relaxing operational flow limits will enable flows to be delivered high enough, and long enough, for water to flow through connector channels into wetlands, anabranches and low-lying floodplains areas, 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, allowing for more wetlands to be protected.

This Environmental Benefits and Risks 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 (erosion) risks.

The flow limit options being investigated by the program for the strategic business case and assessed in the EBRA are listed in Table 2. The flow limit options comprise linked flow limits at both the Doctors Point and downstream of Yarrawonga Weir gauges on the Murray 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 Murray system

Flow limit option	Hume to Yarrawonga Flow measured at Doctors Point (D) (ML/d)	Yarrawonga to Wakool Junction Flow measured below Yarrawonga Weir (Y) (ML/d)
Base case (Y15D25)	25,000 [1]	15,000 [2]
Option 1 (Y25D25)	25,000	25,000
Option 2 (Y30D30)	30,000	30,000
Option 3 (Y40D40)	40,000	40,000
Option 4 (Y45D40)	40,000	45,000

[1] current water sharing plan limit at Doctors Point, however noting that environmental flows are also limited by the lower flow limit of 15,000 ML/d further downstream below Yarrawonga Weir
[2] current temporary operational limit

For each 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 the 'Hume to Yarrawonga' and 'Yarrawonga to Wakool Junction' program project areas, as well as the Murray River downstream of these project areas to Wentworth.

Environmental outcomes were compared between the base case (current operational flow limits) and relaxed constraint flow limit options (see Table 2), using modelled flow scenarios (modelled daily time series of flow at a variety of gauges) described in Section 2.1. 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.

The flow scenarios were used as the key input to each environmental assessment. Some themes also used inundation modelling to represent the extent of potential wetland and floodplain inundation based on the amount of flow passing an indicator gauge. The River Murray Floodplain Inundation Model (RiM-FIM) was used for most themes (Overton et al. 2006; Sims et al. 2014). It is the most appropriate product available for representing long-term patterns of inundation associated with the modelled flow time series. While more recent, higher resolution and higher accuracy hydraulic models have been developed as part of the program for the purpose of impact identification, these hydraulic models are best suited to estimating inundation extents over short periods (30–60 days); for example, for single flow events or flow rates (e.g. representing the maximum potential inundation extent for a flow of 30,000 ML/d at downstream of Yarrawonga Weir). Hydraulic models are not well suited to quantifying patterns of inundation extent over longer time scales such as the 124-year period used in this EBRA. More information on the inundation modelling used can be found within the technical report prepared for each theme.

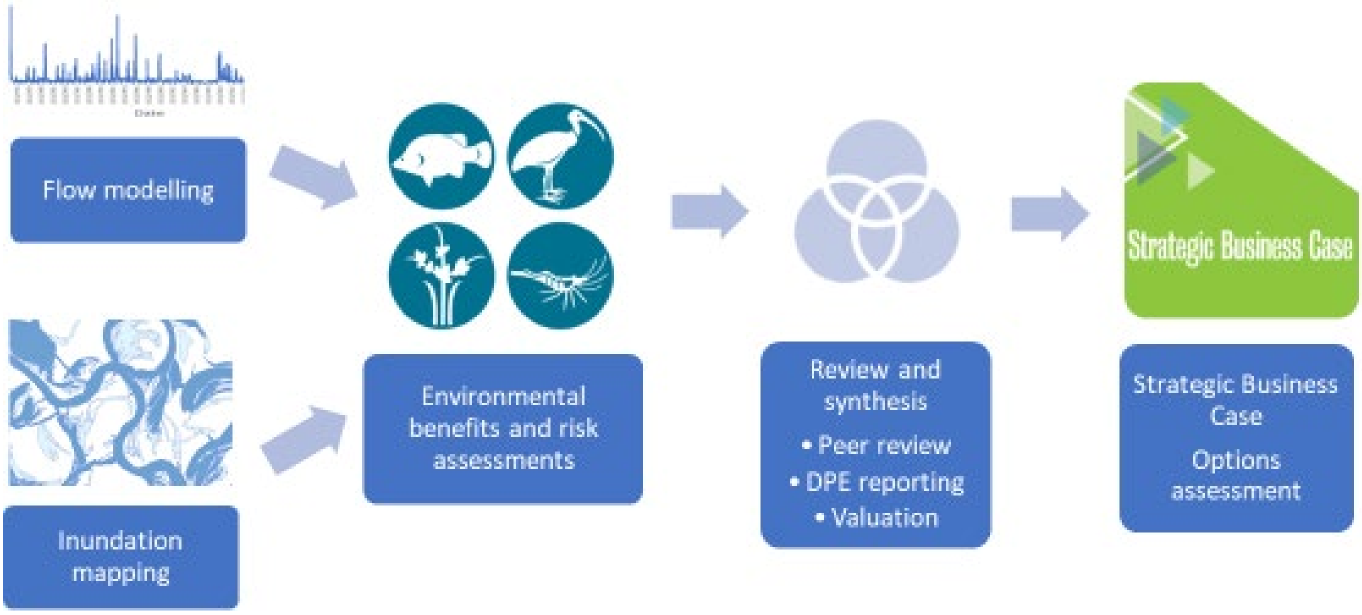


Figure 3: The EBRA process to inform the strategic business case

2 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 Murray–Darling Basin. Outcomes of the hydrological modelling have been used as direct inputs to environmental benefit and risk assessments, reflecting likely environmental water deliveries through time.

River system modelling has been undertaken using the Source Murray Model, a hydrological model of the River Murray system developed and owned by the Murray–Darling Basin Authority. The model version used for this work represents current system operations, current environmental water recovery, and historical climate over the period 1 July 1895 to 30 June 2019 (124 years). The use of the Source Murray Model for this purpose was a collaboration between the department and the Murray–Darling Basin Authority, with the department providing the flow scenarios and water delivery strategies for representation in the model by the Murray–Darling Basin Authority.

2.1 Flow limit options modelled

Table 3 shows the flow limit options represented in the modelling, including the flow constraint limits adopted in the Goulburn, Murrumbidgee and Lower Darling rivers.

Table 3: Flow limit options modelled and associated flow constraints adopted in the model

Flow limit option	Murray River at Doctors Point (ML/d)	Murray River downstream of Yarrawonga Weir (ML/d)	Goulburn River at McCoys Bridge (ML/d)	Murrumbidgee River at Balranald (ML/d)	Darling River at Weir 32 (ML/d)
Base case (Y15D25)	25,000	15,000	8,500	9,000	9,000
Option 1 (Y25D25)	25,000	25,000	17,000	12,000	9,000
Option 2 (Y30D30)	30,000	30,000	17,000	12,000	9,000
Option 3 (Y40D40)	40,000	40,000	17,000	12,000	9,000
Option 4 (Y45D40)	40,000	45,000	17,000	12,000	9,000

2.2 Environmental water recovery represented in the modelling

The modelling assumes that environmental water held as at December 2019 by the Commonwealth Environmental Water Office (CEWO; 967 GL of entitlements) and The Living Murray (TLM; 257 GL of entitlements) is available for use in delivering environmental flows under the flow limit options. No allowance has been made at this stage for coordination with Barmah–Millewa Forest Environmental Water Allocation or River Murray Increased Flows (Snowy recovery).

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

2.3 Environmental water delivery strategy

2.3.1 Murray system

For the Murray system the modelling assumes that environmental flows that would be delivered under the flow limit options are ordered downstream of Yarrawonga Weir. The environmental flow orders are based on the Environmental Water Requirements (EWRs) specified in the Murray–Lower Darling Long Term Water Plan (DPIE 2020b) at downstream of Yarrawonga Weir (Planning Unit 2). The model achieves these orders through releases of environmental water from Hume Dam, in combination with other releases from Hume Dam and unregulated flows from the Ovens and Kiewa rivers. The EWRs at Yarrawonga Weir are the basis of the environmental flow orders; however, this approach has been adopted with the understanding that these orders would provide environmental outcomes along the river system, both upstream and downstream of Yarrawonga.

The Murray–Lower Darling Long Term Water Plan includes EWRs ranging from very low flows and baseflows through to large freshes and overbank flows. Orders were created in the model for the full suite of EWRs within the constraint limits associated with the flow limit options, with the following exceptions:

- Baseflow 1 was not included as an order as the EWR was assessed as being already met
- Nesting Support 1 (for nesting of Murray cod and trout cod) was also not included due to complexity in representing this EWR in the model.

Table 4 shows the orders included in each of the flow limit options (flows of 15,000 ML/d or above are shown). For all EWRs rate of rise in flow was set to 25 per cent increase in flow rate per day, and rate of fall set to 10 per cent decrease in flow rate per day.

The EWRs in the Long Term Water Plan are not intended as a fixed set of environmental water orders 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, the flow rates and durations for some EWRs were adjusted to give a spread in flow rates and durations for each flow limit option. These are identified explicitly in Table 4.

Table 4: EWRs included as environmental orders at Yarrawonga for each flow limit option modelled

OB = overbank; LF = large fresh; BK = bankfull. Shaded cells are additional environmental demands to provide variability in flow magnitude and duration. EWRs from very low flows up to LF2 (12,000 ML/d) are not included in the table. These were included and kept constant for all flow limit options.

EWR	Modelled flow (ML/d)	Modelled duration (days)	Flow limit option (Y= Yarrawonga, D= Doctors Point)				
			Base case (Y15D25)	Option 1 (Y25D25)	Option 2 (Y30D30)	Option 3 (Y40D40)	Option 4 (Y45D40)
OB2	15,000	150	✓	✓	✓	✓	✓
LF3	18,000	8	✓ Flow = 15,000 ML/d	✓	✓	✓	✓
OB1	18,000	45	✓ Flow = 15,000 ML/d	✓	✓	✓	✓
OB3	25,000	21	✗	✓	✓	✓	✓
BK1	29,000	15	✗	✓ Flow = 25,000 ML/d	✓	✓	✓
OB4	35,000	14	✗	✓ Flow = 25,000 ML/d	✓ Flow = 30,000 ML/d	✓	✓
OB5	35,000	30	✗	✓ Flow = 25,000 ML/d	✓ Flow = 30,000 ML/d	✓	✓
OB6	40,000	21	✗	✗	✓ Flow = 30,000 ML/d	✓	✓
OB6a	40,000	14	✗	✗	✗	✓	✓
OB6b	45,000	14	✗	✗	✗	✗	✓

The modelling has adopted a delivery strategy 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 below.

All orders are timed so that flows return to in-channel levels before the end of November, except OB2 where flows of 15,000 ML/d may be maintained beyond November to complete waterbird breeding events.

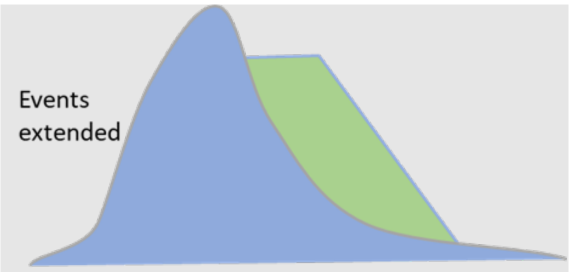
The model also estimates the volume of environmental water required to deliver the orders and only delivers those that are considered feasible given the amount of environmental water available at that time. Where multiple orders trigger concurrently the model will prioritise the highest flow order (flow rate), as these are typically hardest to achieve from a water availability perspective and opportunities need to be taken when they arise.

In addition to the environmental orders described above, the Source Murray Model includes a range of environmental orders reflecting existing environmental watering priorities, including (as examples) deliveries to TLM icon sites, and baseflows and freshes through the Edward/Kolety–Wakool system. These have been retained in the model; however, the delivery of higher flows through the relaxation of constraints will impact on the pattern of deliveries to these sites.

Delivery types used to schedule environmental flow orders

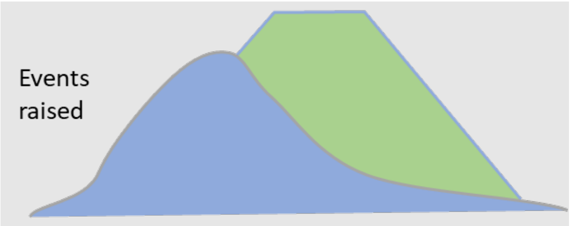
1. Extending and/or raising an existing 'high' flow event

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 (August to November), and the model will seek to implement this delivery type each water year if the opportunity arises.



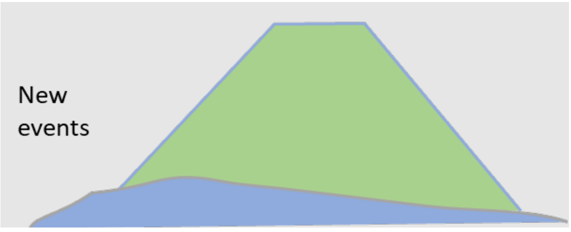
2. Raising and extending an existing 'medium' flow event

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 (September 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 (October) to give first opportunity for higher flows triggering the other delivery approaches.



2.3.2 Goulburn and Murrumbidgee valleys

The Goulburn and Murrumbidgee valleys provide inflows to the Source Murray Model at McCoys Bridge and Balranald respectively, with input flow time series provided from previous runs of the respective valley models. Constraints Management Projects are concurrently under investigation in both of these valleys. At the time that this modelling for the Murray system was undertaken, similar modelling of flow delivery under relaxed constraint scenarios was not available for the Goulburn and Murrumbidgee valleys. For the purposes of this modelling in the Murray system, environmental water contribution to end of system flows from the Goulburn and Murrumbidgee was represented in the following way:

- annual allocations for CEWO and TLM entitlements are derived using the valley models
- it was assumed that 80 per cent of the volume of CEWO and TLM annual allocation volumes in the Goulburn and Murrumbidgee would be available within both the Goulburn and Murrumbidgee valleys
- delivery losses to end of valley are assumed to be 9 per cent in the Goulburn and 26 per cent in the Murrumbidgee valleys.

The annual volume of return flows is added to the baseline flow time series at McCoys Bridge and Balranald in a pattern derived using the Murray–Darling Basin Authority's 'Hydro Cues' delivery approach that was adopted for Sustainable Diversion Limit Adjustment Mechanism modelling (MDBA 2017b) up to the flow rates listed in Table 3.

2.3.3 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 flows at Rocky Point on the Ovens River exceed minor flood level, to reduce risk of orders at Yarrawonga being exceeded
- not ordering high flows when the Goulburn River has experienced flows above minor flood level at McCoys Bridge in the last 30 days.

These 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.

2.4 Modelled environmental flow outcomes

Modelled flow time series for the program base case and flow limit options have been 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 outcomes are presented and discussed here.

Key observations from the modelling are:

- There is sufficient environmental water to deliver the higher flow events enabled by the relaxation of flow constraints and significantly increase the frequency of associated flows (Table 5, 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 40 per cent increase in frequency of wetland and low-level floodplain connecting flows between Hume Dam and Yarrawonga (reflecting that this area receives infrequent flows at present due to the effects of Hume Dam)
  - 10–20 per cent increase in frequency of flows downstream of Yarrawonga and through the Edward/Kolety–Wakool system
  - 2–5 per cent increase in frequency of flows from Torrumbarry downstream to Wentworth along the Murray.
- The achievement of EWRs (both proportion of years EWRs achieved and duration of dry spells) shows significant improvement for flows within the range at which constraints are relaxed, for the Hume to Yarrawonga, Yarrawonga to Barmah, and Edward/Kolety–Wakool areas. Other areas along the Murray show smaller levels of EWR improvement.
- The less significant flow outcomes from Torrumbarry downstream to Wentworth may be due, in part, to limitations in considering enhanced flows from the Goulburn and Murrumbidgee rivers, and current lack of coordination between the valleys in the modelling. Further modelling for the final business case should investigate this further and improved outcomes are considered likely.
- The model shows the potential for significant improvements in environmental flows during prolonged dry periods such as the late 1890s/early 1900s (Federation Drought) and 2000s (Millennium Drought) (Figure 4).
- There are no modelled high flow deliveries in the very dry years (e.g. 2006–2009) owing to reduced environmental water availability and no existing flow events to extend or raise (Figure 4).
- There are no modelled high flow deliveries in the very wet years (e.g. 1956, 1974, 1993) owing to environmental water requirements already being met (together with adverse flooding impacts in some parts of the Basin) and no orders placed in the model.
- The frequency of flows above the relaxed constraint limit reduces relative to the base case as greater environmental flow releases enable greater dam air space creation and flood mitigation benefits (Table 6). This effect is greatest for the higher flow limit options and reduces significantly for the lower flow limit options (Figure 4).

Table 5: The number of years with flow orders for each model scenario, for specified flow ranges (total length of modelled flow record is 124 years)

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

Flow range (ML/d)	Base case (Y15D25)	Option 1 (Y25D25)	Option 2 (Y30D30)	Option 3 (Y40D40)	Option 4 (Y45D40)
15,000–24,999	90	68	52	57	61
25,000–29,999	–	85	76	72	78
30,000–39,999	–	–	59	52	48
40,000–44,999	–	–	–	46	36
45,000	–	–	–	–	40

Table 6: The number of years with flows of at least 14 days duration at downstream of Yarrawonga weir (total length of modelled flow record is 124 years)

Flow threshold (ML/d)	Base case (Y15D25)	Option 1 (Y25D25)	Option 2 (Y30D30) [1]	Option 3 (Y40D40)	Option 4 (Y45D40)	Without development
20,000+	87	105 (+18)	104 (+17)	104 (+17)	104 (+17)	115
30,000+	61	60 (–1)	64 (+3) [1]	88 (+27)	89 (+28)	97
40,000+	41	40 (–1)	39 (–2)	41 (0)	60 (+19)	75
50,000+	36	34 (–2)	30 (–6)	30 (–6)	31 (–5)	58

[1] The version of the Source Murray Model used for the Y30D30 scenario for environmental benefit and risk assessments did not include the mechanism to cancel or adjust orders in response to elevated Ovens River inflows. Subsequent testing showed that the increased occurrence of events above the flow constraint limit associated with this flow limit option (i.e. +3 events) would be reduced significantly if those strategies were implemented in the model.

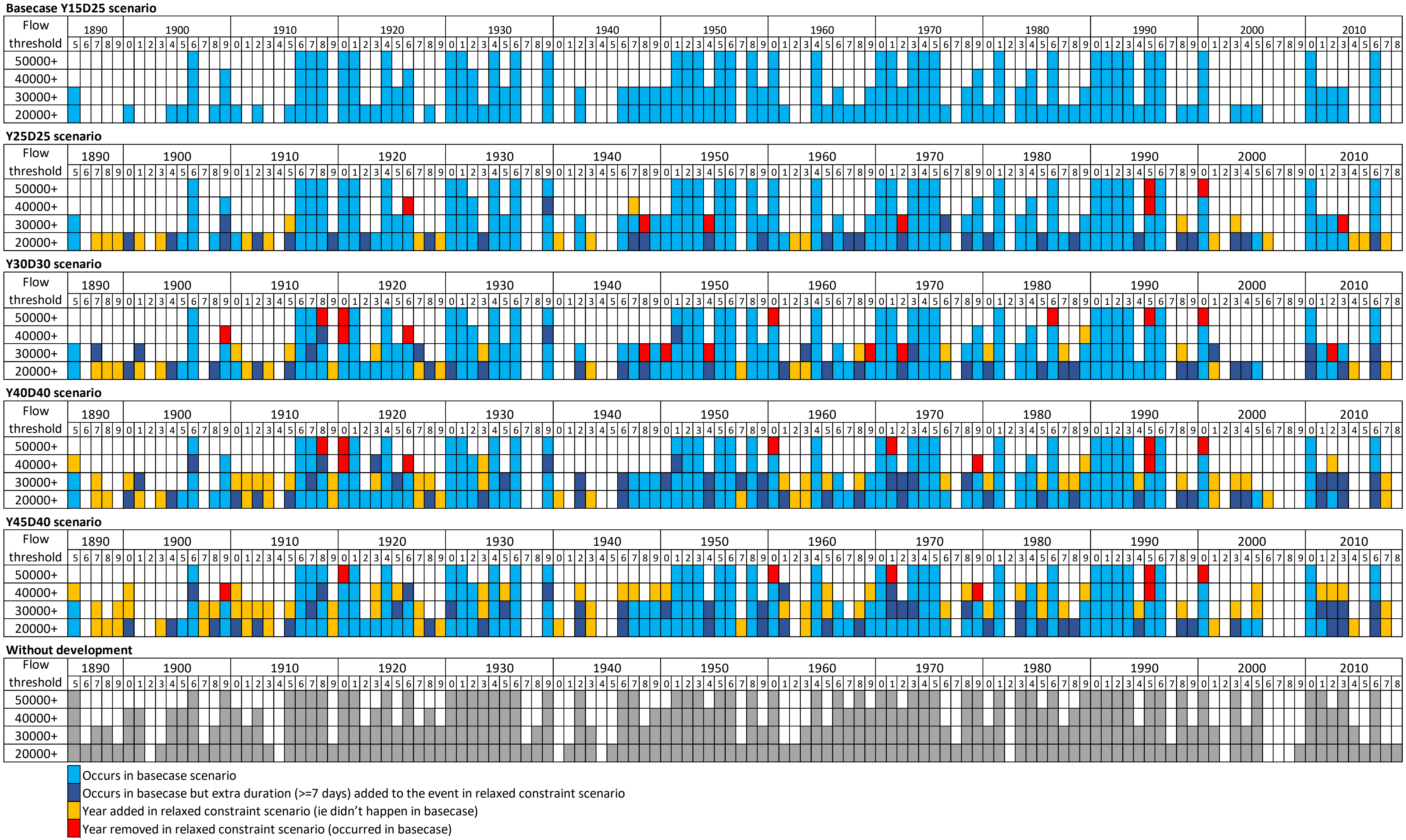


Figure 4: Years when flows exceed selected thresholds for a total duration of 14 days or more at Yarrawonga for program flow scenarios

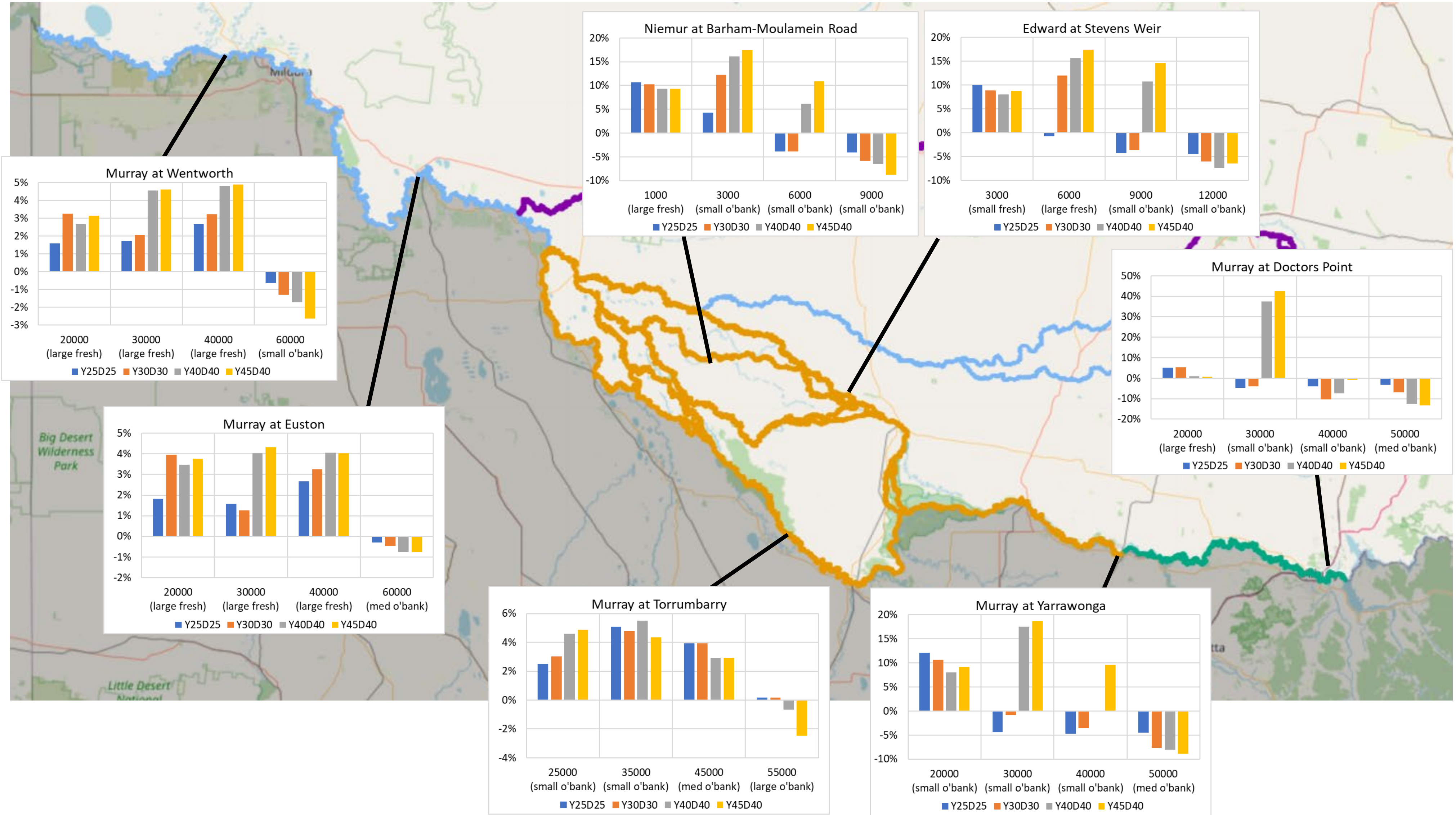


Figure 5: Change in proportion of years flows experienced at sites through the Murray system for program flow scenarios

