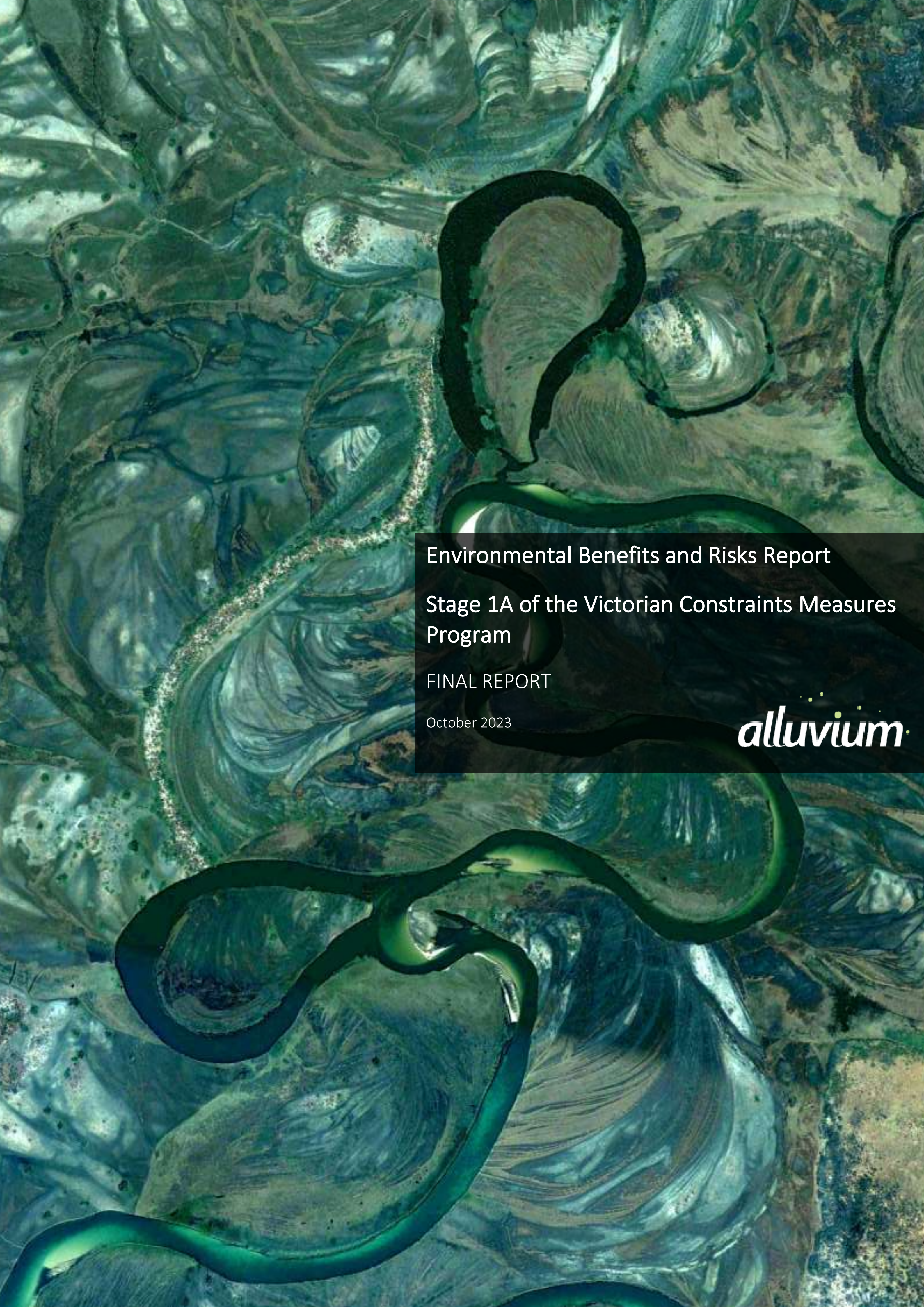

Environmental Benefits and Risks Report

Stage 1A of the Victorian Constraints Measures Program

FINAL REPORT

October 2023

alluvium

Alluvium recognises and acknowledges the unique relationship and deep connection to Country shared by Aboriginal and Torres Strait Islander people, as First Peoples and Traditional Owners of Australia. We pay our respects to their Cultures, Country and Elders past and present.

Artwork by Vicki Golding. This piece was commissioned by Alluvium and has told our story of water across Country, from catchment to coast, with people from all cultures learning, understanding, sharing stories, walking to and talking at the meeting places as one nation.

This report has been prepared by Alluvium Consulting Australia Pty Ltd for Sequana Pty Ltd under the contract titled '**Environmental Benefits and Risks Feasibility Assessment**'.

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Acknowledgements

The assessment of environmental benefits and risks conducted for feasibility stage of the Victorian Constraints Measures Program uses modelling and inputs from a range of expert inputs. The assessment covers three reaches over two river systems and builds on much of the work previously conducted for the NSW Reconnecting River Country Project and the University of Melbourne investigations into the Goulburn River.

The report makes use of these previous studies, but also synthesises work and input from various sources. In addition to the members of the Alluvium Group team (encompassing Alluvium Consulting Australia and EcoFutures), the inputs and expertise of the following groups are recognised and acknowledged:

- La Trobe University (Luke McPhan, Nick Bond)
- Arthur Rylah Institute (Rob Hale, Jarod Lyon, Charles Todd, Zeb Tonkin, Wayne Koster)
- Rivers and Wetlands (Darren Baldwin)
- University of NSW (Gilad Bino, Kate Brandis)
- EnviroDNA (Josh Griffiths)
- University of Melbourne (Andrew John, Avril Horne)
- NSW Department of Planning and Environment (Iwona Conlan, Ian Burns)

The work conducted for the NSW Reconnecting River County Project was particularly important for the completion of this study. The majority of the work completed for the Murray River has been either informed directly by the NSW project, or the modelling results cropped to a Victoria extent. Any information from that project has been drawn on and interpreted by the original authors of the work as listed above.

Highlights

Current project importance and position

- The relaxation of constraints will create real and significant benefits for the environment.
- The relaxation of constraints reconnects rivers to their floodplain by enabling environmental water to be used on floodplains for the benefit of the floodplain and riverine ecosystems. This use of environmental water on floodplains, increases environmental water managers capacity and flexibility to make the best use of environmental water and, by extension, the best use of public funds invested in environmental water.
- Relaxation of constraints on the delivery of environmental water will benefit important habitats in Victoria and NSW. Although benefits will be seen all along the floodplain, key sites that will benefit include, but are not limited to:
  - Barmah (Vic) and Millewa (NSW) Forests
  - Horseshoe Lagoon (NSW)
  - Koondrook -Perricoota Forests (NSW)
  - Gunbower Forest (Vic)
  - Doctors Swamp (Vic)
  - Gemmill Swamp (Vic)
  - Loch Garry Wildlife Reserve(Vic)
  - Lower Goulburn River floodplain forests (Vic)
- The future climate is uncertain, and constraint relaxation will promote ecological resilience to future climate change. Constraint measures have the potential to significantly offset declines in ecological outcomes arising from climate change under potentially drier and hotter conditions. This will be achieved, in part, because environmental water managers will be able to deliver environmental water to the assets facing the greatest risk.
- The hydrologic modelling undertaken for the Vic CMP has not sought to optimise water delivery, through the coordination of releases with tributary events. In this respect the modelling does not include the 'foresight' of events in tributary streams to which a release could be coordinated. Such foresight is currently available to river operators via existing event forecasting tools. As such, the expected environmental outcomes documented in this report are conservative i.e. less than that which could be expected to be achieved if the system were operated with such foresight and existing forecasting tools.
- Relaxing constraints is a critical tool in achieving Basin Plan objectives. However, it is only one tool. The Enhanced Environmental Water Delivery program (EEWD), a complementary SDLAM measure, seeks to improve the existing forecasting, hydrologic modelling, and coordination of environmental water delivery across the Southern Connected Basin to improve the efficiency of environmental water deliveries. Together, these two programs (Vic CMP and EEWD) have potential to create significant environmental benefits that are 'greater than the sum of their parts'.

Current conditions/'do nothing' scenario

<u>Hydrology</u>

- Under the do-nothing scenarios there will be an ongoing failure to achieve Basin Plan objectives, specifically, delivery of essential over bank events as recommended by environmental flow studies for the Goulburn River and as sought for the Murray River under the Basin Plan.

- Climate change is likely to negatively impact on stream flows in the Goulburn and Murray Rivers, increasing the likelihoods of droughts and severe flooding. Climate change is expected to decrease mean annual flows, decreased occurrence of overbank events and freshes, increase tributary cease-to-flow events and increase the occurrence of summer flood events. These changes are expected to have negative impacts on ecosystems including declines in vegetation condition, habitat availability, and population resilience to stressors and increase adverse water quality events.

Geomorphology

- Regulated water deliveries will remain in channel where it applies 'work' on riverbanks, resulting in ongoing, accelerated rates, of channel erosion in the Goulburn and Murray Rivers.

Water quality

- The current operations and storage of water maintains the current and increasing potential for uncontrolled spills and associated adverse water quality events, especially if these occur in summer.
- Organic matter will continue to accumulate on Murray River floodplains with the potential to increase carbon load and associated water quality risks to rivers in uncontrolled summer flood events.

Vegetation

- An ongoing decline of *river red gum* and *black box* communities is expected under a do-nothing scenario. While mature *river red gum* and *black box* can use a variety of water sources, recruitment, understory vegetation and water dependent fauna species rely on inundation. Long- term age-related decline in trees is expected. This will be accompanied by reduced recruitment, and as a result, a long-term loss in vegetation communities. A 75% loss in the existing *river red gum* community has been identified for the Goulburn River under the 'do nothing' scenario.
- Significant areas of aquatic, semi aquatic, and terrestrial flood adapted, and semi-aquatic vegetation will not receive environmental water, leading to declines in condition, decreased primary productivity, decreased resilience to dry and drought conditions and decreased provision of breeding and forage habitat for riverine, wetland and floodplain fauna.
- An ongoing decline in the resilience of *river red gum* and *black box* communities to drought, reducing capacity to respond to wetter conditions following drought. This decline makes the *river red gum* and *black box* communities more vulnerable to drought with the frequency and duration of drought likely to increase due to climate change. Widespread tree death will be inevitable.

Habitat and fauna

- The current reduced floodplain water availability will adversely impact water-dependent fauna including macroinvertebrates, fish, birds and terrestrial species.
- Macroinvertebrate diversity and abundance will decline. Limitations on the availability of macroinvertebrates as a food source for larger animals will impact species such as platypus, turtles, waterbirds, fish, and frogs.
- Continued accelerated rates of erosion will adversely affect bank habitat and dependent fauna including fish, platypus, and turtles.

- Continued and increasing adverse water quality events will impact on fauna including macro invertebrates and fish.
- Declines in vegetation communities will adversely impact on dependent fauna including fish, water birds and terrestrial species.
- Waterbird populations will continue to decline in the Southern Basin, through loss of breeding and foraging habitat.

Connectivity

- Under the do-nothing scenario there will be;
    - continued reduced rates of native vegetation seed transport/dispersal , germination and recruitment.
    - continued absence of some flow cues that are important for supporting recruitment and breeding of flow-responsive fish species (continued decline of Golden Perch populations, which are currently reliant upon stocking).
    - no complementary program of constraint relaxation on the NSW side of the Murray River and as a result an ongoing decline in NSW floodplain wetland and forest ecosystems.

Environmental benefits for Victoria

Hydrology

The relaxation of constraints will;

- improve the seasonality of flows, and in particular winter/spring overbank events, as recommended by the Kaiela (Lower Goulburn River) Environmental Flows Study (2020) and as sought for the Murray River within the Basin Plan.
- reduce the likelihood of out-of-season floods through reduced spills that can cause hypoxic blackwater.

Geomorphology and erosion

- The relaxation of constraints will not increase erosion rates.
- To the contrary, relaxation of constraints will redistribute environmental water that is currently delivered via the river channel to the floodplain. This redistribution of environmental water has the potential to reduce the rate, extent and occurrence of bank erosion in the Goulburn and Murray Rivers. A reduction in erosion potential of up to 12% has been identified for the Goulburn River with the relaxation of constraints.
- Significant improvements in geomorphic complexity (and hence instream habitat) are predicted to occur in the Goulburn River, similar increases can be expected for the Murray River.

Water quality

- The relaxation of constraints will not increase the risk of hypoxic blackwater events.
- To the contrary, the relaxation of constraints has the potential to decrease the risk of hypoxic blackwater events by;
    - improving the use of available environmental water and reducing the potential for out-of-season (summer) spill events

- reducing the build-up of carbon on the floodplain of the Murray River by increasing the frequency of floodplain carbon returning to the river channel in the winter/spring months when it is cooler.

Realignment of the delivery volume and timing enables the return of carbon into the river during colder water periods (winter, spring) encouraging instream productivity and reducing the potential for hypoxic blackwater occurring in late spring–summer periods.

<u>Macroinvertebrates and productivity</u>

- Significant instream macroinvertebrate and productivity benefits are expected for the Goulburn and Murray Rivers. These benefits arise from the periodic and in-season delivery of food sources (carbon) from the floodplain.
- For the Murray River modelling indicates that up to 15% increase in average annual production potential of large-bodied fish in Yarrawonga-Wakool reach such as *Golden Perch*. Up to 12% increase in production potential during drier periods.
- The modelling shows strong improvement in production in the Goulburn River when constraints are relaxed beyond 20,000ML/d in the Lower Goulburn Reach.
- Benefits to macroinvertebrates and productivity are predicted to result in improved food availability to the larger consumers in the river system (such as fish, platypus etc).

<u>Vegetation</u>

- Relaxation of constraints increases the area that can be watered with environmental water. This includes:
    - creating over four times the area (5,900ha increase) of aquatic, semi-aquatic and flood-adapted terrestrial vegetation capable of being inundated by environmental water on the Goulburn River floodplain downstream of Lake Eildon at the maximum level of constraint relaxation assessed (M14L25).
    - creating four times the area (30,000Ha increase) of aquatic, semi-aquatic and flood-adapted terrestrial vegetation capable of being inundated by environmental water in the Yarrawonga to Wakool reach under a constrain relaxation of 40,000Ml/d.
- Relaxation of constraints improves the condition and prevents the loss of vegetation communities. Modelling has revealed that;
    - For the Goulburn River system relaxation of constraints will;
        - Create an almost 6-fold (572%, 6,753ha) increase in the area of *river red gum* in good or moderate condition in the Lower Goulburn River over the duration of the model run.
        - Protect up to 6,000ha of *river red gum* from loss
        - Increase the area of *black box* woodland in good condition in the Lower Goulburn by 550ha (representing 26% of the total area). This compares with all *black box* confined to a critical condition under the ‘do nothing’ scenario.
    - For the Murray River system in Victoria relaxation of constraints will.
        - Protect up to 6,000Ha of *river red gum* vegetation community from imminent loss (critical condition). This represents a 31% increase in river red gum held in good condition at the end of the model timeseries

Native Fish

The relaxation of constraints will;

- connect the main channel to important floodplain wetland fish habitats. Floodplain wetlands provide a rich source of food to support larval growth and survival.
- provide significant improvements for native fish populations assessed in the Murray and Goulburn Rivers including up to 39% increase in *golden perch* abundance (Hume to Torrumbarry)
- provide improved opportunities for breeding and foraging by floodplain specialist species.
- result in increased opportunities for migratory native fish such as *golden perch* to move upstream and repopulate areas.

Waterbirds

- The relaxation of constraints and associated increase in the inundation of wetlands improves habitat (see vegetation outcomes above) and foraging opportunities for waterbirds.
- The Goulburn River has been identified as playing an important role in sustaining waterbirds during dry periods. The relaxation of constraints will improve waterbird abundance in dry years and therefore reduces the likelihood and scale of declines in dry periods.
- The modelling reveals up to 48% increase in waterbird abundance in Gunbower-Koondrook-Perricoota.

NSW Murray benefits extracted from the Reconnecting River Country project (NSW)

Vegetation

- Relaxation of constraints will;
  - approximately double (97% or 6,400ha increase) the area of wetlands that can be inundated by environmental water between Hume Dam and Wentworth at the highest constraint relaxation scenario
  - create three and a half times (257% or 57,600ha increase) the area of native vegetation that can be reached by environmental flows
- The ecological response modelling for the Murray River reveals that relaxation of constraints will;
  - increase the mean area of *river red gum* in good condition in Hume to Yarrawonga by 39%
  - increase the mean area of *river red gum* in good condition in Yarrawonga to Wakool by 16%
  - increase the area of healthy *river red gum* forest and woodland in dry periods by 50%
  - increase the resilience and reduce the decline in condition (75% less decline) of *river red gum* communities during extreme drought.

Waterbirds

- The greatest benefits of relaxed constraints to waterbirds were identified to occur in dry and drought conditions
- In the Barmah Millewa Forest, relaxed constraints at the highest relaxation scenario were found to result in;

- an 80% increase in waterbird density (based on the 25th percentile waterbird density)
- increased probability of colonial waterbird breeding including up to 17% improvement (in 25th percentile probability) for dry conditions

- In the Gunbower Koondrook-Perricoota Forest relaxed constraints were found to result in;
  - Up to 48% increase in total waterbird abundance.
  - Up to 34% increase in waterbird abundance in drier years (25th percentile waterbird abundance).

Potential ecological risks of relaxed constraints

<u>Carp</u>

- The relaxation of constraints has potential to create an increase in carp. To date, the occurrence of overbank flows, whether regulated or unregulated has varying effects on carp, but even in situations where carp have increased, there have still been environmental benefits, in part because juvenile carp are an important food source for waterbirds. This is based on existing literature, with future modelling recommended.

<u>Blackbox decline where constraints cannot water</u>

- Negative outcomes may be experienced at higher floodplain elevation vegetation communities such as *black box* – larger environmental water release rates create more air space in storages that may reduce the magnitude of spills during natural events, decreasing the magnitude of small unregulated overbank events. While the modelling found some loss in the area of *black box* community arising from constraint relaxation (518ha or 24% of the total area), that which remains was found to be in better condition than the do-nothing scenario and therefore in a better condition to withstand subsequent dry and drought conditions.

<u>Geomorphic assessment</u>

- The geomorphic assessment revealed the potential for relaxed constraints to reduce erosion. However, this outcome is at risk as a result of other drivers of ongoing bank erosion.

Summary

Introduction

Alluvium Consulting Australia Pty Ltd was engaged by Sequana Partners Pty Ltd to undertake the 'Assessment of Environmental Benefits and Risks' of relaxing constraints on the delivery of environmental water in the Murray River and Goulburn River. The assessment was undertaken to inform the Stage 1A Feasibility Study for the Victorian Constraints Measures Program. The Constraints Relaxation Program is being explored as part of a package of measures under the Basin Plan. The Feasibility Study was commissioned by Victoria's Department of Environment, Land, Water and Planning (DELWP).

This report documents the approach to and outcomes from the assessment of environmental benefits and risks associated with relaxing constraints on the delivery of environmental water in the Goulburn and Murray Rivers. The assessment forms part of the Stage 1A Feasibility Study, being the first stage of the Victorian Constraints Measures Program. As such it is not the role of the environmental benefits and risk assessment to identify the feasibility of the Constraints Relaxation Program, rather, to provide input to the Constraints Relaxation Program Feasibility Study.

A complementary project the 'Reconnecting River Country Program (RRCP) is currently underway, exploring the relaxation of delivery constraints in NSW, including the NSW side of the Murray River. The RRCP has modelling and investigations that this project has either drawn on, or replicated in order to develop a consistent approach across the two projects.

The scope of the investigations undertaken by the project team and documented in this report was developed by DELWP and informed by a Community Consultative Committee. Details of the Community Consultative Committee composition and engagement are reported elsewhere.

Note: This report has been prepared to contribute to the Stage 1 Constraints relaxation program feasibility study, to investigate the environmental benefits and risks of the constraints relaxation program. For the purpose of this investigation and report, the term 'risk' has been largely used to describe the potential 'disbenefits' of constraints relaxation. i.e. the investigation and report have sought to identify the ecological benefits and disbenefits of constraint relaxation. Risks to the attainment of program outcomes have also been explored.

The context for the Victorian Constraints Measures Program

River regulation and consumptive use of water have interrupted many of the natural river and wetland processes needed by native plants and animals to grow, reproduce, move and ultimately survive. River regulation has significantly modified natural river flow regimes, including the timing, duration, rates, and variability of flows. This modification has adversely impacted the condition of river systems, and the flora and fauna that depend on the system for survival. Overbank flows, a component of the flow regime, have been significantly modified with reductions in their frequency, extent, and duration, severing the connection between the river channel and the floodplains and wetlands.

Many monitoring studies are available to describe the current condition of the subject reaches. The Sustainable Rivers Audit (SRA) found the mid-slopes and lowland sections of the Goulburn River to be in very poor condition. The fish community was in extremely poor condition (with the Goulburn River valley ranked 17th out of 23 valleys) while vegetation was in poor condition (18th out of 23 valleys). The fish community was dominated by alien species with several native species missing and recruitment reduced among native species present. The vegetation community was reduced in abundance, fragmented, with increased alien species. The Victorian Index of Stream Condition (ISC) found the Goulburn River to be in moderate condition with reaches in best condition being in the headwaters. The mid-Murray region was rated as poor overall with the fish community also in very poor condition but the vegetation community being in good condition.

The Murray-Darling Basin Plan (the Basin Plan) was developed to improve the health of the river systems of the basin and its floodplains. Such improvements include efforts to reduce the impact of river regulation and consumptive water use on the frequency, duration and extent of overbank events.

Since implementation of the Basin Plan, environmental flows within the Goulburn River have been delivered in channel to enhance native fish spawning, reduce the extent of bank erosion, and enhance productivity and littoral vegetation. Floodplain watering with environmental water has been limited to icon sites. The provision of in-channel and icon site environmental water has been associated with movements and breeding of Golden and Silver Perch. While improvements in vegetation and productivity and fish spawning have been observed, these have not translated into changes in the macroinvertebrate community or increases in young-of-year fish.

In the Murray River channel, similar outcomes have been observed to those in the Goulburn River, with large variations in fish numbers from year to year, but no clear improvement in populations and increases in the proportion of invasive species (Brown and Whiterod, 2021; Raymond et al. 2018).

Constraints refer to physical and operational barriers that prevent environmental water being delivered to floodplains and wetland ecosystems. These constraints exist to protect private and public assets and land use, but they also limit the outcomes that environmental water holders and managers can achieve from using environmental water. By extension these constraints present a risk that the Basin Plan objectives will not be achieved. The Victorian Constraints Measures Program has potential to improve the environmental outcomes from environmental water delivery by 'relaxing' these constraints on environmental water delivery and enabling improved inundation of floodplain and wetland ecosystems.

The Constraints Measures program (CMP) is a component of the Murray-Darling Basin Plan being delivered by the State of Victoria. Stage 1A of the Victorian CMP aims to assess the feasibility of relaxing flow constraints, to enable system scale delivery of environmental water to the floodplain element of the river ecosystem.

The Basin Plan seeks healthy and resilient ecosystems with rivers and creeks regularly connected to their floodplains and, ultimately, the ocean. The Basin Plan also highlights the importance of connectivity where this refers to the movement of water between water-dependent ecosystems that comprise the larger system. This includes ground-water dependent, estuarine and marine ecosystems. These issues, identified in Chapter 5 of the Basin Plan, provide the foundation for our conceptual model of river systems.

A conceptual model of the river system

Flow is major determinant of habitat at a variety of scales. Over short periods of time, depth, current speed, and turbulence will influence the animals and plants that can occupy a site. Over longer periods of time, variations in flow including frequency, magnitude and duration of events will influence the capacity of biota to benefit or survive. Over larger scales, flow interacts with channel morphology and the landscape to create a mosaic of habitats that support diverse communities. Even apparently homogenous areas such as red-gum forests support a heterogeneous mosaic of understory plants that adapt and respond to cycles of flooding and drying.

In altering flows, regulation has changed the amount and availability of habitats while at larger scales, regulation and land use changes have affected the habitat mosaic with profound effects on the diversity of habitats and key processes that maintain the diversity. These processes include sediment erosion, deposition and disturbances to vegetation communities.

Without human intervention, hydrological connectivity is driven by gravity and so changes in flow manifest downhill as changes in connectivity. As a consequence, sequential changes accumulate as one moves downstream meaning that some of the greatest impacts on connectivity manifest at end of the system. The Coorong being a stark example.

Figure 1 *Hydrological connectivity and flows (MDBA, 2020)*

Broadly, connectivity is important for three reasons. First and most obvious is that it would not be possible to deliver water to water dependent ecosystems without transferring water from one part of the system to another. What is less obvious is that, in some areas, achieving appropriate connectivity requires coordinated delivery across multiple parts of the system. The Murray River in South Australia is a clear example of this where delivery of water to representative ecosystems is not possible without coordinated management of longitudinal connectivity through the Southern Connected Basin (SCB).

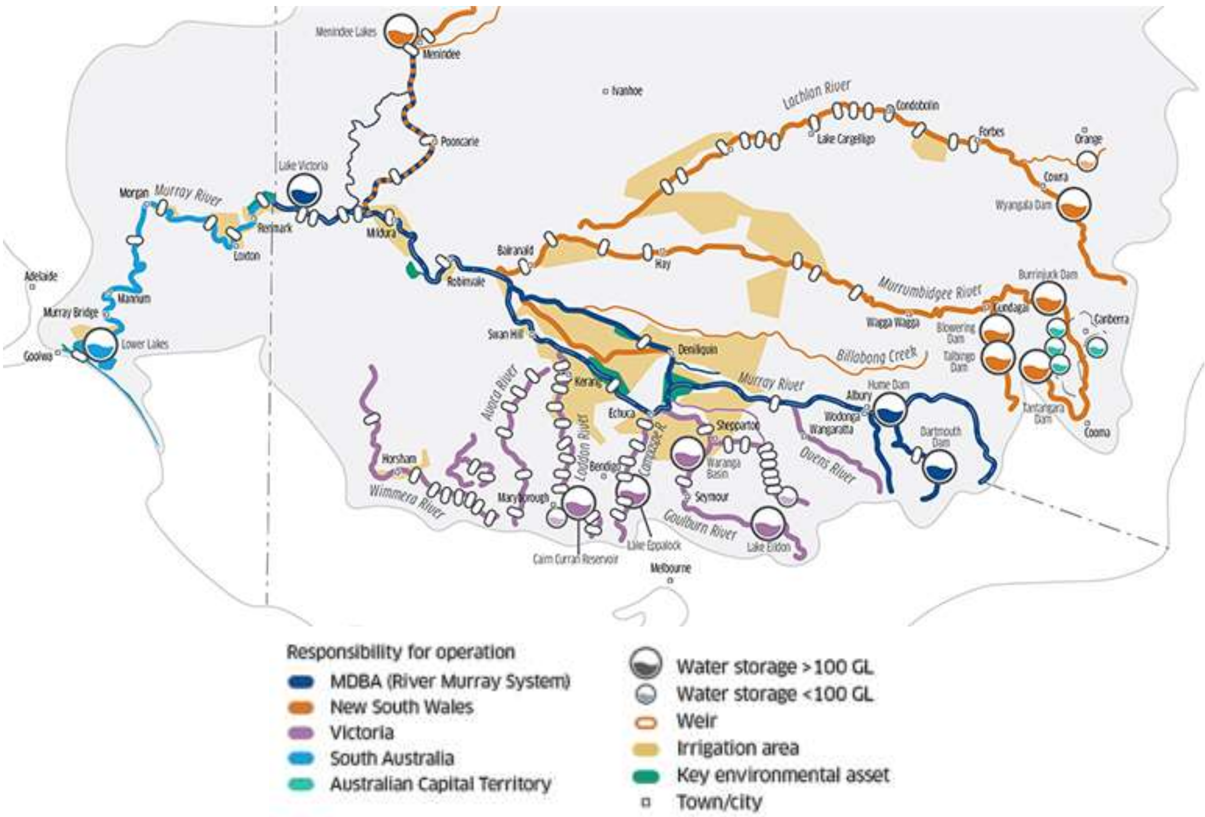

Figure 2. *Schematic of the Southern Connected Basin showing the importance of tributary flows (MDBA, 2020d)*

Hydrological connectivity is also important because of the processes it supports. Among these processes is the erosion, transport and deposition of sediment. These processes are heavily influenced by flow and contribute to the availability of habitat within channels and the floodplain mosaic. The erosion and deposition of sediment on floodplains drives soil formation which is one of the main reasons that much of Australia's most productive agriculture is located on floodplains. Hydrological connectivity is also important for nutrient and carbon cycles with ecosystems dependent on the subsidy that is carried into the ecosystem.

Finally, hydrological connectivity is important to the movement of biota through the system. Water-dependent ecosystems in Australia are characterised by cycles of boom and bust or disturbance and opportunity. Many species are dependent on the booms associated with flooding to maintain condition or reproduce. Connectivity is also important to resilience with biota dependent on flows to recolonise areas. Many plant species rely on flows to disperse their seeds, while flows are important for the dispersal of both adult and larval native fish.