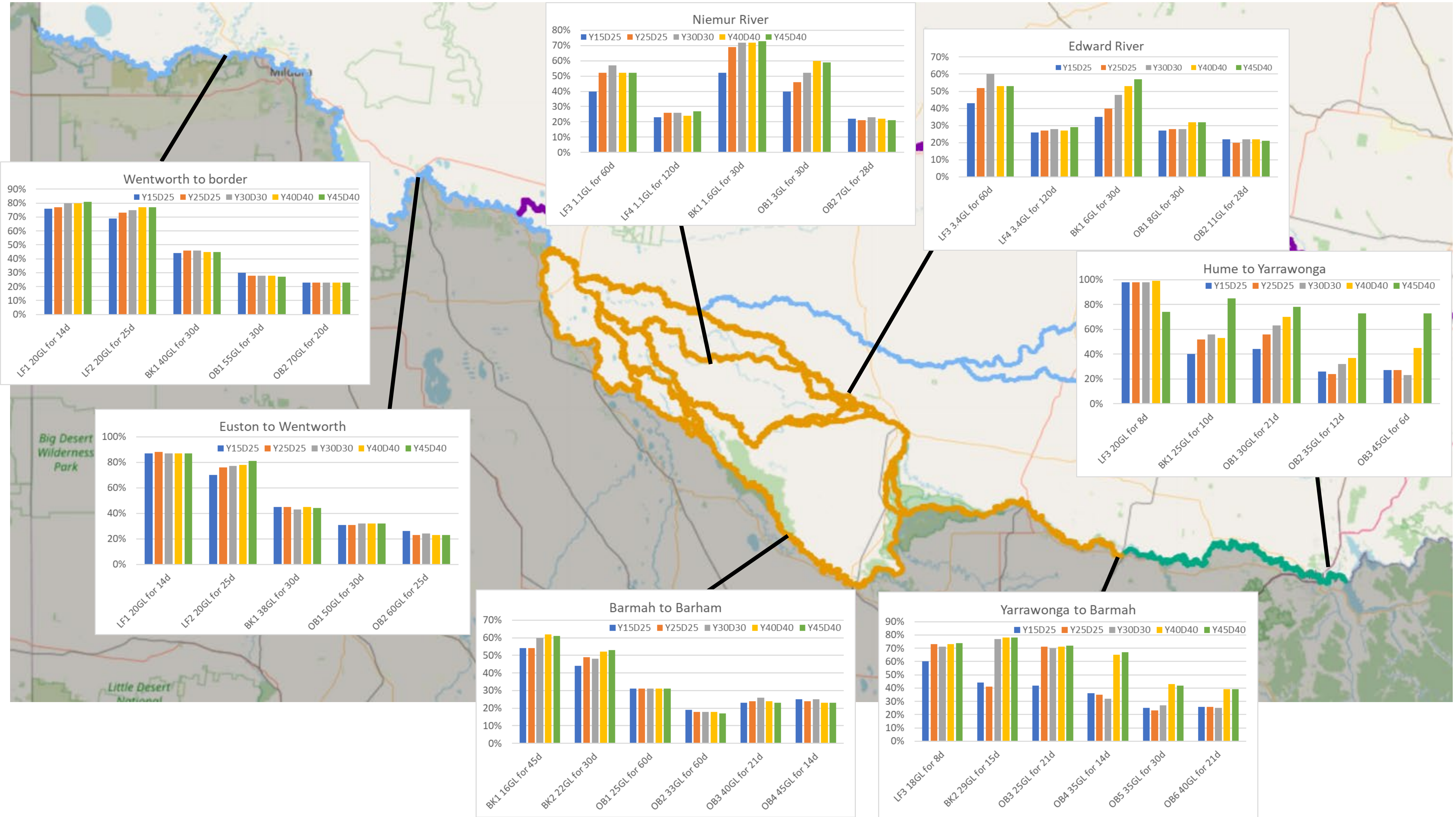


Figure 6: EWRs – proportion of years EWRs achieved (selected EWRs within the flow range potentially affected)

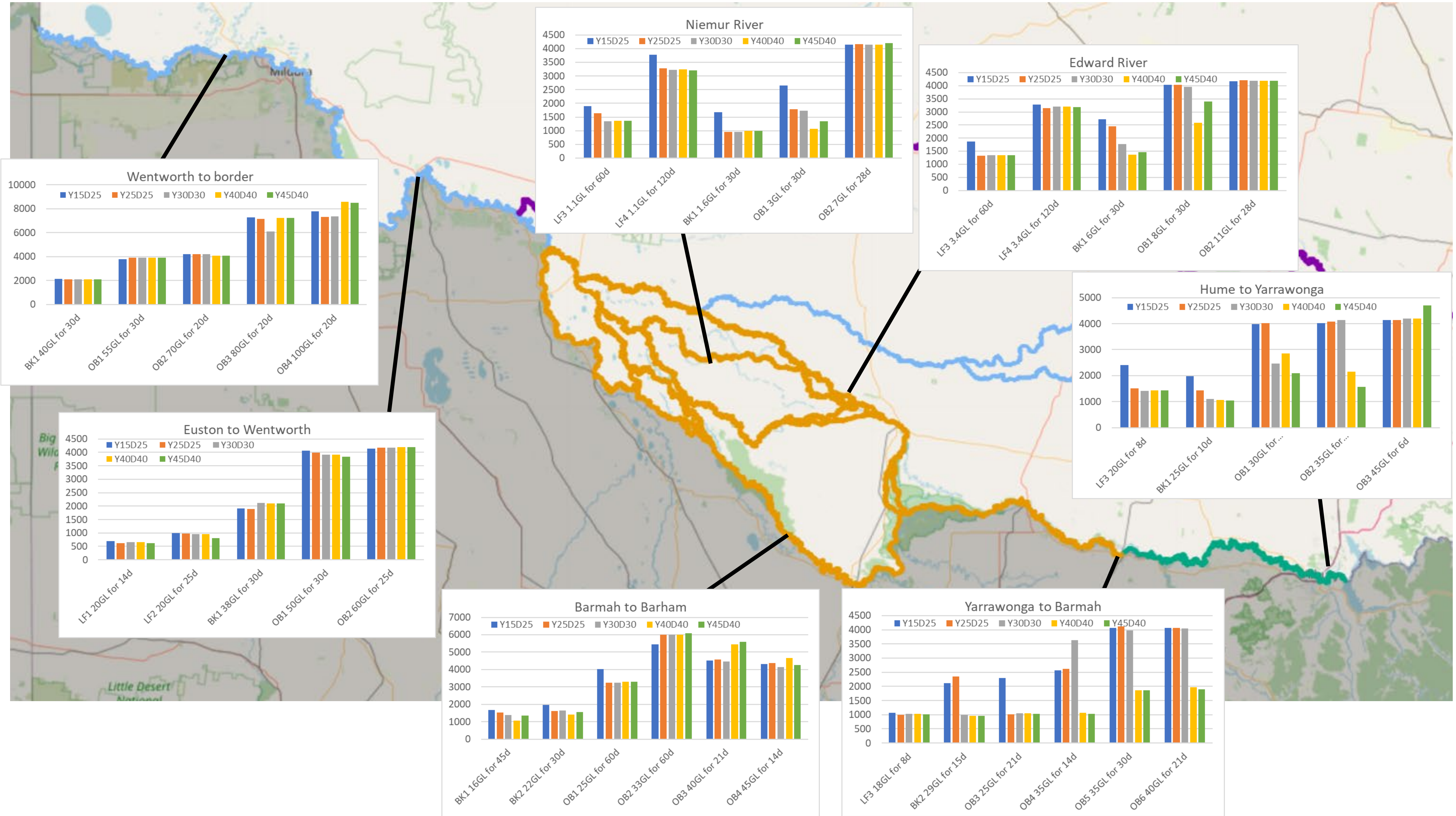


Figure 7: EWRs – 95th percentile duration of dry spells between EWRs (selected EWRs within the flow range potentially affected)

3 Environmental benefit assessments

3.1 Lateral connectivity

Raised flow limits will significantly increase the area of wetland environments (up to +97 per cent), and native vegetation communities (up to +294 per cent) that can be inundated by environmental flows. 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 instream productivity, and providing habitat and food resources for native fish, waterbirds and other animals.

Flow regulation in the Murray River has reduced lateral connectivity by increasing the permanence of in-channel river flows and reducing the frequency of flows that inundate wetlands, anabranches and low-lying floodplain areas (Rolls and Bond 2017). This reduction can be seen in Table 7 where only 15 per cent of total floodplain wetland areas across the Hume to Wentworth project area 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 operational flow limits will allow environmental water deliveries to laterally reconnect wetlands, anabranches and low-lying floodplain areas, thus partially mitigating the effects of regulation.

Table 7: Percentage of the total area of wetlands in each project area that can be inundated by an environmental flow delivery at investigated flow limits

Flow limit option	Percentage of the total area of wetlands inundated (%)		
	Hume to Wentworth	Hume to Yarrawonga	Yarrawonga to Wakool Junction
Base case (Y15D25)	15	21	9
Option 1 (Y25D25)	20	21	14
Option 2 (Y30D30)	24	26	16
Option 3 (Y40D40)	29	47	19
Option 4 (Y45D40)	30	47	20

The impact of raised flow limits 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 the RiM-FIM and the Edward–Wakool Floodplain Inundation Model (EW-FIM; Overton et al. 2006; Sims et al. 2014). Flow rates associated with each flow limit option were estimated for each RiM-FIM zone using analysis of observed flow data to derive correlations back to reference gauges such as downstream of Yarrawonga. Vector maps of wetlands (Brooks 2021; Crossman and Li 2015), and vegetation types (NSW OEH 2016; DELWP 2018) on the floodplain were cross-tabulated with the inundation models 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 8,600 ha (Option 1) to 12,900 ha (Option 4) of wetlands would be inundated between Hume Dam and Wentworth under the flow limit options being considered (Figure 8). This is 2,100–6,400 ha more than the ~6,500 ha of wetlands that can be inundated under the current operational flow limit of 15,000 ML/d. This corresponds to a +33 to +97 per cent increase in area of wetlands potentially inundated (20–30 per cent of the total wetlands area respectively; Table 7). For the Hume to Yarrawonga project area, significant gains in the area of wetlands potentially inundated are not realised until the Y40D40 option (Option 3), where an additional ~700 ha (+123 per cent) of wetland is reached. This non-linear 'jump' in area is characteristic of reaches where the bankfull threshold exceeds proposed flow limits. For the Yarrawonga to Wakool Junction project area (including the Edward/Kolety–Wakool system) a more uniform increase in wetland area is gained with each flow limit increase, ranging from a 1,800 ha (+45 per cent; Option 1) to 4,573 ha (+116 per cent; Option 4) increase (Figure 8).

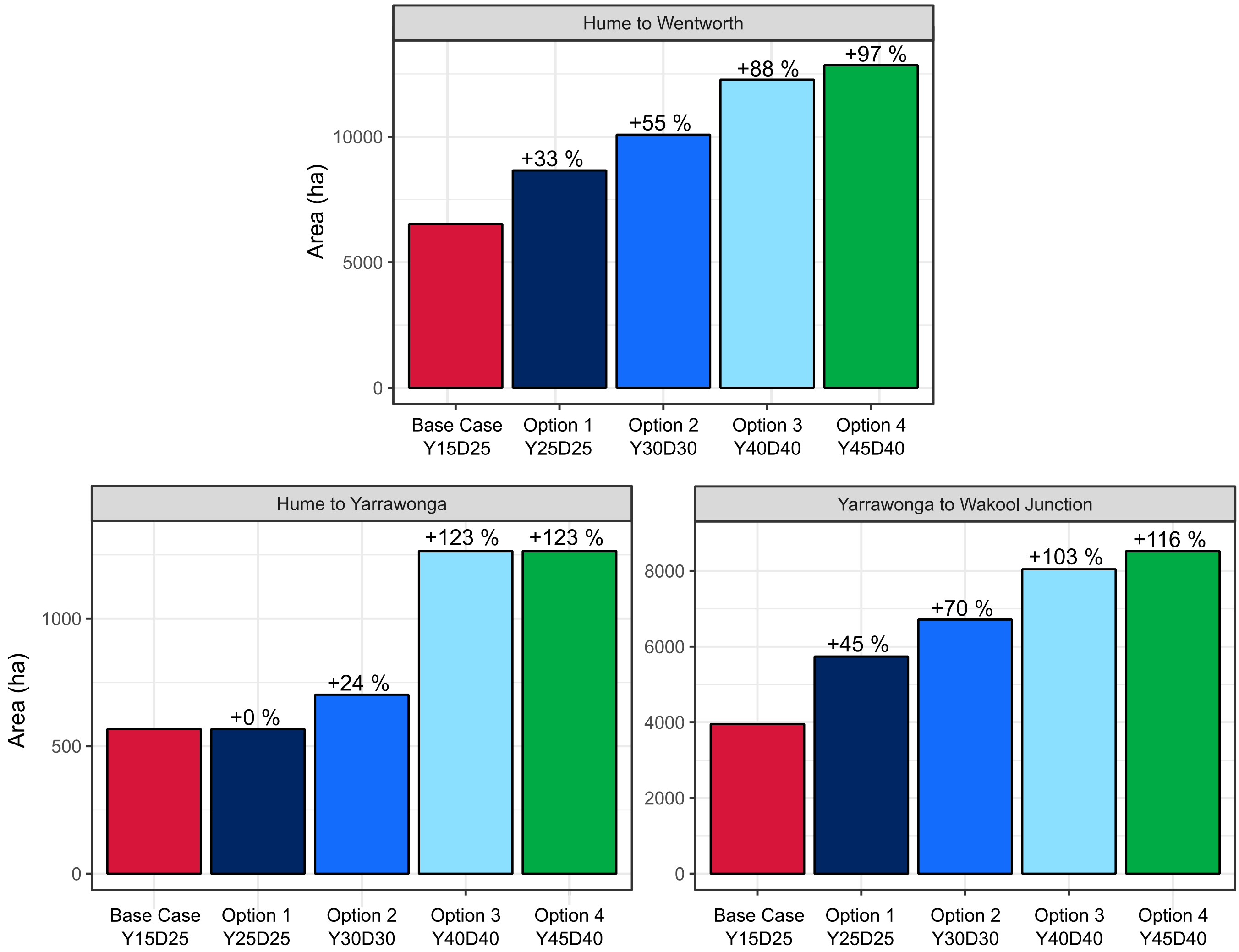


Figure 8: Maximum potential area of wetlands inundated under different flow limit options in the Murray catchment (Hume to Wentworth, Hume to Yarrawonga, and Yarrawonga to Wakool Junction)

Labels above columns represent the percentage increase in area relative to the base case. Here inundated area was determined using RiM-FIM; however, these results will be updated with outputs from ongoing hydraulic modelling.

For floodplain vegetation, raised flow limits bring major increases in the area potentially inundated (Appendix B). For example, environmental watering under raised flow limits can water between 27,000 ha (+77 per cent; Option 1) and 60,000 ha (+294 per cent; Option 4) of river red gum forest between Hume Dam and Wentworth – increases of 12,000 and 45,000 ha respectively above the 15,000 ha of river red gum that can be watered under current constraints.

Similar to the wetlands results above, we see a major increase in the area of vegetation inundated by the Y40D40 option (1,100 ha, or 84 per cent increase) in the Hume to Yarrawonga project area (Appendix B). For the Yarrawonga to Wakool Junction project area we see raised flow limits increase the area of river red gum forest inundated by between 11,400 ha (+109 per cent; Option 1) and 42,500 ha (+405 per cent; Option 4). As detailed in Section 3.4 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.

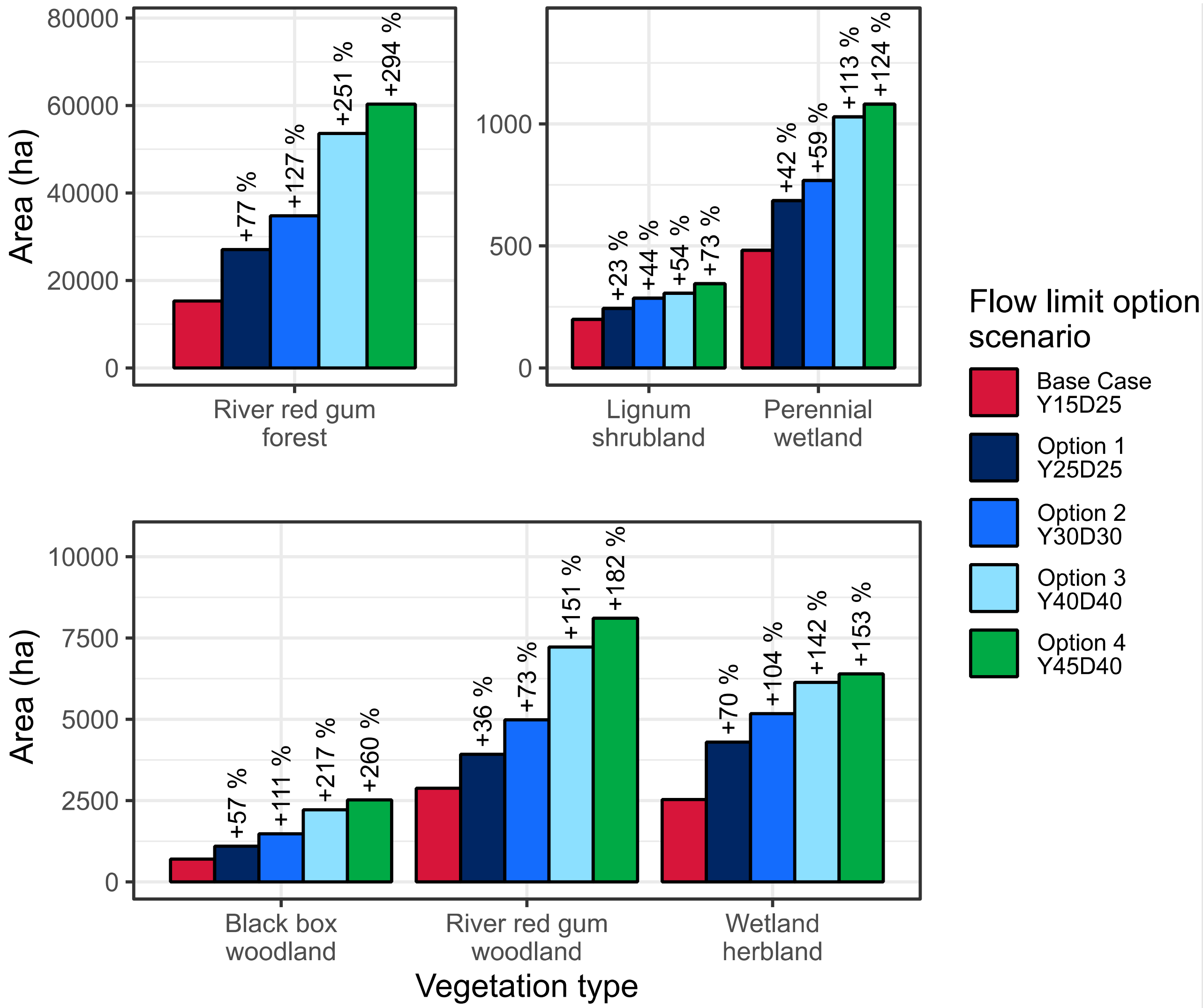


Figure 9: Maximum potential area of vegetation type inundated under different flow limit option scenarios in the Murray catchment (Hume to Wentworth)

Labels within columns represent the percentage increase in area relative to the base case flow limit option scenario. Note that sub-figures are presented on different y-axis scales for readability. Here inundation area was determined using RiM-FIM; however, these results will be updated with outputs from ongoing hydraulic modelling. Both NSW (NSW OEH 2016) and Victorian (DELWP 2018) state areas were analysed.

Figure 10 and Figure 11 show the predicted areas of inundation under different flow limits for Barmah–Millewa and Koondrook–Perricoota forests, two of the Murray River's most significant cultural and ecological sites and listed under the RAMSAR convention. Here we see the spatial patterns of increased lateral connectivity, with lower-lying wetlands and flood runners/anabranches increasingly activating and eventually larger areas of floodplain becoming inundated as bankfull thresholds are exceeded. Under the current flow limit (15,000 ML/day at Yarrawonga) 13,500 ha (18 per cent) of Barmah–Millewa can be inundated; however, no inundation in Koondrook–Perricoota Forest occurs – a combination of a higher bankfull threshold at Koondrook–Perricoota and declining flow peak as the delivery attenuates downstream. The Y40D40 flow limit option would increase the inundated area in Barmah–Millewa to 40,700 ha (55 per cent of site), and the Y45D40 leading to a 9,300 ha (27 per cent of site) increase for Koondrook–Perricoota. Both sites would therefore experience greatly enhanced lateral connectivity under a raised flow limit water regime.

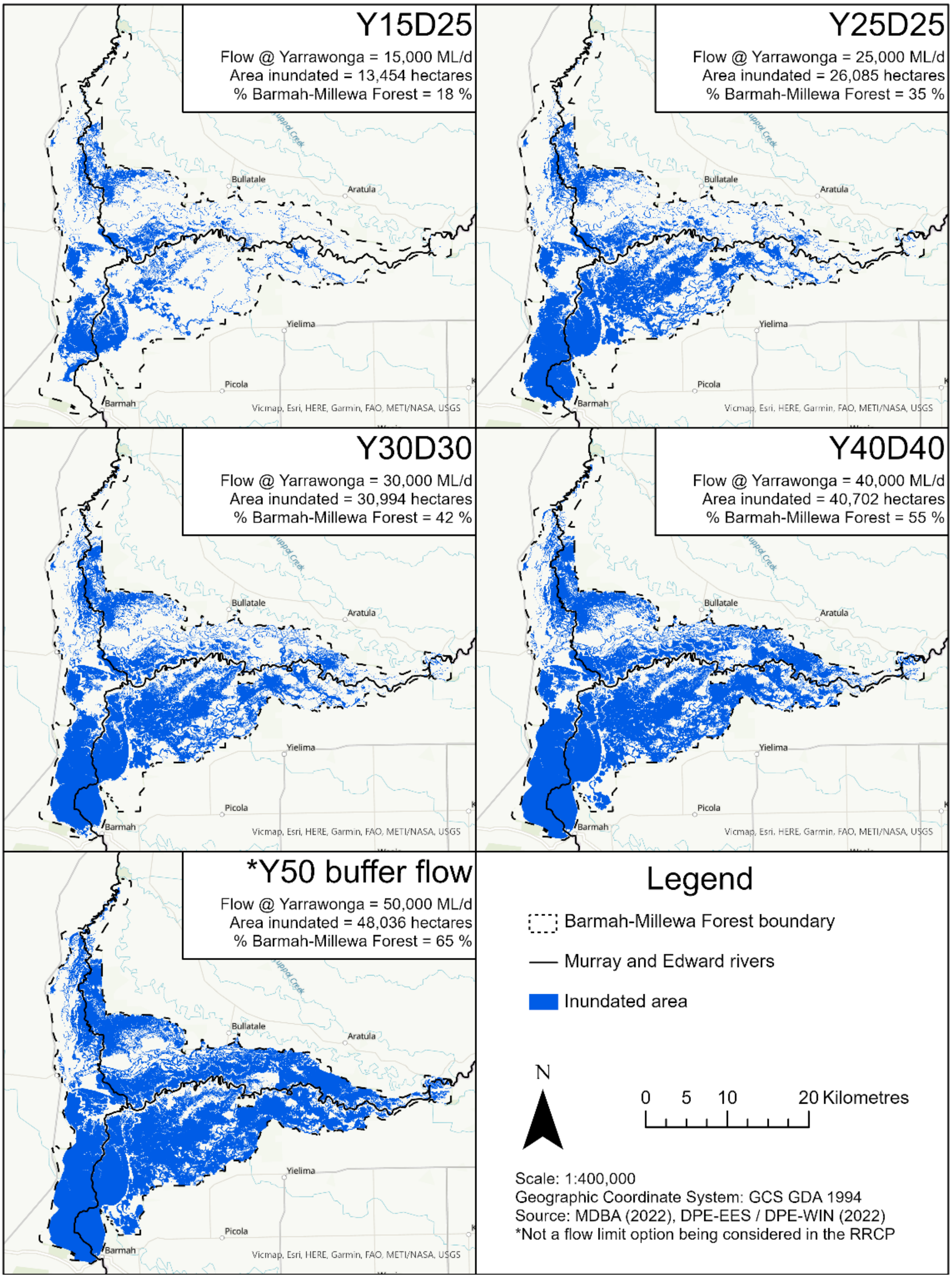


Figure 10: Maps of inundation extent under each flow limit option for Barmah–Millewa Forest

Inundation extents were generated from recently undertaken hydraulic modelling (MDBA 2022). Note that a 50 GL order at Yarrawonga (Y50) is not an option being considered by the program. At the time of report writing, no hydraulic modelling data for the Y45D40 scenario was available for this site.

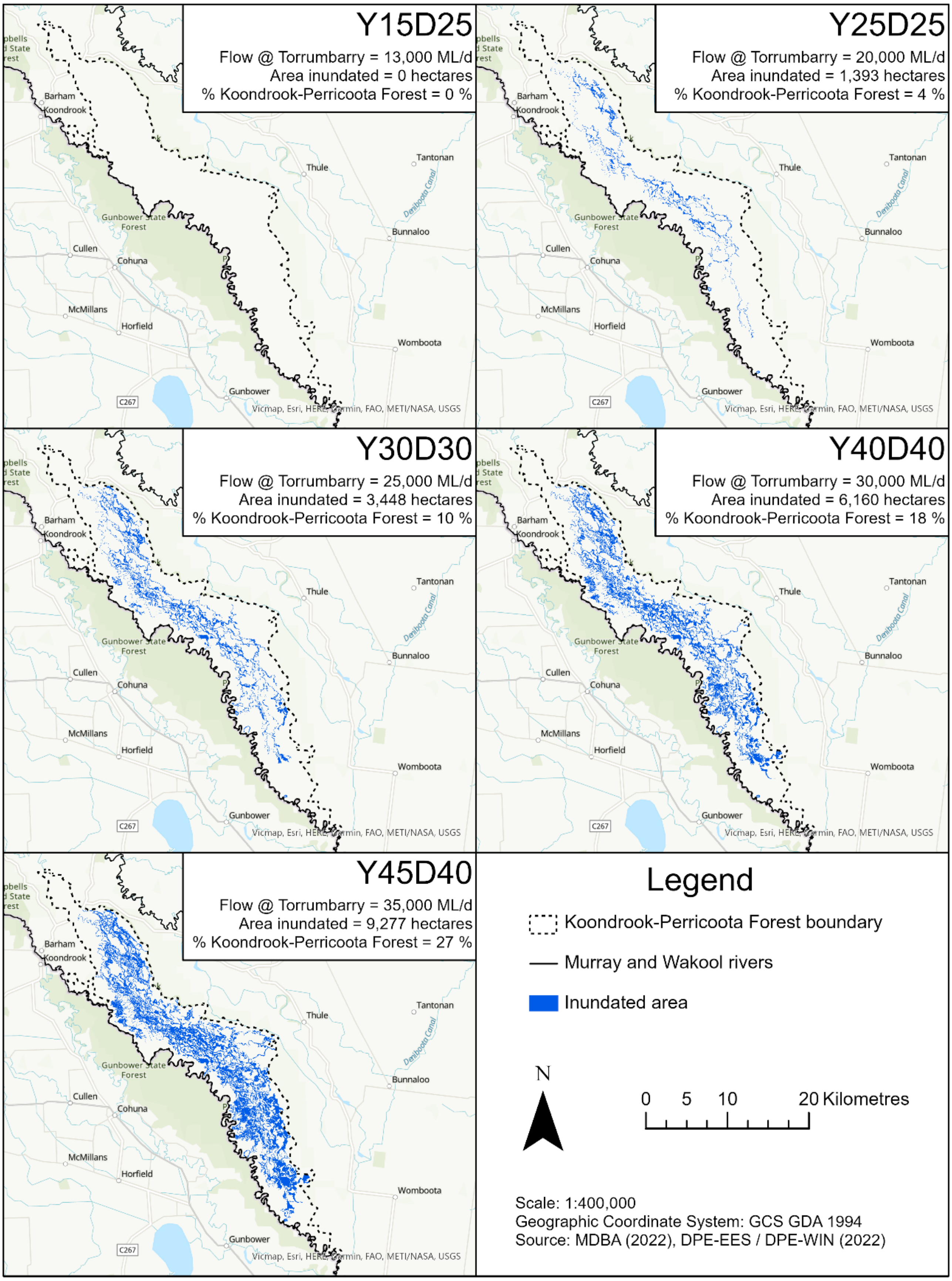


Figure 11: Maps of inundation extent under each flow limit option for Koondrook–Perricoota Forest

Inundation extents were generated from recently undertaken hydraulic modelling (MDBA 2022).

3.2 Native fish

Fish population modelling predicts that raised flow limits in the Murray would increase long-term average golden perch populations by up to 29 per cent, and minimum populations by up to 45 per cent during dry periods. These benefits are predicted to all modelled reaches, the project areas and the southern-connected system, including the lower Murray River in South Australia and the lower Darling River. Similar benefits might be expected for other flow-pulse specialist fish like silver perch, although this species has not been modelled for this project.

For Murray cod, fish population modelling predicts neutral outcomes for the Murray River.

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

The program area from Hume Dam to Wakool Junction supports 18 native fish species across four functional groups. This includes six Commonwealth and NSW threatened species: flathead galaxias, southern pygmy perch, Murray crayfish, Murray cod, trout cod and silver perch (NSW DPI 2016; DPIE 2020a). A full species list is provided at Appendix C.

Native fish populations in the program area are in poor to very poor condition (NSW 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, which limits habitat for breeding and recruitment opportunities for native fish and contributes to the deterioration of wetland habitat (e.g. aquatic vegetation and water quality). For example, floodplain specialist native fish that require regular wetland connection for breeding and recruitment have not been detected in the reach since 2010 (Pearce et al. 2018)
- rapid fluctuations in flow that can wash away or desiccate nests of nesting fish species like Murray cod and trout cod
- cold water pollution that limits fish breeding
- limited available spawning habitat due to fast-flowing instream habitat being limited to main rivers (Murray and Edward/Kolety rivers) except during natural unregulated higher flows, limiting opportunities for flow cued spawning species like golden and silver perch.

Existing flow limit constraints mean that environmental water managers are unable to deliver flows that connect wetlands at the scale required to support larger-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 (NSW DPI 2022a). The isolation of native fish in wetlands also means they cannot contribute to maintaining and building the broader native fish community in the River Murray and southern-connected basin more broadly.

3.2.1 Methods

The program's fish modelling project targeted two iconic native fish species: the Murray cod (*Maccullochella peelii*) and golden perch (*Macquaria ambigua*), which 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 and Todd 2012; Koehn et al. 2020a, 2020b) despite extensive restocking programs.

Golden perch and Murray cod were selected for modelling due to their significance to communities and expected response to raised flow limits. Golden perch rely on flow cues for spawning, movement and migration, and their growth and recruitment success is enhanced by increased river productivity and access to off-channel habitat through floodplain inundation (Ellis et al. 2016, 2022; Stuart and Sharp 2020). 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 be enhanced through improved river productivity and connectivity with floodplain habitats (Ellis et al. 2022).

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 Hume Dam to Lock 10 (Wentworth) for the Murray cod model; also including the Murray downstream of Wentworth and the Lower Darling River for golden perch (Figure 12, Figure 13) (Todd et al. 2022)
- set parameterization and management units for each of the sub-populations, including the local context, such as fishway passage, flow rates, physical structure and fish movement
- run models and evaluate outcomes of modelled program flow scenarios, followed by validation of model predictions using existing empirical data (model validation was in progress at the time of writing). These were all performed by Todd et al. (2022).

The populations models for each species were run in a series of spatial zones, including Lake Hume to Murray Mouth (golden perch), Lake Hume to Wentworth (Murray cod), Edward/Kolety–Wakool system (both native species), and lower Darling River (golden perch). A range of flow scenarios (Table 8) associated with the program flow limit options were modelled for each program reach to allow for exploration of the flows that are predicted to provide the most benefit for fish.

The models integrated 124 years of modelled hydrological data from 1896–2019, including anoxic blackwater and productivity components, providing a powerful tool to predict the effects of environmental water and other interventions on fish population dynamics.

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 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 the full technical report (Todd et al. 2022 – in prep.).

Table 8: Flow scenarios for fish population modelling

Modelled flow scenario for fish population models	Murray at Doctors Point ML/d	Murray below Yarrawonga Weir ML/d	Murrumbidgee [1] at Wagga ML/d
Base case (Y15D25)	25,000	15,000	22,000
Option 1 (Y25D25)	25,000	25,000	32,000
Option 2 (Y30D30)	30,000	30,000	36,000
Option 3 (Y40D40)	40,000	40,000	40,000
Option 4 (Y45D40)	40,000	45,000	40,000

[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.

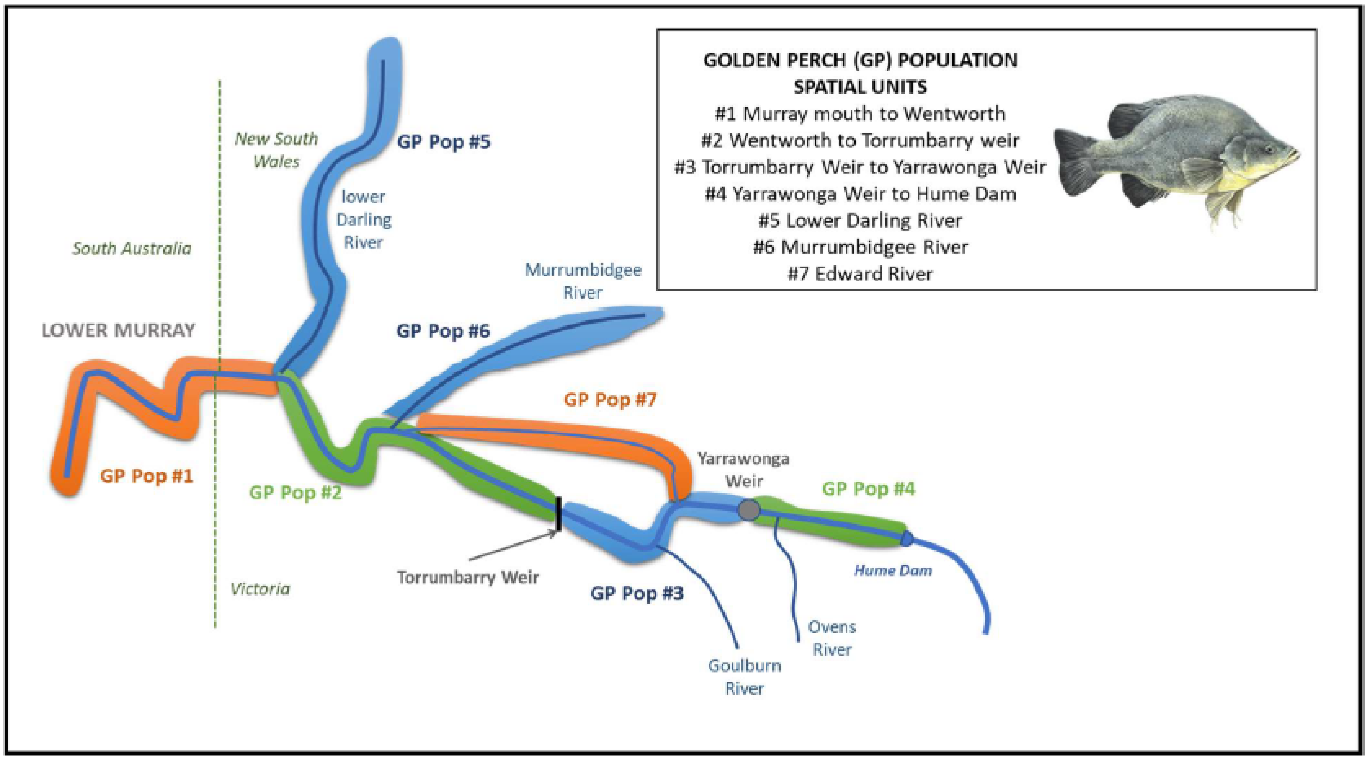


Figure 12: Spatial structure of golden perch populations modelled for the program

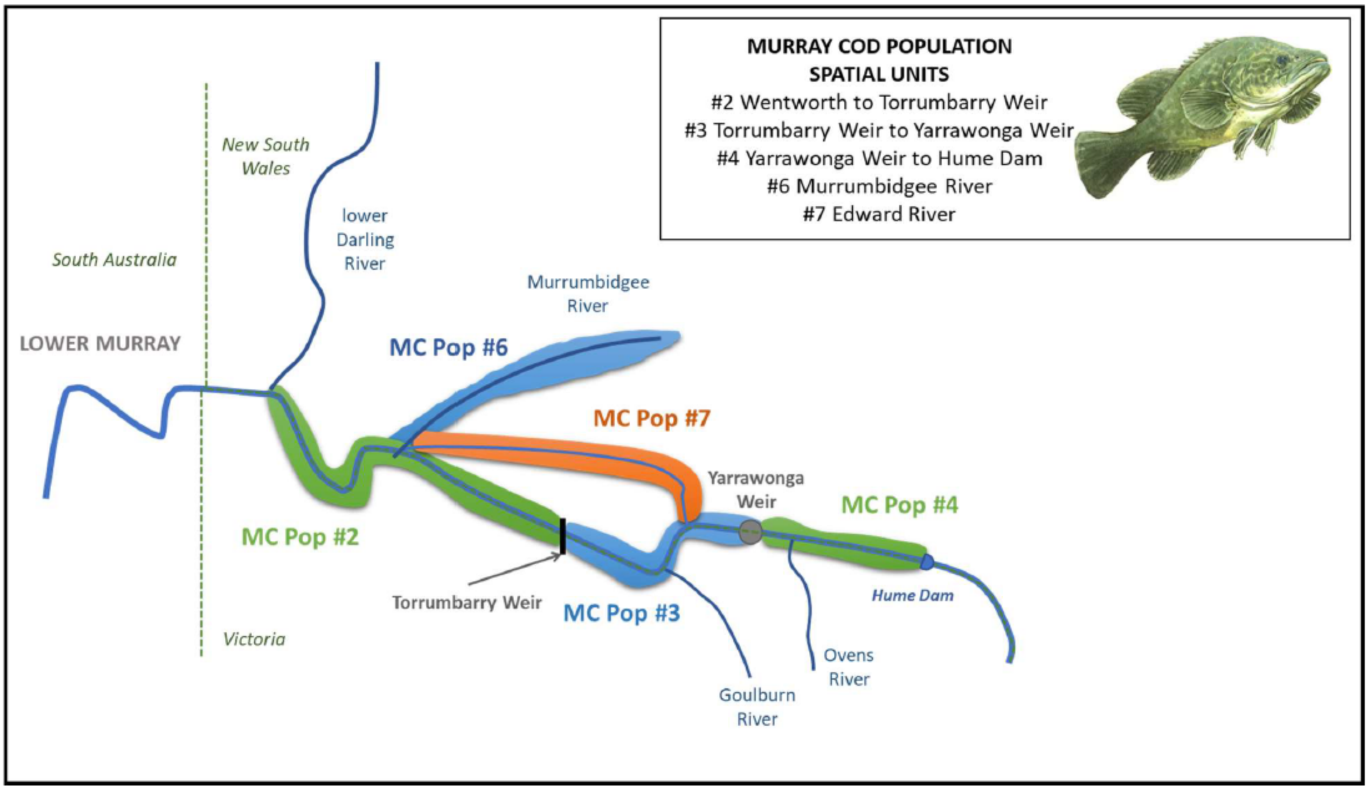


Figure 13: Spatial structure of Murray cod populations modelled for the program

3.2.2 Key outcomes

Fish population modelling predicts that relaxing flow constraints will provide significant benefits to golden perch populations in the Murray system and the southern-connected basin as whole, with the benefits increasing substantially with the higher flow limit options at Doctors Point and Yarrawonga. 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.

Golden perch outcomes

Golden perch population modelling predicts that relaxed flow limits will increase long-term average golden perch abundance (population size) in the Murray system by up to 29 per cent compared to the base case. The benefits increase substantially with increasing flow limit, from a 10 per cent increase for the lowest flow limit option of 25,000 ML/d (Y25D25) to a 16 per cent increase for 30,000 ML/d (Y30D30), 23 per cent increase for 40,000 ML/d (Y40D40) and 29 per cent increase for the highest flow limit option of 45,000 ML/d at Yarrawonga (Y45D40) (Figure 14).

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

- Hume to Yarrawonga – up to 39 per cent increase in mean abundance (Figure 15)
- Yarrawonga to Wakool Junction – up to 34 per cent increase (Figure 15).

Population increases are also predicted for reaches downstream of the program area:

- Torrumbarry to Wentworth – 12–28 per cent increase in mean abundance
- Lower Murray below Wentworth, including South Australia – 19–49 per cent increase
- Lower Darling River – 9–20 per cent increase.

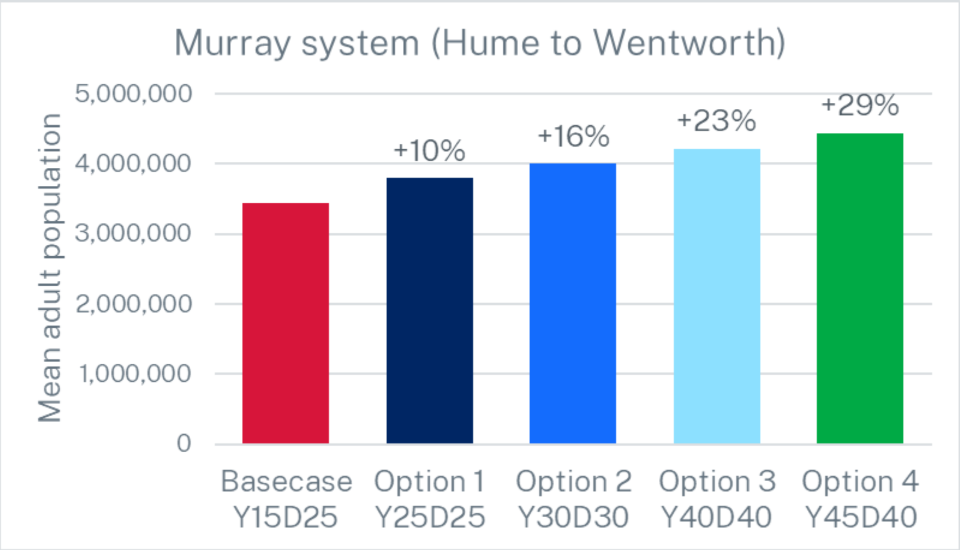


Figure 14: Mean adult golden perch population size (abundance) under the base case and relaxed constraint flow limit option scenarios for the Murray system (Hume to Wentworth), including the Edward/Kolety River

Labels above columns represent the percentage increase in area relative to the base case.

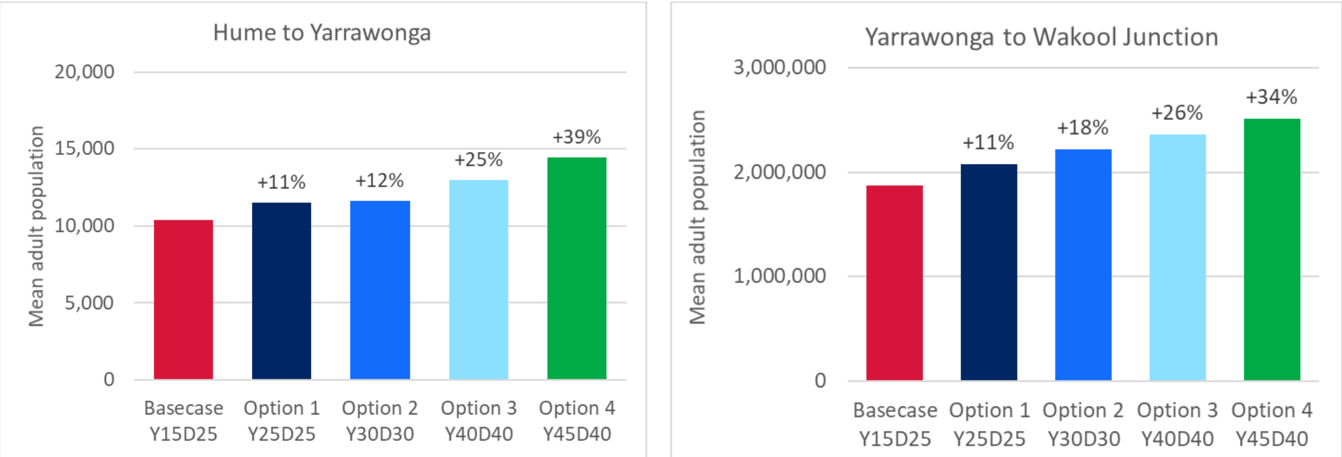


Figure 15: Mean adult golden perch population size (and per cent difference from base case) for the two project areas

Left panel: Hume to Yarrawonga and right panel: Yarrawonga to Wakool Junction.

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, golden perch abundance drops significantly during the Millennium Drought in the 2000s and is also generally low in first three decades of the modelled time series between the 1890s and 1915, around the time of the Federation Drought[1].

[1] Note that flow modelling assumes current regulation and water extraction throughout the 124-year historical period so these results will not represent actual golden populations in the 1890s to early 1900s. The 124-year synthetic time series provides an opportunity to explore potential fish population outcomes under relaxed flow limit options during wet, extended dry and average periods.

Nevertheless, the results indicated considerably higher 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 16). This suggests that relaxing constraints has the potential to buffer natural population declines during drier periods and boost population increases during average and wetter climate conditions to build greater resilience.

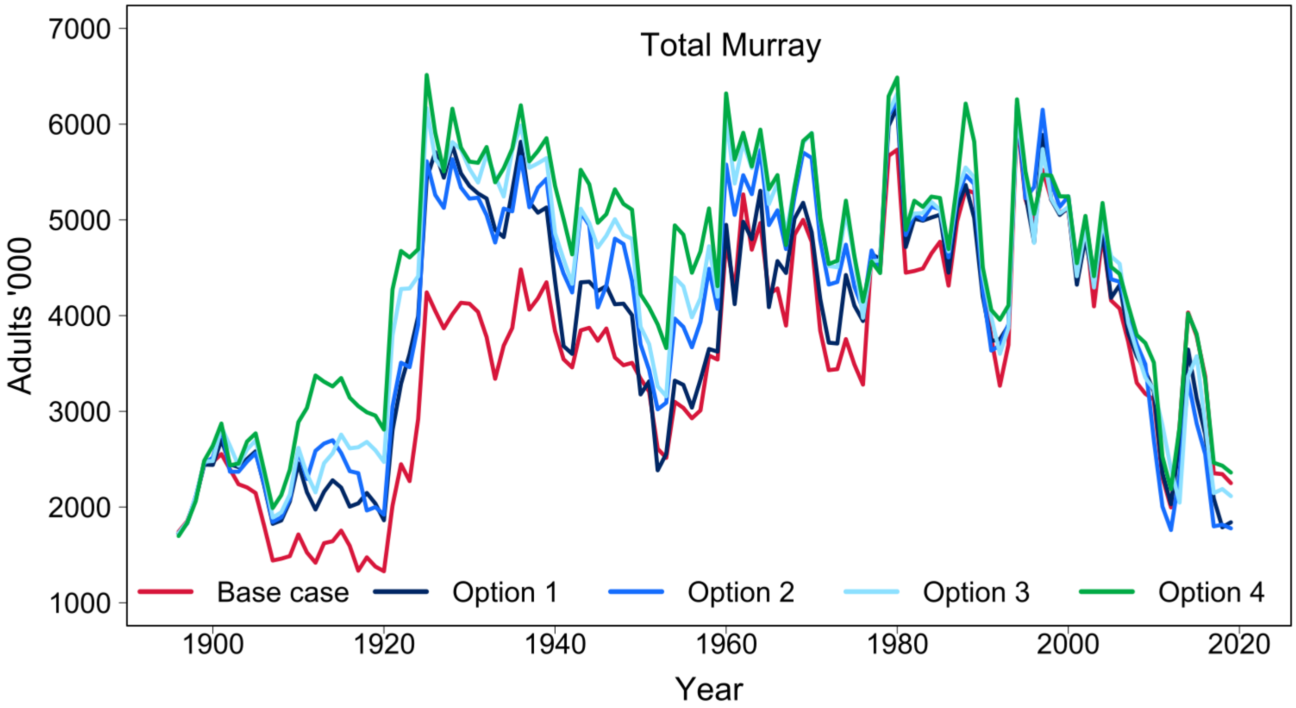


Figure 16: Modelled 124-year time series of the mean golden perch population in the Murray River (Hume to Wentworth) and including the Edward/Kolety River

There are considerably greater modelled population benefits under the increased flow scenarios. Note that the modelled time series assumes current levels of river regulation and water extraction throughout the whole period. The base case trajectory therefore does not represent actual fish populations under observed historical flows.

The 10th percentile of modelled golden perch abundance over time provides further evidence of improved outcomes for golden perch under relaxed constraints during drier periods. The 10th percentile represents periods of time when populations are close to their lowest over the modelled time period and can be used to understand how golden perch populations respond during dry periods and droughts. For the Murray system scale (Hume to Wentworth and including the Edward/Kolety River), golden perch populations during dry periods are up to 45 per cent higher under relaxed flow limit options compared to the base case (Figure 17). These substantial benefits during dry periods are also predicted for the program areas, with dry period populations being up to 51 per cent higher under relaxed flow limits than the base case in the Hume to Yarrawonga project area and up to 52 per cent higher in the Yarrawonga to Wakool Junction project area.

Overall, fish population modelling indicates that relaxing flow constraints in the Murray is likely to have significant benefits for golden perch abundance at the reach, project and Murray-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).

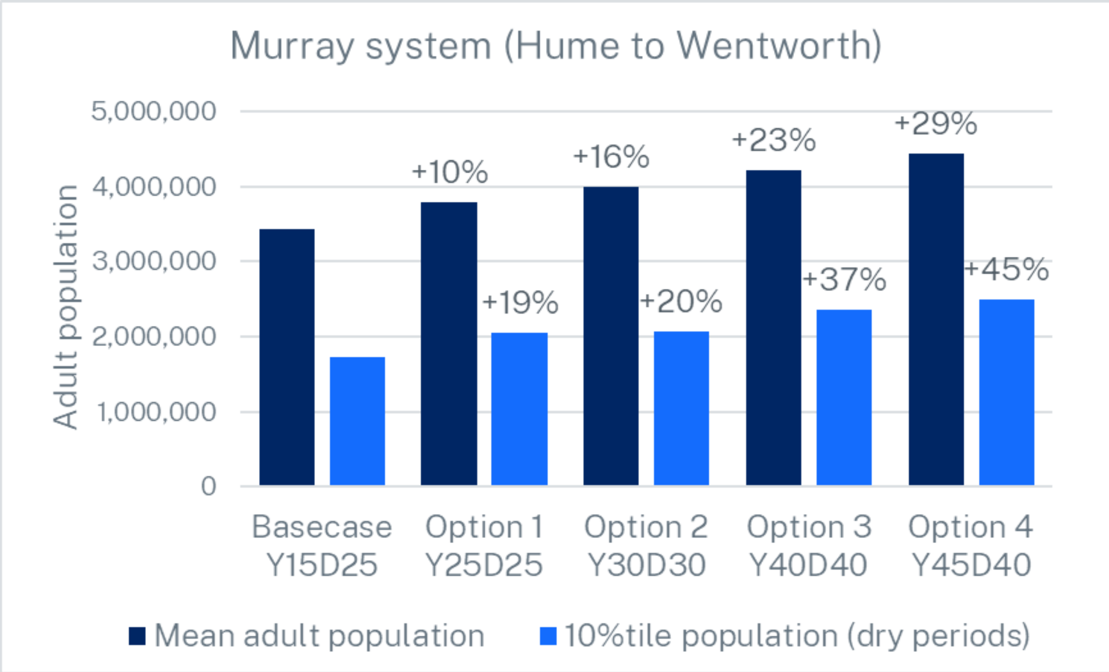


Figure 17: Long-term average and 10th percentile adult golden perch population size under the base case and relaxed constraint flow limit option scenarios for the Murray system (Hume to Wentworth), including the Edward/Kolety River

Labels above columns represent the percentage increase in area relative to the base case.