From a system perspective hydrological connectivity provides the foundation for delivery of flows and the maintenance of key ecosystem functions that ultimately link all the water dependent ecosystems into a system that is a cohesive group of interdependent components.

Reaches and scenarios assessed

In this study, the potential to relax constraints has been explored on the Goulburn River, from Lake Eildon to the confluence with the Murray River. The Murray River has been assessed from Lake Hume to the junction with the Wakool River near Kyalite. For this assessment, both the Goulburn River and Murray River have each been divided into 2 reaches (Table 1 and Figure 3).

For this study, constraint relaxation scenarios have been developed to represent different potential levels of constraint relaxation. These scenarios have been developed to explore and better understand the potential environmental benefits and risks from constraint relaxation. The scenarios that were investigated for the Murray River were derived from those used for the RRCP to ensure (as far as practicable) consistency in the assessments with those that are already underway for NSW and allow the modelling and research that has been conducted for that project to be used to inform the Victorian assessment.

Figure 3 *Victorian Constraints study reaches*

A 'range-finding' process was completed by the project team and the University of Melbourne in consultation with Sequana and DELWP to identify a range of scenarios that could be investigated for the Goulburn River. Feedback from the consultative committee was used to refine scenarios.

The scenarios adopted for the investigations to support the feasibility study and this ecological benefits and risk assessment are set out in Table 1.

Table 1 *Investigation reaches and scenarios*

River	Reach	Current constraint (ML/day)	Scenario 1 (ML/day)	Scenario 2 (ML/day)	Scenario 3 (ML/day)	Scenario 4 (ML/day)
Goulburn	Mid-Goulburn (Eildon to Goulburn Weir)	10,000	10,000	10,000	12,000	14,000
	Lower Goulburn (Goulburn Weir to Murray)	9,500	17,000	21,000	21,000	25,000
Murray	Hume to Yarrawonga	25,000	25,000	30,000	40,000	40,000
	Yarrawonga to Wakool	15,000	25,000	30,000	40,000	45,000

A possible flow regime for the Goulburn River and for Murray River systems has been modelled by others for each of the constrain relaxation scenarios. The flow regime was modelled using the eWater Source software package and included the consumptive water demands and environmental water requirements for each of the stream systems.

The frequency, timing, and duration of overbank events included in the daily hydrologic modelling of the scenario's environmental delivery constraint[1] are set out in Table 2 below.

Table 2 *Frequency, timing, and duration targets*

River	Frequency	Timing	Duration of overbank flows
Goulburn	• Overbank environmental flow deliveries preferred once a year • In dry/drought years (around 1 in 4) this changes to in channel only • Therefore, one overbank event is preferred around 7 years in 10 • Managed overbank events would not be planned if a natural event has achieved the target that year	• July to October (winter and spring)	• 5 days at peak flow • Rise length around 6 days, fall beginning around 11 days
Murray	• Align with ecological requirements and pre-regulation flow patterns • Depends on season, storage volumes, tributary flows	• Mostly August to October, though occasionally earlier or later	• Will vary depending on flow size, water availability, river operations and environmental needs but mostly around 7 to 14 days at target flows • Occasionally up to 30 days for flows • Gradual recession to reduce erosion risk and stranding of fish

[1] While finalised daily timestep hydrologic modelling was available for the Murray River ecological assessments, only preliminary daily timestep hydrologic modelling was available for the Goulburn River ecological assessments. A qualitative assessment was undertaken to identify any implications arising from the final hydrologic model runs for the Goulburn River.

Investigation approach

This investigation has sought to identify the environmental benefits and risks associated with the implementation of the constraint relaxation scenarios proposed and the resultant related hydrologic regimes.

A limited set of ecological values or themes were assessed in this investigation. The investigations into the benefits and risks of relaxed constraints considered the following themes:

- Floodplain vegetation
- Instream water quality
- Instream productivity
- Instream macro invertebrates
- River and floodplain dependent fish
- Waterbirds
- Platypus and turtles
- Channel geomorphology / erosion rates

The approach estimated the likely reach scale and system-wide environmental outcomes of relaxing constraints. The assessment methods used a bottom-up approach based on our understanding of the environmental water requirements of individual species and processes contained within these themes.

The assessment approach has been based on the use of existing available ecological response modelling if and as available. No new ecological response modelling approaches were developed, although some existing approaches were adapted to suit the requirements of the project

The assessment process included quantitative modelling originally developed for the NSW RRCP. The investigation included:

- a review of the RRCP assessments methods and modelling outputs for Victoria's purposes on the Murray River and
- the application of the RRCP approach to assess impacts on vegetation and birds in the Goulburn River.

The Murray River modelling was originally conducted for the RRCP project, with the instream modelling (such as native fish response) directly informing this work, and the overbank results being either clipped to a Victorian extent (native vegetation which was clipped to NSW for the RRCP reporting) or recreated for a Victorian result. All the modelling and interpretation was then provided to the VCMP project by the teams that were part of the NSW RRCP project. This allowed efficiencies to be captured, and ensure best practice and consistency with the similar work in NSW. It also allows the results to be considered concurrently, particularly those with overbank dependencies, as ecosystem response is unlikely to be restricted by legislative boundaries.

The Goulburn River assessment also included stochastic ecological modelling developed by the University of Melbourne. The Goulburn River assessment therefore comprises multiple lines of evidence.

The investigations applied a suite of separate ecological response models that represent the best science currently available. This quantitative modelling involved the integration of:

- **Daily time step (hydrologic) water balance modelling** for the 'without development', 'base case (current constraints)' and individual scenarios. The water balance modelling was based on the demands for all water users and included environmental water demands (i.e., the timing, duration and frequency of these demands), including those sought for overbank inundation.
- **Hydraulic modelling of inundation extents.** Two-dimensional hydrodynamic hydraulic modelling has been undertaken to identify the extent of inundation under alternative levels of relaxed constraint.
- **Ecological response modelling.** Ecological response models developed by specialists for each of the values assessed, were applied to the modelled hydrologic regime arising from the proposed constraint relaxation scenarios. These ecological response models had been developed by the subject matter specialists, for previous related projects including Environmental Flow Assessment for the Goulburn River (University of Melbourne stochastic models) and the NSW Reconnecting River Country Program. The ecological response

models are based on research and monitoring into the behaviour and response of Australian ecosystems to flood events, the delivery of environmental water and to spells between events including droughts.

Where gaps were identified, the modelling was supplemented by semi quantitative and qualitative assessments by experts in that that field of science.

Assessment outcomes

The assessment found that substantial environmental benefits can be expected from the relaxation of constraints. These benefits are spread widely across the landscape and across the themes assessed. These benefits occur within each reach assessed but also cumulatively across the whole system.

The assessment also identified some ecological risks (potential disbenefits) associated with the relaxation of constraints. These risks include the potential for carp breeding and a potential reduction in spill events that provide watering to outer extents of floodplain vegetation communities.

- Carp: There is some risk that an increase in the occurrence of overbank inundation provides increased opportunity for carp breeding. However, other investigations identified that the risk of carp breeding can be managed through the timing and duration of events. While it is expected that this issue can be managed it is recommended that this issue be the subject of further investigation.
- Reduction in uncontrolled spills: Greater use of the environmental water portfolio is likely to occur as a result of relaxed constraints. Greater use of the environmental water portfolio has been identified to lead to a reduction in the uncontrolled spills. Uncontrolled spills have been identified to provide benefits to the outer edges of floodplain vegetation communities that will not be serviced by the relaxed constraint scenarios assessed. Some loss of this outer lying vegetation is expected. However, this impact (disbenefit) is more than offset by the benefits to larger areas of floodplain vegetation watered as a result of relaxed constraints.

On balance, the ecological benefits identified from the investigations have been identified to overwhelmingly outweigh the identified disbenefits.

Importantly the benefits of relaxed constraints are contingent on achieving overbank inundation. Indeed, the assessments reveal that the more constraints are relaxed, the greater the benefit. Conversely, relaxation of constraints without achieving overbank inundation is unlikely to achieve significant ecological benefit. In the scenarios where constraints are relaxed to the level that allows significant inundation of the floodplain, the benefits to the whole ecosystem are maximised. The role that the floodplain has in sustaining habitat, ecosystem functions and resilience is critical to achieving Basin Plan objectives. From an ecosystem functions perspective, floodplains are an important influence on food-webs which affect floodplain, riparian and downstream river reaches.

Vegetation benefits and risks

The project sought to assess the feasibility of relaxing constraints based on our understanding of the effects increased high flows on the condition of water dependent vegetation.

Up to 50,000 ha of native vegetation communities in Victoria would potentially benefit from the relaxation of constraints to the highest levels explored in this assessment across the three river reaches.

In the Goulburn River a 3-fold increase in the area of vegetation inundated with environmental water is possible as a result of relaxed constraints, with inundation extending from approximately 1,280 Ha to almost 7,200 ha. In the Yarrawonga to Wakool reach of the Murray River a 4-fold increase in inundation extent is possible in Victoria, with the potential for over 30,000 ha of semi-aquatic and terrestrial flood-adapted vegetation to benefit from relaxed constraints (Figure 4).

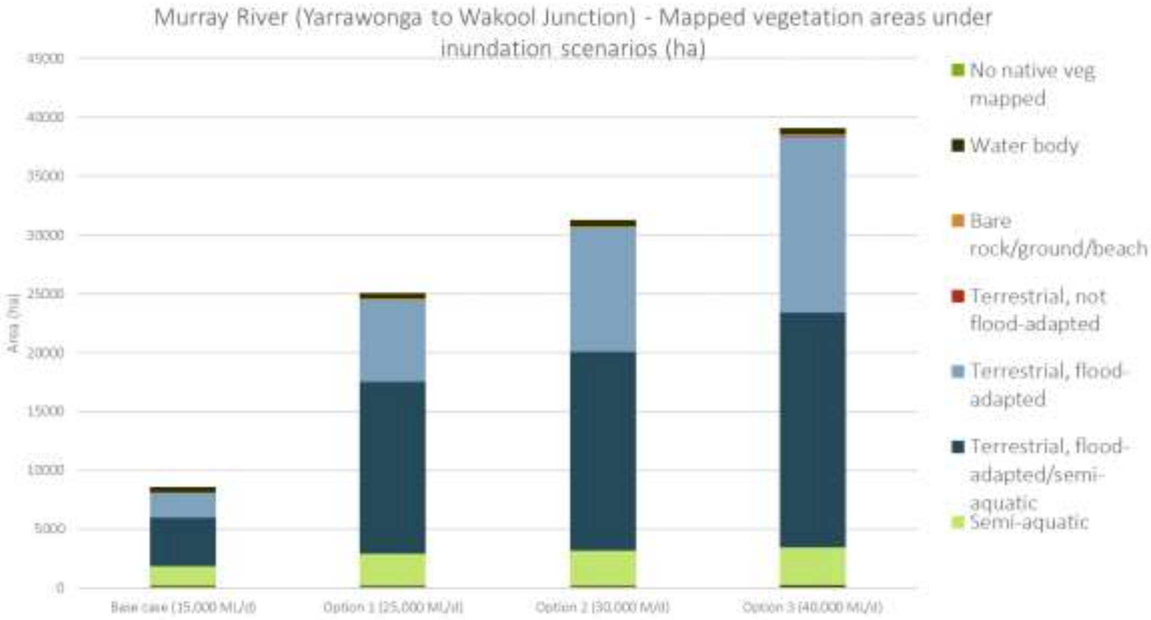

Figure 4 *Murray River (Hume to Wakool Junction) – Mapped vegetation areas under inundation scearios*

Improving resilience was found to be a further benefit. Relaxing constraints will increase the proportion of water-dependent vegetation communities held in good condition between dry spells. This helps to keep the vegetation communities out of the critical condition status (i.e., 'near death') and increases the likelihood of surviving extended dry periods. This is demonstrated in the results of the state transition vegetation modelling (Figure 5). The state transition modelling revealed that the relaxation of constraints in both the mid and lower Goulburn River were needed to produce an increase in the area of vegetation held in good and average condition. Relaxation of constraints in the Lower Goulburn River without relaxation of constraints in the Mid Goulburn River produced marginal outcomes for river red gum and resulted in a decline in black box woodlands in good and average condition. Only the relaxation of constraints in both the mid and lower Goulburn produced benefits in both river red gum and black box.

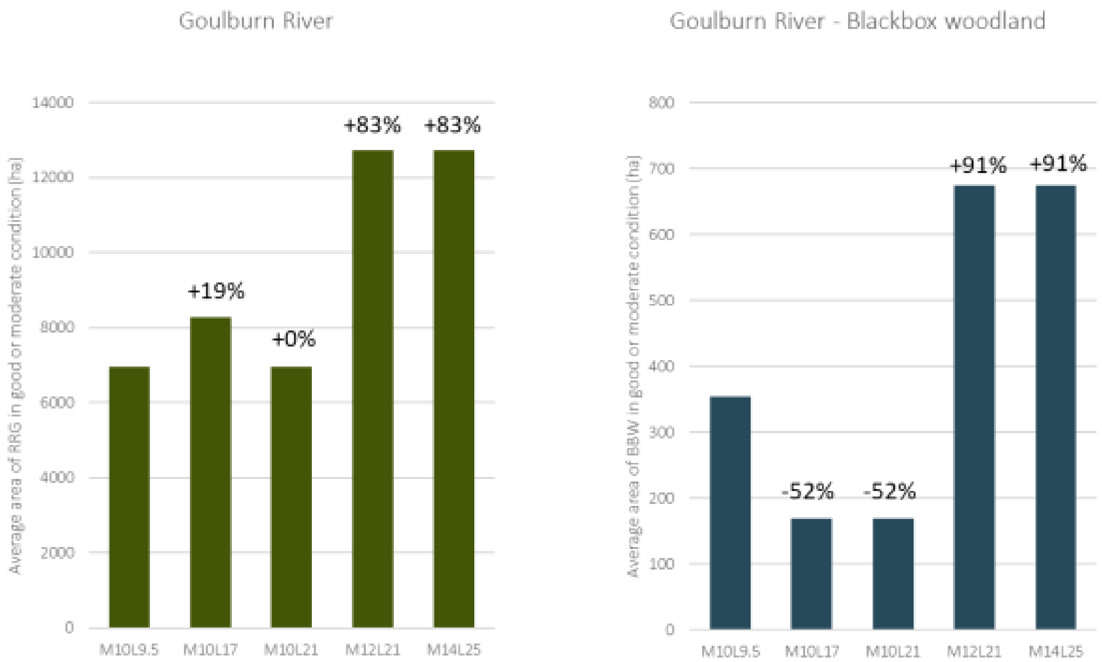

Figure 5 *Average area of vegetation in good or moderate condition in the Goulburn River: Note different vertical scale for RRG and BBW figures*

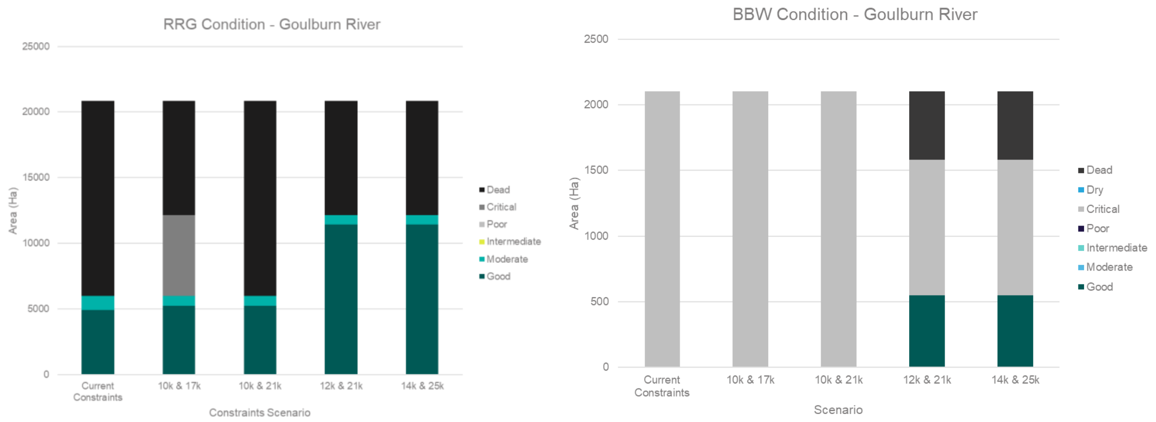

Figure 6 *End state condition for Goulburn River river redgum and black box communities. Note the different axis values across the two graphs*

However, relaxation of constraints up to 25,000 ML/day does not meet the environmental water requirements of all flood-dependent vegetation. On the Goulburn River floodplain, there will be areas of vegetation (red gum and black box) that would not receive environmental water, delivered under any of the constraint relaxation scenarios assessed. These vegetation communities require greater flow rates to achieve inundation than that assessed. This vegetation is influenced by uncontrolled spills from Lake Eildon, rainfall and groundwater. The assessment found that uncontrolled spills will be less frequent under the highest levels of constraint relaxation due to the targeted, more effective releases of environmental water. It is likely that mature trees in these areas may persist without these spills, however, long-term population viability beyond the extent watered as a result of relaxed constraints will be at risk given the role of floods in tree recruitment. Similar outcomes may occur in the Murray River. Figure 7 shows the results of the ecological modelling undertaken for this project on the Goulburn River for black box communities. This figure shows the expected good condition of black box vegetation under relaxed constraints, and the accompanying loss of vegetation with the loss of spill events.

Ultimately, the vegetation modelling results indicated that the relaxation of constraints will improve the overall condition of floodplain vegetation. Benefits in the higher relaxation scenarios are focussed on the areas of controlled inundation, with a likely reduction in uncontrolled spills. This would keep vegetation in a more resilient condition, with the trade-off being the outer areas (i.e., further from the channel) that would only be watered during unregulated floods from spills. The areas inundated by controlled releases would be expected to benefit in two ways. The primary benefit is a general increase in the areas that would spend time in good condition, which is a result of a reduced period in the poorer condition state or reduced areas dying off completely. The secondary, though related, benefit is through the greater resilience of the surviving vegetation. The increased average time on the good condition state is supported by the reduction in variation of the results. Vegetation appears more likely to lift to good condition and remain there, built off the more frequent capacity to water overbank areas. Watering from spills would only keep vegetation in a critical condition (rather than the more resilient 'good' condition) making them extremely vulnerable to complete die off in drought events.

This better condition and more resilient vegetation is important because the condition of vegetation communities has direct consequences for animals that rely on that vegetation for habitat and food. Fauna that would benefit would include reptiles, bush birds and waterbirds who rely on healthy vegetation to roost and nest.

The vegetation results suggest that the relaxation of constraints will make a substantive contribution to achievement of Basin Plan objectives by improving lateral connectivity and restoring floodplain habitats.

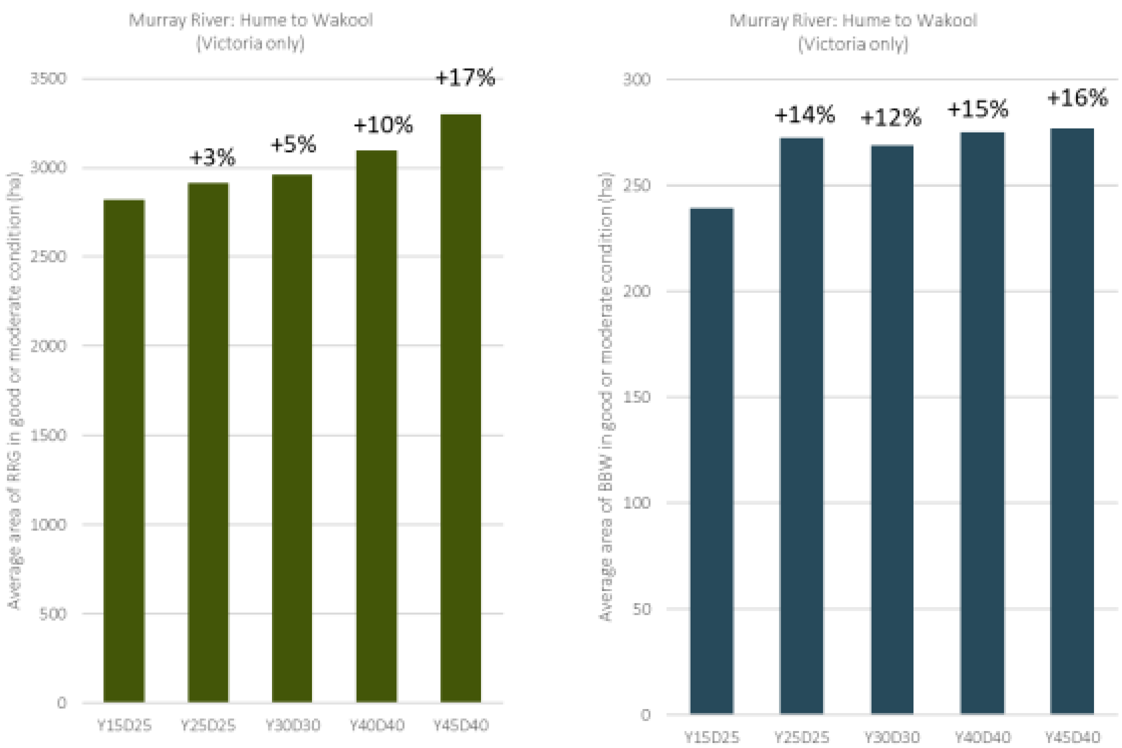

Figure 7 *Average area of RRG and BBW in good or moderate condition – Murray River Hume to Wakool: Note different vertical scale for RRG and BBW figures*

Water quality benefits and risks

The assessment did not identify any additional disbenefits associated with relaxing constraints as proposed and assessed. There are existing and potential water quality risks associated with the return of carbon and nutrients from the floodplain into the river systems in the peak of summer. The management scenarios considered here seek the delivery of environmental water delivery in winter and spring and include the return of organic matter and nutrients to the channel which will influence productivity in downstream reaches and assets. Management of environmental water does not include inappropriate summer floodplain inundation. As a consequence, any risks arising from summer inundation of floodplains is not linked to the management of environmental flows.

Within this context, relaxing constraints will provide regional biodiversity and productivity outcomes through effects on habitat and connectivity and system scale outcomes in terms of the movement of nutrients and organic matter in ways that will not pose a risk to downstream systems.

Instream production and macro invertebrate benefits and risks

The assessments revealed improvements in instream productivity associated with increasing level of constraint relaxation. This benefit reflects the increased, timely, carbon input to the stream system. The expected productivity increase on floodplains was not assessed but is expected to be significant due to its effects on the growth of algae, understory plants and trees.

The University of Melbourne Stochastic modelling explored the outcome for macro invertebrates. This assessment identified improvements in macro invertebrate populations associated with the relaxation of constraints in both the Mid and Lower Goulburn River. Similar outcomes could be inferred for the Murray River reaches. No significant risks were identified. Like the instream production assessment, the University of Melbourne stochastic macro invertebrate modelling for the Goulburn River only assessed in-channel macroinvertebrate communities, and so, this is also likely to under-estimate the benefit of relaxed constraints given that large areas of macroinvertebrate habitat would be created in wetlands and floodplains and that these invertebrates provide a food resource for bush- and waterbirds. There is abundant data from around the world to suggest that delivery of flows to floodplain and wetland ecosystems is associated with a boom in productivity that supports a range of predatory bats, birds, frogs and reptiles.

The assessment has found that that the restoration of lateral connectivity will lead to benefits for food webs locally and regionally with increases in the amount and quality of habitat and increased productivity. The regional outcomes will also contribute to system scale outcomes through the contribution of organic matter and nutrients to downstream systems and also in supporting bird populations whose health is influenced by large scale habitat availability.

Fish benefits and risks

The assessments predicted significant benefits for some fish species in the Goulburn and the Murray Rivers. However only limited benefits were identified for some large, bodied fish.

In the Murray River, the ARI modelling approach adopted for the RRC Program found the periodic flow pulse specialist Golden Perch to benefit to some extent, while the equilibrium species Murray Cod showed no improvement (Figure 8 and Figure 9). In the Hume to Yarrawonga Reach and the Yarrawonga to Torrumbarry Reach of the Murray River, up to 39% increase in expected mean population size of Golden Perch, and up to 28% increase from Torrumbarry to Wakool. Similar results were found for the Goulburn River.

The University of Melbourne stochastic modelling for the Goulburn River identified some benefit to all three guilds of fish assessed – Equilibrium (e.g., Murray Cod), Opportunistic (e.g., native carp gudgeon and Australian smelt) and Periodic (e.g., Golden Perch).

The difference between the University of Melbourne stochastic modelling result and the RRC based modelling results can be attributed to

1. the University of Melbourne stochastic modelling using a more complex food web that includes greater links and response to instream production, and
2. the RRC Program modelling assuming a lower level of reliance on river flow for spawning and recruitment for Murray Cod and Golden Perch.

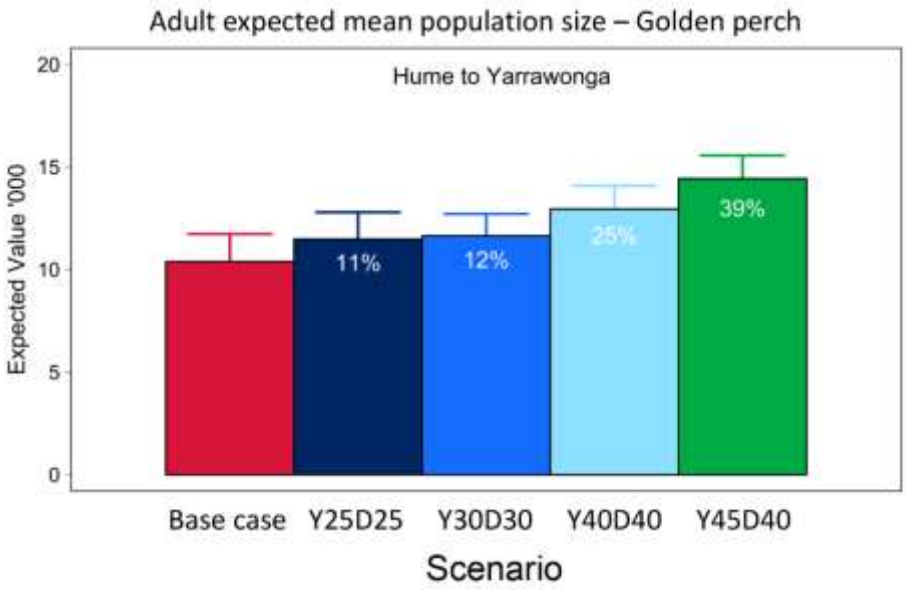

Figure 8 *Modelled Golden Perch in the reach Hume to Yarrawonga for the base case and four constraints flow scenarios. Expected mean population size with % change from Base case shown in each bar. Error bars are one standard deviation (Todd et al. 2022)*

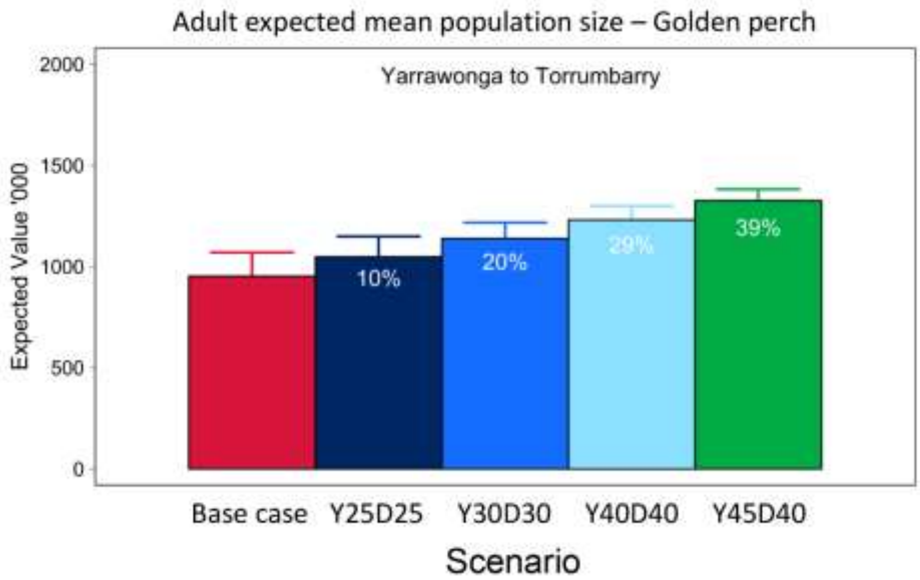

Figure 9 *Modelled Golden Perch in the reach Yarrawonga to Torrumbarry for the base case and four constraints flow scenarios. Expected mean population size with % change from Base case shown in each bar. Error bars are one standard deviation. (Todd et al. 2022)*

The relationship between flow and fish populations is complex due to the multiple pathways by which flow can influence different aspects of each species' life history. Despite this, the modelling found improvements in species populations (RRCP) and outcomes (University of Melbourne) for floodplain dependent species associated with the relaxation of constraints. There are a number of areas of uncertainty that should be addressed around the benefits to fish communities. Among these is the influence of changes in longitudinal and lateral connectivity of fish movements both regionally and across the SCB. Improved understanding will be important in the next stage and also to provide advice to environmental flow managers. Further investigations are also required into the potential for relaxed constraints to benefit Carp reproduction and populations.