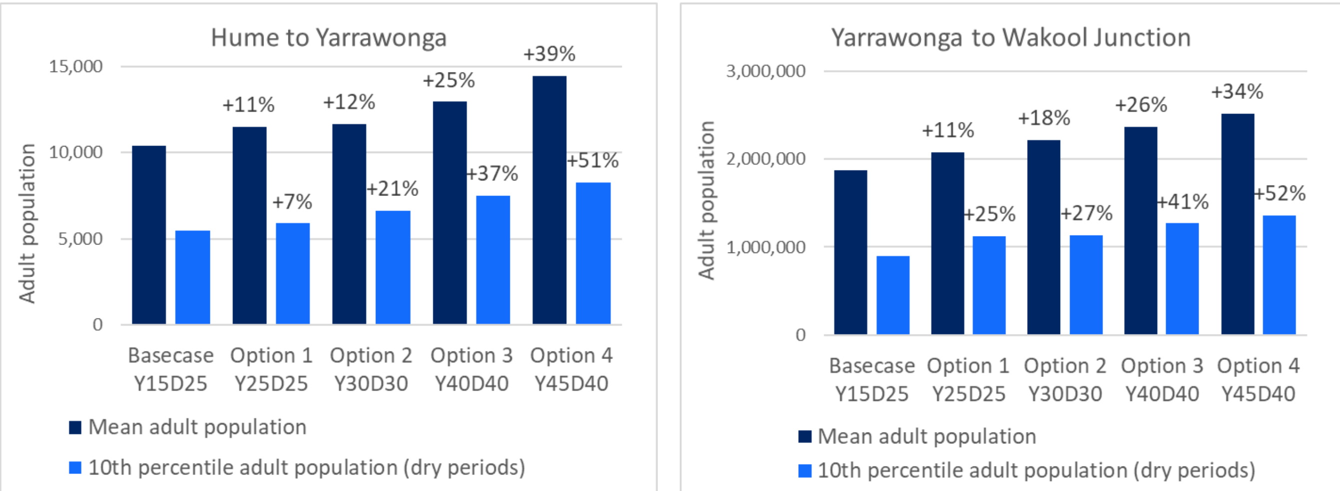


Figure 18: Long-term mean and 10th percentile adult golden perch population size under the base case and relaxed constraint flow limit option scenarios for the Hume to Yarrawonga (left panel); and Yarrawonga to Wakool Junction (right panel) project areas

Labels above columns represent the percentage increase in area relative to the base case.

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 all modelled reaches of the Murray and Edward/Kolety rivers.

While improvements in abundance were expected in the Murray and Edward/Kolety rivers under higher flow limits, the results likely reflect that Murray cod spawning and recruitment is less dependent on flow than for golden perch. Although not investigated through fish population modelling for the program, relaxed flow limits may enhance flow conditions (deep and fast-flowing habitat) for Murray cod in smaller anabranches and creek systems such as those in Barmah–Millewa Forest and the Edward/Kolety–Wakool system.

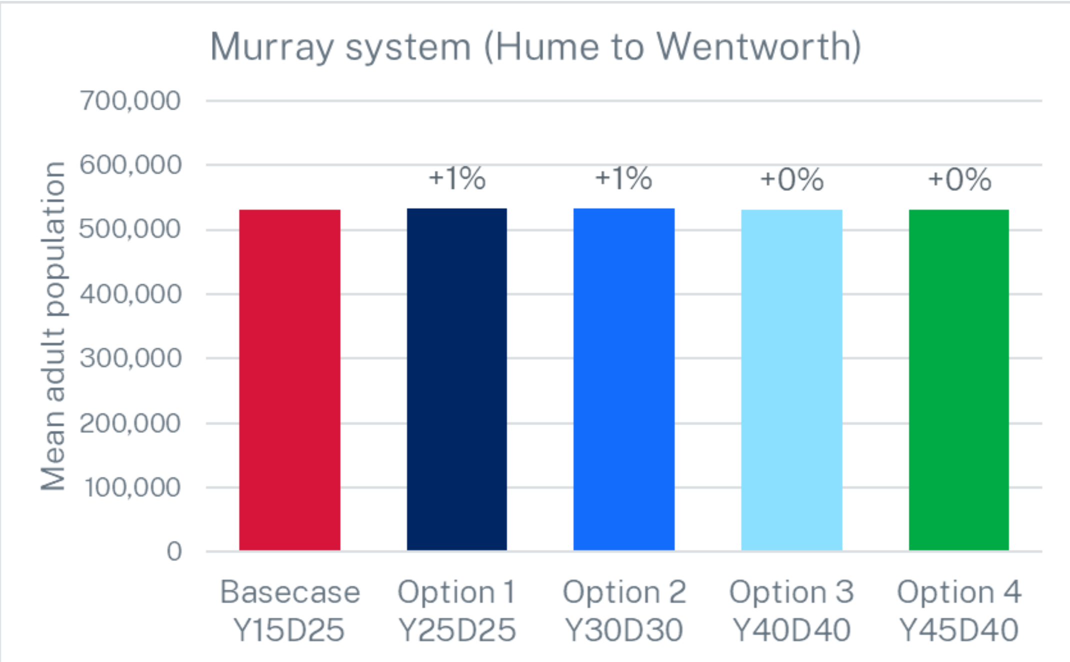
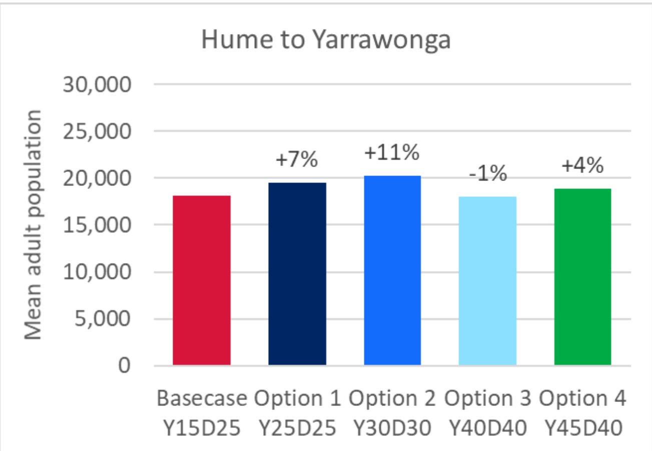


Figure 19: Long-term average Murray cod populations for the Murray system (Hume to Wentworth)



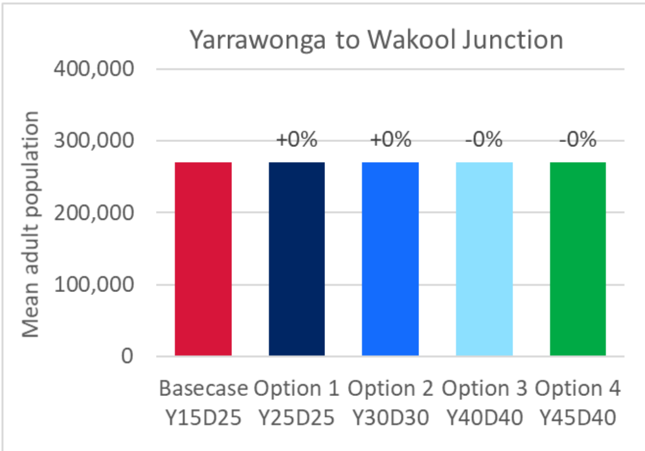


Figure 20: Long-term average Murray cod populations for the Hume to Yarrawonga and Yarrawonga to Wakool Junction areas

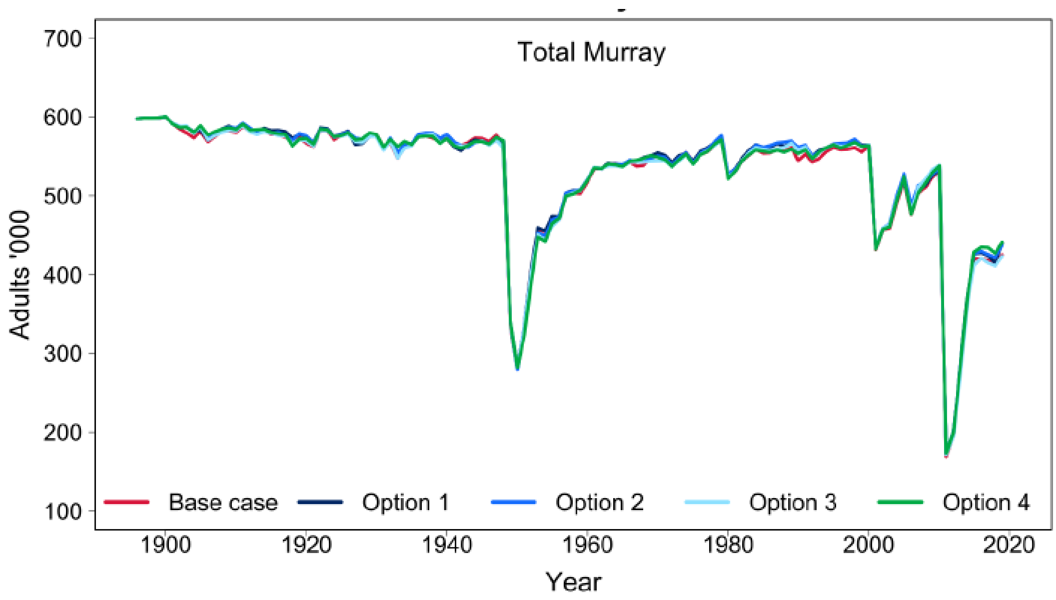


Figure 21: Modelled 124-year time series of the mean Murray cod populations in the Murray River (Hume to Wentworth)

Expected benefits for other native fish species

Raised flow limits in the Murray River are expected to provide benefits for other native fish species that have not been modelled as part of the program. These include: generalists; floodplain specialists that require regular wetland connection to complete their life-cycle; silver perch, which 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; and diadromous species that migrate between the sea and Murray River to complete their life-cycle.

Examples of how raised flow limits might benefit these species and functional groups:

- **Floodplain specialists** like the critically endangered 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). Current flow limits mean only limited areas of wetland habitat can be connected at the required frequency to sustain populations of floodplain specialists. Raised flow limits would double the area of wetland habitat that can be supported with water for the environment (Figure 8). 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.
- **Diadromous species** such as the short-headed lamprey found in the Murray River, undertake lengthy migrations from the sea to freshwater as juveniles and adults to spawn as part of their life-cycle (DPIE 2020a). Fish in this functional group rely on flow to provide cues for movement and hydrological connectivity (Ellis et al. 2022). Raised flow limits in the Murray River would provide opportunities to deliver large flow pulses along the entire length of the river, which would provide more frequent migration cues for short-headed lamprey and other diadromous species. This is expected to provide potential for range expansion and increased prevalence of these species in the mid and lower Murray River. Enhanced productivity

associated with flow may also enhance individual condition prior to spawning (Ellis et al. 2022; DPIE 2020a).

3.2.3 Risks of not proceeding with the program

Populations of both the iconic and protected Murray cod and the flow event responder golden perch species are declining in the Murray River system. At present, populations are maintained by restocking by Department of Primary Industries – Fisheries agencies. This is a suboptimal 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. Recovery of native fish populations would be slower following these disturbance events.

3.3 Waterbirds

An increase in waterbird density and number of species is expected to be achieved in the long term in Barmah–Millewa Forest with a 13 per cent increase in waterbird density (birds/ha) and 5 per cent increase in the number of waterbird species predicted for median years. It is expected that the program would provide most benefit to waterbird populations during drier years (the 25th percentile), by inundating the forest, providing waterbird habitat when it would otherwise remain dry. Compared to the base case scenario, predicted waterbird density increased by up to 80 per cent and predicted species richness increased by 25 per cent for these drier years in the relaxed constraint scenarios. The probability of colonial waterbird breeding in Barmah–Millewa Forest is also expected to increase by up to 11 per cent (median) and 17 per cent (drier 25th percentile) under relaxed flow scenarios in the program.

Total waterbird abundance increased across the long term for Gunbower–Koondrook–Perricoota Forest with a 48 per cent increase predicted for median years. An increase was seen in drier years (25th percentile) with a 34 per cent increase from the base case scenario. Although a small increase in number of waterbird species was only predicted in the higher flow scenarios the increase in abundance predicted indicates that the relaxation of constraints is likely to provide benefits to waterbirds due to larger areas of inundated habitat than currently observed in these forests.

Waterbirds are reliant on floodplain wetlands for breeding and foraging habitat. Regulation has impacted their habitat and waterbird populations in 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 Murray environmental benefit analysis for waterbirds in the program investigated the benefits that might occur from relaxed constraints and specifically focused on outcomes in Barmah–Millewa Forest and Gunbower–Koondrook–Perricoota Forest. These are nationally significant wetland areas and form part of the Central Murray Forests Ramsar site in NSW, and the Barmah Forest and Gunbower Forest Ramsar sites in Victoria. They are also nationally recognised as icon sites in the TLM program.

A relaxation in flow constraints would potentially allow more areas of these two forests to be inundated more regularly and provide habitat for up to 61 and 40 species of waterbirds, respectively (Bino et al. 2022). An increase in flow volumes that will be able to be achieved under the program will potentially allow flow thresholds required for small-scale colonial waterbird breeding in Barmah–Millewa Forest and Gunbower–Koondrook–Perricoota Forest to also be met, increasing opportunities for breeding of colonial and non-colonial species.

3.3.1 Methods

The waterbird environmental benefits assessment used observed data and modelled relationships between key predictor flow variables and waterbird responses (number of species, waterbird abundance), the probability of colonial waterbird breeding activity and the number of breeding colonial waterbird species.

The observed data consisted of aerial and ground waterbird survey data, and historical inundation mapping from Barmah–Millewa Forest and Gunbower–Koondrook–Perricoota Forest, and river flow data from the nearest river gauges. Ground survey data was used to develop predictions of waterbird species richness and waterbird abundance (represented as waterbird density) in Barmah–Millewa Forest. Aerial survey data was used to develop predictions of waterbird species richness and total waterbird abundance for Gunbower–Koondrook–Perricoota Forest. A combination of all records (including aerial and ground survey data) was used to compile presence/absence data for colonial waterbird breeding in Barmah–Millewa Forest.

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 baseline (or current conditions) and without development scenarios, to determine the relative benefits of the four relaxed constraint flow scenarios.

3.3.2 Key outcomes

Barmah–Millewa Forest

- The area inundated in the three months (90 days) prior to the spring surveys was a key predictor for observed waterbird abundance and species richness in Barmah–Millewa Forest.
- Based on this predictor of waterbird responses at this key site there was some relative increase in the median waterbird density from 4.33 waterbird/ha for the base case scenario to 4.89 waterbirds/ha under the highest flow limit option, which is a +13 per cent change. There was no increase for the lowest two flow scenarios (Figure 22). Increase in inundation is expected to provide more habitat availability for waterbirds that are reliant on floodplain habitat for feeding and breeding.
- An increase in the 25th percentile waterbird density is predicted for Barmah–Millewa Forest under the relaxed constraint flow scenarios compared to the base case. This percentile would represent drier scenarios and provide a strong indication of when the program is having

greatest benefit for waterbirds, when large natural flows are not available within the system. An increase in waterbird density (25th percentile) was seen across all constraint relaxed flow scenarios with an increase in percent change from +29 per cent under Y25D25 (Option 1) to +80 per cent (Y40Y45) (Figure 22).

- Similarly, an increase was seen in the median number of waterbird species and 25th percentiles for each flow scenario. The median number of species only increased for the upper two flow scenarios (Y40D40 and Y45D40) with percent increases of +4 per cent and +5 per cent relative to the base case, respectively. For drier periods (represented by results for the 25th percentile), the number of species increases with increasing flow limit, ranging from +10 per cent increase relative to the base case for Y25D25 to +25 per cent for Y45D40 (Figure 23).
- These results indicate that the program would have a positive influence on waterbird outcomes in Barmah–Millewa Forest, especially in drier years when waterbird breeding and foraging habitat would otherwise be limited. The benefits increase with increasing flow limit, with the greatest benefits predicted for the Y45D40 flow scenario.

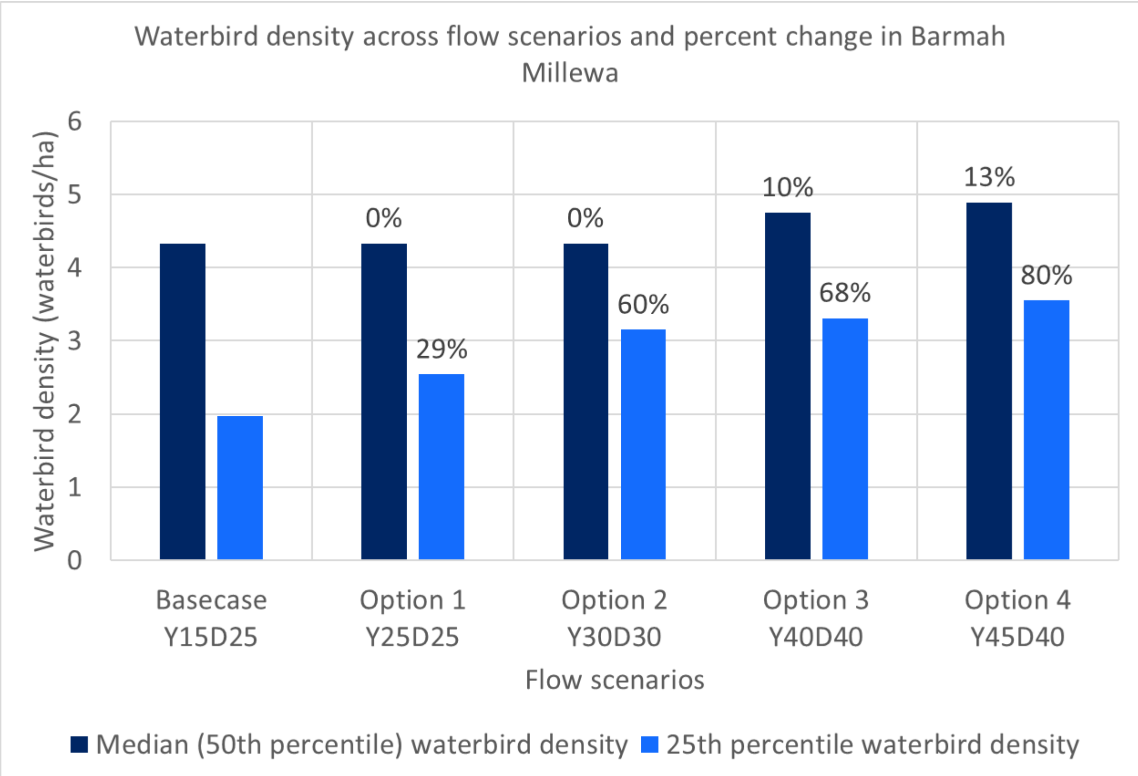


Figure 22: Predicted waterbird density (waterbirds/ha) and percent change from the base case for the median and 25th percentile for each flow scenario based on maximum inundated area in the three months prior to spring surveys

Note that modelled responses are based on ground survey data and inundated area for Barmah–Millewa Forest.

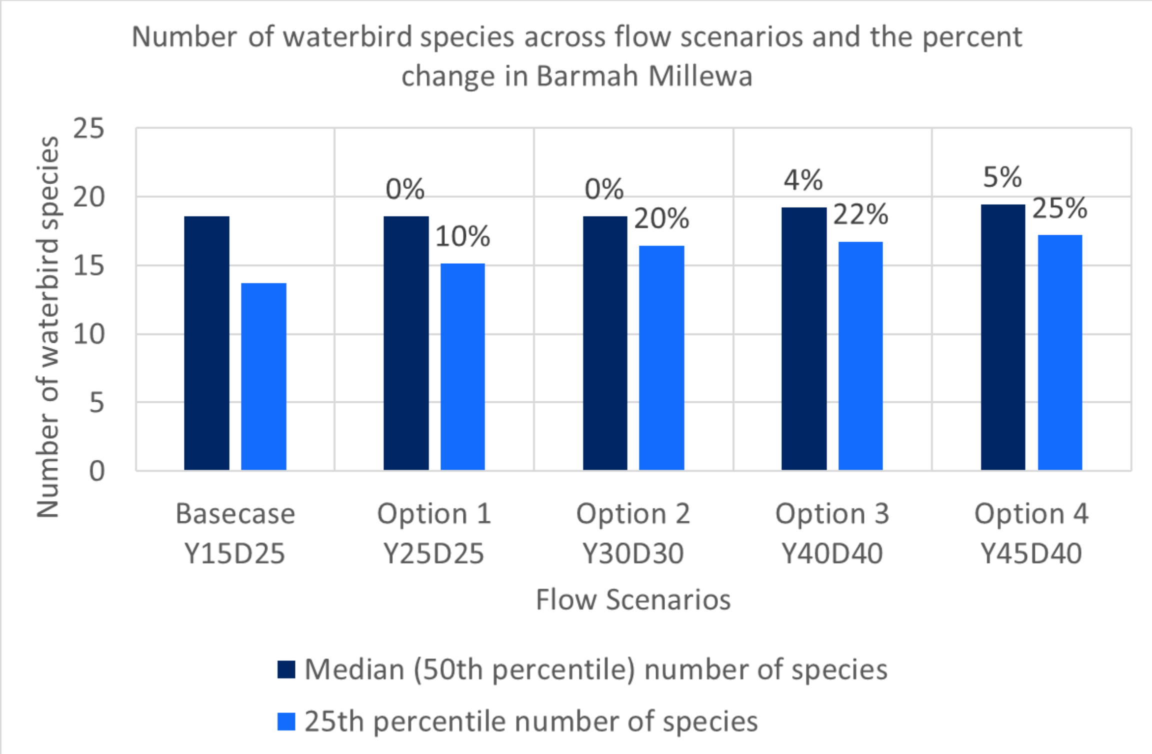


Figure 23: Predicted number of waterbird species and percent change from the base case for the median and 25th percentile for each flow scenario based on maximum inundated area recorded in the three months prior to spring surveys

Note that modelled responses are based on ground survey data and inundated area for the Barmah–Millewa Forest.

Gunbower–Koondrook–Perricoota Forest

- Cumulative river flows 180 days prior to spring surveys was a key predictor of number of observed waterbird species whilst inundated area in October each year was the key predictor for total waterbird abundance observed in Gunbower–Koondrook–Perricoota Forest. The observed relationships where not as strong as for Barmah–Millewa Forest, and it was not possible to fully incorporate inundated area in the modelling, due to limited availability of cloud-free satellite imagery for the months prior to each annual survey.
- Modelled median waterbird abundance increased from 201 waterbirds in total under the base case to 297 waterbirds in total under the highest relaxed constraints flow scenario (Y45D40), which had the best expected benefit. The percent improvement in total waterbird abundance over the base case ranged from +8 per cent for the lowest flow scenario (Y25D25) to +48 per cent for the highest flow scenario (Y45D40) (Figure 24). Increase in inundation of the forest is expected to provide more habitat availability for waterbirds who are reliant on floodplain habitat for feeding and breeding.
- The program will likely have a positive influence on waterbird abundance in drier years by providing critical habitat for waterbirds. The predicted waterbird abundance in Gunbower–Koondrook–Perricoota Forest increased for the drier years (represented by the 25th percentile results) across all flow scenarios, increasing from 64 waterbirds in total under the base case to 78–86 waterbirds in total for the relaxed constraints flow scenarios. This is an increase of 22–34 per cent over the base case (Figure 25).

- The predicted median number of species (species richness) only increased in the highest two flow scenarios (Y40D40 and Y45D40) relative to the base case, and only marginally (3–4 per cent increase). Under the 25th percentile the number of species only improved under the highest flow scenario (Y45D40) (+2 per cent) (Figure 24).
- The relatively small change in number of species predicted by the models reflects the current poor condition of the forest and the low number of species recorded in the observed data used to develop the models. As habitat quality is expected to increase at this site under relaxed constraints, a larger increase in species richness than currently predicted by the models might occur. A larger predicted response might also be expected if inundated area could be fully incorporated as a predictor variable in the modelling.