Waterbird benefits and risks

The waterbird assessment found that relaxing constraints favours some species but results in some decline in others. The assessment found that while waterbird abundance would significantly improve in dry years, there was no overall improvement in waterbird abundance.

Perhaps most importantly, the modelling revealed that the minimum population size would increase, and this has a number of population implications. First, when breeding opportunities arise, there will be better population responses. Second, modelling found high mortality rates suggesting they are vulnerable to changes in the frequency of breeding events. Improvements in foraging habitats on floodplains may reduce mortality rates and act as a buffer to declines in breeding in the southern basin.

The change in risks associated with waterbird breeding and abundance are difficult to link to a specific location given the migratory patterns of many bird species, however the more locations that the waterbirds are able to use as habitat, the greater chance that species have of avoiding irreparable decline. This is shown in the modelling results, with the greatest impact of relaxed constraints being a reduced likelihood of poor outcomes for birds. By providing more waterbird species with greater areas for habitation, the better chances they have of maintaining or growing species numbers.

The relaxation of constraints in the Goulburn River needs to be considered within the context of the whole system because waterbird populations respond to large (basin or continental) scale changes in habitat availability. The investigation revealed that the Goulburn River floodplain may play an important role in sustaining waterbirds during dry periods. This finding and outcome may be important for the attainment of Basin Plan targets and meeting national treaty obligations. The Murray River reach from Yarrawonga to Wakool is acknowledged as supporting waterbird populations and the assessment confirmed that relaxation of constraints appears to be appropriate and beneficial for waterbird populations.

Platypus and turtle benefits and risks

Platypus and turtle benefits and risks were only modelled in the Goulburn River. The results were mixed, possibly reflecting the greater uncertainty around the flow requirements of platypus and turtles and comparatively low data availability. Increases in productivity and invertebrates are expected to improve conditions for platypus and turtles. However, the modelling identified risks for both platypus and turtles related to the influence of high flows on nest success.

In the case of platypus, high flows over the breeding season have the potential to inundate nesting burrows. However, there remains considerable uncertainty around this hypothesis. Firstly, these species have evolved and or adapted in this region to annual winter and spring flood events. While platypus monitoring programs have identified breeding may start as early as August (and therefore impacted by winter spring inundation), there are observations from Tasmania and Victorian high country of breeding starting in October (and therefore not impacted by winter and early spring inundation). The hypothesis also appears inconsistent with observations that platypus populations have dramatically decreased over the last three decades at the same time that river regulation has reduced winter spring flow events. This raises questions about how platypus respond to changes in flow. It is possible that platypus take cues from winter flows when locating and constructing their burrows. Environmental flow managers may need to consider antecedent flows (e.g. bank full events) when planning overbank inundation events to mitigate the risk of impacting nesting burrows.

The University of Melbourne models made similar predictions for turtles. All three species of turtle were modelled together which may increase uncertainty around the modelled forecasts, given that each species has different breeding habitats. There is also evidence that some species of turtle use flows as a cue for nest site selection.

For both platypus and turtles, managing the timing of flow events and the quality of bank habitat may be the most effective ways a constraints relaxation program can influence the availability of suitable nesting sites and success of breeding.

Overall, the modelling provides a cautionary message about potential risks to these two important values. This risk needs to be considered within the broader context of how these species have evolved and persisted in these systems for millennia, including the way they have adapted to late winter and spring events. Further investigations including the identification of the risk triggers and responses through ongoing research, monitoring and adaption of environmental water delivery programs is recommended, rather than using these risks as a basis to not proceed with the further development of relaxed constraints.

Geomorphology benefits and risks

River regulation has been identified as a major factor in stream related erosion in the Goulburn and Murray River systems. River regulation stores high flow events, that may have created overbank events, in winter and spring, and delivers this water in-channel over the summer irrigation season. Stream flows apply force to (or 'work' on) the bed and banks of the river and on the floodplain. The process of river regulation decreases the occurrence of overbank events and associated expenditure of the energy on the floodplain with a complementary increase in energy expenditure in the river channel. By increasing the occurrence and duration of in-channel flow events, river regulation has increased the potential for energy expenditure in the river channel including the riverbank. This can lead to increased rates of channel erosion in regulated rivers. Returning or increasing the occurrence of overbank events, redistributes this energy to the floodplain and can reduce the rate and extent of bank erosion.

There is evidence of accelerated rates of erosion in both the Goulburn River and Murray River. This has been attributed to river regulation and other factors such as boat wake and bed load sediment starvation downstream of Lake Hume.

The investigations undertaken for this environmental benefits and risks assessment sought to assess the amount of excess energy in the river system to 'do work' on the banks of the Lower Goulburn River. The assessment found that the current flow regime has increased the erosion potential compared to the 'without development' flow regime. Relaxing constraints to increase the occurrence of overbank events was found to reduce the bank erosion potential. The investigations were limited in extent and further work on the erosion potential is warranted.

An assessment of erosion potential in the Murray River system was beyond the scope of the investigation. However, a review of the occurrence of overbank events in the Murray River under current and alternative levels of relaxed constraints revealed the potential to reduce erosion in the Hume to Yarrawonga Reach. The benefits in the Yarrawonga to Wakool reach of the Murray River are more limited but may be significant in reaches such as the Barmah Millewa Forest.

Constraints relaxation has some potential to indirectly increase erosion risk from boat wake. It has been noted that during the Millennium drought low water levels in lakes and high levels in rivers (due to irrigation flows) led boater/skiers transitioning their boating activities from lakes to rivers. High river levels arising from relaxed constraints also has the potential to encourage increased boat use and resultant boat wake. The issue of boat wake and its management is discussed under complementary measures.

In terms of benefits and risks, the assessment found no evidence to suggest that the relaxation of constraints would increase erosion risk in the lower Goulburn and Murray Rivers. To the contrary, the investigations revealed that relaxing constraints would reduce erosion potential. However, the assessments were limited in scope and further investigations should be undertaken to explore the implications of relaxed constraints on bank erosion and anabranch development in the subject reaches and river systems.

Climate change and constraints

All constraints study reaches are predicted to experience a warmer and drier future climate, with increased likelihood of extreme droughts and floods. Such changes are predicted to negatively impact on hydrological metrics in both rivers, causing substantial decreases in mean annual flows, overbank events, and freshes and increases in cease-to-flow events. Climate change represents significant risks for ecological outcomes with the condition of ecological values expected to decline as the climate warms and dries. Environmental water shortfall volumes are also expected to increase under climate change as tributary flows and entitlements decrease. The investigations have revealed that constraint relaxation has the potential to significantly (although not completely) offset declines in ecological outcomes arising from climate change. The relaxation of constraints will be particularly important for supporting the resilience and climate adaptation of ecological values to future climate impacts.

Reach based synthesis

Following the theme-based assessments (ecological values and processes) and the synthesis of the interactions, the assessment of constraints scenarios has been collated to document the benefits and risks within each of the study reaches.

For the Goulburn River (Table 3), the assessments showed that the base case scenario, where no change to constraints is made, provides the highest risk scenario for the environmental themes assessed. The condition of vegetation, the instream ecosystem led by production and fish, and the erosion risk in the base case scenario shows a high likelihood of degradation (in line with the observed decline of the system). The scenario assessments have revealed 'step changes' as constraints are relaxed. Some benefits can be expected in the lower relaxation scenarios, but it is only once significant floodplain engagement occurs, via constraints relaxation, that ecosystem recovery is possible.

The lower relaxation scenarios (e.g., M10L17 and M10L21) have the capacity to slow some of this decline, though still pose some risk. These lower constraint relaxation scenarios in the Goulburn River pose risks for Black box communities. Some of the elements within the system, such as native fish, would see improvement against the base case, with other benefits such as river red gum vegetation mainly benefiting from uncontrolled spills from storage rather than controlled delivery. It is not until the higher scenarios with greater inundation of the floodplain that a reversal of the decline is possible and benefits for black box communities are achieved. These higher constrain relaxation scenarios allow a more resilient ecosystem to be maintained, providing opportunity for the mosaic of native species to endure future drought events and climate change pressures.

The results for the Murray River (Table 4 and Table 5) were very similar to those in Goulburn. The base case scenario with no change to constraints poses the highest risk to the Murray River ecosystem. The relaxation of constraints has potential to mitigate some of this risk for floodplain and river vegetation, particularly in the

Hume to Yarrawonga reach. The investigations reveal that the higher relaxation scenarios provide the greatest benefits.

The current condition of the subject waterways and related ecological values is poor, with indications of ongoing decline. The assessments undertaken for this assessment reveals that the base case scenario (no change to constraints) will lead to ongoing decline in condition and potential for accelerated loss under expected climate change. The base case (do nothing more) scenario has the greatest level of ecological risk (disbenefit) of the scenarios assessed.

The evidence provided by the investigation reveal the ecological benefits overwhelmingly outweigh the identified disbenefits of relaxed constraints. The risks include potential increases in carp breeding opportunities, and vegetation loss on the outer margins of the areas that can be watered under relaxed constraints. These disbenefits require further investigations together with remaining unknowns arising from the investigations. However, these disbenefits do not outweigh the substantial ecological benefits of constraint relaxation. The disbenefits and uncertainties identified with a constraints relaxation program should be areas for further investigation under an ongoing program of work aimed at securing and delivering relaxed constraints in the Goulburn and Murray River systems.

Table 3 *Summary of outcomes – Goulburn River*

Theme	Summary of outcomes of relaxing constraints, compared to base case
Hydrologic connectivity	Improved longitudinal connectivity with up to 9% increase in August flows at Shepparton. Up to 4% increase in flows in July and October. Changes in lateral connectivity assessed via themes below
Vegetation quality	Relaxation of constraint to low levels (less than 22,000ML/day) likely to provide some support to native vegetation but likely to remain vulnerable. High relaxation will allow targeted vegetation to be held in good condition, though some sacrifice of fringe areas as a result of reduced spills. Significant improvements in black box and river red gum will require relaxation of constraints in both the mid and lower Goulburn
Vegetation quantity	Increased inundation of semi-aquatic, terrestrial flood-adapted/semi-aquatic, and terrestrial flood-adapted ecological vegetation classes in the Mid Goulburn and Lower Goulburn River. Negligible inundation of terrestrial (not flood-adapted) vegetation.
Production	Negative impacts on production (compared to base case) if constraints are relaxed below 22,000 ML/day. Increased production (compared to base case) above 22,000 ML/day, as floodplains are engaged.
Water quality	Relaxation of constraints as proposed and assessed is unlikely to adversely impact on any water quality parameters in this reach
Macroinvertebrates	Benefits to macroinvertebrate biomass and diversity are predicted if constraints in Mid Goulburn are relaxed above 11,000 ML/day and lower Goulburn constraints are relaxed above 21,000 ML/day
Native fish	Benefits for equilibrium, periodic and opportunistic fish increase with progressive relaxation of constraints up to ~20,000 ML/day in the Lower Goulburn River and ~12,000 ML/day in the Mid Goulburn River. Sustained benefits above these flows. Benefits to large fish such as Murray Cod are limited, however floodplain specialists are expected to significantly benefit from relaxed constraints that enable proposed frequency of floodplain inundation.
Waterbirds	Mixed outcomes are predicted for waterbirds. Increased median probability of waterbird breeding (up to +5%), +12% overall probability of waterbird breeding with relaxation of constraints. Decreased chance of large breeding events by up to 11%, but an increased chance of small breeding events by 11%. Overall reduction of long-term breeding occurrence by 3% with relaxation of constraints. Declines in long-term average waterbird abundances with relaxation of constraints, particularly for Large Waders (13% decline in 90th percentile, increased 25th percentile by 14%)
Platypus	Disbenefits have been identified if Lower Goulburn constraints are relaxed above 22,000 ML/day during nesting periods. Platypus have evolved and adapted to winter and spring overbank inundation. Potential disbenefits are unlikely if events occur outside nesting season. The timing of environmental flow delivery is important. Nesting is expected to improve with reduced bank erosion.
Turtles	Negative impacts on turtle populations are predicted if overbank events occur during critical nesting periods. The timing of environmental flow delivery is important.
Geomorphology	Decreased erosion is predicted as constraints are relaxed in the Lower Goulburn. Relaxation of constraints at above 12,000 ML/day (creating overbank flows) in the Mid Goulburn is also expected decrease erosion potential

Table 4 *Summary of outcomes for the Murray River – Hume to Yarrawonga*

Theme	Summary of outcomes of relaxing constraints, compared to base case
Hydrologic connectivity	No adverse impacts to longitudinal connectivity. Lateral connectivity assessed through the themes below.
Vegetation quality	Both black box woodland and river red gum forests/woodlands were responsive to the relaxation of flow constraints. Broad benefits of constraint relaxation to higher flow scenarios were representative of greater areas of woody species in good condition and reduced areas in critical condition
Vegetation quantity	Over 2,289 ha of additional vegetation (81% increase) inundated through relaxation of constraints compared to base case, including 1562 ha terrestrial flood-adapted vegetation (154% increase), and 447 ha terrestrial flood-adapted semi-aquatic vegetation (77% increase). A negligible (1ha) of terrestrial not flood-adapted vegetation inundated at the highest constraint relaxation scenario.
Production	Up to 2% increase in mean annual production potential
Water quality	Relaxation of constraints as proposed and modelled is unlikely to adversely impact on any water quality parameters in this reach
Macroinvertebrates	Not directly assessed. Macroinvertebrate production is expected increase in response to constraint relaxation.
Native fish	Up to 39% increase in expected mean population of Golden Perch. No change to Murray Cod population size with relaxation of constraints. Floodplain specialists are expected to significantly benefit from relaxed constraints that enable the proposed frequency of floodplain inundation.
Waterbirds	Not assessed – significant waterbird sites in Murray River are located downstream of Yarrawonga.
Platypus	Not assessed
Turtles	Not assessed
Geomorphology	Decreased erosion potential expected when constraints are relaxed to 30,000 ML/day and higher.

Table 5 *Summary of outcomes for the Murray River – Yarrawonga to Wakool*

Theme	Summary of outcomes of relaxing constraints, compared to base case
Hydrologic connectivity	No adverse impacts to longitudinal connectivity. Lateral connectivity assessed through the themes below.
Vegetation quality	Similar results as seen in the Goulburn, however the rate of decline may not be as rapid due to tributary flows supporting vegetation communities
Vegetation quantity	An additional 30,000 ha (xixpprox..) of vegetation will benefit, including 15,000 ha (xixpprox..) of terrestrial flood-adapted/semi-aquatic vegetation and 13,000 ha (xixpprox..) terrestrial flood-adapted vegetation. A potential disbenefit of a relatively negligible 19ha of additional not flood-adapted terrestrial vegetation may be inundated.
Production	Up to 15% increased mean annual production potential.
Water quality	Relaxation of constraints as proposed and assessed is unlikely to adversely impact on any water quality parameters in this reach
Macroinvertebrates	Not directly assessed. Macroinvertebrate production is expected increase in response to constraint relaxation.
Native fish	Up to 39% increase in expected mean population size of Golden Perch from Yarrawonga to Torrumbarry. Up to 28% increase Golden Perch population between Torrumbarry to Lock 10. No change to Murray Cod population size with relaxation of constraints. Floodplain specialists are expected to significantly benefit from relaxed constraints that enable the proposed frequency of floodplain inundation.
Waterbirds	4-5% increases in median waterbird species richness and 10-13% increase in waterbird density in Barmah-Millewa Forest. Up to 11% increase in probability of colonial waterbird breeding in Barmah-Millewa Forest with relaxation of constraints. 1-4% increase in the median number of species, and 8-48% increase in median waterbird abundance in Gunbower Koondrook-Perricoota Forest with relaxation of constraints.
Platypus	Not assessed
Turtles	Not assessed
Geomorphology	Decreases in erosion potential are expected as constraints are progressively relaxed beyond 25,000 ML/day.

Knowledge gaps, further investigations, and complementary measures

Knowledge gaps and further investigations

The Feasibility Study Environmental benefits and risks assessment has identified knowledge gaps that have potential to impact on the scale of beneficial outcomes sought and identified. Further investigations that would improve the confidence in the assessments and the benefits are set out below.

System scale implications

The river system conceptual model includes both the mosaic of ecosystems within a reach and their influence on the functioning of the whole system, facilitated or moderated by hydrological connectivity. Due to limited capacity to model system scale interdependencies, this assessment has focussed on modelled ecosystem responses within the reaches, and a qualitative assessment of outcomes across the system. Improving our system scale understanding of interdependencies and responses to environmental flow management will be increasingly important to the implementation of the Basin Plan as managers apply adaptive management approaches to the provision and delivery of environmental flows.

Invasive carp

Carp are an existing threat across the Murray Darling Basin and readily respond to overbank flows. This is an existing threat across the study reaches. Relaxation of constraints will benefit targeted native species, but may also favour carp. Limits on the duration of floodplain events may limit the benefits to carp and related risks to the river system.

While carp pose a risk to the health of the river system, this risk does not warrant a cessation in further investigation into and development of a constraints relaxation program.

It is noted here though that the potential response of carp has not been included in the modelling for this feasibility stage assessment (or the RRCP at the time of writing) as no functional ecological response model was available for the investigations. It is recommended that the potential carp response to relaxed constraints be further investigated including the development and application of ecological response model to enable exploration of environmental flow regimes that maximise opportunities for native species while limiting the benefits for carp.

Platypus and turtle models

The investigations have revealed uncertainties in the platypus and turtle models. Further work is required to refine and update these ecological response models to reflect;

1. the requirements of individual species (turtles) and
2. research into platypus response to antecedent conditions and overbank inundation in winter and early spring.

Geomorphic impacts/ bank erosion

The scope of the investigation limited the extent of investigations that could be undertaken into geomorphic processes such as bed and bank erosion and anabranch development. Further investigations are required to confirm the preliminary outcomes identified in this report and to pursue issues not examined such as the potential for anabranch development e.g., in the Hume to Yarrawonga reach of the Murray River

Complementary measures

There are ongoing issues beyond the scope of this investigation, within the subject stream systems that have the potential to limit or risk the outcomes sought via relaxed constraints. These issues are discussed below and should form a part of a program of work to complement a constraint relaxation program.

Grazing risks

Riparian areas are vulnerable to grazing pressures as they are often fertile and provide easy access to drinking water. Grazing is one of the major causes of riparian degradation and has significant impacts on riparian function and biodiversity.

Grazing stock causes reductions in vegetation cover, biodiversity loss, streambank erosion, water eutrophication and degradation of instream processes (Lunt et al. 2007). It can also contribute to increased sediment loads delivering to the waterways when livestock access the riverbanks and accelerate instream and bank erosion. Grazing of riparian lands has the potential to undermine some of the outcomes sought from constraints relaxation. Measures aimed at expanding existing efforts to control stock access to riparian frontages on the Goulburn and Murray River systems should be explored to complement the outcomes sought through a constrain relaxation program.

Invasive vegetation

Invasive vegetation has the potential to undermine the expected benefits of relaxed constraints. Flow pulses have the potential to disperse invasive vegetation seeds to a wider area and provide water to support the germination and establishment of such species. With riparian areas already subject to pressures from anthropogenic activity such as vegetation clearing, erosion from flow regulation and river activity and biodiversity loss, invasive vegetation can further disrupt the system, particularly in riparian areas.

Managing weeds across the rivers is a complex issue that is likely to be influenced by multiple sources. It is expected to require a holistic approach that considers riparian areas and the adjacent floodplain. Weed management is vital to river system health and should be considered as a complementary measure to a constraints relaxation program.

Boat wake

Boat wake has been identified as a major cause of streambank erosion in some of the river reaches assessed for this investigation. Ongoing erosion through boat wake has potential to limit any erosion benefits sought from a constraints relaxation program. Further effort will be required to address boat wake in order to realise the erosion reduction benefits of constraint relaxation.

Contents

OFFICIAL

Attachments

Figures

Tables

Abbreviations

DELWP	Department of Environment, Land, Water, and Planning
EEWD	Enhanced Environmental Water Delivery
EPI	Erosion Potential Index
EWFIM	Environmental Water Floodplain Inundation Model
IVT	Intervalley Transfers
MDBA	Murray-Darling Basin Authority
NSW	New South Wales
NTU	Nephelometric Turbidity Units
RiM-FIM	River Murray Floodplain Inundation Model
RRCP	Reconnecting River Country Program
SDLAM	Sustainable diversion limit adjustment mechanism
VMFRP	Victorian Murray Floodplain Restoration Project

1 Introduction

This report

Alluvium Consulting Australia Pty Ltd was engaged by Sequana Partners Pty Ltd to undertake the Assessment of Environmental Benefits and Risks to inform the Stage 1A Feasibility Study for the Victorian Constraints Measures Program. The related and complementary NSW Reconnecting River Country Program (RRCP) is exploring the relaxation of delivery constraints in NSW, including the NSW side of the Murray River.

This environmental benefits and risk report documents the approach and results from an assessment of the environmental benefits and risks expected to arise in Victoria through the relaxation of delivery constraints in the Hume to Yarrawonga reach of the Murray River, the Yarrawonga to Wakool Junction reach of the Murray River and Goulburn River downstream from Lake Eildon.

The assessments included in this report have been undertaken with the support of subject matter experts and supplementary resources including:

- Hydrologic and hydraulic modelling
- Ecological investigations, response modelling, and reporting conducted by the University of Melbourne for the Goulburn River,
- the review and use of investigations, ecological response modelling and reporting for the NSW RRCP for the Murray River, and adaption and application of these investigations and ecological response modelling for the Goulburn River
- Other assessments as required to support the investigations.

This document is both a stand-alone assessment and an attachment to the Victorian Constraints Measures Program Feasibility Study. The assessment identifies gaps in the data and available information to inform the decision point prior to the development of a business case.

This study forms part of the Stage 1A feasibility assessment, being the first stage of the Victorian Constraints Measures Program (Figure 10).

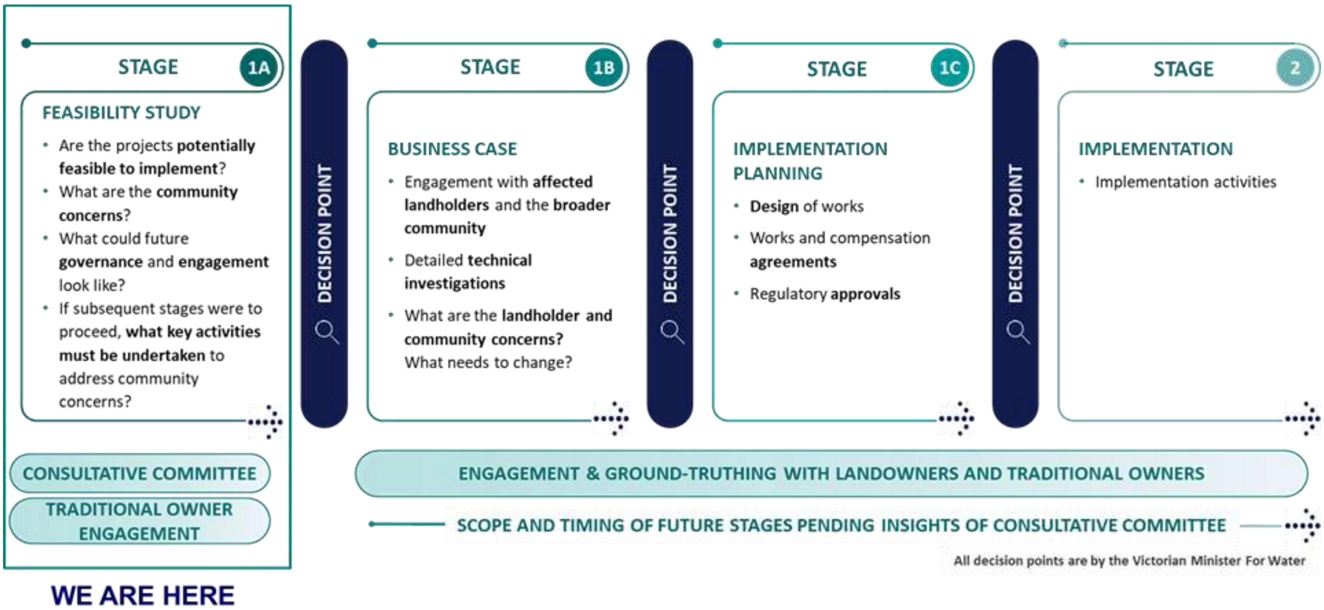

Figure 10 *A staged approach to the Victorian Constraints Measures Program (Sequana, 2022)*

The scope of the investigations undertaken by the project team was developed by DELWP and informed by a Community Consultative Committee engagement process. Engagement of the Community Consultative Committee is reported elsewhere.

The project team including subject matter experts met twice through the investigation phase in a workshop setting to discuss the findings under each of the themes assessed and to discuss the system wide assessment included in this report.

This report structure is set out below:

Context

- **Section 0**: Summary
- **Section 1**: Introduction – contains the background for the study and an overview of the study areas.
- **Section 2**: Constraints program context – provides the context for the study, including factors that influence the assessment. Context is provided for the systems condition and the legislative setting for the program
- **Section 3**: Conceptual understanding of system behaviour – provides background information on the underlying processes that impact the river systems and the processes that link to the assessment themes

Approach

- **Section 4**: Reaches and scenarios explored – provides an overview of the physical locations of the assessment reaches and the constraints relaxation scenarios considered.
- **Section 5**: Assessment approach – provides detail on the objectives and method used to assess each of the environmental themes.

Results and interpretation

- **Section 6:** Study area benefits and risk assessment – detailed reporting on the benefits and risks for each of the environmental themes.
- **Section 7:** Climate Change – Details on the expected impact of climate change on the environmental benefits.
- **Section 8:** System scale assessment: Summarises the results of an expert panel workshop undertaken to explore system scale outcomes from relaxed constraints.
- **Section 9:** Synthesis of findings – This section brings together all of the information and gives a summarised description of the expected benefits and risks.

Additional information

- **Section 10:** Risks and uncertainties: A description of the identified risks to the environmental outcomes and uncertainties in the approach.
- **Section 11**: Further investigations – Provides a brief discussion on areas of further investigation that should be included should the project continue to Stage 1B and a Business Case.

Attachments

- **Attachment 1:** Detailed assessment methods – more detail on the assessment methods used
- **Attachment 2:** Do nothing more scenario – provides an overview of trajectories for the study area, if current constraints were maintained
- **Attachment 3:** Expert panel reach based synthesis workshop outcomes and suggestions for further investigation
- **Attachment 4:** Implications from updated hydrologic modelling – Qualitative discussion on on the potential changes from the most recent hydrologic modelling results
- **Attachment 5:** Reconnecting River Country – Overview of the NSW Murray River project findings.
- **Attachment 6:** EVCs allocated to vegetation groups for quantity assessment
- **Attachment 7:** Vegetation quality assessment detail – More detail on the vegetation quantity results
- **Attachment 8:** Murray River vegetation quantity results – More detail on the vegetation quality results
- **Attachment 9:** Modelled benefits on hydrological metrics and ecological models in the Goulburn River system
- **Attachment 10:** System benefits workshop Mural board

What are "constraints"?

Constraints refer to existing river operations and structures that keep environmental water within the river channel and prevent environmental water being delivered to floodplains and wetland ecosystems. These constraints exist to protect private and public assets and land use, but they also limit the outcomes that environmental water holders and managers can achieve from using environmental water, and by extension present a risk that the Basin Plan objectives will not be achieved. Identifying ways to 'relax' these constraints may assist to optimise the environmental outcomes from environmental water delivery.

The subject river systems

The scope of the investigation included three river reaches: the Goulburn River, the Murray River (Hume to Yarrawonga) and the Murray River (Yarrawonga to Wakool Junction), Figure 11. The rivers are important because of their inherent environmental values and the role they play in delivering flows to downstream environmental assets. They also have critical social and economic value for their role in delivering consumptive water, including essential human supplies to South Australia.

Figure 11 *Victorian Constraints study reaches*

For the purpose this assessment the Goulburn River has been assessed based on relaxation of constraints in two sub reaches:

- Mid Goulburn between Lake Eildon and Goulburn Weir
- Lower Goulburn between Goulburn Weir and Murray River

In addition, the investigation has sought to provide a system wide assessment within and beyond the subject reaches. A further discussion on the reaches is provided in Section 4.

Defining environmental risks

As part of Stage 1 of the Constraints Management Program, this report considers the benefits and risks to the ecological values and processes arising from reconnecting low-lying river landscapes. For the purpose of this assessment, the risk to ecological values and processes has been assessed in terms of potential 'disbenefits' to these values and processes. As such the investigation has sought to identify the potential environmental benefits and disbenefits of relaxed constraints.

The report recognises that risk can be defined as the likelihood and consequence of a hazard impacting on an asset or objective as set out in publications such as AS31000, ISO3100 and the Victorian Government Risk Management Framework. This approach to the identification of risk has not been applied.

In addition to the identification of ecological 'disbenefits' arising from relaxed constraints the investigation has also sought to identify factors that pose a 'risk' to the attainment of the outcomes sought from constraint relaxation. These risks include both uncertainties arising from the investigations and issues that are external to the constraint relaxation program. These issues are discussed in terms of further investigations and complementary measures that may be required to achieve the benefits identified in this report and sought by the program.

Reconnecting River Country

The Murray River modelling in this project was originally conducted for the RRCP project, with the instream modelling (such as native fish response) directly informing this work, and the overbank results being either clipped to a Victorian extent or recreated for the Goulburn River. All the modelling and interpretation was then provided to the VCMP project by the teams that were part of the NSW RRCP project. This allowed efficiencies to be captured, and ensured best practice and consistency with the similar work in NSW. It also allows the results to be considered concurrently, particularly those with overbank dependencies, as ecosystem response is unlikely to be restricted by legislative boundaries.

2 Constraints program context

System context – the problem

River regulation and consumptive use of water have interrupted many of the natural river and wetland processes needed by native plants and animals to grow, reproduce, move and ultimately survive. River regulation has significantly modified natural flow regimes, including the timing, duration, rates, and variability of flows. This modification has adversely impacted the condition of river systems, and the flora and fauna that depend on the system for survival. The threat to water-dependent ecosystems and species within the MDB posed a substantive risk to achievement of Australia's international treaty obligations to biodiversity conservation. In response the Murray-Darling Basin Plan (the Basin Plan) was developed to improve the health of the river systems of the basin and its floodplains. The Basin Plan recognises the importance of connectivity through high flows and includes "healthy and resilient ecosystems with rivers and creeks regularly connected to their floodplains" as one of the Plan's overall outcomes.

Environmental flows are designed to support water-dependent ecosystems, by mimicking components of the natural flow regime. While environmental flows have increased longitudinal connectivity in the Murray Darling Basin (MDBA, 2018), flow constraints have limited the ability of environmental water managers and river operators to deliver the overbank flow components of the flow regime.

While some (selected) wetlands and off-channel sites in the Murray River can be watered by pumping activities, the vast majority of the Basin's wetlands and floodplains are located above current constraints and depend on unregulated flood events for inundation. Perhaps unsurprisingly, the 2020 Basin Plan Evaluation concluded that the Plan was *'unable to effectively support many floodplain and wetland ecosystems until implementation of critical improved water infrastructure and river operating rules are in place*' (MDBA 2020a). Constraints (relaxation) projects are essential components of the proposed improvements and are key instruments for enhancing the efficiency of environmental flows and the condition of ecosystems that cannot be watered under current environmental flow rules.

Many monitoring studies are available to describe the current condition of the subject reaches. The Sustainable Rivers Audit (SRA) found the mid-slopes and lowland sections of the Goulburn River to be in very poor condition. The fish community was in extremely poor condition (with the Goulburn River valley ranked 17^{th} out of 23 valleys) while vegetation was in poor condition (18th out of 23 valleys). The fish community was dominated by alien species with several native species missing and recruitment among native species present as reduced. The vegetation community was reduced in abundance, fragmented, and increased alien species. The Victorian Index of Stream Condition (ISC) found the Goulburn River to be in moderate condition with reaches in best condition being in the headwaters. The mid-Murray region was rated as poor overall with the fish community also in very poor condition but the vegetation community being in good condition.

Since implementation of the Basin Plan, environmental flows within the Goulburn River have primarily been delivered to enhance native fish spawning, reduce the extent of bank erosion, and enhance productivity and littoral vegetation. The flows have been associated with movements and breeding of Golden and Silver Perch. While improvements in vegetation and productivity and fish spawning have been observed, these short-term responses have not translated into changes in the macroinvertebrate community or increases in young-of-year fish.

In the Murray River channel, similar outcomes have been observed to those in the Goulburn River, with large variations in fish numbers from year to year, but no clear improvement in populations and increases in the proportion of invasive species (Brown and Whiterod, 2021; Raymond et al. 2018). There are, however, exceptions with increases in Murray Cod populations in the Murray at Gunbower and in Gunbower Creek. It is worth noting that this increase appears to be due to recruitment while the population continues to lose large adults, a pattern also seen at Hattah Lakes, though populations of both Murray Cod and Golden Perch have been supplemented by stocking.

In contrast to the Goulburn River, managers of icon sites along the Murray River floodplain have some capacity to deliver environmental water, even with constraints in place.

In the Goulburn, waterbird numbers declined during the millennium drought. Since the drought broke, there has been an enduring decline in large wading birds and piscivores, leaving the community dominated by ducks and herbivores. Assessments of bush birds in Barmah have showed significant variation through time, ranging from poor in 2008 through to very good in 2012. Of note is that the number of species recorded declined to 61 in 2008 and had not recovered by 2017. Fish populations that provide important food sources for waterbirds have undergone similar significant variation due to cycles of wetting and drying. Wetlands, when wet, tend to be numerically dominated by small native species of fish (such as carp gudgeon, Australian smelt and unspecked hardyhead) though carp dominate overall biomass. The delivery of environmental flows to these ephemeral systems provides important habitat for small fish that provide an important link in the food web between zooplankton and macroinvertebrates to large native fish and waterbirds.

Environmental flows have been effective at achieving improvements in condition in floodplain and wetland ecosystems. It could be argued that the degraded condition of the Lower Goulburn represents a point in time in a long-term gradual decline in condition (MDBA. 2012). Eildon dam was completed in 1927 and since then, society's capacity to regulate flows has increased while water availability has declined and become more variable. Over the same period demands on water resources have increased. The changes in flow imposed on the Goulburn River have long-term impacts that are still emerging including channel and floodplain morphology and associated vegetation changes. The do-nothing scenario essentially endorses this ongoing and uncertain change and likely decline in character and condition.

Treaty Obligations

Biodiversity Convention

The United Nations Convention on Biological Diversity (CBD) was established recognising that global biodiversity has intrinsic social and economic value and is immensely important to the health and continuation of present and future generations. The CBD remains a legally binding international agreement which has three objectives.

- The conservation of biodiversity.
- The sustainable use of biodiversity, and,
- Fair and equitable sharing of the benefits arising from the use of genetic resources.

Australia has been a party to the CBD since 1993 and is dedicated to meeting its obligations in alignment with its national priorities. As a signatory to the CBD Australia developed The National Strategy for the Conservation of Australia's Biological Diversity (1996). This was Australia's first national strategy for the protection and conservation of biodiversity. The strategy has since undergone review and revisions to address emerging and evolving challenges e.g., climate change, with Australian governments making collaborative commitments to manage shared natural resources.

Ramsar

The Ramsar Convention is an international intergovernmental treaty to protect and prevent the loss of wetlands around the world and it includes actions to reduce the loss of wetlands where possible. Australia has made the following commitments under the convention:

- To add a set of suitable wetlands to the List of Wetlands of International Importance
- To promote the conservation of wetlands
- To establish a strong knowledge base through and support the exchange of data and publications
- Support training and other capacity building effort for fields of wetlands research and management
- Reporting on the condition of the wetlands this included coordinating actions and updating information in the Ramsar national report and information sheets.
- Leading the development of proposed Ramsar site nominations within the jurisdiction including consultation and liaison with the Australian Government (Department of Sustainability, Environment, Water, Population and Communities [DSEWPC], 2012).
- Consult with other contracting parties to the Convention to review and promote the implementation of the Convention; and
- Represent Australia at the triennial Conference of the Contracting Parties, collating the National Report for these meetings and other reporting to the Convention.

These obligations extend to state and territorial governments that have their own legislative and policy instruments to protect the wetlands – both Ramsar listed and non-Ramsar listed. The implementation of the Ramsar Convention is supported by the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) and the *Water Act 2007*.

There are several Ramsar listed wetlands within the Murray and Goulburn River systems, such Gunbower Forest, the Barmah-Millewa Forest, Hattah-Kulkyne Lakes and the Kerang Wetlands.

Migratory Bird agreements

The Murray-Darling basin provides habitat for many migratory birds each year with Australia playing a key role in conserving birds in the East Asian – Australasian Flyway. To this end Australia has established bilateral migratory bird agreements with Japan (JAMBA – Japanese-Australia Migratory Bird Agreement), China (CAMBA – China-Australia Migratory Bird Agreement) and the Republic of Korea (ROKAMBA – Republic of Korea-Australia Migratory Bird Agreement). Each of these agreements contributes to the protection and conservation of migratory shorebirds and the habitats they use.

Legislative context

The Basin Plan

The Murray-Darlings *Basin Plan 2012* (the Basin Plan) was developed to manage the Basin connected system after years of natural droughts, and increasing consumptive use of water. The Basin Plan aims to return the Murray Darling Basin to a more sustainable and healthier state, while providing ongoing support to farming and other industries that benefit from the Murray-Darling Basin. It sets the amount of water that can be taken from the Basin for human needs whilst protecting sufficient water for rivers, lakes, wetlands, plants, and animals that rely on these water bodies (referred to as sustainable diversion limits).

The Basin Plan is managed across New South Wales, Victoria, South Australia, Queensland the Australian Capital Territory and the Australian Government. Water is managed by applying limits on water consumption, providing water for the environment, maintaining infrastructure development and operations, managing groundwater, maintaining water quality, supporting water markets and trade for effective water use, and monitoring and evaluating the effectiveness of water management. The Basin Plan applies an adaptive management approach which allows the stakeholders to adjust their approach based on current climatic conditions and to help achieve the best possible outcomes.

The Basin Plan environmental objectives include ecosystem functions to protect water-dependent ecosystems. The major ecosystem function identified is connectivity within and between water-dependent ecosystems by protecting habitats, longitudinal, lateral, and vertical connectivity, the Murray Mouth and Lower Lakes and by mitigating barriers to the passage of biological resources (including biota, carbon and nutrients). High level ecosystem function objectives are listed in Text Box 1.

Text Box 1
Basin Plan Ecosystem Function Objectives (8.06)

(2) An objective is that the water quality of Basin water resources does not adversely affect water-dependent ecosystems and is consistent with the water quality and salinity management plan.

(3) An objective is to protect and restore connectivity within and between water-dependent ecosystems.

(4) An objective is that natural in-stream and floodplain processes that shape landforms (for example, the formation and maintenance of soils) are protected and restored.

(5) An objective is to support habitat diversity for biota at a range of scales (including, for example, the Murray-Darling Basin, riverine landscape, river reach and asset class).

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

(7) An objective is to protect and restore ecological community structure, species interactions and food webs that sustain water-dependent ecosystems, including by protecting and restoring energy, carbon and nutrient dynamics, primary production and respiration.

The longitudinal connectivity of rivers provides a physical connection between upstream and downstream river reaches to facilitate the movement of materials and biota. This connectivity fulfils important environmental functions, among them distributing nutrients, sediments, and carbon/energy, allowing biota to disperse and migrate. It can influence the export of materials (e.g., salt, sediment, nutrients) from river systems and affects species that move between marine, estuarine and freshwater systems to complete their life cycles (e.g., lamprey).

Natural longitudinal connectivity has been impacted by river regulation (the construction of structures, water storage and diversions). The impacts of river regulation and diversions often increase cumulatively downstream. Some of the largest impacts are seen at the downstream end of large rivers including the Darling, Narran, Macquarie, Gwydir, Murrumbidgee, and Lachlan Rivers. The lower lakes and estuary at the downstream extent of the Murray River have also been impacted.

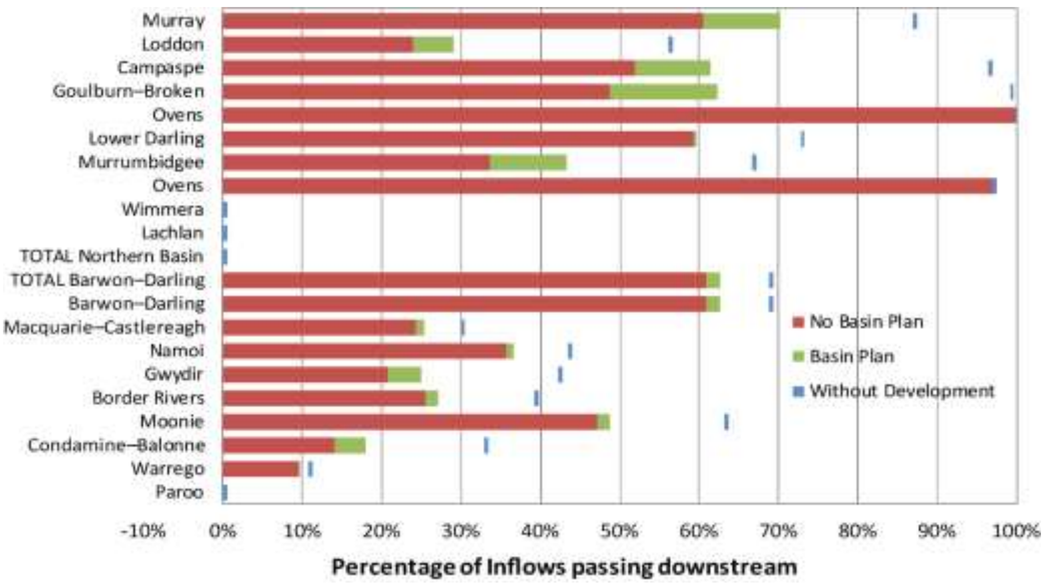

Figure 12 *Proportion of catchment inflows flowing out the end of river catchments across the Basin. (Source Basin wide environmental watering strategy 2019)*

The importance of longitudinal connectivity varies among rivers. Some rivers including the Wimmera, Lachlan and Paroo have almost no hydrological connection with the downstream system except in major flood events, while for major rivers in the southern connected Basin (Campaspe, Goulburn-Broken, Ovens and Murray), over 90% of inflows passed downstream prior to regulation (Figure 12). The impact of development has been greater in the southern Basin than the northern Basin, reflecting historically higher levels of development and extraction. The Basin Plan is seeking to achieve proportionally greater improvement in longitudinal connectivity in the more developed southern valleys.

Connectivity is not just about volumes, but also about patterns of connection including timing and duration. The protection and restoration of environmental values requires restoration of historical patterns of longitudinal connectivity to optimise social, economic, and environmental outcomes arising from the use of Basin water resources. From the perspective of the Goulburn River, constraints affect managers' capacities to sustain environmental values associated with the floodplains, wetlands, and watercourses of the Goulburn Valley. Constraints also affects managers' capacities to restore connectivity patterns that link the Goulburn to the rest of the southern connected basin. Environmental water delivery such as that in the Murray River (as is shown in Figure 13) aims to deliver water for the environment in the periods of late winter and spring when they provide the most environmental benefit.

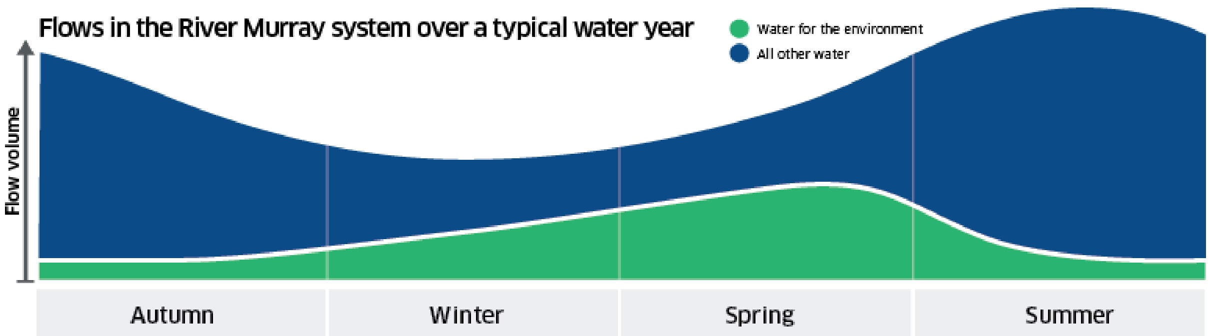

Figure 13 *Flows in the Murray River system over a typical water year (MDBA, 2022)*

To provide flexibility, the Basin Plan includes a mechanism to adjust the sustainable diversion limits in the southern Basin. The mechanism requires a suite of projects to be implemented – some projects allow the Basin Plan environmental outcomes to be achieved with less water (these are called "supply projects"). This means that more water can remain in the system for other users, including households, industry, and irrigated agriculture. Other projects improve the efficiency of water use (these are called “efficiency projects”).

Constraints Management

The Murray-Darling Basin Authority’s Constraints Management Strategy, released in 2013, set out areas where physical or operational barriers that impact delivering water in the system could be addressed to maximise the benefits of environmental water delivery in the southern connected Basin. These are referred to as the constraint’s projects. Constraints projects can include changes to river operating practices and rules, and the installation of physical features such as crossings and bridges to mitigate the impacts of higher environmental flows. These projects are intended to provide water managers with more flexibility in how to release and move water through the system.

Enhanced Environmental Water Delivery (EEWD)

The Enhanced Environmental Water Delivery (EEWD) Project is one of a suite of projects underway in the Basin to improve the delivery of water for the environment (known as Sustainable Diversion Limit Adjustment Mechanism (SDLAM) program). The EEWD project aims to maximise the benefits from water for the environment across the southern connected Basin, which includes parts of New South Wales, South Australia, and Victoria. The project aims to enhance environmental outcomes by improving system-wide coordination and developing new tools and strategies.

The project will develop delivery strategies for a range of flows, including low flows, regulated flows (from storages), and ‘piggybacking’ on unregulated flows. These strategies will build on the work already undertaken regarding coordination and alignment of flows across different river systems to meet the requirements of water for the environment. These strategies will help to use the higher flow limits achieved through constraints projects and provide tools and information that improve the confidence and the ability of environmental water holders to plan, coordinate and deliver water for the environment to improve the health of the environment, enable connectivity with floodplains and wetlands and through to the Coorong and Murray mouth.

The EEWD project has been partially driven by the opportunity to relax ‘constraints’ on delivery of water and establish new maximum operational flow limits environmental water. The EEWD project demonstrates how to better link rivers with their floodplains, and it helps water holders and river operators to deliver water safely and accurately within new regulated flow limits. Implementation of both the EEWD project and constraints projects allows environmental water to be delivered to maximise environmental outcomes.

Managing constraints will require physical works, flood easements and changes to river operations to enable higher flows to be delivered through the system, while the EEWD Project will improve the strategies, systems and tools for delivery of water including forecasting, modelling, coordination and administration.

Victorian Murray Floodplain Restoration Project (VMFRP)

The Victorian Murray Floodplain Restoration Project (VMFRP) aims to remove blockages that prevent water flowing into creeks and implement opportunities to better manage water across nine high-value floodplains along the Murray River within Victoria. These projects will return a more natural watering regime to these nine floodplains. The program will also utilise existing water delivery infrastructure such as irrigation channels and upgrades to the system such as pumps to move water from the river and across targeted floodplains

The VMFRP has multiple sites that are shared with the study areas covered in this feasibility study, including:

- Burra Creek
- Nyah-Vinifera Park
- Guttrum and Benwell Forests
- Gunbower National Park

The VMFRP project does not rely on the constraints projects for the supply of water. However, if constraints are relaxed, there may be opportunities for enhanced outcomes at VMFRP site projects, with the two achieving the best results in partnership. Details of a combined watering program have not been developed but inter-project benefits should be included as part of the future stages of both projects.

The Living Murray

The Living Murray (TLM) is a joint partnership funded by the New South Wales, Victorian, South Australian, Australian Capital Territory and the Commonwealth governments, and coordinated by the Murray–Darling Basin Authority. TLM is a long-term program aimed at improving the ecological condition and health of a series of Icon Sites along the river. These sites are:

1. The Barmah-Millewah Forest
2. Gunbower-Koondrook-Perricoota Forest
3. Hattah Lakes
4. Lindsay-Mulcra-Wallpolla Island

These sites are regionally, nationally, and internationally significant and are recognised under international agreements such as the Ramsar Convention on Wetlands. They significant forests, wetlands and lakes along the Murray River as part of helping deliver the Basin Plan objectives and outcomes. The 'First Step' of TLM was to recover 500 gigalitres of water for return to the environment and to use this water to achieve environmental objectives at the icon sites.

TLM and constraints relaxation have many shared goals and intended outcomes, however TLM is focussed on the narrower region of the listed Icon Sites, whereas the constraints program is one of a suite of projects that take a strategic approach to environmental outcomes across the Murray Darling Basin.

3 Conceptual understanding of system behaviour

In achieving Basin Plan objectives, environmental flow managers deliver environmental flows to protect and restore a subset of all water-dependent ecosystems. In doing this, there is a clear causal linkage between flow management and Australia meeting relevant international agreements on conservation of biodiversity. The Basin Plan also has an outcome of healthy and resilient ecosystems with rivers and creeks regularly connected to their floodplains and, ultimately, the ocean. These issues, identified in Chapter 5 of the Basin Plan, provide the foundation for our conceptual model of river systems.

Flow is major determinant of habitat at a variety of scales. Over short periods of time, depth, current speed, and turbulence will influence the animals and plants that can occupy a site. Over longer periods of time, variations in flow including frequency, magnitude and duration of events will influence the capacity of biota to benefit or survive. Over larger scales, flow interacts with channel morphology and the landscape to create a mosaic of habitats that support diverse communities. Even apparently homogenous areas such as red-gum forests support a heterogeneous mosaic of understory plants that adapt and respond to cycles of flooding and drying.

In changing flows, regulation has changed the amount and availability of habitats while at larger scales, regulation and land use changes have affected the habitat mosaic with profound effects on the diversity of habitats and key processes that maintain the diversity. These processes include erosion, deposition and disturbances to vegetation communities.

The Basin Plan also highlights the importance of connectivity where this refers to the movement of water between water-dependent ecosystems that comprise the larger system. This includes ground-water dependent, estuarine and marine ecosystems. Without human intervention, hydrological connectivity is driven by gravity and so flow changes manifest downhill as changes in connectivity. As a consequence, sequential changes accumulate as one moves downstream meaning that some of the greatest impacts on connectivity manifest at end of the system. The Coorong being a stark example.

Figure 14 *Hydrological connectivity and flows (MDBA, 2020)*

Broadly, connectivity is important for three reasons. First and most obvious is that it would not be possible to deliver water to water dependent ecosystems without transferring water from one part of the system to another. What is less obvious is that, in some areas, achieving appropriate connectivity requires coordinated delivery across multiple parts of the system. The Murray River in South Australia is a clear example of this where delivery of water to representative ecosystems is not possible without coordinated management of longitudinal connectivity through the SCB.

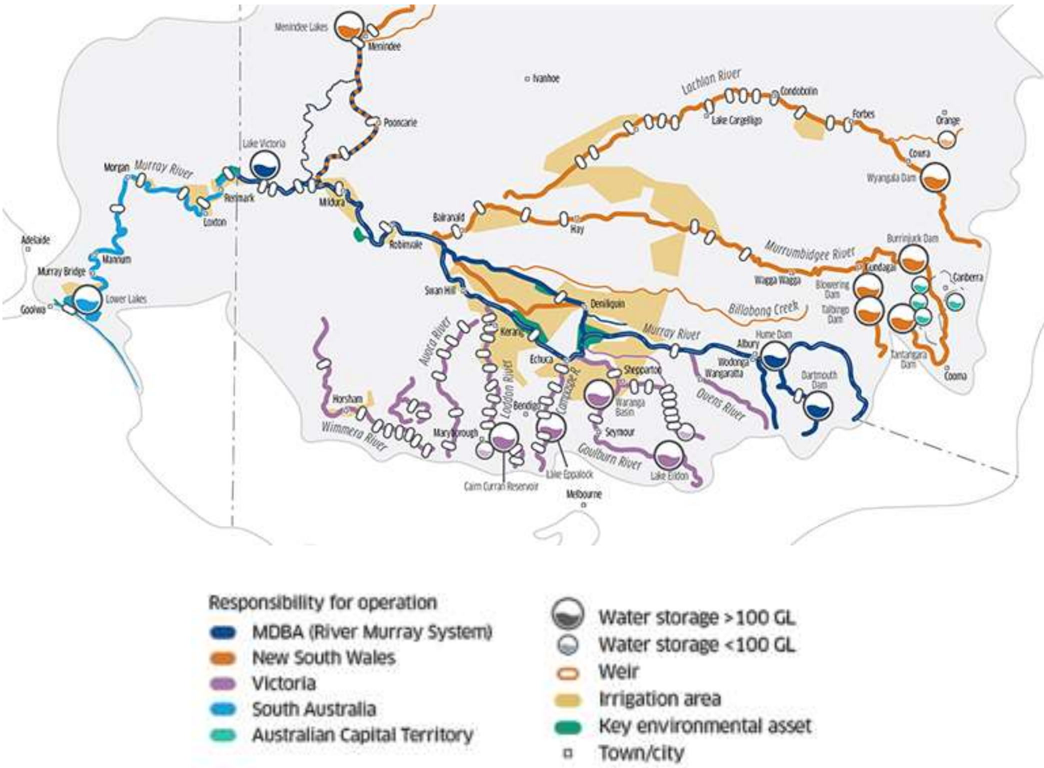

Figure 15. *Schematic of the Southern Connected Basin showing the importance of tributary flows (MDBA,2020d)*

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Hydrological connectivity is also important because of the processes it supports. Among these processes is the erosion, transport and deposition of sediment. These processes are heavily influenced by flow and contribute to the availability of habitat within channels and the floodplain mosaic. The erosion and deposition of sediment on floodplains is drives soil formation which is one of the main reasons that Australia's most productive agricultural land is on floodplains. Hydrological connectivity is also important for nutrient and carbon cycles with ecosystems dependent on the subsidy that is carried into the ecosystem.

Finally, hydrological connectivity is important to the movement of biota through the system. Water-dependent ecosystems in Australia are characterised by cycles of boom and bust or disturbance and opportunity. Many species are dependent on the booms associated with flooding to maintain condition or reproduce. Connectivity is also important to resilience with biota dependent on flows to recolonise areas. Many plant species rely on flows to disperse their seeds, while flows are important for the dispersal of both adult and larval native fish.

From a system perspective flow and geomorphology influence habitat at a site, but hydrological connectivity provides the foundation for delivery of flows and the maintenance of key ecosystem functions that ultimately link all the water dependent ecosystems into a system that is a cohesive group of interdependent components.

Assessment themes

This investigation has sought to identify how the constraint relaxation scenarios and related hydrologic regimes impact on ecological values and processes. A limited set of ecological values or 'themes' were assessed in this investigation. The investigations into the environmental benefits and risks of relaxed constraints considered the themes summarised in Table 6:

Table 6 *Summary of assessment themes*

Theme	Summary of outcomes of relaxing constraints, compared to base case
Floodplain vegetation	Basin Plan target, Important to character of ecosystems, provide habitat and food for other biota. Includes listed species
Production	An important ecosystem function
Water quality	Basin Plan target, determinant of suitability for water use
Macroinvertebrates	Important link in food web, good indicator of long-term water quality and habitat availability
Native fish	Basin Plan target, important predators, and source of food for people and birds. Includes listed species
Waterbirds	Basin Plan target, international treaty obligations. Includes listed species
Platypus	Near threatened and iconic species
Turtles	Listed species in decline and important part of ecosystem
Geomorphology	Important influence on habitat availability and water quality

In addition, elements of hydrologic connectivity are discussed with reference to outcomes of hydrologic modelling undertaken by others and made available for the environmental benefits and risks assessment.

Assessment concepts

This section describes the influence of flow on each of the indicators used in the assessment. Further information on each indicator is provided in the attachments to this report and provide important concepts for each theme applied to this assessment. The literature relevant to the environmental benefits and risks assessment for a constraints relaxation program often refers to the influence of 'floods' on the themes assessed. We have retained the use of this terminology as a generic descriptor for overbank inundation.

The concepts here are a summary. For more detail see Attachment 11.

Vegetation

The water regime is a major determinant of vegetation community structure and distribution (Brock and Casanova 1997; Casanova and Brock 2000). Maintaining a hydraulic habitat mosaic leads to diverse vegetation communities and plant species, as the gradient of physical and chemical characteristics and competition among species both cater for a wide range of species and prevent competitive exclusion. Flow variables, such as frequency, duration, depth and timing are all key habitat characteristics that will determine whether species can complete their life cycle at a particular site.

Flow also influences dispersal through transportation of seeds. Dispersal has a profound influence on the diversity of plant communities. For species dependent on flow, current speed will determine whether a seed will be entrained (Gurnell et al. 1998) and how far it is carried (Groves et al. 2009). Flow conditions will also affect the distance dispersed and deposition (Merritt and Wohl 2002; Nilsson et al. 2002). Floods are important (Cellot et al. 1998) due to large distances they transport seeds (Moggridge and Gurnell 2010). Floods are also associated with increases in the arrival of seeds (Jansson et al. 2005). Rising flows tend to entrain seeds and fragments (Merritt and Wohl 2002) while settlement occurs in areas of low flow or as the flood recedes (Merritt and Wohl 2002).