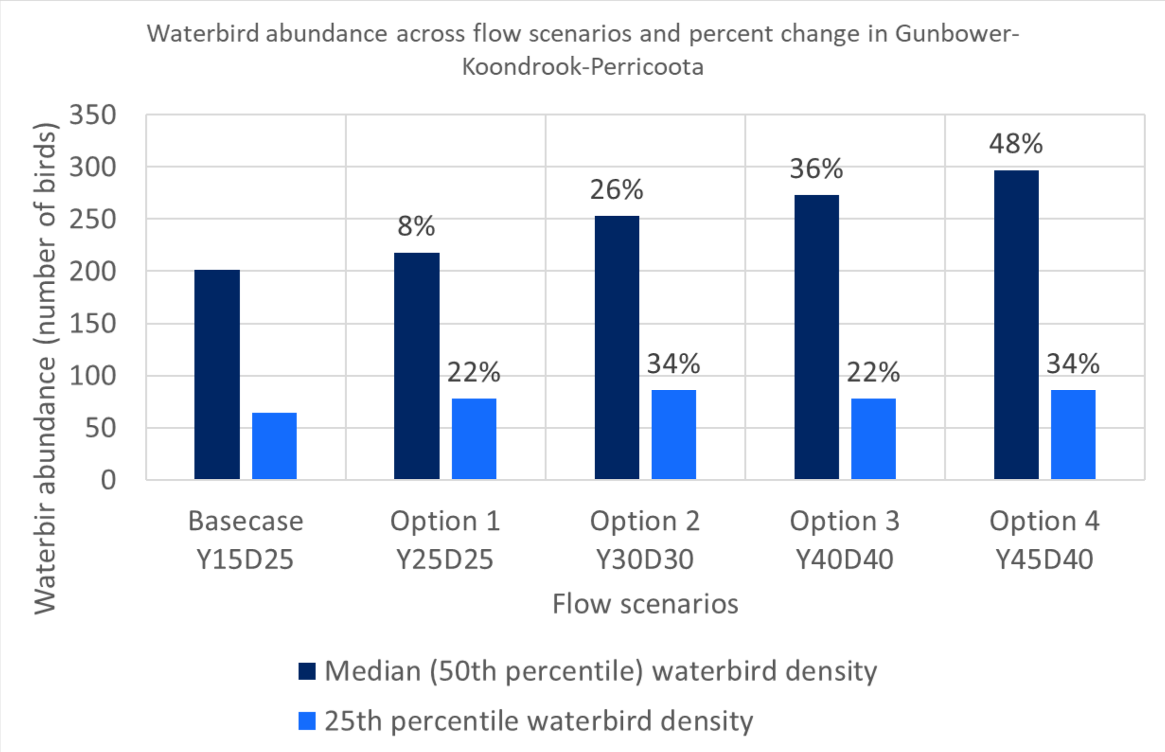


Figure 24: Predicted waterbird abundance (number of species) and percent change from the base case for the median and 25th percentile for each flow scenario based on inundated area in October each year at the time of the spring surveys

Note modelled responses are based on aerial survey data for the entire Gunbower–Koondrook–Perricoota Forest.

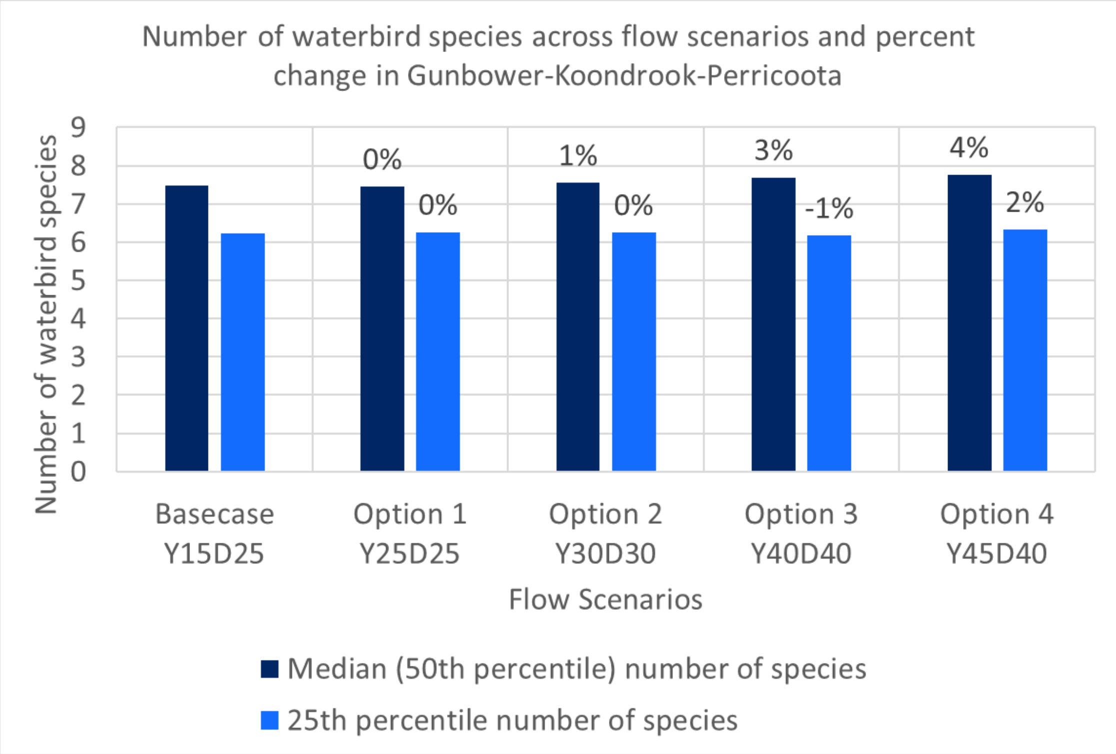


Figure 25: Predicted waterbird number of species and percent change from the base case for the median and 25th percentile for each flow scenario based on cumulative river flows 180 days prior to spring surveys

Note modelled responses are based on aerial survey data for the entire Gunbower–Koondrook–Perricoota Forest.

Colonial waterbird breeding in Barmah–Millewa

The opportunities for colonial waterbird breeding are expected to increase as a result of the program from both increased frequency and duration of inundation of Barmah–Millewa Forest.

- Observed colonial waterbird breeding was most strongly predicted by cumulative river flows 180 days prior to the surveys and this predictor was used to determine changes in the probability of breeding for each flow scenario at Barmah–Millewa Forest.
- Colonial waterbird breeding was not investigated at Gunbower–Koondrook–Perricoota Forest due to too few records of breeding over the last 20 years. However, it is expected that the increased inundation into the forest as a result of the program will improve habitat condition across the forest including historical colony locations, providing future breeding opportunities.
- An increase in the median probability of breeding was seen for all scenarios from 82 per cent under the base case to 91 per cent under the highest flow scenario (Y45D40). The percent change from base case reflected this with a 6–11 per cent increase in probability of breeding from the lowest to highest relaxed constraint scenarios (Figure 26).
- There was a higher probability of colonial waterbird breeding in a higher number of years under relaxed constraints, particularly for the highest flow scenario (Y45D40; Figure 27).
- An increase in the probability of breeding for colonial waterbird species was also seen for all flow scenarios when looking at the 25th percentile, which represents drier years when less breeding may be expected. Under the 25th percentile the probability of breeding increases from +63 per cent under the base case to between +70 and +74 per cent under the relaxed

constraint flow scenarios. This represents a +9 to +17 per cent improvement over the base case (Figure 26).

- This represents increased opportunities for small-scale colonial waterbird breeding in Barmah–Millewa Forest in drier times when habitat availability is limited in the surrounding region. Although population changes were not investigated in the waterbird benefits assessment, increased colonial waterbird breeding opportunities, even when small-scale, are expected to have a positive impact on broader waterbird population numbers over time (Brandis et al. 2021).

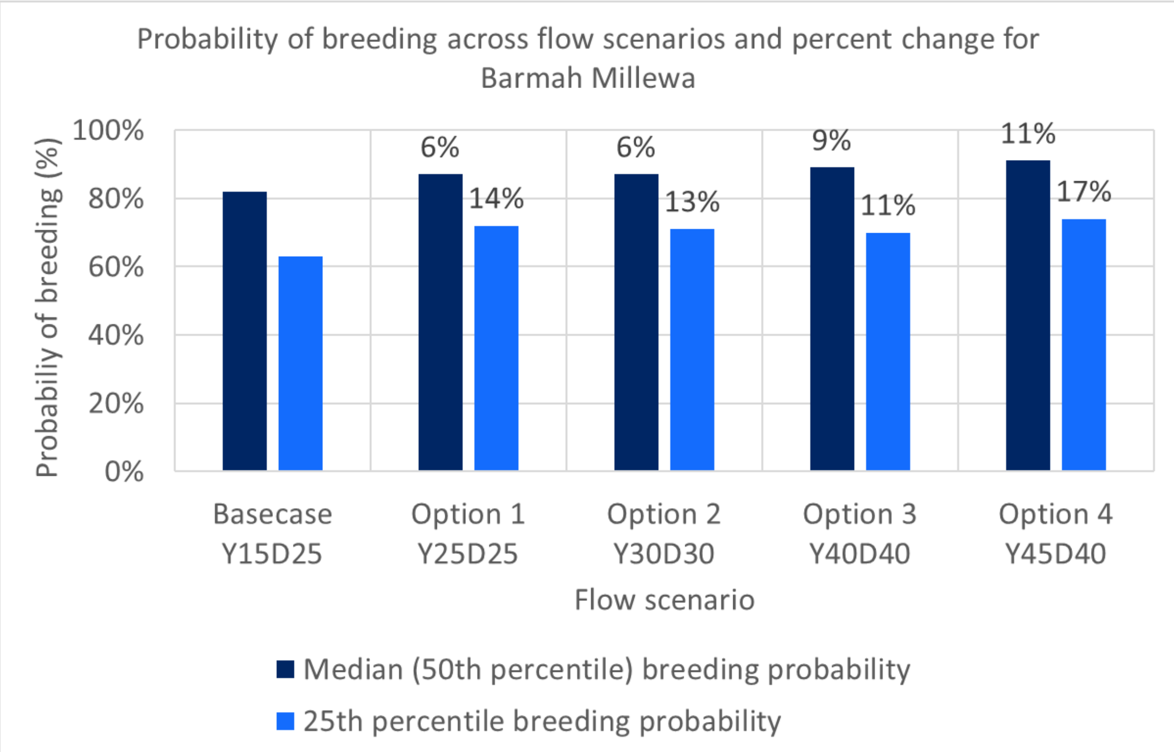


Figure 26: Predicted probability of colonial waterbird breeding and percent change from the base case for the 50th (median) and 25th percentiles for each flow scenario based on 180 days cumulative river flows prior to surveys (1896–2019) in Barmah–Millewa Forest

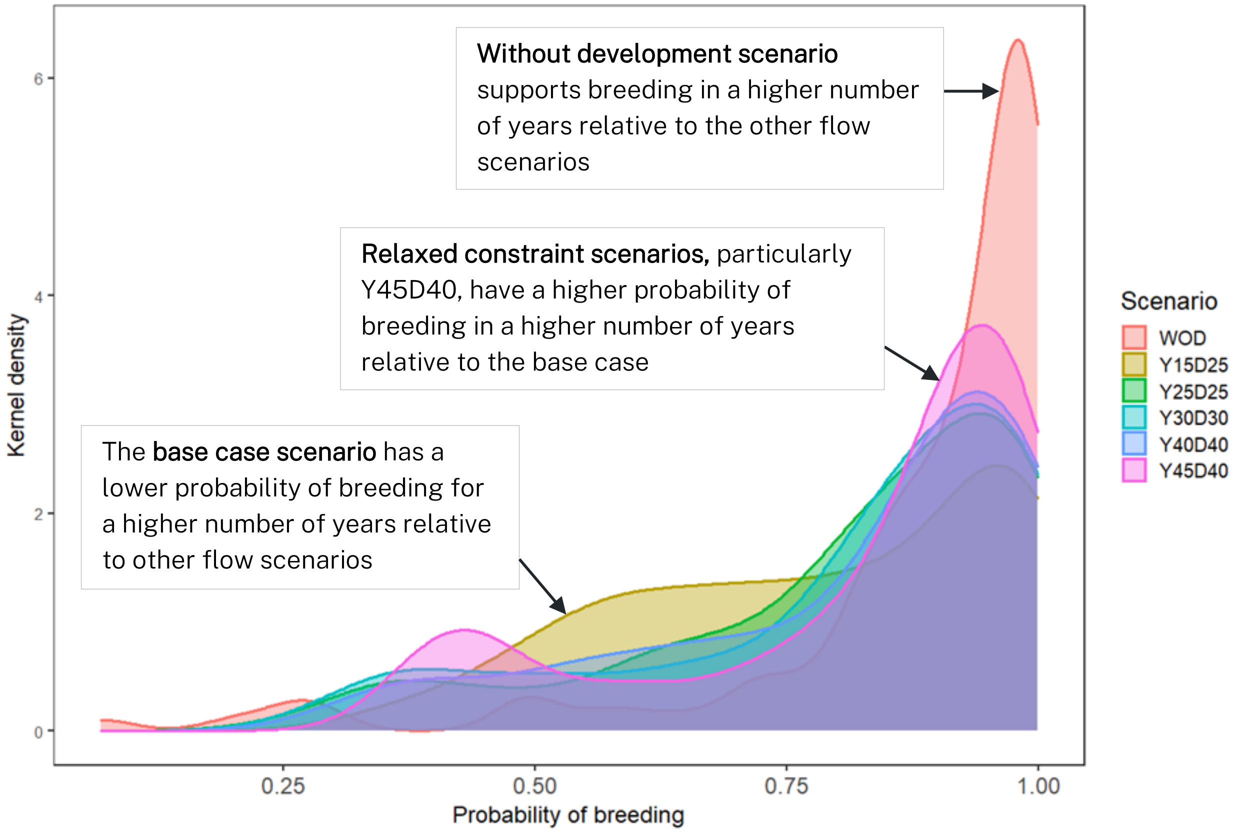


Figure 27: Modelled probability of colonial waterbird breeding in Barmah–Millewa Forest across the modelled time series (from Bino et al. 2022) based on the best predictor variable, which was cumulative river flows 180 days prior to the start of the breeding season in spring

Kernel density is the count of frequency for each probability.

3.3.3 Risks of not proceeding with the 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:

- the flows will not be large enough to reach key waterbird sites 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)
- if constraints are not relaxed there would be limited ability for the key sites of Barmah–Millewa and Gunbower–Koondrook–Perricoota forests to contribute to restoring waterbird populations in the Murray–Darling Basin, a key objective of the Basin Plan.

3.4 Native vegetation

Raised flow limits will substantially benefit native wetland and floodplain vegetation with an increase of up to 15 per cent in the area of healthy (good or moderate condition) river red gum forest and woodland. Benefits are greater during dry periods with an increase of up to 50 per cent in healthy river red gum forest and woodland. Average improvement is highest in the Hume to Yarrawonga reach; however, Yarrawonga to Wakool Junction will benefit to a greater degree during dry periods. Moderate increases of healthy black box woodland (up to +5 per cent), lignum shrubland (up to +11 per cent), and perennial wetland grass, sedge, and rush species (up to +10 per cent) are also possible.

Floodplain vegetation communities within the Murray and Murrumbidgee catchments have been impacted by changes to the river's hydrological regime; 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 a relative 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 catchment 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. Generally riparian fringes are dominated by river red gum forests, with higher elevated areas supporting black box woodlands, and lower-lying, regularly inundated areas featuring shrub or herblands (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. For example, a 2.9 times larger area of river red gum forest can be inundated under the Y45D40 scenario limit relative to the current operational limit (Y15D25; Figure 9).

3.4.1 Methods

A quantitative assessment of potential benefits to floodplain vegetation condition under constraints-relaxed flow regimes (flow scenarios in Table 2) was undertaken by researchers at La Trobe University using the newly developed Floodplain Vegetation Condition Model (FVCM). The FVCM is a state-and-transition simulation model that uses spatial data of vegetation type and condition, and flow data to provide a dynamic time series of vegetation condition in response to different inundation sequences (defined in terms of frequency, timing and duration; SPELLS analysis). The response of vegetation types to inundation was parameterised via expert elicitation and current literature. These results are temporally and spatially explicit; meaning the condition of a specific vegetation type at a location on the floodplain can, each year, be simulated based on the vegetation type's current condition and response to inundation. For the Murray catchment the FVCM used the Source-modelled flow data (Section 2.1), the RiM-FIM and the EW-FIM, and a combined NSW and VIC vegetation spatial dataset built using the *Plant Community Type* (NSW OEH 2016) and *Ecological Vegetation Class* (DELWP 2018) datasets respectively, as key inputs.

The FVCM model used the Source-modelled flow data combined with inundation models RiM-FIM and EW-FIM to generate a time series of inundation durations across the Murray. This inundation time series was analysed to identify inundation spells that influenced vegetation response in an annual step-wise iteration to project change in vegetation health over the modelled time series. Each discrete unit of the floodplain (pixels of 125 m resolution = 1.56 ha area) denoting a vegetation type was tracked over time, with past inundation dictating the condition of vegetation at any given point in the time series. Inundation was predicted using a SPELLS analysis to take the flow-at-gauge from the Source Murray Model and translate that into area inundated with the RiM-FIM and EW-FIM. All vegetation was started in the highest possible condition ('good' condition), so changes in vegetation health are a direct result of the inundation regime under each scenario of flow constraint. The different flow scenarios result in differing inundation spells across the floodplain, which leads to changes in the simulated vegetation health.

3.4.2 Key outcomes

The vegetation condition modelling predicts that relaxing flow constraints will provide net benefits to the condition of native vegetation communities, with the benefits increasing substantially with the higher flow limit options (Table 9).

- River red gum forests and woodlands showed the largest positive response to increased flow limits with an increase of up to 15 per cent (~14,000 ha) in the average area of river red gum in good or moderate condition across the Murray catchment (Hume to Wentworth).
- Black box woodland showed the smallest net benefits of raised flow limits largely because this species resides at elevations beyond the extents that can be influenced by the flow limit options under investigation (McPhan et al. 2022).

Table 9: Average area (and percentage change from the base case) of vegetation types in 'good' or 'moderate' condition across the entire modelled time series (Hume to Wentworth)

Flow limit option	Black box woodland (ha)	Lignum shrubland (ha)	Perennial wetland [1] (ha)	River red gum forest and woodland (ha)
Base case (Y15D25)	18,157	514	1,027	91,714
Option 1 (Y25D25)	18,843 (+4%)	550 (+7%)	1,040 (+1%)	94,032 (+3%)
Option 2 (Y30D30)	18,369 (+1%)	518 (+1%)	1,056 (+3%)	95,004 (+4%)
Option 3 (Y40D40)	17,849 (-2%)	524 (+2%)	1,126 (+10%)	97,642 (+6%)
Option 4 (Y45D40)	19,114 (+5%)	572 (+11%)	1,098 (+7%)	105,554 (+15%)

[1] The perennial wetland vegetation category includes grass, sedge and rush land vegetation types.

The model results also show that benefits to vegetation under the different flow limit options vary by location within the catchment (Figure 28), with relative benefits for river red gum larger than +15 per cent predicted for some sub-reaches within the system.

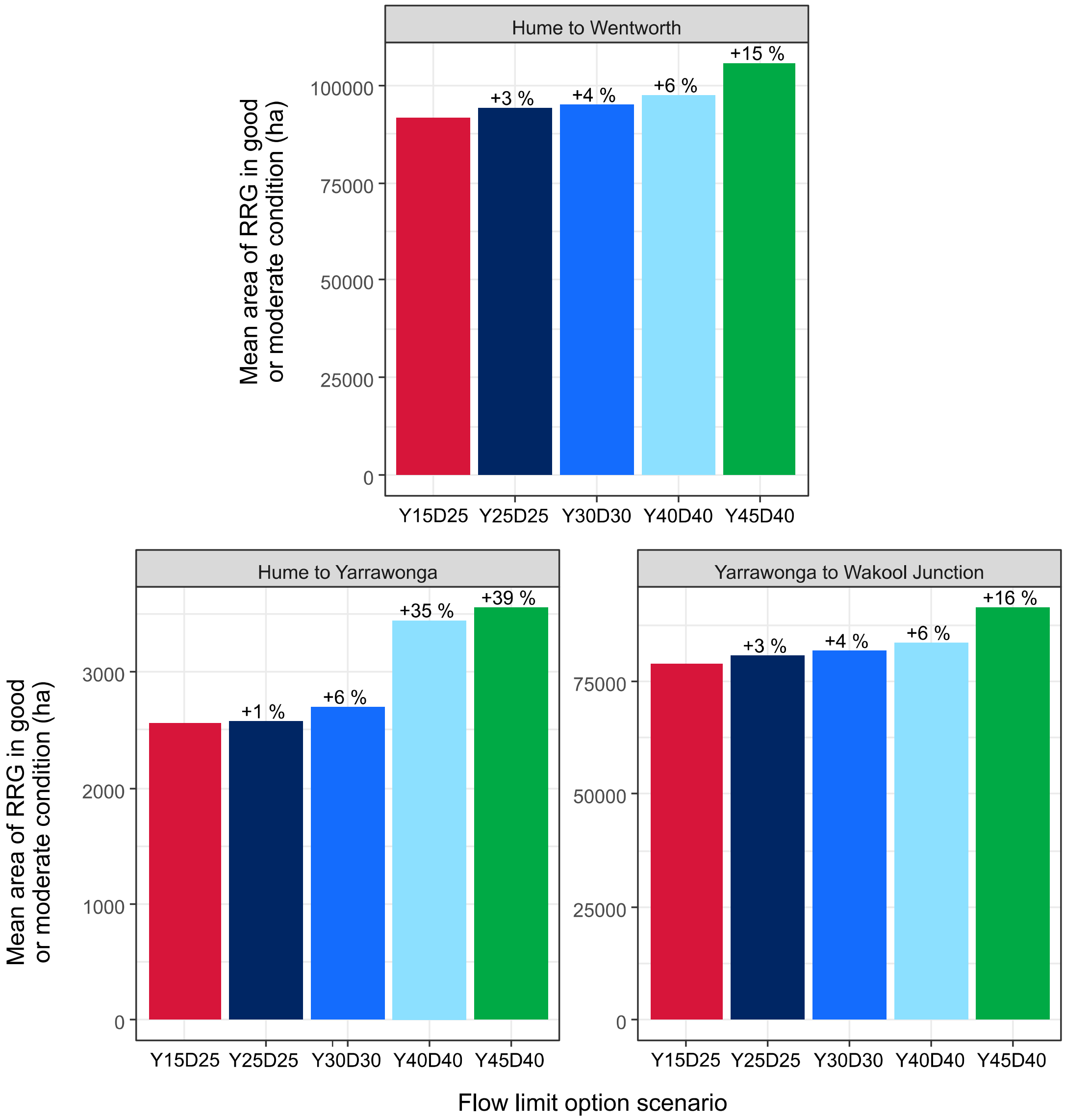


Figure 28: Mean area of river red gum in good or medium condition in each flow limit option scenario, for the greater Hume to Wentworth reach, and Hume to Yarrawonga and Yarrawonga to Wakool Junction program areas

Here we can see that the level of vegetation condition improvement by raised flow limits varies between the project areas.

Generally, upstream areas experienced greater net benefits to vegetation condition from raised flow limits, with the largest improvements (an increase of up to 39 per cent) in modelled mean area of good or moderate condition river red gum evident in the Hume to Yarrawonga project area (Figure 28). Over the long term, Y45D40 provides a 15 per cent increase in the area of river red gum in good or moderate condition between Hume and Wentworth, a 39 per cent improvement in Hume to Yarrawonga, and a 16 per cent improvement in Yarrawonga to Wakool Junction areas. This may be caused by flow peaks of environmental deliveries declining as they travel downstream due to natural flow attenuation; and potential variation in the distribution of the vegetation community on the floodplain at a catchment scale.

Also, areas containing a larger relative proportion of low-lying floodplain (e.g. Barmah–Millewa Forest; Figure 10) experience greater benefits to vegetation condition from raised flow limits than areas with higher elevation floodplains (e.g. Koondrook–Perricoota Forest; Figure 11). As is intuitive, areas with less floodplain 'out-of-reach' from environmental water deliveries will experience greater benefits.

The magnitude of benefit achieved by raised flow limits varies over time (Figure 29).

Only minor differences were evident between flow limit option scenarios during highly wet periods of climate (e.g. the 1990s). When the climate is highly wet, inundation event patterns are dominated by natural unregulated flows rather than environmental water deliveries, leading to less difference in vegetation outcomes between flow limit options. Conversely, during relatively dry periods, environmental water deliveries under higher constraint relaxation options provide an opportunity to break long dry spells for water-dependent vegetation and achieve a reduction in vegetation condition decline (Figure 30). During dry and moderate conditions, environmental deliveries can recreate watering event frequencies more in line with species' requirements.

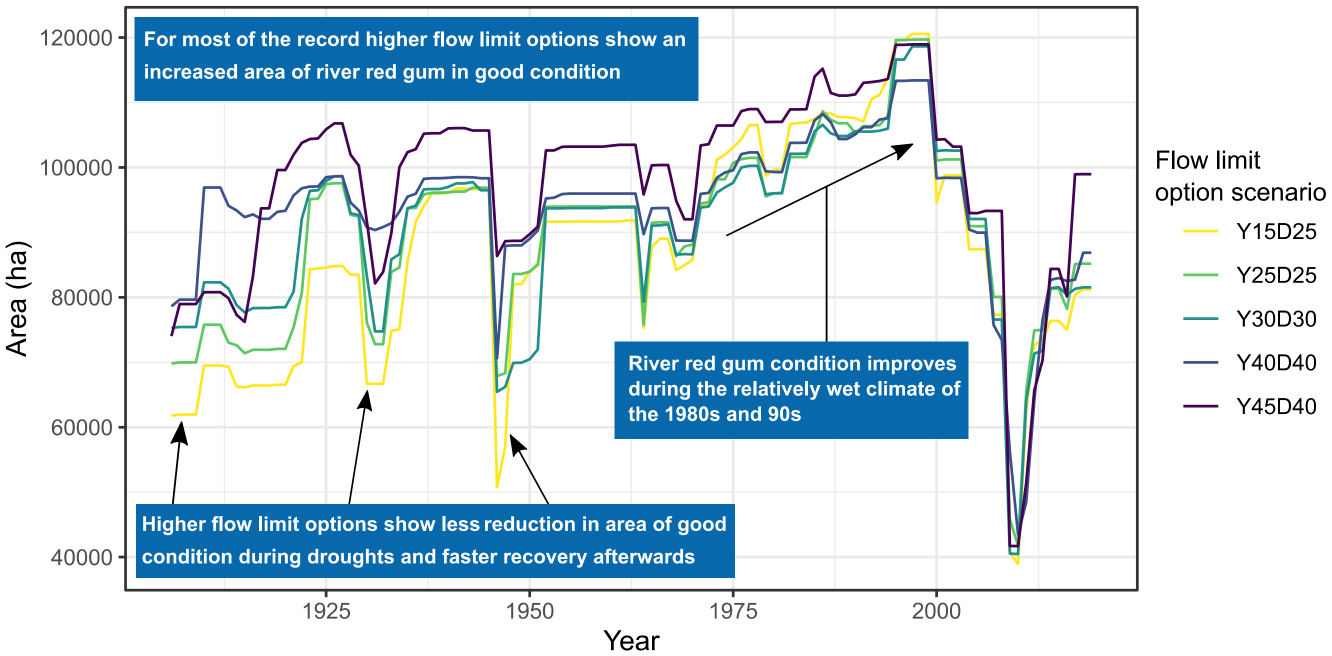


Figure 29: Area of river red gum in 'good' condition over the modelled time period (1905–2019) for the base case and four flow limit option scenarios

The model assumes all river red gum start in good condition at the start of modelling period in 1896, so the figure is truncated to post-1905 to showcase changes following initial, assumption driven, patterns. Total area of river red gum stand is 270,620 ha.