Production

In this context, production refers to the creation of organic matter that can be used as food by animals. Organic matter can be created by converting carbon dioxide to sugars by photosynthesis, undertaken by plants and algae, or recycled from dead matter a role undertaken by fungi and bacteria. Flow influences productivity through its influence on habitat and the provision of the raw materials including light, carbon dioxide, nutrients, organic matter. The availability of these materials is often dependent on connectivity to move material from a source to the habitats favorable to the plants and fungi. In some instances, flow initiates the release of nutrients and organic matter from sediments, making it available to producers.

Water quality

Flow regimes are an important influence on water quality risks. The risks are often associated with one of two causal pathways. The first is that flow conditions create ideal habitat that promotes rapid growth of, usually, bacteria or algae. Examples include blue-green algal blooms and some adverse DO events. The second causal pathway is that flow transports material into a system where it causes adverse outcomes. Examples include salinity, nutrients (eutrophication) and sediment (turbidity). In some cases, it can be that declines in connectivity can also cause issues which is the case with salinized floodplains and acid-sulfate sediments.

Macroinvertebrates

At a landscape scale flow influences invertebrate diversity and abundance through its influence on the diversity of ecosystems present including temporary and permanent wetlands, channels, backwaters, shallow lakes, and the main river channel. Within an ecosystem, substrate (influenced by flow), current speed and depth will all influence habitat quality for invertebrates. Perhaps more importantly, the constantly changing hydraulic conditions create a habitat mosaic in which disturbance and resilience help sustain high levels of species diversity.

Floods are associated with a boom in macroinvertebrates that provide an abundant source of food for bush birds (Ballinger et al. 2005, 2007). This boom in productivity has been found to be significant for the surrounding landscape (Ballinger and Lake 2006). Similarly in wetlands, inundation is associated with a boom in macroinvertebrates (McInerney et al. 2017, Hillman & Quinn 2002)

Native fish

The relationship between native fish and flow is complex for several reasons. Firstly, each species has evolved to occupy its own niche which means it can be difficult to generalise about native fish responses to changes in flow. Secondly, fish life cycles include several developmental stages, each with its own habitat, food and sources of mortality and understanding impacts at one life stage and its implications for other life stages can be difficult. Thirdly, flow affects fish through several causal pathways including physical (e.g. hydraulics, vegetation) and chemical (DO, salinity) habitat, food availability and quality, connectivity, disturbance and vulnerability to predation. Finally, fish are subject to a range of potentially interacting threats including invasive species, diseases, and over harvesting. In many cases, there is limited information on whether the presence or magnitude of these threats influences a species' capacity to deal with changes in flow.

Freshwater fish species adopt one of three life-history strategies (Equilibrium, Periodic and Opportunistic) based on size, time to maturation, fecundity, yolk size, juvenile survivorship, larval swimming ability and responsiveness of breeding strategies to flow (Table 7).

Table 7 *Life history traits for opportunistic, periodic and equilibrium fish species*

Trait	Size	Fecundity	Size at hatching	Yolk size	Larval swimming ability	Breeding response to flows	Example
Opportunistic	Small	Low	Tiny	Small	Poor	Flexible breeding strategies	Carp gudgeon, Australian smelt
Periodic	Medium to Large	Very High	Small	Small	Very poor	Breeding cued by changes in flow	Golden Perch, Silver Perch
Equilibrium	Medium to Large	Low	Large	Large	Good	Breeding not cued by flow	Murray Cod, Trout Cod

Opportunistic fish respond quickly to breeding opportunities, with larvae that are small, have little yolk and need to start feeding quickly. Periodic species are larger species that lay large numbers of eggs that then disperse widely but again have little yolk and need to start feeding soon after hatching. In contrast, equilibrium species lay relatively few eggs, and have a large yolk reserve which means that larvae can locate sources of food before needing to feed (Humphries et al. 2019). In the context of the Goulburn and Murray Rivers, small species such as Carp gudgeon are opportunistic and respond quickly to wetland inundation (according to existing literature). Golden Perch are a periodic species whose breeding is cued by increased flows with larvae travelling long distances while feeding on food generated by the increase in flow. Murray Cod is an equilibrium species who breed at the same time each year, with more limited response to floodplain inundation events.

The range of flow characteristics and the related flow requirements for native fish populations have been compiled (Horne et al 2020) and set out later in this report.

Waterbirds

Waterbird numbers in Australia and worldwide are in decline and their populations are now also facing a changing climate. Waterbirds are important to the ecology of water dependent ecosystems with different species fulfilling a range of roles from top predator, herbivore, transport for biota and food for raptors. Australia's waterbird species are, for the most part, nomadic, moving to exploit patches of productive or suitable habitat as they become available across a highly variable and dynamic continent (Kingsford and Norman. 2002, Kingsford et al. 2010). Waterbird capacity to respond to cues and locate suitable habitat varies among species with some species such as darters and bitterns being relatively sedentary while others, for example, Eurasian coot and pelican move over large distances. Food availability and, importantly, opportunities to breed are highly variable and are associated with flooding and the associated increases in habitat and productivity. Australian waterbirds are no different from waterbirds elsewhere, with their behavior reflecting broad-scale resource availability. They respond to changing patterns of resource distribution, with movements at spatial and temporal scales that reflect the distribution of surface water, vegetation and food. The most serious conservation threat to waterbirds is the overall reduction in habitat, in particular the loss of overbank flooding that provides the boom in productivity required to successfully fledge chicks. The reduction in habitat availability during dry times is also an important driver that leads to higher rates of mortality and reduces the species capacity to recover when floods return (McGinness et al. 2019).

Due to the wide variety of life-history, movement and foraging strategies across species, waterbirds are commonly grouped into guilds, based on their foraging habitat or feeding. As with many areas of ecology, the guilds provide a guide to aspects of waterbird ecology, but waterbirds have been found to be opportunistic in their feeding habits with, for example, swamp hens preying on chicks of other species and swans consuming invertebrates when both species are considered to be herbivores. The major guilds are:

- Ducks: includes most ducks, grebes and Teal; wide variety of feeding modes including diving and dabbling for a range of food including plants, invertebrates and fish
- Herbivores: includes swans and wood duck; species whose diet is mainly comprised of plants and algae
- Large Waders: Egrets, Spoonbill and Ibis; very broad and diverse dietary needs
- Piscivores: Silver gull, Pelican, Cormorants; primarily fish but includes large invertebrates e.g., yabbies, shrimp
- Shorebirds: Stilts, Lapwings, Red-necked avocet.

Platypus

Platypuses are semi-aquatic and inhabit a range of freshwater habitats including rivers and creeks, shallow lakes, wetlands, and artificial impoundments. Individuals construct burrows in consolidated earth banks in riparian zones, often where vegetation is overhanging the channel (Bino et al. 2019). Platypus have been found to prefer foraging in areas with an average depth of 0.8 m, while other observations have reported platypus foraging in habitats up to 5m deep. Current speed is also believed to be important with platypus preferring relatively slow flow. The depth and current speed limitations are probably related to their diving ability which is believed to be less than 9 minutes.

Aquatic connectivity is important for foraging and safe movement, as platypus are vulnerable to predation by foxes and dogs while moving over land. Historical evidence suggest that platypus can move terrestrially between river basins and can negotiate steep terrain (Furlan et al. 2013), although recent whole genome sequencing data suggests that extant populations are highly structured with little geneflow between catchments (Martin et al. 2018).

Turtles

Three species of turtle may be found in the Goulburn and Murray Rivers: the eastern long-necked turtle (*Chelodina longicollis*), broad-shelled turtles (*Chelodina expansa*) and the eastern short-necked turtle or Macquarie River turtles (*Emydura macquarii macquarii*). Each species has its own habitat and breeding preferences. The eastern long-necked turtle is predominantly found in floodplain wetlands such as oxbow lakes, anabranches and swamps. Its ability to persist in these ephemeral habitats is likely due to its capacity to aestivate, resist desiccation and migrate overland. In contrast eastern Macquarie River turtles (*Emydura macquarii macquarii*) is most often found in rivers and their backwaters where they have a preference for deep (>3m), clear and permanent waterbodies.

Broad-shelled turtles are listed as threatened in Victoria. They have less specific habitat requirements occupying both river and wetland habitats, although the wetlands tend to be permanent and located close to the river.

Geomorphology

The geomorphic processes of bed and bank erosion, and the transport and deposition of sediment, control the form of the Goulburn and Murray Rivers. By altering the channel shape and overall planform, erosion and deposition in the Goulburn and Murray Rivers also set the physical template for instream and riparian habitat (Newson et al. 2000; Bond et al. 2003; Bartley et al. 2005). In this way, geomorphology is a supporting function of other environmental values in the Goulburn and Murray Rivers. The type and rate of channel change is controlled by the balance between erosion forces (streamflow) and resistance forces (sediment and instream or riparian vegetation).

River regulation has been found to be associated with accelerated rates of channel erosion.

4 Reaches, flow scenarios, and environmental flow requirements

Reaches

The potential to relax constraints has been explored on the Goulburn River, from Lake Eildon to the confluence with the Murray River. The Murray River has been assessed from Lake Hume to the junction with the Wakool River near Kyalite. For the purpose of this assessment the Murray River has been assessed as two separate reaches. While the Goulburn River has been included in the Constraints Management Program as a single reach, it has been divided into two reaches to aid the development of watering scenarios and assessment (refer to Figure 11).

Goulburn River

The Goulburn River rises in the Victorian Alps before descending to flow into the Murray River upstream of Echuca, making it the longest river in Victoria (654 kilometres). The river is the largest of a suite of northerly flowing Murray River tributaries. The catchment is approximately 16,800 km^2 that makes up less than 2% of the Murray-Darling Basin area. The Goulburn River downstream of Lake Eildon is classified as a Heritage River under the Heritage Rivers Act 1992 (Victoria). Downstream of Goulburn Weir to the confluence of the Murray River, the Lower Goulburn (Kaiela) River along with the adjacent floodplains, lies with the Lower Goulburn National Park and is listed in the 'Directory of Important Wetlands in Australia'.

The subject reach of the Goulburn River (downstream of Eildon Weir) is highly regulated through the operation of Eildon Weir, Goulburn Weir and Waranga Basin. Flows are significantly altered from natural with high winter/spring flows being captured and stored in Lake Eildon and subsequently released for irrigation and other consumptive demands in summer/autumn. The degree of modification from the natural flow regime is tempered by minimum passing flow requirements and the more recent provision of environmental water held in and released from Lake Eildon

The Goulburn-Broken Waterway Strategy (GBCMA, 2014) identifies the Goulburn River as a high priority waterway within the Murray-Darling Basin. It holds significant environmental, social, and cultural values associated with the river and its floodplain and wetland habitats. These habitat support river red gum forest and numerous threatened species such as Murray Cod, Trout Cod, Alpine Tree Frog, Squirrel Glider, and Eastern Great Egret.

The Goulburn River was rated in 'very poor' ecosystem health in the Sustainable Rivers Audit 2 (Murray-Darling Basin Authority, 2012). The report identified fish communities to be in extremely poor condition following the loss of native species richness and a high biomass of non-native fish species. Macroinvertebrates and riverine vegetation were also rated as 'poor' compared to the reference condition. The majority of river reaches in the Mid to Lower Goulburn are in moderate condition under the 2010 Index of Stream Condition, with some reaches rated as excellent. Several tributaries and headwaters received either a 'poor' or 'moderate' score (DEPI, 2010). More recently, there has been a steady recruitment of Murray Cod and Silver Perch in response to environmental water deliveries.

To aid this assessment, the subject Goulburn River has been divided into two reaches. These two sub reaches have been used to explore alternate constraint relaxation scenarios

- Mid Goulburn: This reach extends from Eildon Weir upstream of Molesworth to Goulburn Weir near Nagambie. This is a highly regulated reach providing multiple use including the delivery of consumptive water from Lake Eildon to Goulburn Weir for subsequent delivery to irrigation demands.
- Lower Goulburn River: This reach extends from Goulburn Weir to the confluence with the Murray River. The reach includes the substantial floodplain wetlands of the Lower Goulburn River.

Murray River - Hume to Yarrawonga

The Hume to Yarrawonga reach of the Murray River is located close to the Murray headwaters and comprises the main river channel and its anabranches between Hume Dam and Yarrawonga Weir. Fluvial geomorphic processes have led to the development and movement of anabranches across the floodplain, creating channels and billabongs that connect to the river channel at various flow heights (Murray-Darling Basin Authority [MDBA], 2015, Thoms et al. 2000).

The flow in this reach is highly regulated by releases from Hume Reservoir. The major unregulated flows into the reach come from the Kiewa River and Ovens River, with smaller contributions from Indigo Creek and Black Dog Creek. The regulated flows from Lake Hume have fundamentally changed the flow regime in this reach. Before regulation flows in this reach peaked in winter and early spring. Under current regulation, winter and spring flows are captured in Lake Hume and upstream storages (e.g., Dartmouth) with peak releases now in summer and autumn to provide irrigation to downstream water users.

Two nationally listed wetlands are located in this reach, Ryans Lagoon downstream of Lake Hume and the Lake Mulwala wetland. Ryans Lagoon is a good representation of riverine billabongs and has been critical for the ecological diversity of this reach, however, the flow changes, land clearing and grazing has negatively impacted the Lagoon's ecosystem. In terms of vegetation, much of the native understorey vegetation has disappeared from the river red gum woodland. Bank stability and bank vegetation has been severely impacted as a result of river regulations that has concentrated flows to high in-channel flows.

The Hume Dam, located on the Murray River has a capacity of around 3,000,000 ML. Water is released for consumptive and environmental needs. Dartmouth Dam, located on the Mitta Mitta River is the largest storage in the Murray-Darling Basin with nearly 3,850,000 ML capacity. Dartmouth Dam and Hume Dam operate 'in harmony' to maximise both the water stored and to minimise flood risk downstream. The Yarrawonga Weir, downstream of Hume Dam, is used to create enough hydraulic head to allow water to be diverted by gravity for irrigation to New South Wales (through Mulwala Canal) and to Victoria (through the main channel).

Murray River - Yarrawonga to Wakool Junction

The Yarrawonga to Wakool reach extends from Yarrawonga Weir to the Wakool Junction with the Murray River. The reach includes the Murray River channel and the Edward-Wakool River system in New South Wales, as well as all the associated rivers and creeks through to the Wakool Junction.

The landscape within this region is a broad flat floodplain interconnected through a network of flood runners and creeks resulting in complex hydrology and variable flood events. It houses multiple wetlands and forests of state, national and international significance. The reach includes the Gunbower Island, Australia's largest inland and home to Gunbower National Park and Gunbower State Forest. The area comprises vast areas of floodplain, forest and wetland that is listed as a Ramsar wetland of international significance. It is home to a range of native flora and fauna species as well as holding areas of cultural significance (Murray Regional Tourism, n.d.).

The Barmah-Millewa Forest located within the reach covers 66,000 ha and is home to wetlands listed as internationally significant Ramsar sites. It is Australia's largest living river red gum forest and supports a range of important native flora and fauna (including 74 plant and animal species protected under state and national legislation) and is a significant feeding and breeding site for waterbirds, including bitterns, ibis, egrets, spoonbills and night herons (VEWH, 2022).

Flow scenarios

Flow scenarios represent different potential levels of constraint relaxation assessed within this study. The flow scenarios for both the Murray River and Goulburn River comprise combined levels of constraint relaxation across the 2 reaches assessed for each system.

Note that a 'without development' (or 'natural' condition) scenario has also be assessed. This scenario has been included to provide context to the results and is not proposed as a constraint relaxation scenario.

Goulburn River constraint relaxation scenarios

For the purpose of this investigation, a 'range finding' process was conducted by the University of Melbourne to explore flow scenarios that could be investigated as part of the project. The range finding exercise comprised hydrological modelling of constraint relaxation scenarios for the Mid and Lower Goulburn River and ecological response modelling to the Lower Goulburn River across 100 different combinations of 'constraints-relaxed flows'. The University of Melbourne developed a series of 'stress index' outputs for the ecological themes assessed and a summary assessment across all themes assessed. Further information on the results of the range finding model outputs is covered in the Constraints Management Program Feasibility Report, the attachments to which include this report. The investigations revealed potential thresholds for ecological response that aided the selection of combined constraint relaxation scenarios for the Mid and Lower Goulburn River.

The adopted flow scenarios are set out in Table 8. A discussion on these scenarios is also provided below.

Table 8 *Goulburn River flow scenarios assessed (ML/day)*

Scenario Name	Reach	
	Mid Goulburn	Lower Goulburn
Base case / M10L9.5	10,000	9,500
Goulburn Scenario 1 / M10L17	10,000	17,000
Goulburn Scenario 2 / M10L21	10,000	21,000
Goulburn Scenario 3 / M12L21	12,000	21,000
Goulburn Scenario 4 / M14L25	14,000	25,000

Base case M10L9.5: *Current constraint (10,000 ML/day) in Mid Goulburn; Current constraint of 9,500ML/day in Lower Goulburn*
This scenario uses current constraints (10,000 ML/day) in Mid Goulburn and current constraints (9,500 ML/day) in the Lower Goulburn to provide a point of comparison for the other scenarios. This level of constraint reflects the flow rates above which there is some potential for adverse third-party impacts arising from river operations. In the Mid Goulburn, it is understood that the constraint is largely controlled by inundation of private land and or assets in the Molesworth area including the Molesworth Caravan Park.

Scenario 1 M10L17*: Current constraint (10,000 ML/day) in Mid Goulburn; 17,000 ML/day in Lower Goulburn*
This scenario was adopted as the lowest level of constraint relaxation that had the potential to provide some ecological benefit. The scenario maintains the current constraint in the Mid Goulburn but relaxes the constraint in the Lower Goulburn to a level at which some low-lying floodplain vegetation becomes inundated

Scenario 2 M10L21*: Current constraint (10,000 ML/day) in Mid Goulburn; 21,000 ML/day in Lower Goulburn*
This scenario continues to reflect the current constraint in the Mid Goulburn but enables commencement of some broader floodplain inundation in the Lower Goulburn. The ability to deliver the required flows to the Lower Goulburn may be impacted by the constraint in the Mid Goulburn. This scenario when compared with Scenario 3 M12L21 enables an assessment of the extent to which the existing constrain in the Mid Goulburn impacts on the delivery of environmental water to, and the attainment of ecological outcomes in, the Lower Goulburn River.

Scenario 3 M12L21*: 12,000 ML/day in Mid Goulburn; 21,000 ML/day in Lower Goulburn*
This scenario provides for relaxed constraints in both the Mid and Lower Goulburn Rivers. The scenario maintains the same level of constraint relaxation in Lower Goulburn as Scenario 2 and as a consequence the results can be explored to identify the benefits of relaxed constraints in the Mid Goulburn reach and the degree to which the existing constraint in the Mid Goulburn influences the delivery of flow events to and the ecological outcomes within the Lower Goulburn.

Scenario 4 M14L25: *14,000 ML/day in Mid Goulburn; 25,000 ML/day in Lower Goulburn*
This scenario comprises the greatest level of constraint relaxation explored for this investigation. This scenario provides an 'upper bound' of possible flows which can be managed within the minor flood level in the Lower Goulburn River. The option can be explored to identify potential benefits in the Mid Goulburn and the role of further constrain relaxation in the Mid Goulburn on outcomes in the Lower Goulburn.

Murray River constraint relaxation scenarios
The scenarios that were investigated for the Murray River were derived from those used for NSW RRCP. These scenarios were selected for the feasibility stage of Victoria's Constraint relaxation program to ensure, as far as practicable, consistency with the complementary assessments underway for NSW. This approach has allowed

the hydrologic and ecological response modelling that has been conducted for the RRCP to be reviewed and considered for use to inform the Victorian assessment. The constraint relaxation flow scenarios that have been investigated for the Murray River reaches are shown in Table 9.

Table 9 *Murray River flow scenarios assessed*

Flow limit scenario name	Paired flow limit scenarios for assessment	
	Flow at Doctors Point gauge, ML/day (Hume to Yarrawonga)	Flow at downstream Yarrawonga Weir gauge, ML/day (Yarrawonga to Wakool Junction)
Base case/ Y15D25	25,000	15,000
Scenario 1 / Y25D25	25,000	25,000
Scenario 2 / Y30D30	30,000	30,000
Scenario 3/ Y40D40	40,000	40,000
Scenario 4 / Y45D40	40,000	45,000

Note: The naming convention for these scenarios has been based on that adopted for the RRCP with the more downstream reach included ahead of the upstream reach. This naming convention is different to that adopted for the Goulburn River with the upstream reach preceding the downstream reach. As an example, the Murray River Base Case/ Y15D25 refers to a constraint of 15,000ML/day downstream of Yarrawonga (in the Yarrawonga to Wakool reach) and 25,000 ML/day downstream of Doctors Point (in the Hume to Yarrawonga Reach).

Base case/ Y15D25
This scenario represents the current level of constraint in the Hume to Yarrawonga and Yarrawonga to Wakool Reach of the Murray River.

Scenario 1 / Y25D25
This scenario comprises the lower limit of constraint relaxation that is likely to deliver environmental benefits. This scenario retains the current level of flow constraint downstream of Lake Hume but provides for relaxed constraints downstream of Yarrawonga. This scenario would be expected to provide significantly improved watering through areas such as the Barmah Forest in Victoria

Scenario 2 / Y30D30
This scenario provides for relaxation of constraints in both reaches. The scenario is expected to provide greater ecological outcomes over Scenario 1 / Y25D25 including commencement of floodplain engagement downstream of Lake Hume.

Scenario 3/ Y40D40
This scenario continues to provide for relaxation of constraints in both reaches. The scenario is expected to provide increased in ecological outcomes over Scenario 2 / Y30D30 including further floodplain engagement upstream and downstream of Yarrawonga.

Scenario 4 / Y45D40
This scenario represents the upper limit of that explored for the relaxation of constraints for the RRCP. The option retains the Scenario 3 constraint of 40,000 ML/d between Lake Hume and Yarrawonga, but further relaxes constraints downstream of Yarrawonga. This option would seek to capitalise on flow events from the Ovens River entering the Murray River at Yarrawonga (immediately upstream of Yarrawonga Weir) to provide greater floodplain engagement and ecological outcomes in areas such as the Barmah Forest.

Frequency, timing, and duration of overbank events

A potential flow regime has been modelled and assessed for each of the relaxed constraint flow scenarios set in the discussion above. The frequency, duration and timing of environmental water requirements including overbank events that were used to direct environmental water deliveries in the hydrologic modelling for each of the constraints relaxation scenarios are set out in Table 10. The environmental water requirements including the frequency duration and timing of overbank events were drawn from previous investigations including investigations into environmental water requirement for the Goulburn River by the University of Melbourne

(John et al. 2022) and as part of the RRCP by the NSW government and MDBA for the Murray River. In addition to the environmental water demands, the hydrologic modelling also included consumptive, system and other water demands. Details of the hydrologic modelling can be found in Stage 1A Victorian Constraints Measures Program Hydrology Synthesis Report that is included as an attachment to the Constraints Management Program Feasibility Report (HARC, 2022).

Table 10 *Frequency, timing, and duration targets for overbank events*

River	Frequency	Timing	Duration of overbank flows
Goulburn	• Overbank environmental flow deliveries preferred once a year • In dry/drought years (around 1 in 4) this changes to in channel only • Therefore, one overbank event is preferred around 7 years in 10 • Managed overbank events would not be planned if a natural event has achieved the target that year	• July to October (winter and spring)	• 5 days at peak flow • Rise length around 6 days, fall beginning around 11 days
Murray	• Align with ecological requirements and pre-regulation flow patterns • Depends on season, storage volumes, tributary flows	• Mostly August to October, though occasionally earlier or later	• Will vary depending on flow size, water availability, river operations and environmental needs but mostly around 7 to 14 days at target flows • Occasionally up to 30 days for flows • Gradual recession to reduce erosion risk and stranding of fish

Note: While finalised daily timestep hydrologic modelling was available for the Murray River, only preliminary daily timestep hydrologic modelling was available for the Goulburn River for this assessment. A qualitative assessment was undertaken to identify any implications arising from the final hydrologic model runs.

Approach adopted for water delivery

Environmental water should be delivered as efficiently and effectively as possible to meet the needs of the environment. Where practical, delivery should be timed to complement and supplement tributary inflows to ensure the most efficient use on environmental water.

Environmental flow delivery would vary based on the range of environmental outcomes that would be target, and would occur in one of three ways (Figure 16):

- Extend existing flows when the duration would not be sufficient for environmental outcomes
- Raise existing smaller flows to levels required for environmental outcomes
- Create new flows, focussed on winter and spring in order to recreate natural events

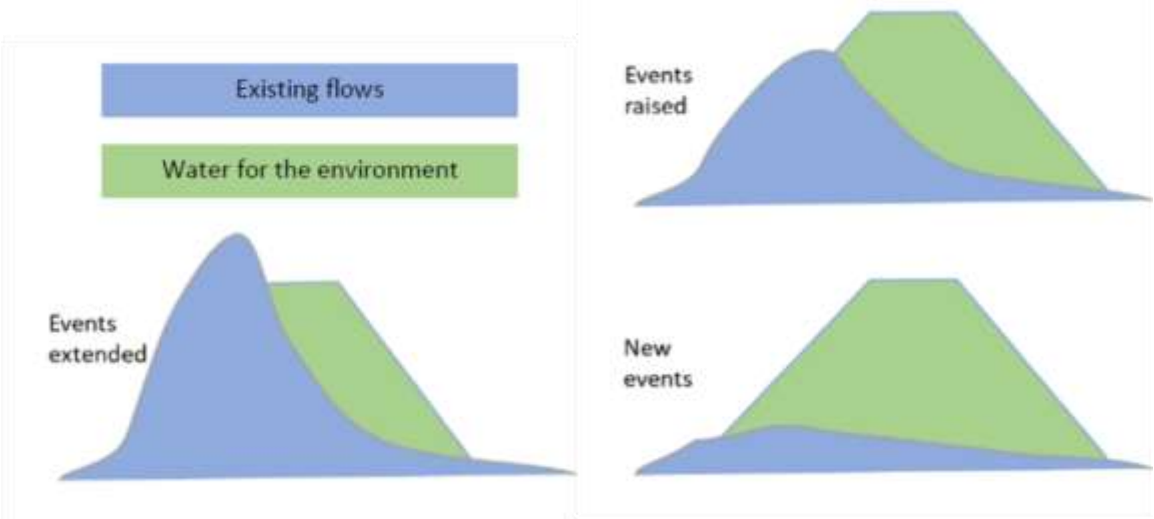


Figure 16 *Delivery types used to schedule environmental flow orders (DPE, 2022)*

The hydrologic modelling undertaken to support this investigation has included release of environmental water from storages to extend flows, raise events and in the event that no such events were available, triggers to enable new events to be created.

Attainment of constraint relaxation target in model runs

The modelling of the environmental demands has been based on daily time step water balance models. These models step through model components such as storage inflows, storage volumes, daily downstream water demands, release rates, water extractions and losses to evaporation and infiltration. The modelling process updates the water available in storage held by the environment and other entitlement holders at a daily timestep. Within the model, as with reality, water may not necessarily be available to meet all demands. In addition, the models only has limited foresight over forecast rain events. As a result, the flow rates attained under the modelling for each scenario may not always achieve the desired flow rate, and will often fall short of the level of constraint relaxation sought.

Details of the hydrologic modelling can be found in Stage 1A Victorian Constraints Measures Program Hydrology Synthesis Report included as an attachment to the Constraints Management Program Feasibility Report (HARC, 2022).

5 Assessment approach

The assessment approach sought to provide a robust, transparent assessment of the benefits and risks of constraint relaxation in the Murray and Goulburn River systems. The approach was based on the use of existing information, models and modelling including hydrologic, hydraulic and ecological response modelling available for the Murray River and Goulburn River. As such the investigations and results comprise multiple

A summary of the conceptual understanding of the processes at work has been provided in section 3 of this report. The assessments have been based on these conceptual understandings and limited by the subject reach extents, scenarios adopted, and the flow regimes modelled. A brief description of the assessment method adopted for each theme is presented here. Detailed methods are provided in Attachment 1.

Assessment objectives

This Environmental Assessment informs the feasibility assessment of proposed constraints management in the Goulburn and Murray Rivers by identifying the potential benefits and risks to environmental values of a range of target constraint relaxation scenarios.

Overall approach

The environmental benefits investigation applied a contemporary understanding of environmental flow requirements and risks to describe the likely environmental outcomes of relaxing constraints in the Goulburn and Murray Rivers. The ecological responses within each reach were assessed, with consideration also given to wider system benefits (cumulative benefits).

In both rivers, we used models that integrate the current understanding of the response of fish, vegetation, and birds to changes in flow.

In the Murray River, we used modelling developed by the Arthur Rylah Institute (fish), La Trobe University (vegetation) and University of NSW (birds), originally prepared for the Reconnecting River Country Project.

For the Goulburn River, the models used were developed by the University of Melbourne to support environmental water planning, as well as adaptions to the fish, vegetation and bird modelling conducted on the Murray River.