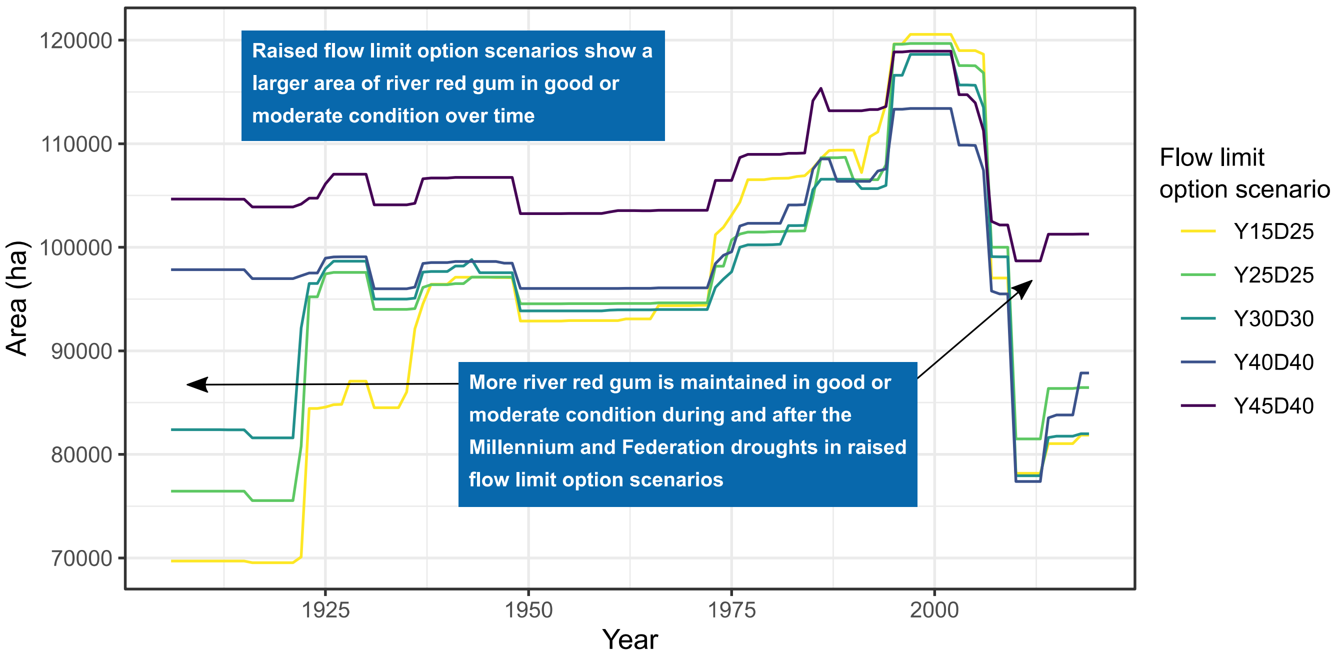


Figure 30: Area of river red gum in 'good' or 'moderate' condition over time (1905–2019) for the base case and four flow limit option scenarios

The model assumes all river red gum start in good condition at the start of the modelling period in 1896, so the figure is truncated to post-1905 to showcase changes following the initial, assumption driven, patterns. Total area of river red gum stand is 270,620 ha.

These time series results, and Figure 31, also suggest that raising flow limits can reduce the negative impact of meteorological drought on vegetation condition. During dry periods Y45D40 provides a 50 per cent increase in the area of river red gum in good or moderate condition between Hume and Wentworth, a 43 per cent improvement in Hume to Yarrawonga, and 61 per cent improvement in Yarrawonga to Wakool. During peak WWII drought conditions (1945–46), for example, the model projected ~ 48,000 ha of river red gum in good condition under current flow limits versus ~84,000 ha under a Y45D40 scenario – a ~75 per cent increase in area persisting in good condition. Declines in 'good' condition river red gum in all flow limit option scenarios during the Millennium Drought highlight that water supply during extreme droughts may limit the potential to prevent declines in native vegetation during these periods. That said, the Y45D40 scenario sustained approximately 20 per cent more area of river red gum in at least 'moderate' condition throughout the Millennium Drought, relative to the base case and all other flow limit option scenarios.

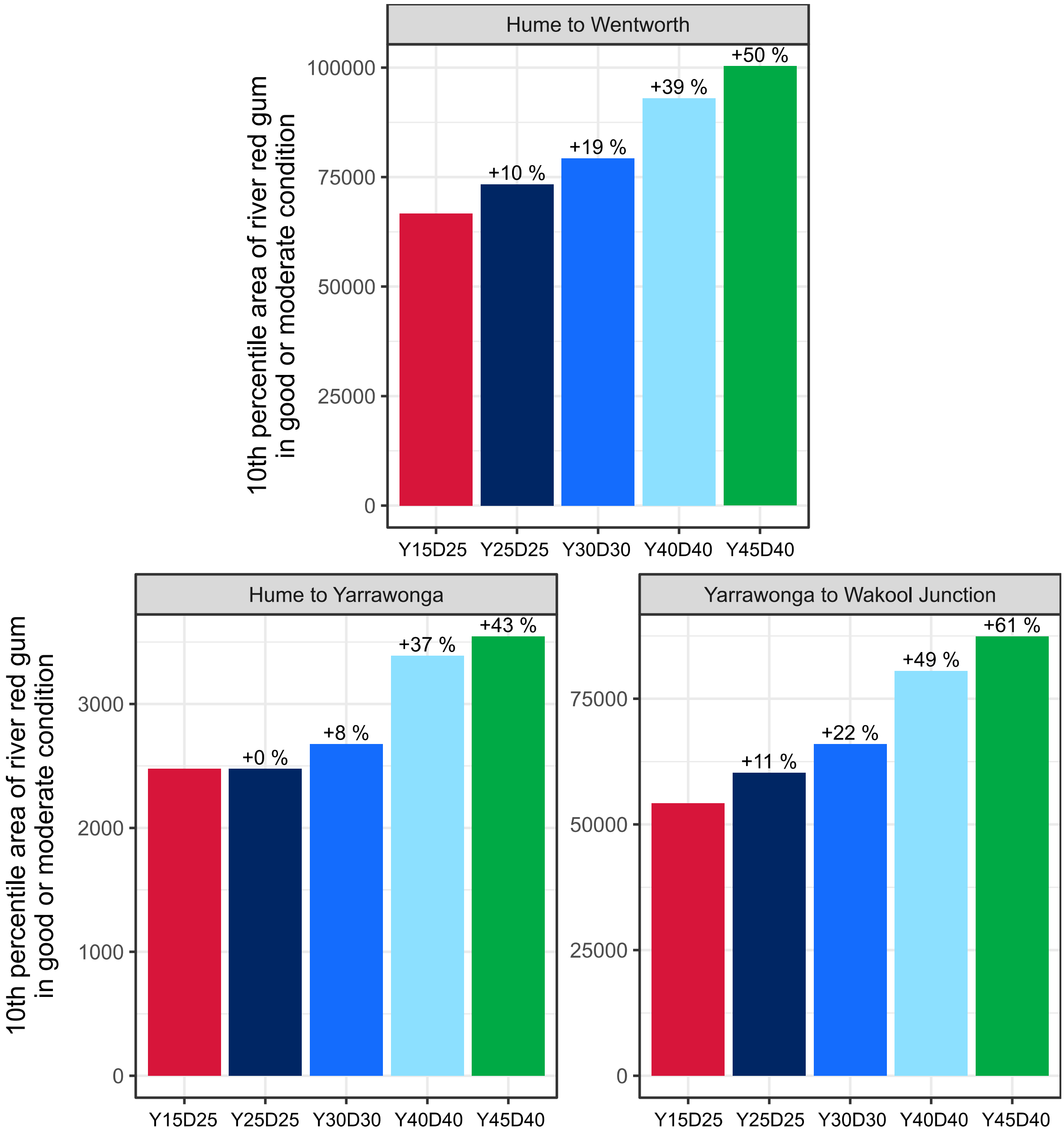


Figure 31: 10th percentile area of river red gum in good or medium condition in each flow limit option scenario, for the greater Hume to Wentworth reach, and Hume to Yarrawonga, and Yarrawonga to Wakool Junction program areas

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 raised flow limits substantially improve vegetation condition during dry climate periods, and more so than during average climates (Figure 28), especially in the Yarrawonga to Wakool Junction area.

While the results show raised flow limits yield net benefits for native vegetation, they also suggest some areas of vegetation may experience negative outcomes from raised flow limits (see McPhan et al. 2022). These areas are typically at higher elevations; that is, areas 'out-of-reach' from environmental water deliveries under the highest flow limit option. This 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 dam spills. This results in smaller unregulated flows and consequently the area inundated during large flows is reduced, thus watering areas 'outside-the-reach' of deliveries at the proposed flow limits less often. Two caveats on this conclusion should be acknowledged:

- Vegetation at higher elevations (e.g. black box) are possibly sustained by water sources in addition to large floods (e.g. soil pore- and groundwater) to a greater degree, while the FVCM model used here exclusively considers the impact of inundation from rivers. As the inundation models do not model water residence time, the FVCM model is conservative with respect to the durations of inundation on the floodplain.
- Spatial patterns of inundation modelled by RiM-FIM and EW-FIM are less accurate at higher elevations due to lack of available satellite data for higher elevations when these inundation models were developed.

As the program proceeds this potential to negatively impact higher elevation riparian zones will be investigated in greater detail.

3.4.3 Risks of not proceeding with the program

There are clear risks of not proceeding with the program with regards to native vegetation condition outcomes. Outside of highly wet climate periods, raising flow limits will achieve substantial net benefits for the large areas of native vegetation accessible by program flows within the Murray 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 75 per cent more vegetation in good to moderate condition would be critical to more efficient recovery post-drought and providing crucial habitat refugia for native fauna. Such benefits will be more pronounced and important in a drier future climate and therefore not proceeding with the program risks losing a potential strategy for mitigating predicted climate change effects.

3.5 Ecosystem production

'Production' or *energetic carrying capacity* modelling predicts that raised flow limits will lead to a consistent increase in the availability of food with median total annual production increasing by up to 12 per cent (relative to the base case) across the project area as a whole for the maximum constraint limit. Benefits are greatest in the Yarrawonga to Wakool reach, with estimates in Hume–Yarrawonga largely driven by persistent inundation in Lake Mulwala. Findings demonstrate the importance of large, unregulated flows as important production events through time. The availability of food is not expected to always influence aquatic communities; rather it will become limiting at key moments in time, particularly during years with lower flows overall.

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 32).

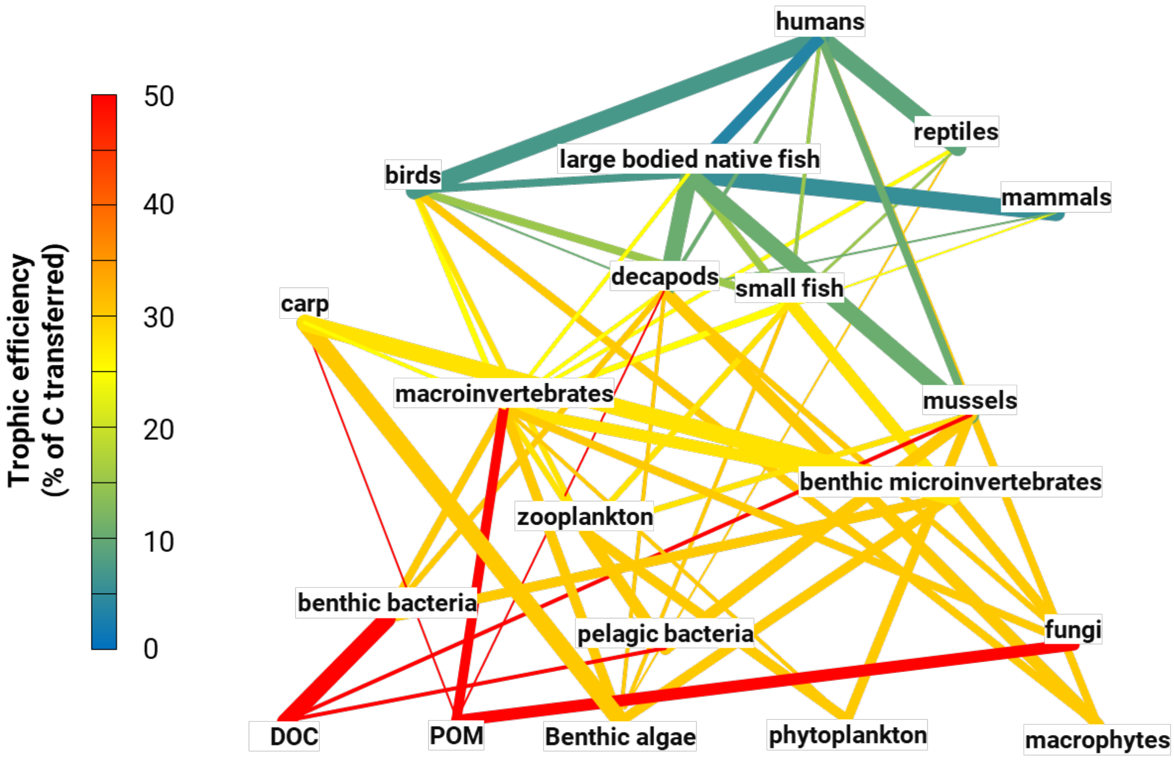


Figure 32: Modelled food web including carp (Siebers et al. 2022)

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. DOC = dissolved organic carbon and POM = particulate organic matter.

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 highly nutritious 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.

3.5.1 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 maximum amount of potential energy produced dependent upon the amount, duration, and type of area that has been inundated. This provides an estimate of the ‘energetic carrying capacity’, a theoretical maximum amount of food available that is one of several factors limiting the number of animals an area can support (hereafter referred to as ‘production’).

For each day in the flow time series, the expected inundation extent was estimated using the RiM-FIM and EW-FIM (Overton et al. 2006; Sims et al. 2014). 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. These 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. Production estimates were calculated for each individual RiM-FIM inundation model zone and added together to yield results for each Murray project area.

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 for each year in the time series.

3.5.2 Key outcomes

Production modelling shows that relaxing constraints will contribute a moderate but consistent increase to the overall amount of energy in the Murray River, with benefits increasing with higher flow limit options (Table 10, Figure 33). Over time, the pattern of total annual production potential is dominated by production during large, unregulated flow events (Figure 34), underscoring the importance of large flows as drivers of enhanced production in river ecosystems. In some years the delivery of higher flows enabled by the relaxation of operational constraints is expected to reduce the magnitude of subsequent unregulated flow events, diminishing potential production benefits. Constraints relaxation does not mean more flows are added to the river, but will allow for more environmental water to be contributed towards spring flow pulses, thereby shifting the timing of ecosystem production with some incremental benefit where increased inundation extent is expected to improve total production.

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

Flow limit option	Median total annual production (% change from base case)	25th percentile total annual production (% change from base case)
Base case (Y15D25)	2,374	2,032
Option 1 (Y25D25)	2,463 (+4%)	2,129 (+5%)
Option 2 (Y30D30)	2,515 (+6%)	2,143 (+5%)
Option 3 (Y40D40)	2,595 (+9%)	2,164 (+6%)

Flow limit option	Median total annual production (% change from base case)	25th percentile total annual production (% change from base case)
Option 4 (Y45D40)	2,652 (+12%)	2,174 (+7%)

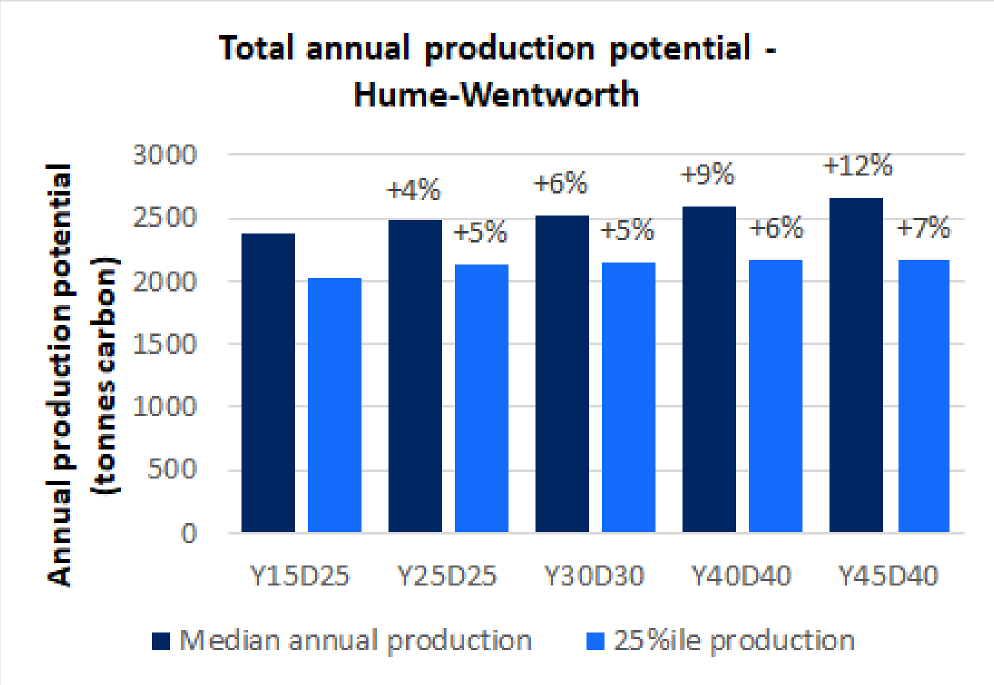


Figure 33: Median total annual production potential for large bodied native fish (tonnes of carbon) for the Hume to Wentworth area

Data are the median and 25th percentile production potential calculated using all water years (n= 124 years).

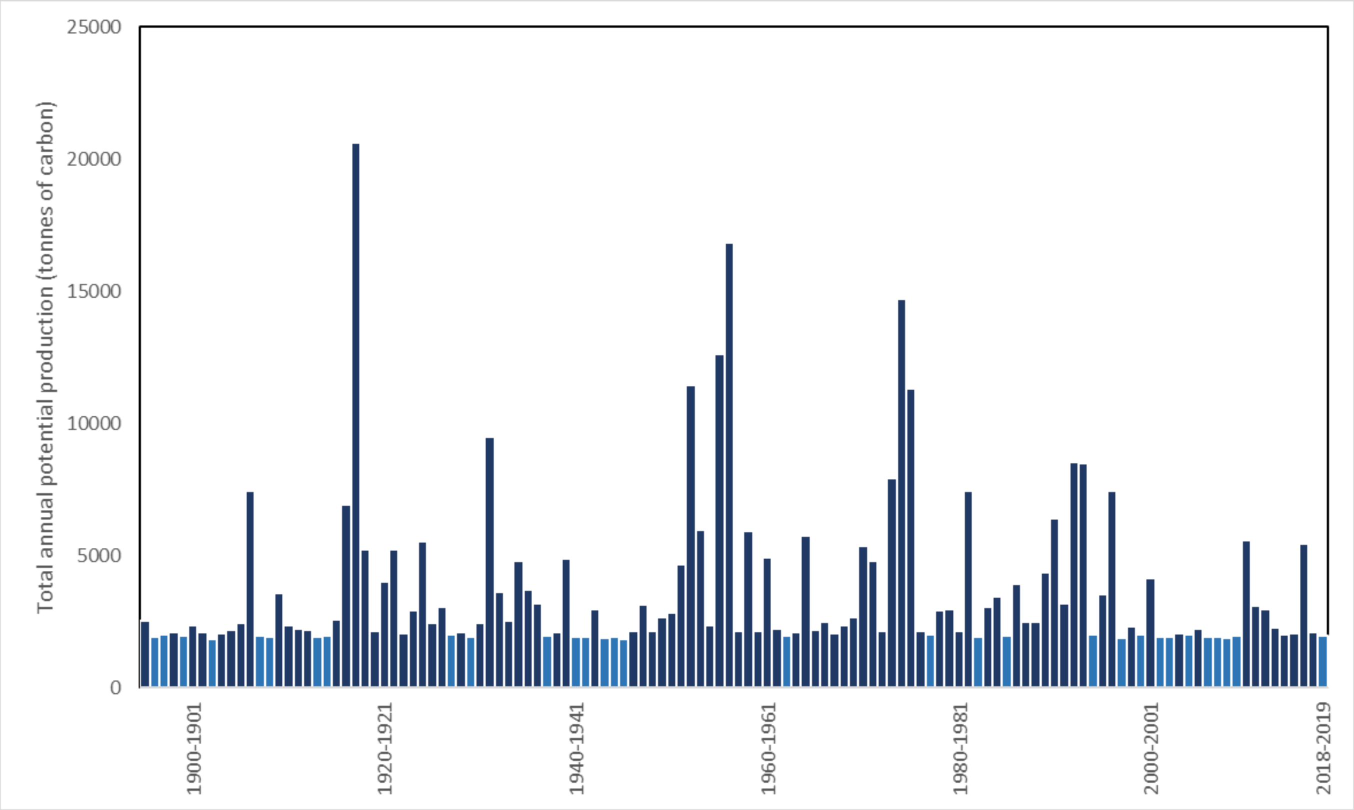


Figure 34: Modelled total annual production for large bodied native fish (tonnes of carbon) for the Hume to Wentworth area

Results are shown for the base case (Y15D25). Light blue lines indicate low production years (i.e. where total annual production potential is less than the 25th percentile).

Most of the expected benefit at the project scale (Figure 35) is attributed to the Yarrawonga–Wakool area, with expected production benefits up to 15 per cent higher than the base case (Table 11). However, there is comparatively little benefit predicted for the Hume–Yarrawonga reach. At least part of this result is due to the influence of Lake Mulwala which, being a large, permanent waterbody, imparts a relatively high, persistent base level of production to the Hume–Yarrawonga reach that is large in proportion to the comparatively small amount of floodplain-derived production in the same reach (Siebers et al. 2022). This baseline does not change among the different flow limit option scenarios and so the model predicts that overbank inundation is less important as a driver of production for the Hume–Yarrawonga reach. Production estimates for the 'without development' flow scenario indicate that the production rates in the Yarrawonga–Wakool project areas should be 50 per cent higher than the base case; however, in the Hume–Yarrawonga reach the without development production estimates are around 7 per cent higher than the base case (Siebers et al. 2022).

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 an improvement of up to 7 per cent upon the base case (Table 10, Table 11); however, this improvement is less than for the overall median.

Table 11: Total annual production potential for large bodied native fish (tonnes of carbon) for the Hume to Yarrawonga and Yarrawonga to Wakool project areas

Data are the median and 25th percentile production potential calculated using all water years (n = 124 years).

Flow limit option	Yarrawonga to Wakool		Hume to Yarrawonga	
	Median total annual production (% change from base case)	25th percentile total annual production (% change from base case)	Median total annual production (% change from base case)	25th percentile total annual production (% change from base case)
Base case (Y15D25)	1,497	1,203	278	272
Option 1 (Y25D25)	1,551 (+4%)	1,282 (+4%)	278 (0%)	273 (0%)
Option 2 (Y30D30)	1,615 (+8%)	1,295 (+8%)	280 (+1%)	274 (+1%)
Option 3 (Y40D40)	1,688 (+13%)	1,324 (+10%)	281 (+1%)	276 (+1%)
Option 4 (Y45D40)	1,717 (+15%)	1,345 (+12%)	284 (+2%)	277 (+2%)

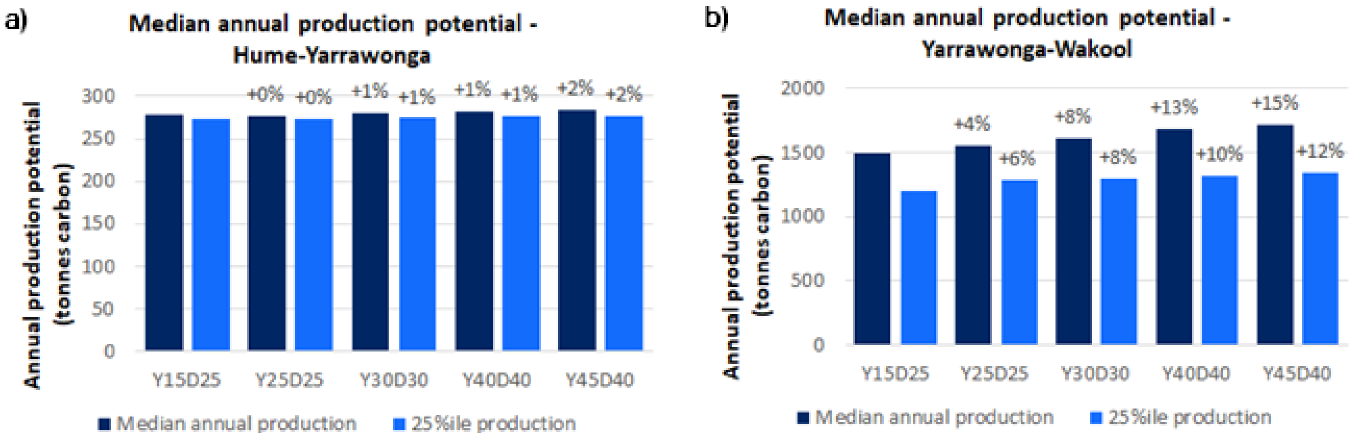


Figure 35: Median total annual production potential for large bodied native fish (tonnes carbon) for the a) Hume-Yarrawonga and; b) Yarrawonga-Wakool project areas

Data are the median and 25th percentile production potential calculated using all water years (n= 124 years).