Additionally, hydraulic and hydrologic modelling were used to investigate the inundation area of vegetation across the Goulburn River and the Victorian side of the Murray River. Changes to erosion risk were assessed through channel investigations on the Goulburn River and used to inform likely changes to both systems. The inundation analysis and erosion risk investigations were conducted by Alluvium.

A possible flow regime for the system has been modelled for each of the relaxed constraints scenarios assessed.

Hydrologic and hydraulic modelling

A summary of the hydrologic and hydraulic modelling has been completed by HARC (HARC, 2022a &2022b) for the Constraints Management Program feasibility study. Details of the scenarios assessed are provided in Section 4 of this report.

Water balance (hydrologic) modelling

Three water balance (hydrologic) models have been used for Stage 1A of the VCMP:

1. The University of Melbourne's Stochastic Goulburn Environmental Flow Model (SGEFM). This model was used to inform the scenario range finding exercise for the Goulburn River and updated to explore , the hydrological and ecological outcomes of relaxed constraints on the Mid Goulburn and Lower Goulburn (John et al. 2021, 2022; University of Melbourne, 2022). The SGEFM comprises both hydrologic and ecological response models

2. DELWP's Goulburn Broken Campaspe Coliban Loddon (GBCCL) Source Model, which was used to analyse in more detail the hydrological outcomes of relaxed constraints on the Mid Goulburn and Lower Goulburn (DELWP, 2022a).
3. MDBA's Source Murray Model (SMM), which was used to analyse the hydrological outcomes for the Murray River if constraints are relaxed at Doctors Point, Yarrawonga Weir and in the Mid Goulburn and Lower Goulburn (MDBA, 2022a).

The University of Melbourne Stochastic Goulburn Environmental Flow Model (SGEFM) is the same model that has been used for the assessment of multiple ecological themes across the Goulburn River (Attachment 1).

The GBCCL Source model version 79 was used as the hydrological input to the RRCP based modelling that was applied to waterbirds and vegetation responses in the Goulburn River. An updated version of the GBCCL Source Model has been completed, the impacts of which are discussed in Attachment 4.

The MDBA SMM was used to inform the NSW Reconnecting River Country Program and as a result informs the Murray River assessments for this Victorian Constraints program feasibility assessment.

Details of the hydrology modelling can be found in Stage 1A Victorian Constraints Measures Program Hydrology Synthesis Report that is included as an attachment to the Constraints Management Program Feasibility Report (HARC, 2022a).

Hydraulic modelling

Hydraulic modelling of the Murray River used in the project was based on the modelling originally conducted for the NSW Reconnecting River Country Program by MDBA and Manly Hydraulics Laboratory (MHL), with MDBA and MHL Contracted to run two additional scenarios for this project.

Additional modelling has been conducted for the Goulburn River by HARC for this feasibility study, however due to the concurrent nature of the project delivery, the environmental benefits and risks assessment for the Goulburn River has been based on earlier hydraulic modelling by Water Technology (2016).

Details of the hydraulic modelling can be found in Stage 1A Victorian Constraints Measures Program Synthesis Report – Hydraulic modelling that is included as an attachment to the Constraints Management Program Feasibility Report (HARC, 2022b).

Connectivity

A connectivity assessment has been undertaken based on the results of the hydrologic modelling conducted as part of the feasibility study by HARC. Details of the hydrologic modelling can be found in Stage 1A Victorian Constraints Measures Program Hydrology Synthesis Report that is included as an attachment to the Constraints Management Program Feasibility Report (HARC, 2022).

The outputs of the hydrologic modelling were used to compare the flow over thresholds that represents bank full flow, and the timing of which these flows occurred. The purpose was to identify any adverse impact on longitudinal connectivity arising from the provision of relaxed constraints.

The assessment approach has been at a high level, aimed at investigating the potential losses or gains in flows that are able to reach the end of the end of the system to maintain the processes required for the health of the river system.

The potential benefits and risks of lateral connectivity have been assessed within the context of the other assessment themes.

SGEFM (Bayesian) model – Goulburn River

Some of the Goulburn River ecological response modelling described in this report has been undertaken within the University of Melbourne's Stochastic Goulburn Environmental Flow Model (SGEFM, John et al. 2022). The SGEFM is based on Bayesian (conditional probability) networks developed by Horne et al. (2020). The model uses a hybrid daily-monthly timestep that enables exploratory analysis of thousands of simulations, which enables assessment of a range of scenarios, where a 'scenario' is a combination of constraints flows in the Mid Goulburn at Molesworth and the Lower Goulburn River at Shepparton. The study modelled combinations of 10 different constraints flows in each of the Mid Goulburn and Lower Goulburn Rivers, for a total of 100 scenarios (Figure 17).

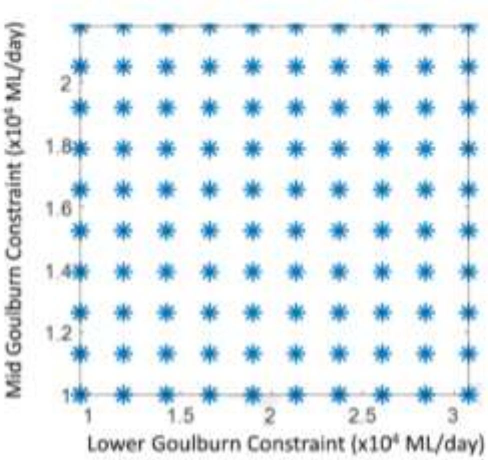


Figure 17 *Combination of constraints flow options assessed in the SGEFM range-finding exercise Combinations of 10 options were assessed for each of the Mid Goulburn and Lower Goulburn, for a total of 100 modelled scenarios (scenarios represented by asterisks, from John et al. 2022).*

The output of each modelled flow scenario is a probability distribution curve. The probability distribution of each given flow scenario was overlaid with the probability distribution of the base case (base case is 10,000 ML/day in the Mid Goulburn and 9,500 ML/day in the Lower Goulburn). A 'stress index' (values from -1 to +1) was developed based on the proportion of overlap between the two probability distribution curves (Error! Reference source not found.). A stress index value was calculated for each of the 100 modelled constraint scenarios, for each ecological theme.

Stress index interpretation:
Positive values (>0) indicate predicted benefits from relaxing constraints and are indicated by blue shading. A stress index value of +1 demonstrates that the relaxed constraints scenario performs wholly better than the base case. 0 indicates that for a given ecological objective the relaxed constraint scenario and base case perform equally (no benefit or disbenefit). Negative values (<0) indicate predicted disbenefits from relaxing constraints and are indicated by red shading. A stress index value of -1 demonstrates that the relaxed constraints scenario performs wholly worse than the base case.

Example plots
The stress indices for the 100 scenarios are plotted in 2D. Example outputs for two different ecological parameters are given in Figure 18 A and B. In Figure 18A, *benefits* are predicted when constraints flow rates in the Lower Goulburn exceed 15,000 ML/day and are maximal when the Lower Goulburn constraint is set above 21,000 ML/day (indicated by intense blue shading). The predicted outcomes are largely unaffected by Mid Goulburn constraint relaxation. In Figure 18B *disbenefits* are predicted from relaxing constraints (indicated by red shading). The disbenefits increase as constraints are relaxed above 12,000 ML/day in the Lower Goulburn and above ~12,000 ML/day in the Mid Goulburn. Greatest disbenefits are predicted when Lower Goulburn constraints of 12,000-15,000 ML/day are combined with Mid Goulburn constraints of 12,500-22,000 ML/day.

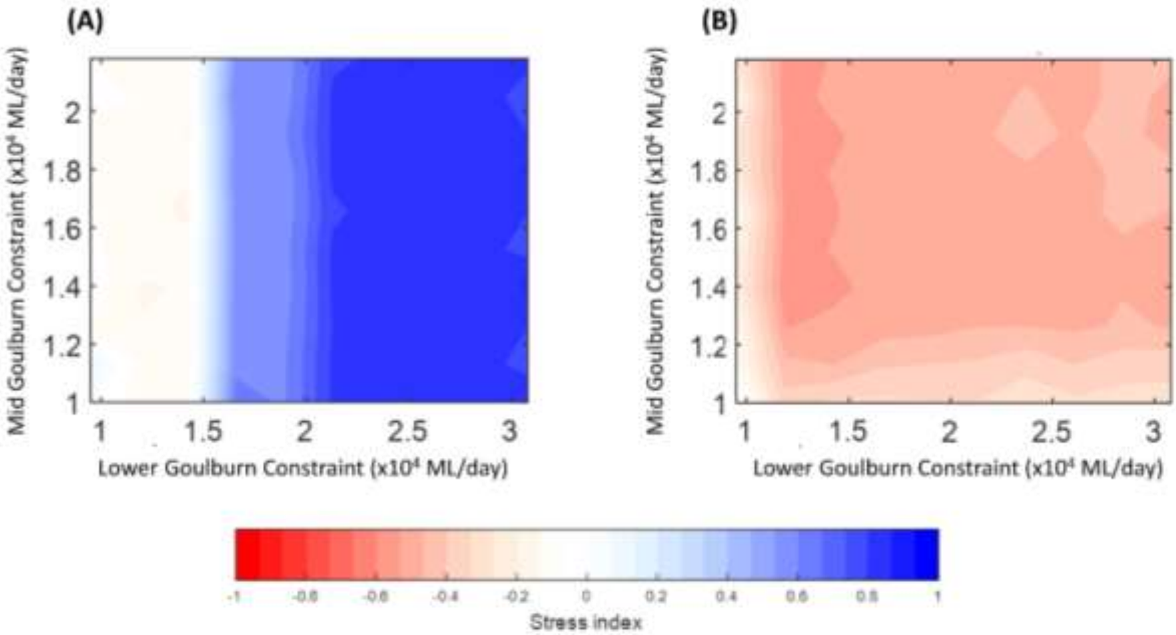


Figure 18 *Example outputs from SGEFM assessments*

The SGEFM model was used to assess the following themes:

- Vegetation (floodplain, littoral and mid-bank)
- Instream Production
- Macroinvertebrates (combined biomass and diversity)
- Native Fish (Equilibrium, Opportunistic and Periodic life histories)
- Platypus population
- Turtle population

Further information on the model set up and inclusions is available in John et al. 2022, and under the themes below.

Vegetation quality assessment modelling

State-transition modelling

A state- transition vegetation quality modelling approach developed for the RRCP was applied to identify the potential vegetation quality outcomes on the Murray River in Victoria. The RRCP state- transition models were also adapted to enable assessment of the outcome in the Goulburn River. This modelling utilises two sets of inputs:

- inundation mapping and associated flow thresholds for vegetation areas
- daily timeseries of modelled flows for identification of frequency and duration of inundation.

These inputs identify the areas, frequency and duration of vegetation inundated when flows reach the threshold required to commence the filling of the vegetated area (Figure 19). The environmental response method was the same for the two river systems however the inputs were developed using slightly different inputs.

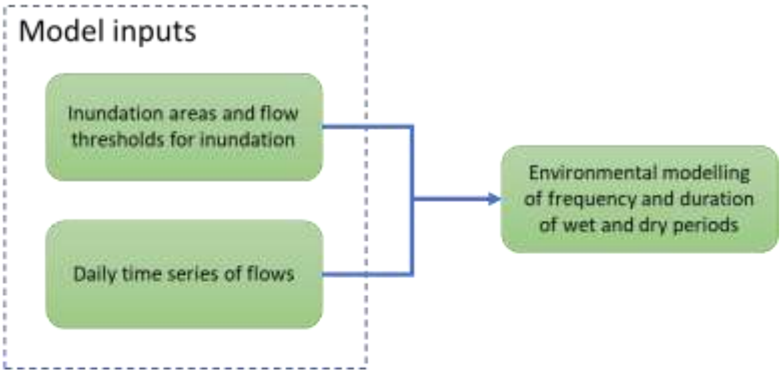


Figure 19 *Vegetation quality assessment*

The modelling framework uses daily timestep data to explore and provide annual timestep outcomes. The framework considers the joint effects of antecedent vegetation state, and antecedent inundation conditions for each annual time-step. The methodology of Bond et al. (2018) was largely adopted for the assessment.

The vegetation condition state-and-transition models developed for the SDLAM ecological elements method (Bond et al. 2018; Overton et al. 2014) was refined and adopted to model the dynamic ecological response of vegetation communities to the variable hydrologic conditions These models simulate the change in condition (i.e., 'state') of vegetation communities in response to inundation events (i.e., 'transitions') on the floodplain. The vegetation condition models use flow timeseries from the 'Source river system modelling' to predicted vegetation responses over the historic climate record.

This modelling approach extends previously developed vegetation condition state-and-transition models (Floodplain vegetation condition model (FVCM); (McPhan et al. 2022, N. R. Bond et al. 2018; Overton et al. 2014) by using expert elicitation to develop 'rules' describing the response of multiple vegetation types to inundation spells (Figure 20). In their most basic form, state-and-transition models (STMs) assume transition probabilities adhere to a constant first-order Markov process (Figure 20) where blue arrows show the pathway of state transitions in response to flood spells and orange arrows show the state transitions in response to 365-day extended dry periods). This means looking only one time step back to determine if a transition occurs.

This approach models spatially discrete vegetation condition at discrete annual time intervals in response to the antecedent hydrological conditions. Changes in vegetation state over time are thus conditional on both environmental conditions (e.g., inundation/drying spells) as well as the state (community type and condition) of the vegetation. Incorporating both of these antecedent conditions (vegetation state and antecedent inundation regime) a set of functions were developed within the R for statistical computing software environment (R Development Core Team, 2020) to run matrix projections of vegetation state (i.e. vegetation type and condition).

Using this model, we generated a time series of state transitions (vegetation condition change) over the 123-year period of flows. Due to model initialisation, the years prior to 1900-01 were not considered in the interpretation. Outputs from the model are presented in two ways:

1. A time series of each condition class (good, critical, dead) for the main vegetation types under different constraints scenarios

2. Total distribution of the proportion of time vegetation spends in each state.

The floodplain vegetation condition model was informed by the following data sources:

- Inundation maps of the floodplain areas
- Daily timeseries of flows for the duration of model projections that are from gauges representative of inundation within each inundation map
- Mapped vegetation types for the inundation map extents and their initial state

- State-transition matrices which project state changes at each time-step given a series of state transitions (hereafter referred to as 'transition rules'), different combinations of antecedent hydrological and ecological states
- Rule set of the inundation requirements for transitions between vegetation states for each vegetation type.

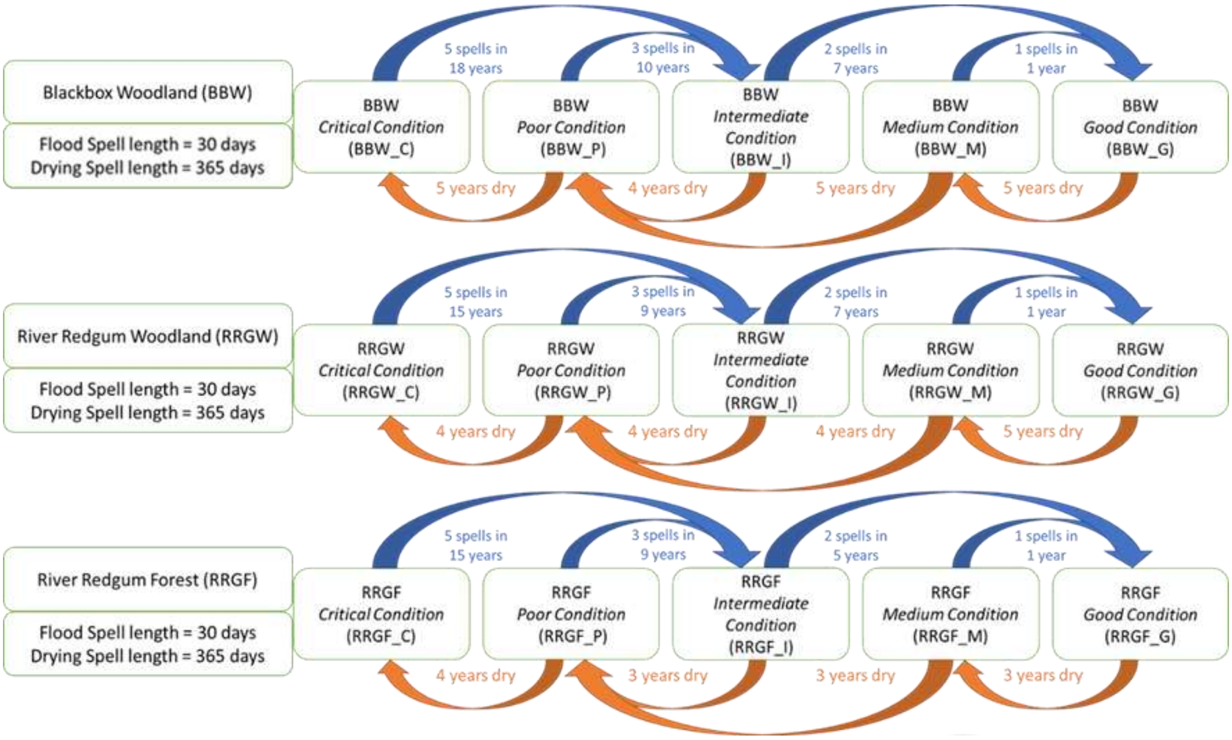


Figure 20 *Visual representation of a subset of transition rules for inundation frequency of broad vegetation categories. (Based on rules from N. R. Bond et al. (2018))*

This modelling was originally conducted as part of the RRCP, with the results from the Murray River (clipped to show Victoria only) used for this project. Further information on the approach is provided in Attachment 1.

Murray River inputs

Inundation areas: The original inundation maps varied in resolution from 5m x 5m to 15m x 15m. To represent vegetation change at the community scale rather than individual plant variation, pixels were aggregated into larger 125m x 125m pixels, using the modal value of aggregated cells as the new value for the larger pixels. Sensitivity analyses were performed to assess the validity of the averaging of the inundation maps. Due to inaccuracies across the inundation maps of the RiM-FIM, some rasters were updated or modified from the original. Where appropriate, the more recently developed EW-FIM model was used instead of the RiM-FIM.

Multiple hydrological scenarios were assessed to determine the influence of different constraint relaxation flows on floodplain vegetation. Flows over a 123-year period (1/07/1895 to 30/06/2020) were modelled with Source Murray Model software. The 123-year time period was separated into individual hydrological years using the hydrostats package. Within each hydrological year a spells analysis (parametrised through expert elicitation) was used to determine the durations of inundation and drying under each flow scenario. Further, to incorporate an aspect of water residence time on the floodplain, a tuning parameter was included in the spells analysis.

Goulburn River inputs

Inundation areas: The hydrological modelling used for the Goulburn River assessment provided flows at multiple gauges across the Goulburn catchment. For this modelling only two-gauge locations that were linked with the inundation areas for upstream (Eildon) and downstream reaches (Shepparton) were used.

Modelling scenarios were considered for inundating two regions (Upstream and Downstream) in the Goulburn catchment. The floodplain inundation areas were based on the hydraulic modelling outputs previously developed by Water Technology and provided by Sequana Partners. Pixels from these raster layers were aggregated to 125m x 125m units (as with the Murray modelling) to represent vegetation change at the community scale rather than individual plant variation.

Daily time series of flows: As with the Murray River system, constraint relaxation was trialled for multiple constraint scenarios. Here the flow limits for the base case were constrained to 10,000 ML/day for the Mid Goulburn, and 9,500 ML/day for the Lower Goulburn River.

Bayesian vegetation response modelling

Bayesian modelling of vegetation dynamics conducted by the University of Melbourne for the Goulburn River assessed three indicators: floodplain vegetation, littoral (water's edge) and mid-bank (riparian) vegetation. The floodplain conceptual model included effects of logging, fire, and rainfall, with the major flow influence being on tree recruitment (Figure 21) rather than adult condition used in the state and transition modelling.

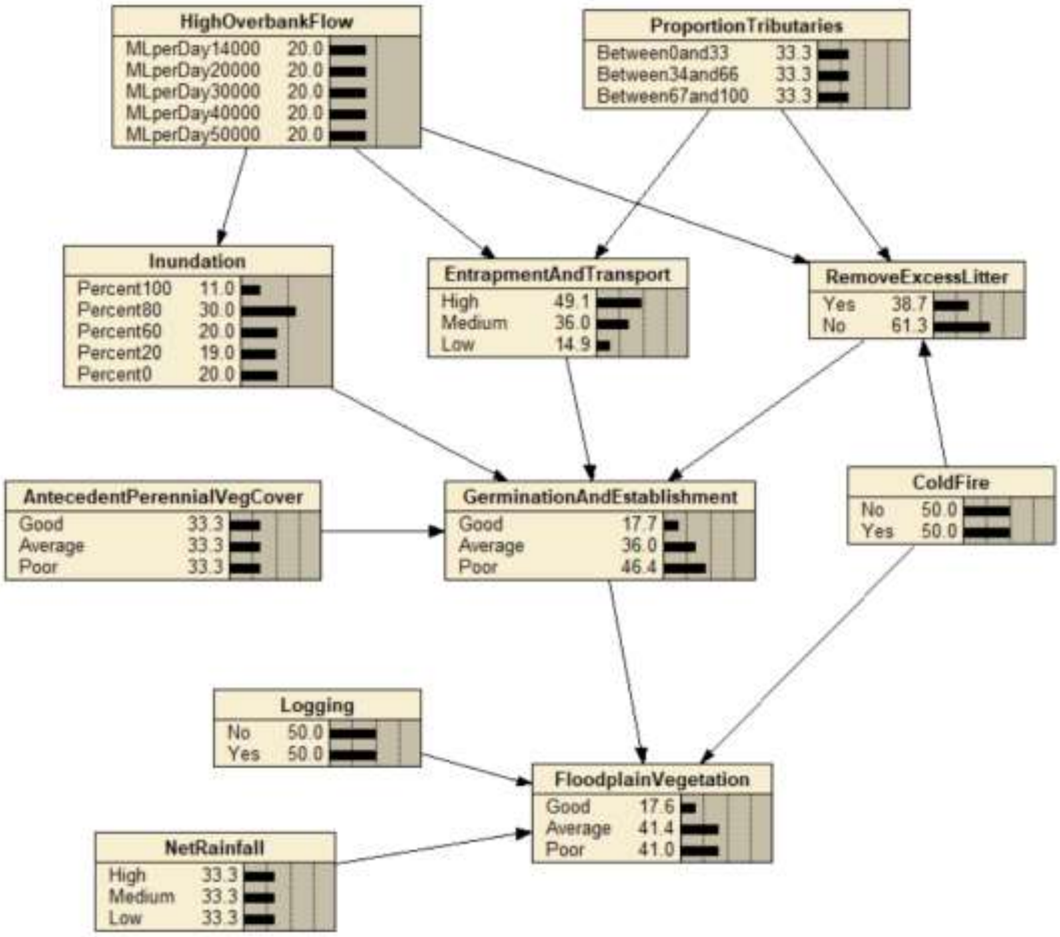


Figure 21 *Final Bayesian conceptual model for floodplain vegetation (Source: Horne et al. 2020)*

Vegetation quantity

This analysis was undertaken to identify the extent of vegetation in Victoria that had potential to benefit from relaxed constraints. The approach overlaid the inundation mapping for the adopted flow scenarios on available vegetation mapping (2005 modelled Ecological Vegetation Class (EVC) mapping) to identify the area of various vegetation types that had potential to benefit from relaxed constraints.

Vegetation groupings

EVCs were allocated to one of five broad vegetation categories across a gradient of water requirements from fully aquatic through to fully terrestrial (defined below, Table 11). Further details of which EVCs and combinations of EVCs were allocated to the categories is provided in Attachment 6 with notes where the allocation of an EVC to a category is uncertain. Allocation of EVCs to categories is informed by the ARI report *A guide to water regime, salinity ranges and bioregional conservation status of Victorian Ecological Vegetation Classes* (Frood, D. and Papas, P, 2016) as well as EVC benchmark descriptions for the four relevant bioregions: Central Victorian Uplands (DSE 2007a), Victorian Riverina (DSE 2005), Murray Fans (DSE 2007b) and Murray Mallee (DSE 2004).

While grouping vegetation types in this manner is a simplification of the highly diverse flooding and water requirements of native vegetation, it serves to identify high-level patterns in changes to inundation areas of broad vegetation groups. The categories capture overall increasing dependence on inundation noting that these categories are not based on specific analysis of elevation or frequency/duration of flooding. As such those in the terrestrial, flood-adapted to semi-aquatic category includes mosaic, aggregate and complex EVCs that include a variety of vegetation types and zones that experience differing inundation depths and durations due to local topography (Frood and Papas 2016). For example, areas mapped as Riverine Grassy Woodland/Plains Woodland/Gilgai Wetland Complex are allocated to this category – with this classification indicating that ecological conditions and characteristics spanning all three may be present and coexist (with the two woodland EVCs considered Terrestrial, flood-adapted and the Gilgai wetland semi-aquatic).

Table 11 *Vegetation categorisations*

Vegetation water requirement category	Example EVCs
Terrestrial, not flood-adapted	Box ironbark forest, Chenopod grassland, Sand ridge forest
Terrestrial, flood-adapted	Floodplain riparian woodland, Lignum shrubland, Sedgy riverine forest
Terrestrial, flood-adapted to semi-aquatic	Riverine Swamp Forest, Intermittent swampy woodland, and areas mapped as more than one EVC e.g. Grassy riverine forest/Floodway pond herbland complex
Semi-aquatic	Rushy riverine swamp, Billabong wetland aggregate, Floodplain grassy wetland
Aquatic	Aquatic herbland, and EVCs including open water such as Tall Marsh/Open water mosaic

Logic, assumptions, uncertainties

This analysis compares areas of vegetation potentially receiving inundation under the scenarios and considers, at a high level, the benefits and risk that may result from the relaxation of constraints. It is assumed that the timing of inundation would be between July to October (winter and spring), the natural season of inundation for many flood-dependent vegetation types. Inundation in the order of that set out in Section 4 of this report has been assumed. This is a high-level analysis that involves a number of uncertainties due to the rapid nature of assessment, and the scale and uncertainty inherent in the mapping of both EVCs and inundation. This analysis does not consider the specific watering requirements of individual vegetation communities in terms of depth, duration, frequency and timing.

It is assumed that EVCs classified here as aquatic, semi-aquatic, and terrestrial (flood-adapted) may potentially benefit from inundation, and that terrestrial (not flood-adapted) vegetation may be negatively impacted by inundation. This is based on the understanding that terrestrial plants tend to tolerate only very brief inundation (e.g., Main et al. 2022). An uncertainty is whether the watering requirements of individual vegetation types (EVCs) would be met, both in terms of timing, frequency, duration, and depth as well as whether appropriate "priming" flood events have occurred which can be important for a range of flood dependent vegetation (Frood and Papas 2016).

It is noted that there is no specific review on climate change through this method0. Climate change should be considered in more detail at the business case stage. Implications of climate change for vegetation likely include that water stress may be experienced by plants more often and vegetation may therefore be more vulnerable to the effects of dry periods. This could potentially further increase the already high importance of flooding to flood-dependent vegetation. If climate change means that increasing water scarcity reduces the frequency of flooding (and therefore watering floodplain vegetation) this could further reduce the health and viability of floodplain vegetation.

Productivity assessment

Few studies have directly assessed productivity before and after flood events, due to safety issues associated with working in and around floodwaters (B. Gawne Pers. Comm.). Productivity assessments in the Murray and Goulburn Rivers were therefore based on modelling.

Murray River

Siebers and colleagues modelled the production potential of the Murray River as part of NSW RRCP under relaxed constraints scenarios, using large-bodied native fish as an indicator of energy transfer through food webs (Siebers et al. 2022). The conceptual model for the study was based on differences in riverine food web function between floodplains, rarely connected rivers and regularly connected rivers (Figure 22). In the conceptual model, floodplain inundation enables the transport of organic matter from the floodplain into connected river channels. Energy is subsequently transferred up the food chain to support fish.