3.5.3 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. The availability of food is not expected to always influence aquatic communities, rather it will become limiting at key moments in time, particularly during years with lower flows overall. 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 resilience of aquatic ecosystems. If constraints are not relaxed the energetic carrying capacity of aquatic ecosystems will be lower overall. In the context of a changing climate, this may result in longer periods of resource limitation.

4 Benefit and risk assessments

4.1 Water quality

Raised flow limits assessed to not increase the risk of adverse water quality events. Benefits to water quality are likely, due to the potential to shift flows from the higher risk summer period to winter (see Table 16).

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 raised flow limits on adverse water quality events for the program (McInerney et al. 2022).

4.1.1 Methods and key findings

Eight adverse water quality issues affecting the Murray 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 thus potentially affected by the raising of flow limits.

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. Sourced from McInerney et al. (2022).

Water quality parameter	Mechanistic link to increased flow magnitude	Positive, negative or both	Increased risk/benefit with increased flow magnitude
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

Three water quality issues – hypoxic blackwater, blue-green algae and salinity – were selected for further assessment as increased flow magnitude under raised flow limits was identified to potentially cause increased risk or benefit (Table 13 to Table 15). 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).

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 Murray 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 Murray 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 in regards to water quality risks/benefits (Table 13 to Table 15). Blue-green algal blooms and hypoxic blackwater are water quality events that are driven by metabolic processes. Metabolic rates increase with higher water temperature (and for blue-green algal blooms, light availability), increasing the identified potential benefit and risk ratings in warmer months (November to April). Understanding these patterns, particularly for hypoxic blackwater, is key for risk mitigation where flows are planned to be delivered before November and risk/benefit relationships have been incorporated into the environmental water delivery strategy (Section 2.3). For hypoxic blackwater, flows greater than 40, 30, and 38 GL/day in the Hume to Yarrawonga, Yarrawonga to Wakool, and Lower Murray 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 the Hume to Yarrawonga, and Yarrawonga to Wakool Junction project areas. For the lower Murray, flows greater than 38 GL/day increase the risk rating for salinity from 'low' to 'moderate', whilst potential benefits remain 'very high' across all evaluated flow thresholds.

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

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

Flow category	Flow event	Risk of a water quality event			Benefit of a water quality event		
Hume to Yarrawonga	Timing	Blackwater	Blue-green algal bloom	Salinity	Blackwater	Blue-green algal bloom	Salinity
>25 GL/day	Summer	High	High	Moderate	High	High	High
	Winter	Moderate	Moderate	Moderate	High	Moderate	High
>30 GL/day	Summer	High	High	Moderate	High	High	High
	Winter	Moderate	Moderate	Moderate	High	Moderate	High
>40 GL/day	Summer	Very high	High	Moderate	High	High	High
	Winter	Moderate	Moderate	Moderate	High	Moderate	High
>45 GL/day	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, Yarrawonga to Wakool Junction

Figure reproduced from McInerney et al. (2022).

Flow category	Flow event	Risk of a water quality event			Benefit of a water quality event		
Yarrawonga to Wakool Junction	Timing	Blackwater	Blue-green algal bloom	Salinity	Blackwater	Blue-green algal bloom	Salinity
>25 GL/day	Summer	High	High	Moderate	High	High	High
	Winter	Moderate	Moderate	Moderate	High	Moderate	High
>30 GL/day	Summer	High	High	Moderate	High	High	High
	Winter	Moderate	Moderate	Moderate	High	Moderate	High
>40 GL/day	Summer	Very high	High	Moderate	High	High	High
	Winter	Moderate	Moderate	Moderate	High	Moderate	High
>45 GL/day	Summer	Very high	High	Moderate	High	High	High
	Winter	Moderate	Moderate	Moderate	High	Moderate	High

Table 15: Collation of water quality event risk/benefit assessment by flow category for events of >7 days duration, for the lower Murray region (Wakool Junction to Wentworth)

Figure reproduced from McInerney et al. (2022).

Flow category	Flow event	Risk of a water quality event			Benefit of a water quality event		
D/S Euston	Timing	Blackwater	Blue-green algal bloom	Salinity	Blackwater	Blue-green algal bloom	Salinity
>20 GL/day	Summer	High	High	Low	High	High	Very High
	Winter	Moderate	Moderate	Low	High	Moderate	Very High
>38 GL/day	Summer	Very high	High	Moderate	High	High	Very High
	Winter	Moderate	Moderate	Moderate	High	Moderate	Very High
>50 GL/day	Summer	Very high	High	Moderate	Very High	High	Very High
	Winter	Moderate	Moderate	Moderate	Very High	Moderate	Very High

The impact of raised flow limits on the risk or benefit of a water quality event was then determined by evaluating how raised flow limits would change the frequency of high flows relative to the base case using the modelled 'flow limit options' scenario data (Table 16).

4.1.2 Overall outcomes

Raised flow limits do not increase the risk of negative water quality outcomes in the Hume to Yarrawonga, and Yarrawonga to Wakool Junction reaches of the Murray River. This is also the case for the lower Murray, which although not included in this synthesis is presented in the technical report (McInerney et al. 2022). For these reaches, raised flow limits will likely benefit water quality outcomes with a raised overall benefit rating from 'moderate' to 'high'. The increased benefit rating is primarily due to the potential to shift flows from the higher risk summer period to winter.

Table 16: Overarching risk/benefit assessment of constraint relaxation scenarios for the Murray 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
Option 1 (Y25D25)	No change	Moderate	Moderate –> High	High
Option 2 (Y30D30)	No change	Moderate	Moderate –> High	High
Option 3 (Y40D40)	No change	Moderate	Moderate –> High	High
Option 4 (Y45D40)	No change	Moderate	Moderate –> High	High

4.2 Invasive species – weeds

The likelihood of change in distribution of suitable habitat decreases for amphibious species and increases for terrestrial species. When considering changes in habitat suitability and weed hotspots in conjunction with the impacts on humans, agriculture and natural environments with existing mitigation measures, there is a slight increase in benefit for each flow scenario in the Murray for assessed priority weed taxa (i.e. slight decrease in impact of weeds across the Murray project area).

Altering hydrological conditions can make rivers susceptible to invasion from exotic weeds, particularly in systems like the Murray River, where regulation has led to a terrestrialisation of many wetland areas (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 (Stokes et al. 2010; Haby et al. 2019). Weed invasion can reduce the biodiversity value and ecosystem functioning of native wetland vegetation communities. However, re-instating flow regimes more similar to historic/natural conditions can also mitigate weed expansion (Catford et al. 2011; Haby et al. 2019). Weeds can negatively impact biodiversity, industry and infrastructure but can also provide benefits for biodiversity when no other vegetation remains (Packer et al. 2016). A review of weed impacts found that in the Murray catchment, 55 species were directly impacting biodiversity (Murray LLS 2017). The program invasive weeds assessment therefore considers both the potential risk and benefits from the four Murray flow scenario options on invasive weed outcomes.

4.2.1 Methods and key findings

Species Distribution Models (SDMs) were used to predict areas providing suitable habitat for each weed species/plant functional group under the Source-modelled flow scenarios and associated inundation patterns determined from RiM-FIM and EW-FIM. Inundated areas were classified into metrics (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 18). 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 plan for the Murray Local Land Services area (Capon et al. 2022; Murray LLS 2017). Functional groups consist of many weed species that have similar habitat requirements and life cycles, allowing them 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 and 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 inundation regimes. An SDM was built for every species/functional group and flow scenario for the program areas in the Murray as well as the Murray catchment below Wakool Junction (to Wentworth), that is influenced by upstream flow from the program.

Weed hotspots, areas of suitable habitat for several weed species or functional groups, were also identified from the SDM outputs. 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 scenarios 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 (corresponding to a slight overall decrease in suitable habitat and consequence) for all flow scenarios in the Murray (includes program areas Hume to Yarrawonga and Yarrawonga to Wakool Junction as well as lower Murray) and very little difference between scenarios (Table 17, Table 18).

Table 17: Summary of overall standardised risk scores for the Murray (scale: benefit –100 to 100 risk)
Modified from Capon et al. (2022).

Flow scenario	Option 1 (Y25D25)	Option 2 (Y30D30)	Option 3 (Y40D40)	Option 4 (Y45D40)
Standardised score	–2.8	–3	–3.2	–2.8
Overall risk	Slight overall benefit	Slight overall benefit	Slight overall benefit	Slight overall 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 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 increases and decreases in suitable habitat were seen in the Murray 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 different flow scenarios amphibious species (i.e. *Phyla scandens* – lippia and *Sagittaria platyphylla* – arrowheads) 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 under relaxed flow scenarios, which help reduce the extent of species such as lippia (Figure 36, Figure 37).
- Terrestrial species were seen to have an increase in suitable habitat area (i.e. *Lycium ferocissimum* – African boxthorn and *Marrubium vulgare* – horehound). This is most likely due to the increase in fringing areas with increased moisture availability but no extended inundation and a potential increase in dispersal (Figure 36, Figure 37). The primary flow driver for this change was periods of dry between flows.

- Weed hotspots (four or more weed species), which represent less than 0.1 per cent (648 ha) of the project area in the Murray and are largely close to major town centres, significantly declined from the base case by between 50 per cent and 67 per cent. These declines reflect the general decline in suitable habitat area for each taxa, particularly for amphibious species.

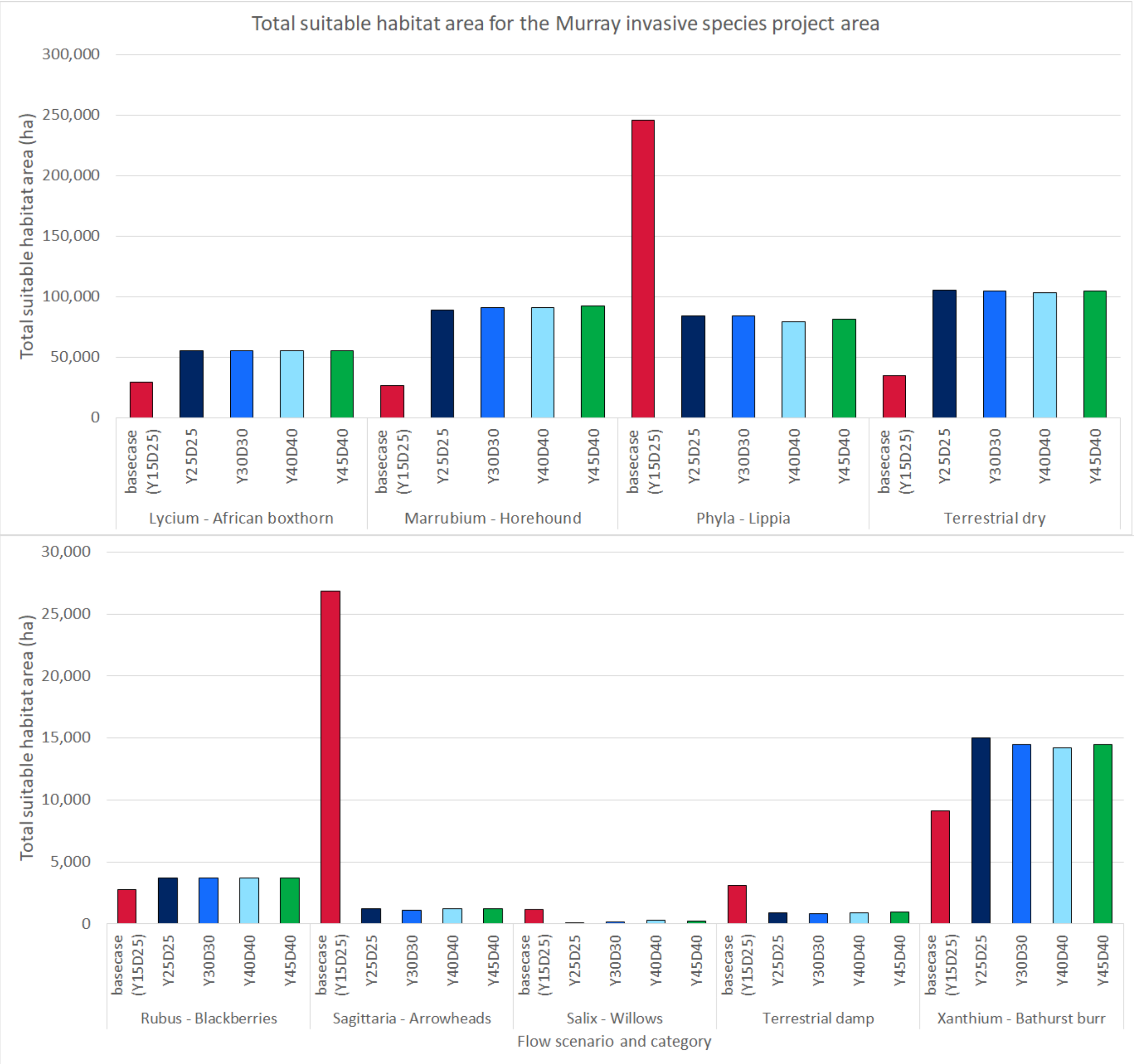


Figure 36: Total area (ha) of suitable habitat predicted by SDMs for all modelled taxa in the Murray under the base case and each flow limit scenario (from Capon et al. 2022)

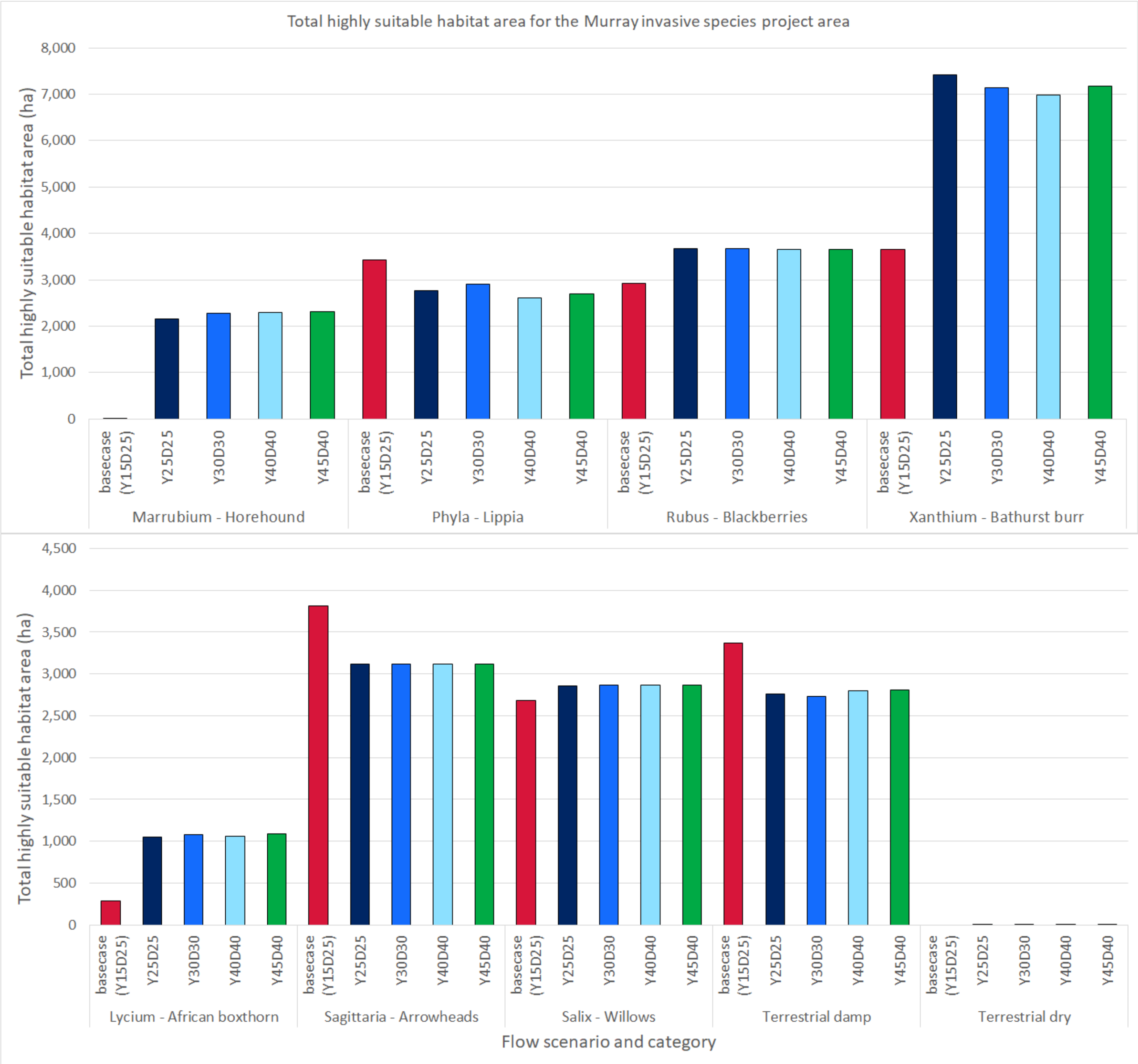


Figure 37: Total area (ha) of highly suitable habitat predicted by SDMs for all modelled taxa in the Murray under the base case and each flow limit scenario (from Capon et al. 2022)

4.2.2 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 Phyla), reducing the number of data points that could be included within the modelling. This leads to lower confidence in modelled distributions for some of the species considered; however, the approach taken used the best knowledge and data available within the timeframe of the project. Future projects could address these limitations through refining the model input datasets and potentially sourcing alternative species records.

4.2.3 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 all flow scenarios (Table 17).

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 in weed extent 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 18: Total risk scores for each weed taxa and weed hotspots under each flow limit scenario 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, red: increased risk, blue: reduced risk, white: no change). Scale for standardised final scores is –100 to 100 (from Capon et al. 2022).

Taxa	Murray			
	Option 1 (Y25D25)	Option 2 (Y30D30)	Option 3 (Y40D40)	Option 4 (Y45D40)
Sagittaria (Arp)	–2,048	–2,048	–2,048	–2,048
Phyla (Atl)	–1,088	–1,088	–1,088	–1,088
Salix (Tda)	–1,512	–1,512	–1,512	–1,512
Rubus (Tdr)	1,071	1,071	1,071	1,122
Marrubium (Tdr)	460	490	500	530
Lycium (Tdr)	1,717	1,717	1,666	1,666
Xanthium (Tdr)	801	747	747	747
Species sub-total	**–599**	**–623**	**–664**	**–583**
Tda species	–104	–104	–104	–104
Tdr species	128	128	128	128
Weed hotspots	–61	–68	–68	–68
Total	**–636**	**–667**	**–708**	**–627**
Standardised score	–2.8	–3.0	–3.2	–2.8
Overall risk	Slight overall benefit	Slight overall benefit	Slight overall benefit	Slight overall benefit

4.3 Geomorphology

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

If unmanaged, there is a *medium* risk of geomorphic change with raised flow limits for the Murray River reaches upstream of Barham, and in the Edward/Kolety–Wakool system. The implementation of existing mitigation strategies, and ongoing monitoring, reduces the risk to *low* for all Murray River sub-reaches and most Edward–Wakool sub-reaches. A *medium* risk rating remains for the mid- and lower-Wakool, and mid-Niemur reaches. This *medium* risk is defined by *low* level consequence, but *possible* likelihood.

Geomorphic risks posed by increased flow limits are primarily associated with the potential acceleration of existing, negatively valued, geomorphic processes, or the reinstation of previously active processes, rather than the creation of new issues.

Medium benefits are predicted in several sub-reaches including the Niemur and Wakool sub-reach sites assessed. Benefits relate to sustaining in-channel and riparian habitat through redistribution of sediment, including deposition on benches, bars and banks.

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 impact of raised flow limits on rates of bank erosion, which is an issue in multiple reaches within the catchment (MDBA 2017a; Rutherfurd et al. 2020; Vietz et al. 2018).

4.3.1 Methods and key findings

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 38). 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 39). These detailed assessments were then used to inform the broader reach and study area risk and benefit assessment.

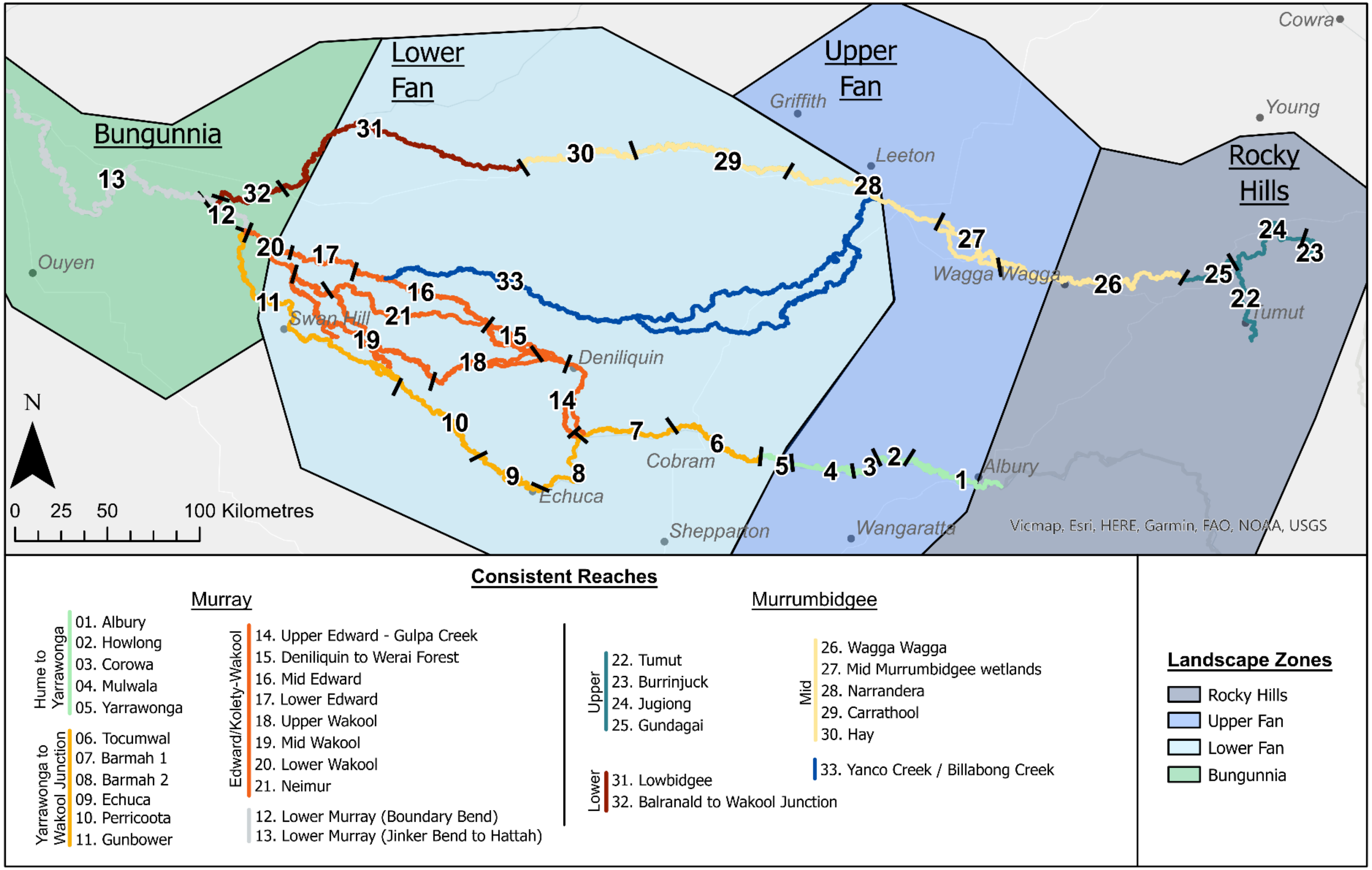


Figure 38: Functionally and morphologically similar reaches established using information on landscape zones, the level of confinement of the river, and the dominant geomorphic features present

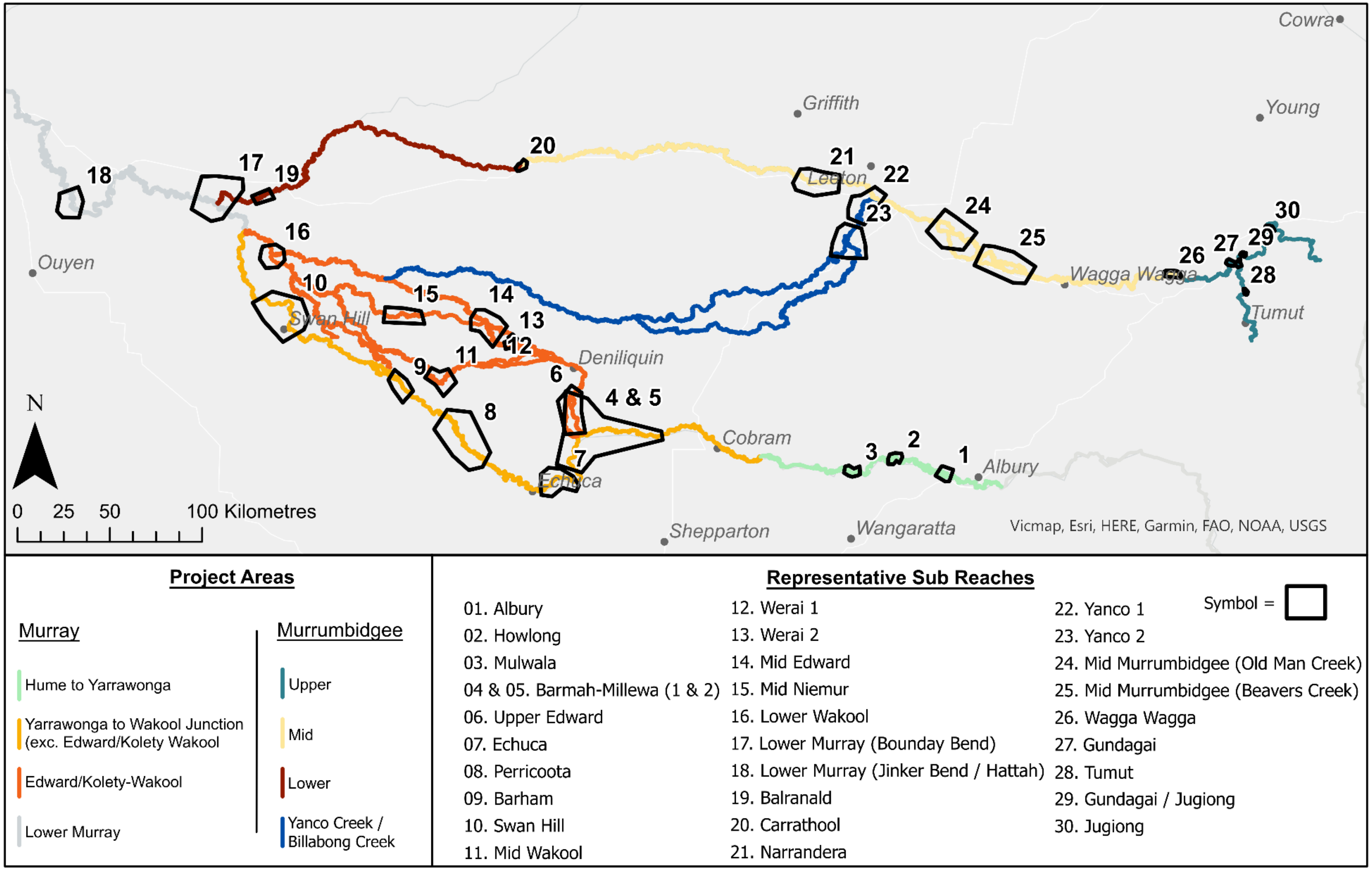


Figure 39: Sub-reaches selected for detailed assessment, which inform the broader reach and study area risk and benefit assessment

To assess the risk and benefit of raised flow limits on geomorphic features and processes within the Murray, two questions needed to be answered:

- What is the likelihood that raised flow limits 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 40). 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 (Table 19).