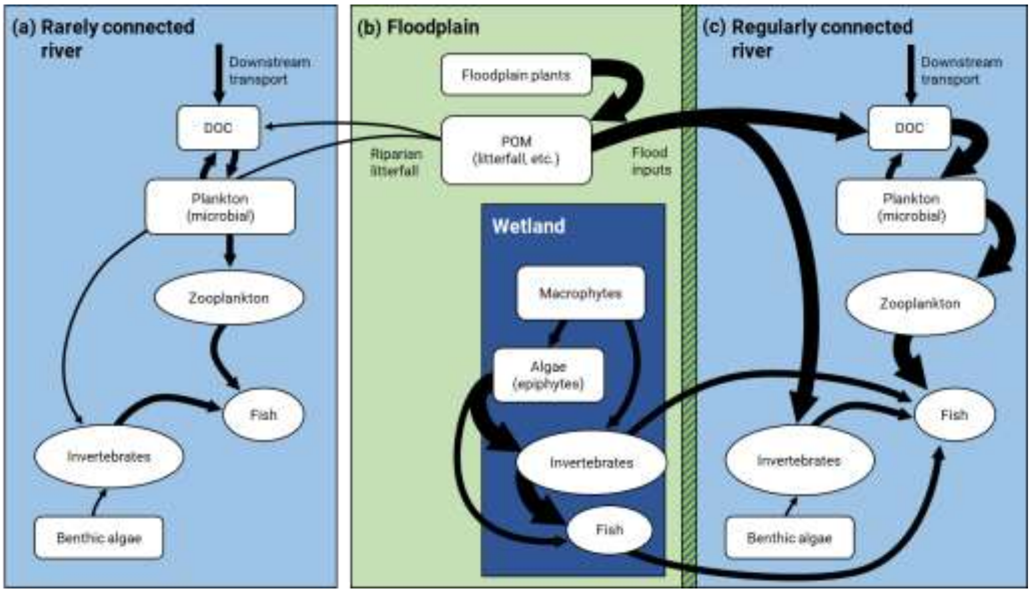


Figure 22 *Productivity conceptual model for a) a rarely connected river, b) floodplain and c) regularly connected river. The width of black arrows indicates the amount of material transferred. (Source: Siebers et al. 2022).*

Operational modelling inputs included inundation spatial datasets, discharges, temperature, recorded productivity rates for key primary producers (bacteria, algae and plants) and a modelled food web structure. Outputs were in the form of 'median total annual production potential for large-bodied native fish'. Outputs were provided for the reaches from Hume Dam to Yarrawonga, Yarrawonga to Wakool junction, and for the total RRCP reach from Hume Dam to Wentworth. Production was assessed for the base case and four relaxed constraints scenarios. For additional information on the model, assumptions and limitations, please refer to Siebers et al. 2022.

Goulburn River

Horne and colleagues modelled instream-productivity as part of a broader Environmental Flows Study and stochastic modelling (SGEFM) in the Lower Goulburn River (Horne et al. 2020). The model has been updated to better reflect the needs of the constraints program feasibility study, including assessment of productivity responses across a range of flows in the Mid and Lower Goulburn River (John et al. 2022). A conceptual model for instream productivity was developed through an expert elicitation process that involved scientists and water resource managers and refined through discussions with a technical panel. Conceptual models were then translated into ecological response models using a Bayesian network approach. Re-elicitation steps were performed to identify issues with model structure, and the models were refined. The Bayesian Network for instream productivity is shown in Figure 23.

The model is based on the concepts that:

1. Instream productivity/photosynthesis (by Benthic Algae, Phytoplankton and submerged plants) requires light penetration into the water column
2. Spring/summer baseflows (300 to 1,000 ML/day) favour benthic algae production, as the water is slow and shallow, and therefore has low turbidity and good light penetration
3. There will be productivity benefits from flows above 14,000 ML/day (overbank), which wash carbon/organic matter from floodplains into the channel.

According to the model, optimal instream productivity is achieved through a combination of overbank flows over 25,000 ML/day, baseflows of 300 ML/day (resulting in shallow depth), high nutrients and high sun light.

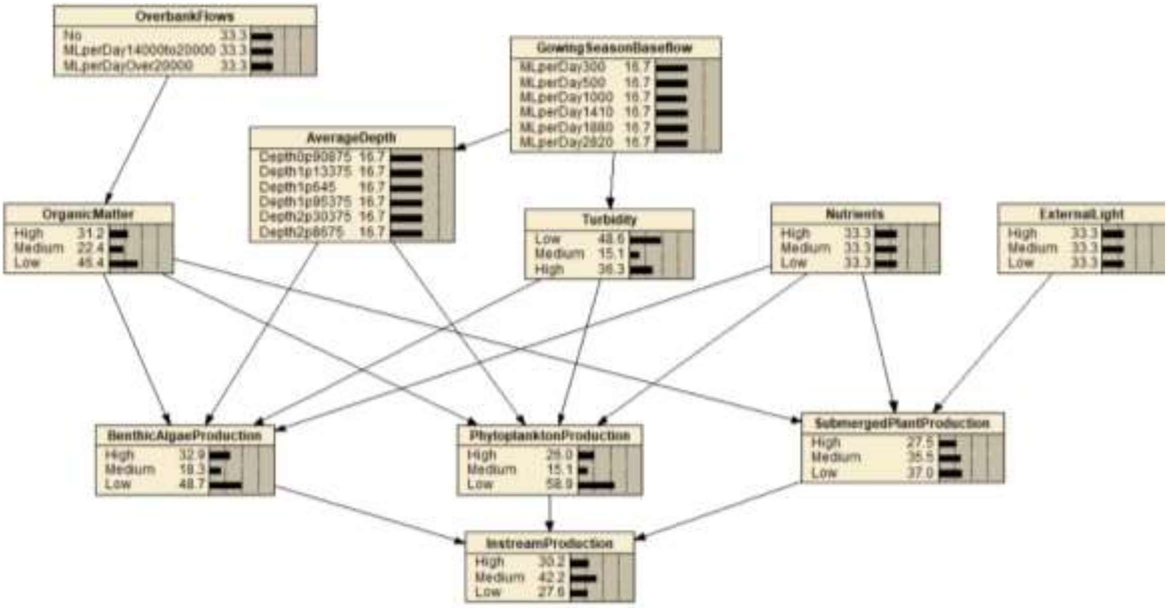


Figure 23 *Bayesian Network for Instream Productivity (Source: Horne et al. 2020)*

The Bayesian networks were then linked with a custom flow-scenario tool, which enabled responses to different flows to be modelled.

The original flow scenarios adopted by the University of Melbourne were expanded for this assessment to include the range of relaxed constraint scenarios contemplated for the Mid Goulburn and Lower Goulburn Rivers (John et al. 2022). Outputs were reported as stress index values, indicating the relative outcome (good to poor) of a given flow scenario compared to the base case scenario.

Water quality

Overview

Changing constraints levels may impact water quality in the Murray and Goulburn Rivers. Eight aspects of water quality that could be impacted by changes to flow magnitude were identified by McInerney et al 2022:

- Hypoxic Blackwater
- Eutrophication
- Blue-green algal blooms
- Salinity
- Turbidity
- Weir pool stratification/destratification
- Acid sulfate soils
- Thermal pollution

These issues are briefly summarised here. For a more detailed analysis the reader is referred to DPE (in prep) and, McInerney et al. (2022) and references therein.

Differences in modelling capacity, resources and timing necessitated that the approach taken to determine the impact of relaxed constraints differed between water quality constituents and river reaches. In some cases, only generalised conclusions could be made.

Murray River

Hypoxic blackwater

River system hydrological models have been developed to provide a realistic indication of the likely flow regimes over a 123-year period arising from the constraints scenarios. These models were used to produce a timeseries of daily flow rates at several locations along the Murray Rivers. The flow at Tocumwal was used as the indicator site for this assessment.

The Blackwater Risk Assessment Tool [BRAT (Whitworth KL, Baldwin DS, 2016)] was developed to predict the likelihood of hypoxia resulting from discrete inundation events of a single floodplain, and used here to predict blackwater risk in the Murray River. The model uses a simple representation of floodplain hydrology, and operates across a fixed floodplain area, configured to reflect a flow event of a specified height, duration, and inundation extent. Complex, multi-peak floodplain flows cannot be easily represented. BRAT can only be applied where floodplain inundation and hydrology are well understood, but it cannot be easily applied to long timeseries. Furthermore, the model is sensitive to a number of critical parameters, including litter loading and water temperature, both of which are highly variable in both time and space. Therefore, the BRAT algorithms was not integrated with the daily time step flow series developed for each scenario. Rather, the approach taken was to create a 'rule set' to determine the risk that a particular flow would create a hypoxic blackwater event, based on the timing and peak height of the flow (the two outputs that could be gleaned from the modelled hydrology, Figure 24). Steps taken for the hypoxic blackwater assessment are described in detail in Attachment 1, and are shown schematically in Figure 24. BRAT was scripted in the R coding environment (R Core Team , 2021)

Outputs from this assessment consisted of hydrological ‘events’, which were described in terms of their maximum peak discharge, the timing (month) of that peak and median modelled water temperature. Each event where potential hypoxia was indicated (17 events) was assessed by an expert panel to determine if, given antecedent conditions, hypoxia was likely. The expert review also considered whether delivered flows that might create hypoxia would be delivered given existing risk-assessment practices.

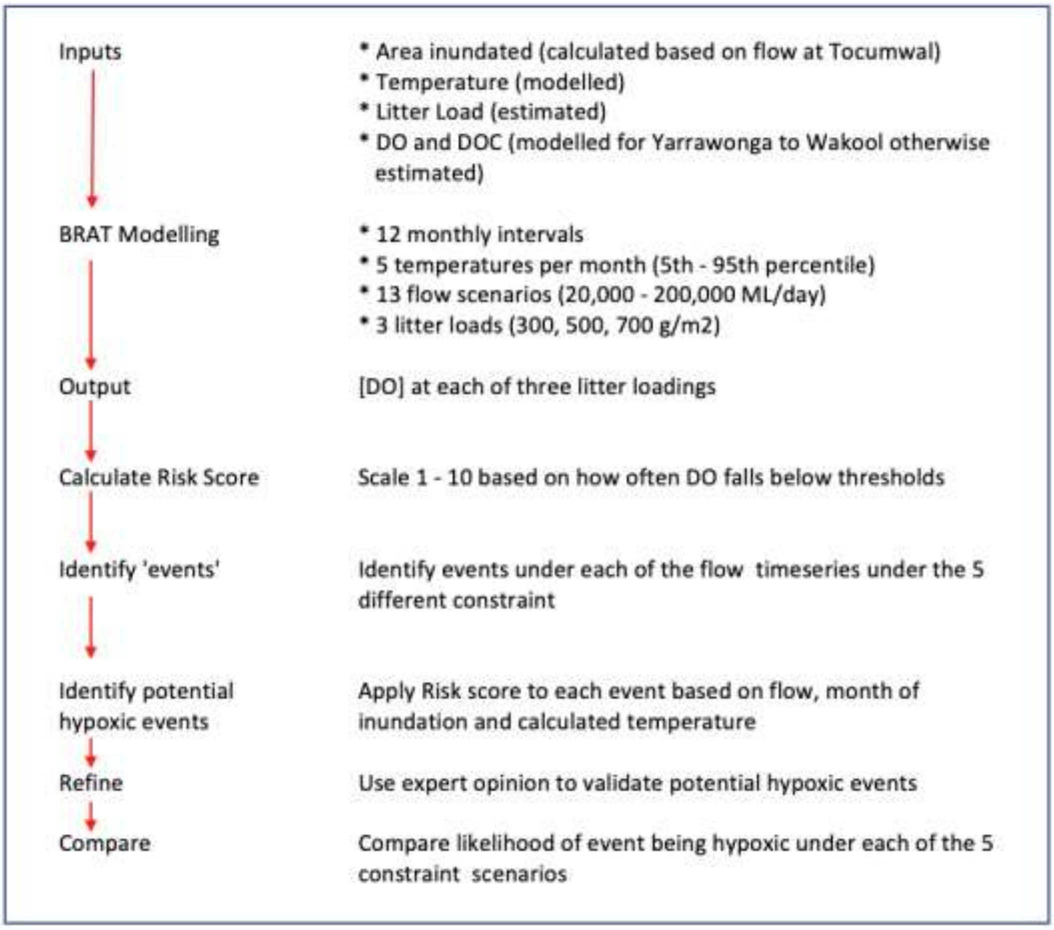


Figure 24 *Schematic representation of the steps undertaken to determine the risk of hypoxia in the Murray River following raising of constraints* (Department of Planning and Environment, in prep)

Other water quality parameters
The impacts of lifting constraints on eutrophication, blue-green algal blooms, salinity, turbidity, weir pool stratification/destratification, acid sulfate soils and thermal pollution in the two relevant reaches was undertaken by McInerney et al. (McInerney P, 2022).

McInerney et al. (2022) undertook a qualitative assessment of the impacts of relaxing constraints on water quality outcomes, based on relevant literature and local expert knowledge. They first determined if there was a mechanistic linkage between flow and the constituent of interest, and if one existed, whether the risk of relaxing constraints was increased above the current risk. Using this approach, they excluded eutrophication, turbidity, weir pool stratification/destratification, acid sulfate soils and thermal pollution from further analysis.

The second step in their analysis was to assess if constraints relaxation increased the risk to the remaining 4 parameters by comparing how the different flow regimes (current +3 constraints relaxed scenarios) would change the number of flow events over specific flow thresholds over the 123 years that were modelled.

Goulburn River

Hypoxic blackwater
Mid Goulburn River Reach: BRAT modelling is based around the leaching of DOC from plant litter - especially litter from river red gums. Although relationships have been developed for the rate of DOC release from other sources of litter (e.g., grasses) and its subsequent uptake by bacteria (e.g. Wallace et al. 2008, Liu et al. 2020), these relationships are based on dead material. For DOC to be leached from living plants following inundation, the inundated plant must first die, and the plant cells subsequently breakdown, releasing carbon. The period

between inundation and cell death is not well documented, so we chose not to incorporate these relationships into BRAT.

The riparian zone in the Mid Goulburn River reach is dominated by grasses and shrubs, therefore an approach similar to that used in the Murray River was not possible. Rather, a detailed assessment of DO concentrations in this reach was undertaken - including during periods when hypoxia was observed in the Lower Goulburn River Reach.

Lower Goulburn River Reach: The riparian corridor in the Lower Goulburn River reach is dominated by river red gums - especially downstream of Murchison. Therefore, an approach similar to that used to assess blackwater risk in the Murray River is appropriate. However, before undertaking a detailed analysis, a scoping exercise was undertaken in which firstly, the area inundated under the three constraint-relaxation flow scenarios was estimated. Then, indicative risk scores, based on a similar area of inundated forest in the Yarrawonga to Wakool reach of the Murray River, were developed. If these scores indicated that constraints relaxation could lead to an increased risk of hypoxia then a more detailed analysis was undertaken.

Other water quality parameters

Like the Murray River (McInerney P, 2022) the impacts of lifting constraints on eutrophication, blue-green algal blooms, salinity, turbidity, weir pool stratification/destratification, acid sulfate soils and thermal pollution in the Goulburn River were based on qualitative assessment and expert opinion. The approach differed from that used in the Murray River where the current changes in the concentration (and where possible, loads[2]) of key constituents along of the reach of interest was estimated based on available water quality monitoring data. Then, an assessment was made on whether it would be possible to detect a noticeable change in the concentration or load of that constituent, if flow constraints were lifted. Except for blue-green algae, all data used were from DELWP's Water Measurement Information System (https://data.water.vic.gov.au). Blue-green algal data was supplied by Goulburn Murray Water.

Macroinvertebrate biomass and diversity

Murray River

Macroinvertebrate biomass and diversity were not directly modelled in the Murray River. It is assumed that macroinvertebrates will largely mirror patterns of productivity in response to relaxation of constraints, as productivity will provide both habitat and nutrition to macroinvertebrate populations. Productivity in the Murray River was modelled by Siebers et al. 2022.

Goulburn River

Macroinvertebrate biomass and diversity were modelled in the Goulburn River using the SGEFM approach of Horne et al. 2020, which has been updated to include a range-finding exercise to suit the needs of the CMP (John et al. 2022). A three-step process was taken:

1. Development of a conceptual model for macroinvertebrate populations, initially in a stakeholder workshop and refined through discussions with technical experts.
2. Development of a conditional probability (Bayesian) network based on the conceptual model through a formal expert elicitation process, predicting the impact of flow conditions on macroinvertebrate population biomass and diversity. Note: instream productivity (output of the Goulburn River productivity assessment) is a key input node in the macroinvertebrate Bayesian network. The conceptual model Bayesian network incorporates data from macroinvertebrate studies at two sites on the Goulburn River. Crustacean biomass was used to populate the macroinvertebrate biomass and diversity node in the Bayesian network. The Bayesian network is shown in Figure 25. In this network, macroinvertebrate biomass and diversity are maximised under combinations of high baseflows, large fresh events, good antecedent conditions, good instream vegetation (habitat) and high instream productivity

[2] Loads were estimated according to the method outlined in Baldwin (2022).

3. Application of an external flow scenario tool, to predict impacts on macroinvertebrate populations over a range of flows in Mid Goulburn and Lower Goulburn River (based on probability distributions obtained from the Bayesian network). Outputs from this tool are in the form of a 'stress' index, where a stress index value of 1 means that the relaxed constraint flow combination is wholly better than the base scenario, and a stress index value of -1 indicates the relaxed constraint flow scenario is predicted to be wholly worse than the current base scenario.

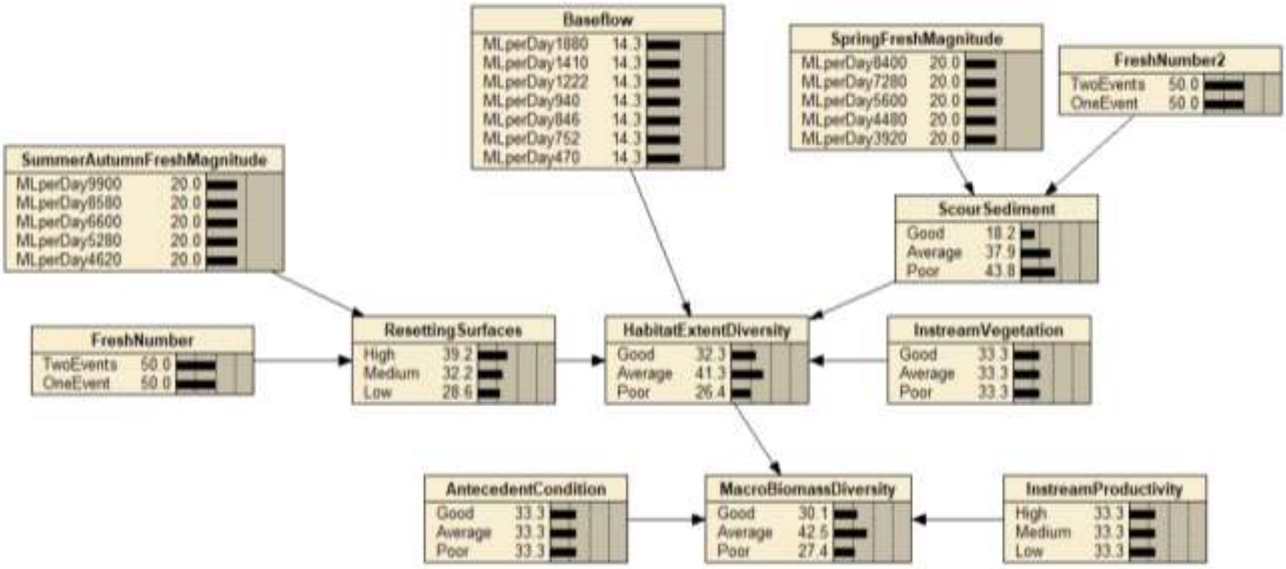


Figure 25 *Bayesian Network for macroinvertebrate biomass and diversity responses to constraint relaxation (Horne et al. 2020)*

Native fish

Murray River

The assessment of potential benefits to native fish from the relaxing of constraints was based on work completed for the NSW RRCP (Todd, 2022). This work used stochastic population models to predict the outcomes of removing constraints on two native fish species: Murray Cod (*Maccullochella peelii*) and Golden Perch (*Macquaria ambigua*). These models were constructed for reaches of both the Murrumbidgee and Murray Rivers, with the two Murray River reaches of interest (Hume to Yarrawonga, and Yarrawonga to Wakool junction) split into three reaches – Hume to Yarrawonga, Yarrawonga to Torrumbarry, and Torrumbarry to Lock 10 at Wentworth – to reflect the ecology of Golden Perch. The population models were used to predict fish responses to hydrological scenarios being assessed in this report.

Goulburn River

The native fish assessment was based on interpreting information from other studies examining fish responses to changes in hydrological conditions in the Goulburn River, including:

- Ecological response modelling using the Stochastic Goulburn Environmental Flow Model (SGEFM) for the Lower Goulburn (Horne et al. 2020, and John et al. 2022)
- Monitoring and stochastic population modelling to examine the effects of hydrological variability and environmental flows on fish as part of the Victorian Environmental Flows Monitoring and Assessment Program (VEFMAP) (Tonkin et al. 2020, Tonkin et al. 2021).
- Long-term monitoring programs undertaken since 2003. This included work funded through the Recreational Fishing Licence (RFL) fund (2003-2006), by Goulburn Broken Catchment Management Authority (2006-2013), and from 2013 through the Long-Term Intervention Monitoring (LTIM) and Flow MER programs (Webb et al. 2021).

Each of these is discussed further in Attachment 1.

Waterbirds

Murray River

Aerial and ground waterbird survey data were used to model waterbird responses (species richness, abundance, and colonial waterbird breeding activity) to river flows and inundated area in Barmah-Millewa Forest and Gunbower-Koondrook-Perricoota Forest in the mid-Murray (Figure 26). Both wetland areas are important waterbird areas in the Murray-Darling Basin and are recognised internationally under the Ramsar Convention.

Ground survey data were used to predict waterbird species richness and waterbird abundance (represented as waterbird density) in Barmah-Millewa Forest. Aerial survey data were 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 then assessed for each flow scenario based on the best flow predictor variable determined from the observed data. These were compared to both the base case (or current constraints) and 'without development' scenarios to determine the relative benefits of the relaxed constraint flow scenarios assessed (it is noted the without development is not being considered under constraints relaxation).

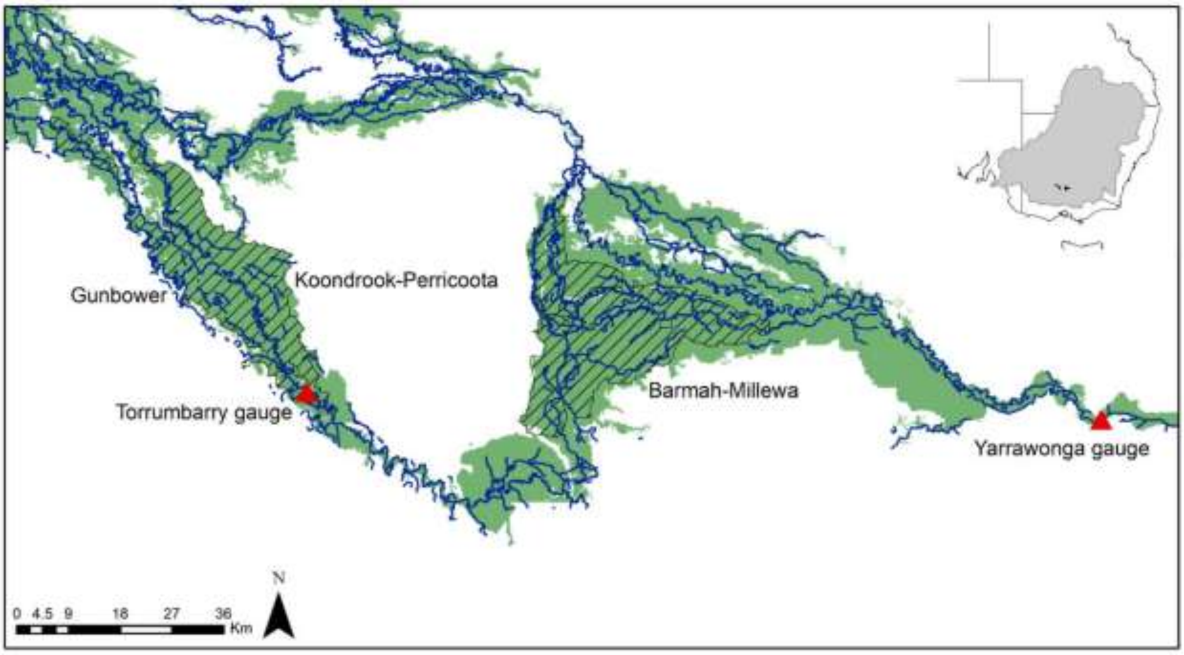


Figure 26 *Locations of Barmah-Millewa Forest and Gunbower-Koondrook-Perricoota Forest (hatched areas) and main river gauges (red triangles) in the Yarrawonga to Wakool project area in the mid-Murray within the Murray-Darling Basin (inset).*

Goulburn River

The methods used to assess waterbird responses in the Goulburn River mirrored that of the previous Murray River study described above, with some minor differences in the data sources relating to flow, inundated wetland area and survey data. For the river flow data, observed and modelled river flows were available for the Goulburn River at the Shepparton gauge. To determine the inundation extent across Goulburn River, selected area inundation raster layers were collated from the Water Observations from Space (WOfS) archive (Geoscience Australia, 2022).

Aerial waterbird surveys of Goulburn River area were completed by the University of New South Wales (UNSW) each spring from 1983-2021 as part of the Eastern Australian Aerial Waterbird Survey (Kingsford et al. 2020) (Figure 27, Figure 28). The aerial surveys are undertaken from fixed wing aircraft using two observers to independently count waterbirds in the wetlands at a height of 30-46 m, within 150 m of the wetland's shoreline where waterbirds are concentrated (Kingsford et al. 2020). All waterbirds are identified to species, except small grebes (Australasian little grebe, hoary headed grebe), small egrets (cattle egret, little egret and Intermediate egret), terns and migratory shorebirds (Charadriformes) which cannot be consistently identified from the air and were instead grouped (Kingsford et al. 2020). This aerial survey data to develop predictive relationships for the Goulburn River selected area.

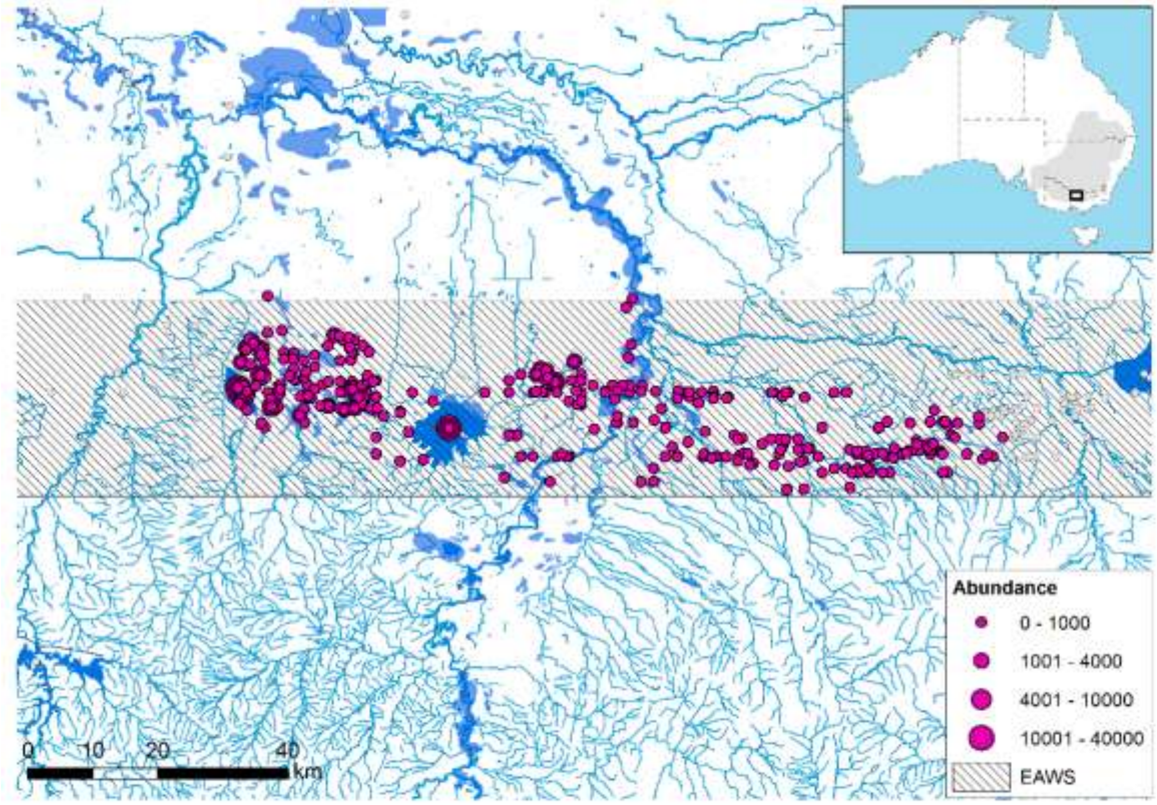


Figure 27 *Waterbird abundances in the selected Goulburn River region (Band 2) counted during the Eastern Australian Aerial Waterbird Survey 1983-2021. The hatched strip across the figure is the Eastern Australian Waterbird Survey (EWAS) transect within which waterbirds are identified and counted. Pink circles are locations where birds were counted with the larger circles representing larger numbers.*

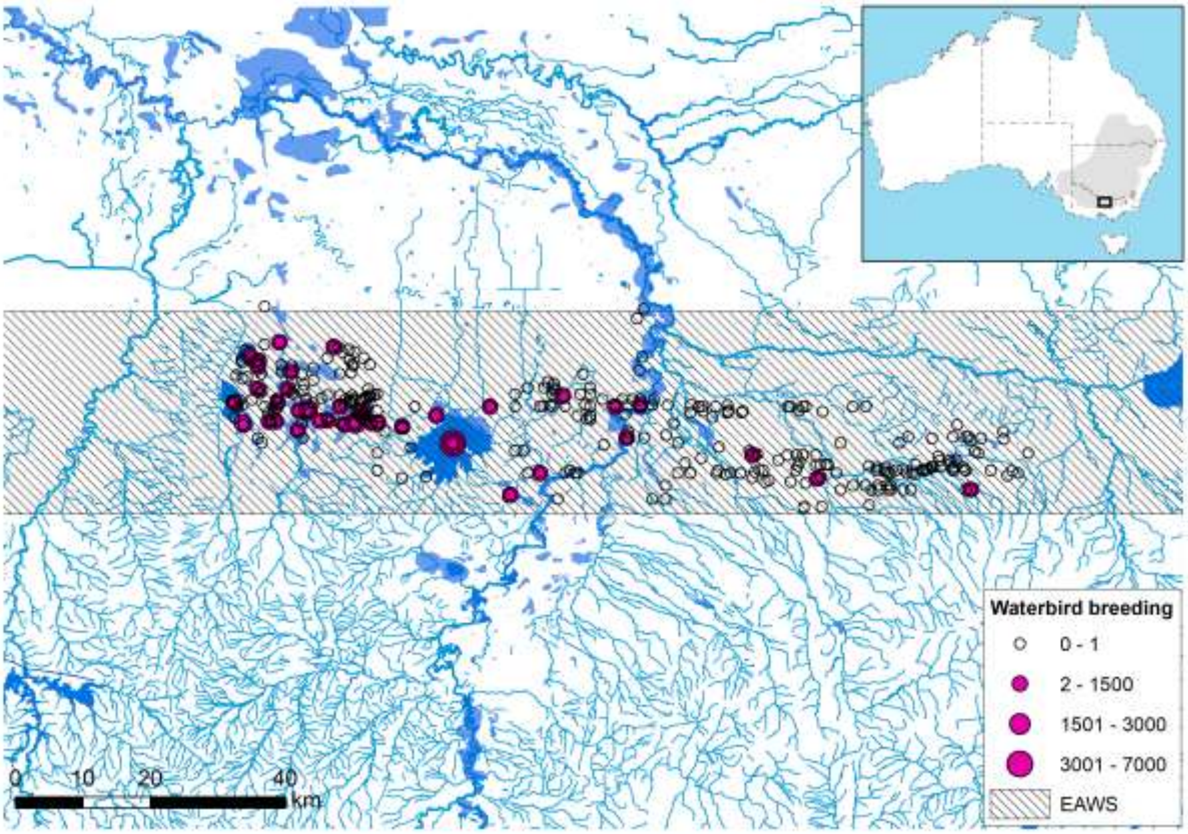


Figure 28 *Waterbird breeding in the selected Goulburn River region (Band 2) counted during the Eastern Australian Aerial Waterbird Survey 1983-2021. The hatched strip across the figure is the Eastern Australian Waterbird Survey (EWAS) transect within which waterbirds are identified and counted. Pink circles are locations where there was waterbird breeding observed with the larger circles representing larger numbers.*

Platypus

Murray River

The impact of relaxing constraints on platypus populations in the Murray River was not performed due to a lack of data and modelling studies on platypus populations in the Murray River. It is assumed that platypus populations will benefit from the provision of food (macroinvertebrates), good condition of riparian vegetation (providing bank stability and cover for burrow entrances), longitudinal connectivity and appropriate timing of high flows.