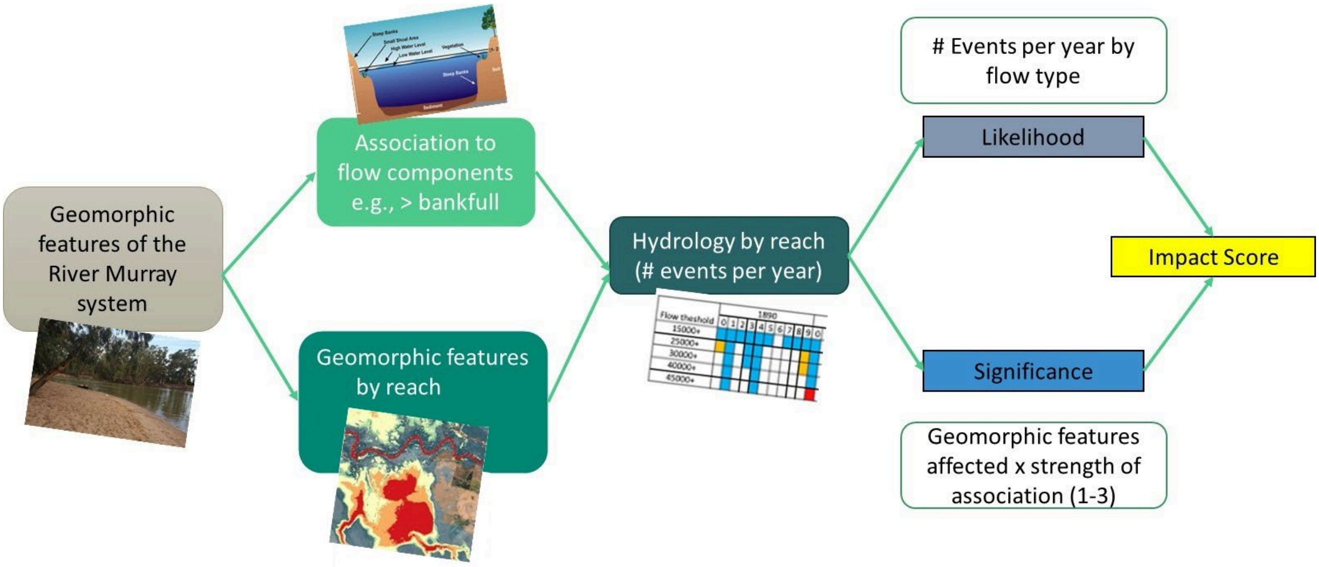


Figure 40: Overview of the method to derive the impact score that evaluates geomorphic features and processes within a sub-reach to different flow conditions (figure reproduced from Lauchlan Arrowsmith et al. (2022))

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 19) to assign a risk and benefit rating to each flow limit option for each sub-reach and project area (Table 20 and Table 21).

The Y45D40 and Y30D30 flow limit options were assessed, and their results discussed below. The other proposed flow limits options (Y25D25 and Y40D40) were 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 Y45D40 and Y30D30 scenarios provides a range of assessments useful for evaluating the risks and benefits of raised flow limits on geomorphic features and processes.

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 20, Table 21).

Table 19: Geomorphology risk assessment matrix

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

Table 20: Risk and benefit assessment ratings for the Murray River

Sub-reaches 1–3 reside within the Hume to Yarrawonga program area, 4–10 within Yarrawonga to Wakool Junction, and 17–18 outside program areas (Lower Murray).

Sub-reach	Reach	Risk		Risk (with mitigation measures considered)		Benefit	
		Y45D30	Y30D30	Y45D30	Y30D30	Y45D30	Y30D30
1	Albury	Medium	Medium	Low	Low	Low	Low
2	Howlong	Medium	Medium	Low	Low	Low	Low
3	Mulwala	Medium	Medium	Low	Low	Low	Low
4	Barmah 1	Medium	Medium	Low	Low	Low	Low
5	Barmah 2	Medium	Medium	Low	Low	Low	Low
7	Echuca	Medium	Medium	Low	Low	Low	Low
8	Perricoota	Medium	Low	Low	Low	Medium	Low
9	Barham	Medium	Medium	Low	Low	Low	Low
10	Swan Hill	Low	Low	Low	Low	Low	Low
17	Lower Murray (Boundary Bend)	Low	Low	Low	Low	Low	Low
18	Wakool (Jinker Bend / Hattah)	Low	Low	Low	Low	Low	Low

Table 21: Risk and benefit assessment ratings for the Edward/Kolety–Wakool region

All sub-reaches reside within the Yarrawonga to Wakool Junction program area.

Sub-reach	Reach	Risk		Risk (with mitigation measures considered)		Benefit	
		Y45D30	Y30D30	Y45D30	Y30D30	Y45D30	Y30D30
6	Upper Edward	Medium	Low	Low	Low	Medium	Low
11	Mid-Wakool	Medium	Medium	Medium	Medium	Medium	Medium
12	Werai	Medium	Low	Low	Low	Low	Low
13	Werai	Medium	Low	Low	Low	Low	Low
14	Mid-Edward	Medium	Low	Low	Low	Medium	Low
15	Mid-Niemur	Medium	Medium	Medium	Medium	Medium	Medium
16	Gunbower Wakool / Lower Wakool	Medium	Low	Medium	Low	Medium	Low

There is a medium risk of geomorphic change under raised flow limits for some reaches of the Murray River if potential risks are unmanaged. Spatially, the pattern of risk decreases in the downstream direction, with risk for the Murray River (Hume to Barham) and Edward/Kolety–Wakool system being medium under the Y45D40 and Y30D30 options, and low from Barham to Wentworth. For all Murray reaches, and most of the Edward/Kolety–Wakool system, this risk rating is reduced to low through the implementation of existing and potential mitigation measures and ongoing monitoring, including but not limited to active management of the flow regime (e.g. suitable rates of rise and fall), use rules, and physical intervention. An example of existing measures is the ongoing River Works Program in the Upper Murray (MDBA 2017a). As is current practice, environmental water deliveries are adaptively managed, meaning any potential risks are considered before water is delivered, and the event is actively monitored.

Accelerating or dampening geomorphic processes will typically have coexistent benefits and risks. This is because geomorphic processes and structures intersect with multiple ecosystems and assets and operate at various scales. For example, enhanced rates of erosion may have localised impacts (which may be negative if they intersect with certain assets) but can benefit downstream sites with increased sediment supply.

Geomorphic risks posed by increased flow limits are primarily associated with the acceleration of existing, negatively valued, geomorphic processes, or the reinstation of previously active processes, rather than the creation of new issues. For example, the Hume to Yarrawonga reach of the Murray is currently (and has been historically) an actively meandering and anabranching system – active processes that raised flow limits may enhance. Further, this area has increased vulnerability to geomorphic change due to other pre-existing stressors including de-snagging, changes in riparian vegetation (land clearing and grazing), and boat-waves, which increase the potential for raised flow limits to be of impact.

Potential geomorphic benefits from raised flow limits 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.

Three reaches within the Edward/Kolety–Wakool system remain rated as medium risk after mitigation measures are considered. The assessed consequence rating for all three sites is low; however, the likelihood of any impact is possible, thus yielding a medium risk rating. All three sites are also assessed to receive medium level benefits under raised flow limits, with the potential for enhanced rates of deposition on banks and bars. Here we provide a short summary of these conditions, associated processes, and causes; however, we direct the reader to the sub-reach assessments for additional detail (Lauchlan Arrowsmith et al. 2022).

- Mid-Wakool (11) – under base case operation, flows within this sub-reach are highly regulated and erosion processes dominate, albeit at a slow rate. Raised flow limits will likely increase the frequency of large fresh flows and potentially reinstate anabranch development and meander migration – processes limited by current regulation. The effect of raised flow limits on bank erosion will depend on the way raised flows are delivered, and can thus be planned for.
- Mid-Niemur (15) – under base case operation this is a low energy system with few active geomorphic processes. A reactivation of geomorphic processes is predicted in response to an increase in the number of near bankfull and small to moderate overbank flows under both assessed flow limits. Likely processes include meander cut-offs and anabranch formation, yet still at a slow rate. Like the mid-Wakool, the reactivation of processes may also be considered a benefit as many of these processes have been restricted by flow regulation.
- Lower Wakool (16) – similar to the mid-Niemur, under base case operation this is a low energy system with few active geomorphic processes. Under a Y45D40 scenario a reactivation of geomorphic processes (meander cut-offs and anabranch formation) is predicted, yet still at a slow rate. The baseline trajectory is unlikely to change under Y30D30 operational constraints. Again, the reactivation of processes may also be considered a benefit as many of these processes have been restricted by flow regulation.

4.3.2 Overall outcomes

With existing mitigation measures in place, and ongoing monitoring and adaptive management, most of the Murray River will not be negatively affected by raised flow limits; however, *medium* risk does exist for some reaches in the Edward/Kolety–Wakool system, which may require more detailed and targeted assessment. This *medium* risk is defined by *low* level consequence, but *possible* likelihood. Expected benefits are typically *low*, however m*edium* level benefits are expected for most reaches within the Edward/Kolety–Wakool system and the Murray sub-reach adjacent to Koondrook–Perricoota National Park under Y45D40 limits – a result of reinstated geomorphic processes increasing sediment transfer.

5 Discussion

The EBRA for the program demonstrates how relaxing constraints could contribute substantial improvements to water-dependent ecosystems in the Murray River catchment (Table 22). Models predict improvements across all modelled environmental themes. The long-term average abundance of native golden perch is expected to increase by up to 29 per cent due to increased spawning and recruitment opportunities, while other environmental indicators (waterbirds, production, river red gum, etc.) show up to 12–15 per cent improvement upon the base case scenario. Overall, results suggest improvements are consistent across all four flow limit option scenarios, with the greatest outcomes predicted for Option 4 (Y45D40). 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 increases in waterbird density for Barmah–Millewa Forest were not predicted for the two lowest flow limit options.

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 beneficial outcomes are achieved by using environmental water to 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 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 environmental water to be used to deliver small overbank flows to low-lying wetlands that do not occur under the base case scenario. Out of 37 years where there are no expected flows to floodplains in the base case, relaxing constraints will support low-lying floodplains in 19 additional 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 densities and overall abundance are higher for almost all the flow limit option scenarios relative to the base case in dry to moderate years, with up to 80 per cent increase in waterbird density under the higher flow limit option scenarios in Barmah–Millewa Forest. Barmah–Millewa also saw an increase in the probability of breeding and an increase in opportunities for small-scale breeding could contribute to maintaining broader population numbers over time (Brandis et al. 2021). Models also predict an increase of up to 50 per cent in the extent of healthy river red gum forest during dry periods by preventing large areas of forest from declining into poor condition. The population of golden perch during dry periods is projected to increase by up to 45 per cent relative to the base case. These findings suggest a much greater capacity for aquatic communities to survive dry conditions if constraints are relaxed.

Although the environmental benefits of relaxing constraints are reported for the project area as a whole, modelling suggests environmental outcomes will be greater for some project areas than others. The area of river red gum forest in a good or moderate condition is expected to increase from the base case by up to 39 per cent in the Hume–Yarrawonga project area, while the equivalent benefit in the Yarrawonga–Wakool project area is expected to increase by up to 16 per cent. Conversely, potential production estimates are much greater in the Yarrawonga–Wakool project area than Hume–Yarrawonga, largely owing to the importance of the permanently inundated Lake Mulwala in providing energy to the reach upstream of Yarrawonga Weir. There may be finer-scale patterns of increasing or decreasing benefit depending on the scale at which the patterns are examined.

The program will enable environmental water deliveries to target small to moderate overbank flows that are heavily impacted by river regulation (Stewardson et al. 2021; Ellis et al. 2016; Gippel and Blackham 2002). While the modelling for the EBRA focuses 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 Murray–Lower Darling Long Term Water Plan (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, predicted an increased benefit (i.e. reduced risk). For water quality, operational decisions prevent environmental flow releases that inundate the floodplain during warmer months or when there is increased risk of hypoxic blackwater. Similarly, although modelling predicts a mix of increase and decrease in suitable habitat of priority weed species and functional groups, when taking into consideration the consequences, impacts and current mitigation (i.e. complementary measures including weed management) there is slight overall benefit for each flow limit scenario in the Murray. Moreover, 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 identified a medium risk of accelerating geomorphic processes in some areas within the Edward/Kolety–Wakool system, with other areas assessed as low risk. Potential risks identified are primarily related to the restoration of geomorphic processes active in the system prior to river regulation. The predicted consequences are considered *low*, and of *possible* likelihood. No new geomorphic issues are expected to be created.

Modelling for the EBRA is used to evaluate potential changes in ecological condition resulting from changes to river flows; however, the models do not perfectly represent the complex ecological systems they attempt to replicate. Rather, they use the current state of knowledge in each field to explore potential responses. The ecohydrological models inherit uncertainties from underlying hydrological and spatial models as well as any datasets they use to define flow–ecology relationships. This creates 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 fixed datasets representing the current state of the river and its floodplain environments; for example, inundation mapping. The reality however is that the river and floodplain environments are dynamic, and change over time. Despite these assumptions and uncertainties, the models used in the EBRA implement the best available science and are useful experimental tools for evaluating the potential ecological outcomes of raised flow limits.

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, an 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 the aquatic communities of the Murray River. The outcomes of the current modelling suggest environmental flows will 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 Murray River. It also raises a relatively small number 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 on the side of environmental benefits.

Table 22: A summary of environmental benefits and risks for the program flow limit option scenarios (Murray system scale: Hume to Wentworth, including the Edward/Kolety–Wakool system)

Theme	Outcome	Description of outcomes
Native vegetation	Overall improvement	Higher flow limit options bring significant benefits to native vegetation. Results show increases in average area of vegetation in good or moderate condition relative to the base case of up to: • river red gum forest and woodland: +15% • black box woodland: +5% • lignum shrubland: +11% • perennial wetland: +10%.
	Improvements during specific periods	During dry periods Y45D40 provides a +50% increase in the area of river red gum in good or moderate condition between Hume and Wentworth; a +43% improvement in Hume to Yarrawonga, and +61% improvement in Yarrawonga to Wakool Junction program areas.

Theme	Outcome	Description of outcomes
	Improvements seen for specific spatial areas	Overall, the Hume to Yarrawonga reach experiences the greatest improvements to area of river red gum in good or moderate condition (up to +39%) versus Yarrawonga to Wakool Junction (up to +16%). Potential decline in higher elevation vegetation community condition due to reduced peak discharge rates during unregulated flood events. Note that in summary statistics (where negligible decline is observed) any decline is typically offset by improvements for lower elevation vegetation. This is most significant for black box woodlands.
	Improvements with higher flow limits	Y40D40 and Y45D45 level flow limits are needed to bring significant benefits to the Hume to Yarrawonga reach both overall and during drier climate periods. Only the Y45D40 option brings significant benefits to average conditions in the Yarrawonga to Wakool Junction area. All options however provide significant benefits during dry periods, but the magnitude of benefit increases significantly with higher flow limits.
Native fish 	Overall improvement	*Flow pulse specialists* – increased populations due to increased spawning, dispersal and recruitment opportunities related to enhanced large fresh flows and more regular access to off-channel habitats. Fish population modelling predicts a 10–29% higher golden perch population in the Murray system under relaxed flow limit options compared to the base case. *Floodplain specialists* – increased breeding and recruitment opportunities in off-channel wetlands and floodplains through delivery of more frequent wetland-connecting flows. Key breeding and nursery sites made more readily available. *Diadromous species* – more frequent migration cues for short-headed lamprey, which historically made long-range migrations from the sea to breeding and recruitment locations along the River Murray
	Improvements during specific periods	Improvements in minimum golden perch populations by up to 45% during dry periods.

Theme	Outcome	Description of outcomes
	Improvements seen for specific spatial areas	Improvements to golden perch populations are predicted to be greatest in the Yarrawonga to Torrumbarry and Hume to Yarrawonga reaches of the Murray River (up to 39% increases in abundance compared to the base case in each reach). Relatively, smaller predicted improvements are predicted for the Edward River (up to 7%).
Waterbirds	Overall improvement	An increase was seen in waterbird abundance across both project areas, Barmah–Millewa and Gunbower–Koondrook–Perricoota forests with a percent long-term change of 13 and 48% respectively, for median years for the highest flow scenario. The number of waterbird species (species richness) in Gunbower–Koondrook–Perricoota Forest increased slightly (3–4%) for the highest flow scenarios; however, an increase of 5 and 25% for median and dry years (25th percentile) respectively, was predicted for Barmah–Millewa Forest under the highest flow scenario. The probability of colonial waterbird breeding in Barmah–Millewa Forest is also expected to increase in both median and dry (25th percentile) years with a percent increase of 11 and 17% respectively, for the highest flow scenario relative to the base case. It is likely that predicted benefits of relaxed constraints for waterbirds will be cumulative with improved wetland condition in the neighbouring Gunbower–Koondrook–Perricoota Forest area providing benefits to waterbirds breeding in the nearby Barmah–Millewa Forest and vice-versa.
	Improvements seen for Barmah–Millewa and Gunbower–Koondrook–Perricoota	**Barmah–Millewa Forest** An increase in waterbird density and number of species is expected to be achieved in the long term in Barmah–Millewa Forest with a 13% increase in waterbird density (birds/ha) and 5% increase in the number of waterbird species predicted for median years. It is expected that the program would provide most benefit to waterbird populations during drier years (represented by the 25th percentile), by inundating the forest and creating waterbird habitat. Compared to the base case scenario, predicted waterbird density increased by up to 80% and predicted species richness increased by 25% for these drier

Theme	Outcome	Description of outcomes
		years in the relaxed constraint scenarios compared to the base case. The probability of colonial waterbird breeding in Barmah–Millewa Forest is also expected to increase by up to 11% (median) and 17% (drier 25th percentile) under relaxed flow scenarios in the program. **Gunbower–Koondrook–Perricoota Forest** Total waterbird abundance increased across the long term for Gunbower–Koondrook–Perricoota Forest with a 48% increase under the highest flow scenario compared to the base case predicted for median years. An increase was seen in drier years (25th percentile) with a 34% increase under the highest flow scenario compared to the base case.
Production	Overall improvement	Increase in production due to increased floodplain inundation with benefits increasing consistently with the level of constraints relaxation.
	Improvements during specific periods	Increased production relative to the base case during dry periods, but not the same level of improvement observed for the full flow regime.
	Improvements seen for specific spatial areas	Increase in production largely observed for Yarrawonga–Wakool project area with a smaller increase for Hume–Yarrawonga.
Water quality	No increased risk	Raised flow limits 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 shift flows from the higher risk summer period to winter relative to the base case.
	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 likelihood of change in distribution of suitable habitat decreases for amphibious species and increases for terrestrial species. Weed hotspots are predicted to decrease. When considering changes in habitat suitability and weed hotspots in conjunction with the impacts on humans, agriculture and natural environments with existing mitigation measures, there is a slight increase in benefit for each flow scenario in the Murray for assessed priority weed taxa (i.e. slight benefit on the impact of weeds across the Murray project area).

Theme	Outcome	Description of outcomes
	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 hotspots.
	Risk for specific functional groups	An increase in the suitable habitat for terrestrial species was seen from the species distribution modelling.
Geomorphology	Low to medium risk that existing geomorphic processes would be accelerated.	Low to medium risk that existing geomorphic processes (e.g. bank erosion and anabranch development) would be accelerated. The risk is reduced to low in most sub-reaches with existing mitigation measures. The risk of reinstating previously active geomorphic processes in some reaches of the Edward/Kolety–Wakool system remains medium after risk mitigation options are considered – processes including enhanced anabranch development and meander migration. This medium risk is defined by *low* level consequence, but *possible* likelihood.
	Benefits for specific areas	Expected benefits are typically low; however, medium level benefits are expected for most reaches within the Edward/Kolety–Wakool system and the Murray sub-reach adjacent to Koondrook–Perricoota National Park under Y45D40 limits. Predicted benefits include nutrient and carbon transfer into the riparian zone and enhanced geomorphic diversity (creating and sustaining in-channel and riparian zone habitat structures).
	Higher flow limit options do not increase risk	Risk is mostly unchanged by higher flow limit options as the frequency of large fresh level flows, which are of particular significance for negative geomorphic outcomes, is relatively unchanged.

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Appendix A

Table 23: The EBRA themes, including current conditions and references

Theme	Current condition	References
Waterbirds	Waterbirds are in decline across the Murray–Darling Basin. Long-term aerial surveys show that waterbird populations are severely degraded. Recent surveys in 2021 show this decline continuing across all guilds. Barmah–Millewa and Koondrook–Perricoota support less colonial waterbird breeding than historically.	Hutton (2017); Kingsford et al. (2017); Leslie (2001); Porter et al. (2021)
Native vegetation	NSW Central Murray forest Ramsar sites and other significant forest areas are in poor condition. In Millewa 11% of forest and 17% of woodland is poor, degraded or severely degraded. In Koondrook–Perricoota 31% of forest and 34% of woodland is poor, degraded or severely degraded. Surveys of Werai Forest in 1995 found it in poor condition with 92% of trees stressed, highly stressed or dead.	MDBA (2016a, b); Harrington and Hale (2011)
Fish	Golden perch populations have declined following alienation of floodplains, reduced river flow pulses and loss of flowing water habitats.	Koehn et al. (2020a); Koehn et al. (2020b); Todd et al. (2020); Todd et al. (2005); Todd et al. (2018)
	Murray cod have experienced population declines despite extensive restocking.	Koehn and Todd (2012); NSW Department of Primary Industries (2022a, b); Sherman et al. (2007)
	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.	Conallin et al. (2012); Stuart and Jones (2006a, b); Brown et al. (2020); Forsyth et al. (2013); Koehn et al. (2018)

Appendix B

Table 24: Area of vegetation types inundated during a delivery at different flow limits – Hume to Yarrawonga

Vegetation type	Area inundated (ha)				
	Base case (Y15D25)	Option 1 (Y25D25)	Option 2 (Y30D30)	Option 3 (Y40D40)	Option 4 (Y45D40)
Lignum shrubland	0	0	0	0	0
River red gum woodland	256	256	302	614	614
River red gum forest	1,241	1,241	1,389	2,283	2,283
Perennial wetland	58	58	68	145	145
Black box woodland	4	4	5	8	8

Table 25: Area of vegetation types inundated during a delivery at different flow limits – Yarrawonga to Wakool Junction

Vegetation type	Area inundated (ha)				
	Base case (Y15D25)	Option 1 (Y25D25)	Option 2 (Y30D30)	Option 3 (Y40D40)	Option 4 (Y45D40)
Lignum shrubland	191	234	266	284	322
River red gum woodland	2,554	3,535	4,413	6,217	7,034
River red gum forest	10,492	21,884	29,072	46,563	53,015
Perennial wetland	424	628	696	880	932
Black box woodland	538	830	1,037	1,638	1,860

Appendix C

Table 26: Native fish observed or predicted (P) to occur in the Murray: Hume to Yarrawonga and Yarrawonga to Wakool Junction program areas, grouped by functional group (NSW DPI 2016; Ellis et al. 2022)

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)
Hume to Yarrawonga			
Australian smelt Carp gudgeon Dwarf flathead gudgeon Flat-headed gudgeon Mountain galaxias Murray–Darling rainbowfish Obscure galaxias Unspecked hardyhead	Flathead galaxias (CE,P) Southern pygmy perch (E,P)	Murray cod (V) River blackfish Murray crayfish (V) Trout cod (E)	Golden perch
Yarrawonga to Wakool			
Australian smelt Carp gudgeon Dwarf flathead gudgeon Flat-headed gudgeon Murray–Darling rainbowfish Obscure galaxias Unspecked hardyhead Bony herring	Flathead galaxias (CE,P) Southern pygmy perch (E)	Murray cod (V) River blackfish Murray crayfish (V) Trout cod (E) Freshwater catfish (eel-tailed catfish)	Golden perch Silver perch