Goulburn River

Platypus responses to environmental flows were based on the SGEFM of by Horne et al. 2020 which had been updated to better suit the CMP, including application of the flow scenario tool to model impacts across a range of flows (John et al. 2022). Similar to the other assessments, the modelling involved a three-step process:

1. Generation of a conceptual model, based on a stakeholder workshop and refined through discussions with technical experts (Figure 29).
2. Development of a conditional probability (Bayesian) network based on the conceptual model through a formal expert elicitation process, predicting the impact of flow conditions and other impacts on platypus populations (Figure 30). Note: Macroinvertebrate abundance from the macroinvertebrate biomass and biodiversity assessment was an input node in the platypus assessment. Horne and colleagues state that the antecedent population node was the biggest driver of platypus populations.
3. Application of an external flow scenario tool, to predict impacts on macroinvertebrate populations over a range of flow rates in Mid Goulburn and Lower Goulburn River (based on probability distributions obtained from the Bayesian network). Outputs from this tool are in the form of a ‘stress’ index, where

a stress index value of 1 means that the flow combination is wholly better than the base scenario, and a stress index value of -1 indicates the flow scenario is predicted to be wholly worse than the current base scenario.

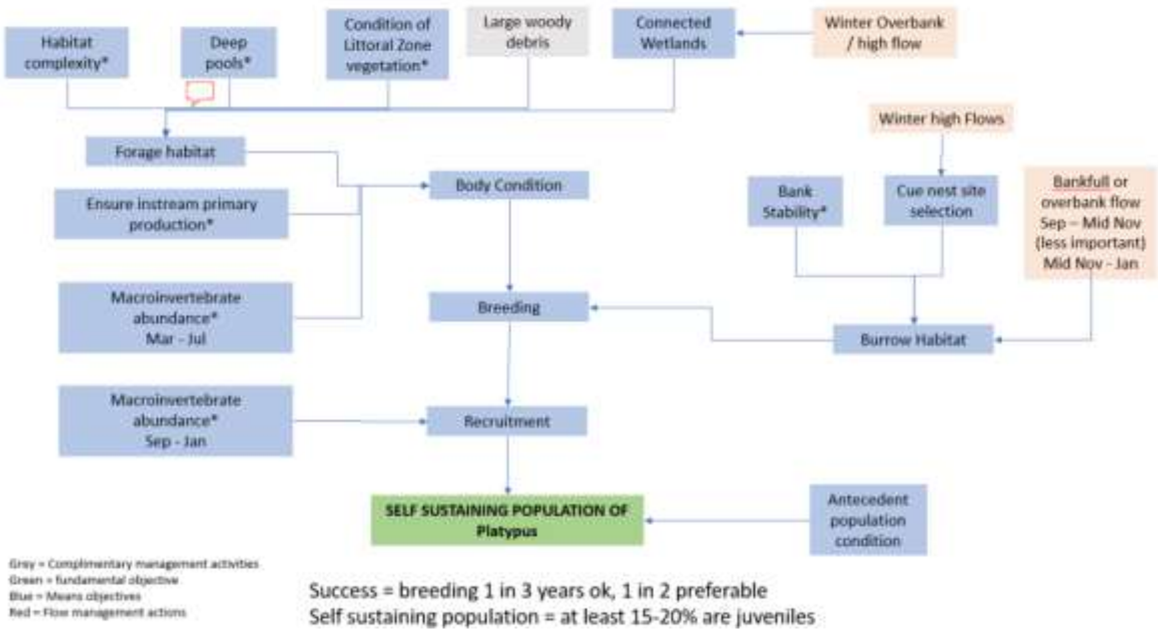


Figure 29 *Conceptual model for platypus (Horne et al. 2020)*

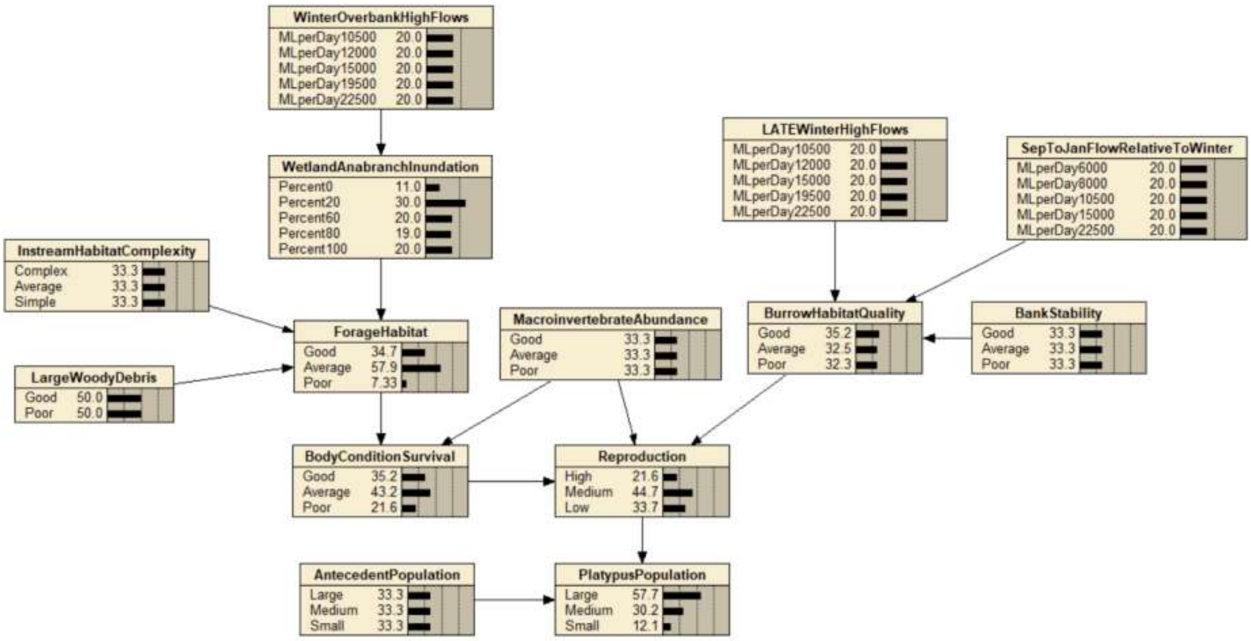


Figure 30 *Conditional probability network for platypus population (Horne et al. 2020)*

Turtles

Murray River

The impact of relaxing constraints on turtle populations in the Murray River was not performed due to a lack of data and modelling studies. Responses in the Murray River can be inferred from expected responses in the Goulburn River

Goulburn River

The Turtle assessment in the Goulburn River was based on the stochastic environmental flow model of by Horne et al. 2020 which has been updated to better suit the CMP, including application of the flow scenario tool to model impacts across a range of flows (John et al. 2022). A three- step process was used:

1. Construction of a conceptual model of turtle responses to environmental flows, developed in a stakeholder workshop and refined through expert elicitation (Figure 31)
2. Development of a conditional probability (Bayesian) network based on the conceptual model to reflect impacts from flow and other inputs on turtle populations (Figure 32). Probability tables were populated through an expert elicitation process. Note: the turtle network included a macroinvertebrate abundance node, which is an output of the macroinvertebrate analysis by Horne et al. 2020. In the model, turtle populations are maximised under the combination of rare foxes and fishing, good macroinvertebrate abundance, habitat complexity, littoral zone vegetation, bank stability and appropriate timing/delivery of flow events (Horne et al. 2020).
3. Application of an external flow scenario tool, to predict impacts on turtles over a range of flow rates in Mid Goulburn and Lower Goulburn River (based on probability distributions obtained from the Bayesian network, John et al. 2022). Outputs from this tool are in the form of a 'stress' index, where a stress index value of 1 means that the flow combination is wholly better than the base scenario, and a stress index value of -1 indicates the flow scenario is predicted to be wholly worse than the current base scenario.

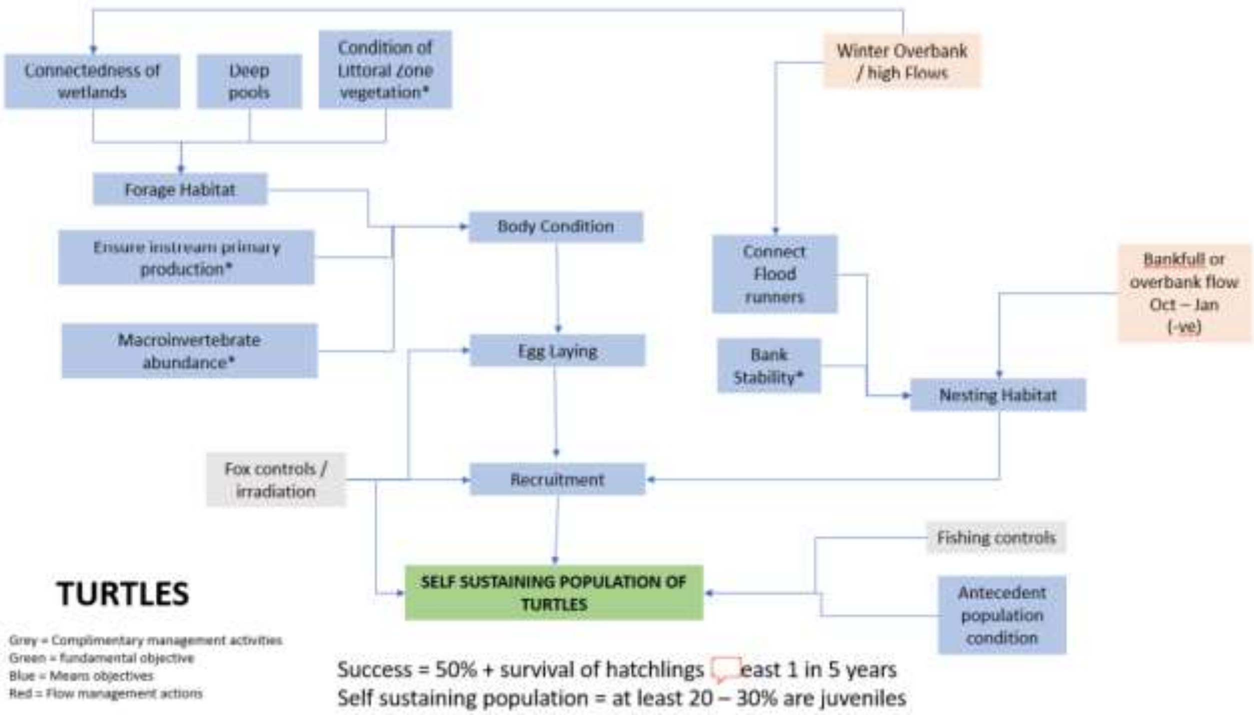


Figure 31 *Conceptual model for turtles (Horne et al. 2020)*

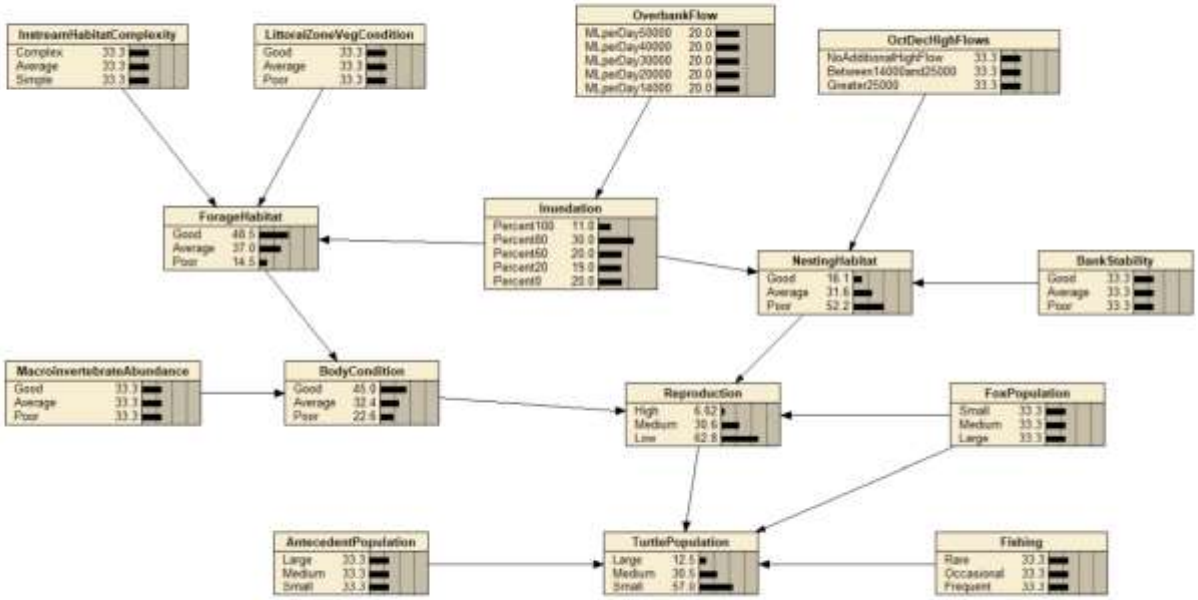


Figure 32 *Conditional probability network for turtles (Horne et al. 2020)*

Geomorphology (erosion)

Changes in the potential for erosion arising from the relaxation of constraints have been assessed using the concept of total effective geomorphic work. The approach was applied to the Goulburn River and inferences drawn for the Murray River. The overall steps in the geomorphology analysis were:

- Quantifying how each constraints relaxation scenario alters the total effective geomorphic work performed on the bed and banks of the Lower Goulburn River. An Erosion Potential Index (EPI) approach (outlined below) was used.
- Quantifying the total number of days flow is above and below bankfull discharge in the Lower Goulburn River and relating this statistic to the EPI results for that reach. Establishing the link between the EPI results and flow statistics allows inferences about erosion potential to be made in reaches where only flow statistics (and not a full EPI analysis) was available.
- Quantifying the total number of days flow is above and below bankfull discharge in the Hume to Yarrawonga and Yarrawonga to Wakool reaches of the Murray River.

Conceptualising erosion potential

Quantifying the change in erosion potential in-channel requires that the total erosive forces that the flow expends on the channel bed and banks be quantified, and then integrated across all flows over time. The frame of reference for the EPI analysis is the main channel of the Goulburn River, and all references to erosion potential refer to the bed and banks of the channel, not erosion of the floodplain (which has not been assessed).

Constraints relaxation will increase the magnitude (peak discharge) and frequency (occurrences per year) of overbank flows (Figure 33). Overbank flows generate greater erosion forces (measured in units of shear stress – N/m^2) in-channel because the flow is deeper. However, as flow spills onto the floodplain, more and more of the additional energy provided by the increased discharge is expended on the floodplain instead of in the channel (Figure 34).

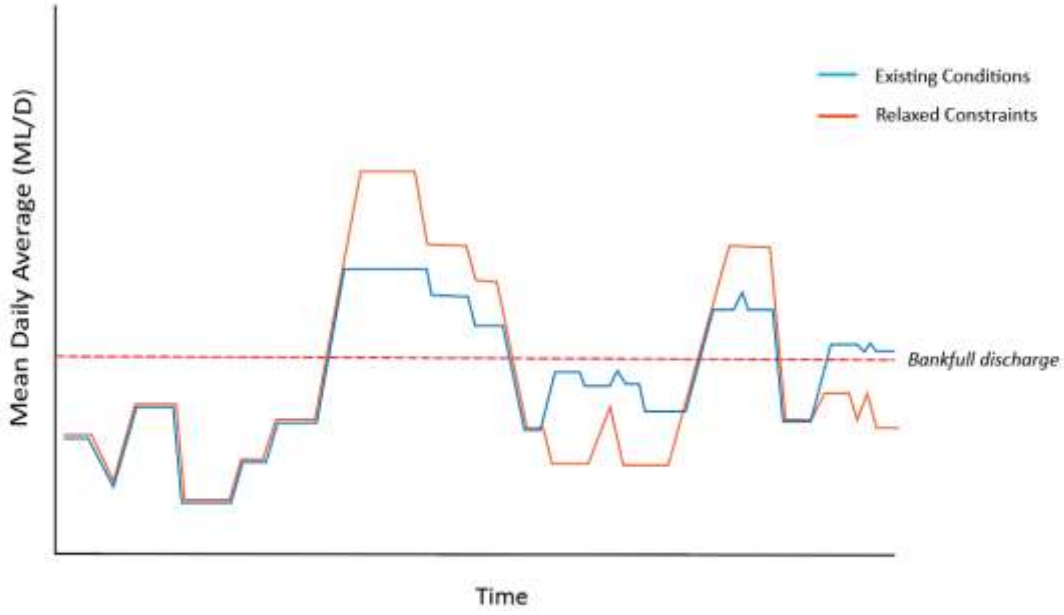


Figure 33 *Example flow conditions*

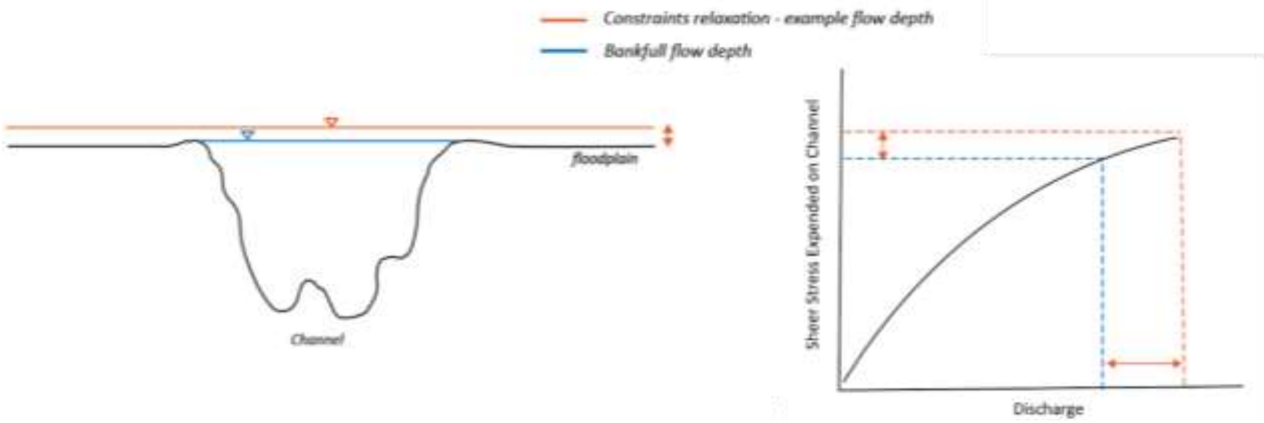


Figure 34 *Example shear stress scenario*

If the frequency of flows that are large enough to exceed the threshold for erosion, but small enough to remain in-channel, decreases, then the net effect will be a decrease in total effective geomorphic work in the channel (the area under the curve in Figure 35). In this way, over time, geomorphic work is re-distributed from the channel to the floodplain. It is this re-distribution of geomorphic work that has the potential to lead to a decrease in bed and bank erosion.

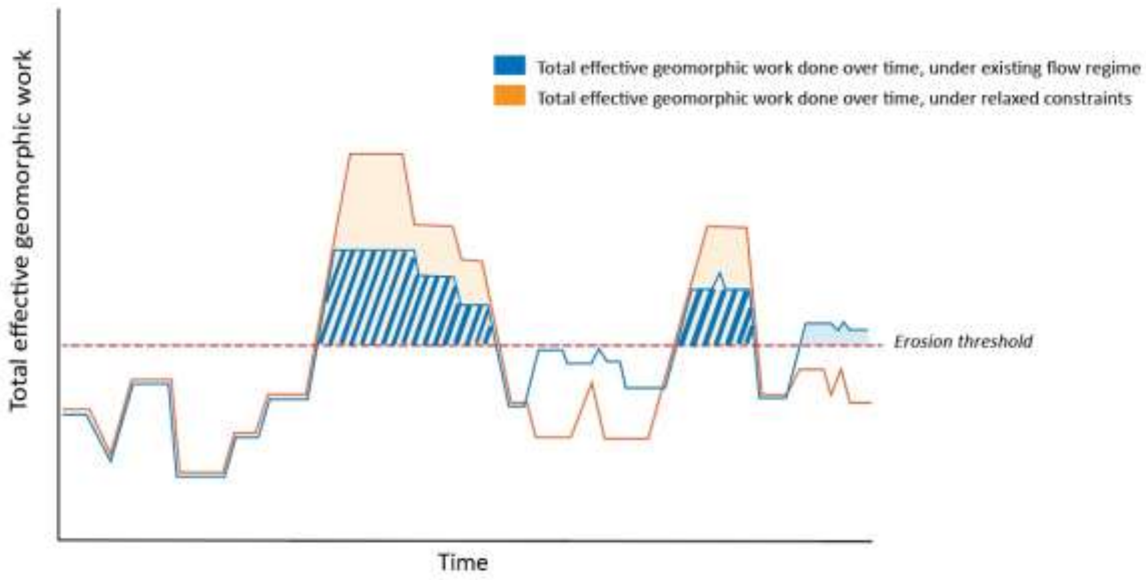


Figure 35 *Example geomorphic work scenario*

Alternatively, if the frequency of flows that are large enough to exceed the threshold for erosion, but small enough to remain in-channel, either remains unchanged or increases (e.g., more overbank flows *and* more bankfull flows are delivered), the outcome will be an overall increase in total effective geomorphic work.

We have undertaken a pilot analysis on the Lower Goulburn River to assess whether total effective geomorphic work is likely to increase or decrease under each constraint relaxation scenario.

Analysis methods

Total effective geomorphic work (the area under the curve in Figure 35) was calculated by calculating an Erosion Potential Index (EPI) for each scenario for the Lower Goulburn River only. The four scenarios of the Lower Goulburn River were used as a case study to demonstrate the EPI approach, and to assess, at a high level, whether the flow regimes modelled for each scenario are likely to lead to an increase or a decrease in the erosion potential. Simple flow statistics for the Lower Goulburn River were calculated, so that the proportion of flow delivered over bank and in-channel under each scenario could be compared to the relevant EPI value. By establishing the link between these simple flow statistics and the calculated EPI values, the same statistical analysis could be applied to the Murray River flow series and make inferences about erosion potential in those reaches, even in the absence of a complete EPI analysis in those reaches.

All Lower Goulburn EPI values were normalised so that the natural (pre-development) flow regime had an EPI value of 1.0. An EPI of greater than one indicated an increase in total effective work compared to natural (without development) conditions, and an EPI of less than one indicated a decrease in total effective work compared to natural (without development) conditions. An EPI of one indicates the stream will remain in equilibrium over a period of years, although there may be localised erosion and deposition at the flow event time scale. If the EPI is greater than one the analysis indicates more sustained bed and bank erosion is likely to occur.

Alignment with RRCP

The EPI approach described above differs to the approach utilised by the Reconnecting River Country Program (RRCP). The RRCP categorised the magnitude of benefits for several geomorphic processes using qualitative methods whereas the analysis in the VCMP used quantitative methods to test the hypothesis that constraints relaxation may provide benefits to a single geomorphic process. The VCMP did not assess the ‘magnitude ‘of those benefits. The RRCP categorised the 'likelihood of potential geomorphic change’ by deriving an impact score and then identified how mitigation measures could alter the impact score. No impact scores were derived in the VCMP and mitigation measures were not identified. The two approaches are complimentary. The approach used in VCMP is essentially a more focused and quantitative analysis of one of the processes that were considered in a more generalised and qualitative manner by the RRCP. Future work can assess the magnitude of the benefits identified by the VCMP and expand the geomorphic processes considered to include those assessed by the RRCP.

Summary of assessment sources

Table 12 *Key assessments and reports used in environmental assessments*

Theme	Goulburn River assessment	Murray River assessment
Connectivity	New analyses based on hydrologic modelling provided to HARC by GBCMA	Stewardson et al. 2020
Vegetation quality	New analyses. Extends models and work of McPhan et al. 2022, N. R. Bond et al. 2018; Overton et al. 2014 Horne et al. 2020, with new range-finding analyses for CMP (John et al. 2022)	Uses models and work of McPhan et al. 2022, N. R. Bond et al. 2018; Overton et al. 2014 conducted for the NSW RRCP
Vegetation quantity	New analyses based on hydraulic modelling conducted by HARC	New analyses based on hydraulic modelling for RRCP
Productivity	Horne et al. 2020, with new range-finding analyses for CMP (John et al. 2022)	NSW RRCP assessment (Siebers et al. 2022)
Water quality	New analyses using BRAT tool.	New analyses using BRAT tool.
Macroinvertebrates	Horne et al. 2020, with new range-finding analyses for CMP (John et al. 2022)	Not assessed
Native fish	Horne et al. 2020, with new range-finding analyses for CMP (John et al. 2022). Modelling from VEFMAP (Tonkin et al. 2020, Tonkin et al. 2021)	NSW RRCP assessment (Todd et al. 2022)
Waterbirds	New analyses using data from the UNSW Eastern Australian Aerial Waterbird Survey	New analyses using ground survey data from the Barmah-Millewa Forest and Gunbower-Koondrook-Perricoota Forest and Waranga Basin
Platypus	Horne et al. 2020, with new range-finding analyses for CMP (John et al. 2022)	Not assessed
Turtles	Horne et al. 2020, with new range-finding analyses for CMP (John et al. 2022)	Not assessed
Geomorphology	New analyses based on effective geomorphic work in the Lower Goulburn River	New analyses using inferred results from the Goulburn River

6 Environmental benefits and risks

Connectivity

Environmental water plays an important role in maintaining connections to downstream reaches. In the 2018-19 water year environmental flows from Eildon into the Goulburn River contributed 13% of the total streamflow volume across 30% of days within the year. These environmental water releases were able to translate to 31% of total streamflow volumes over the 30% of days at McCoys Bridge (Figure 36), located towards the end of the river (Stewardson and Guarino, 2020).

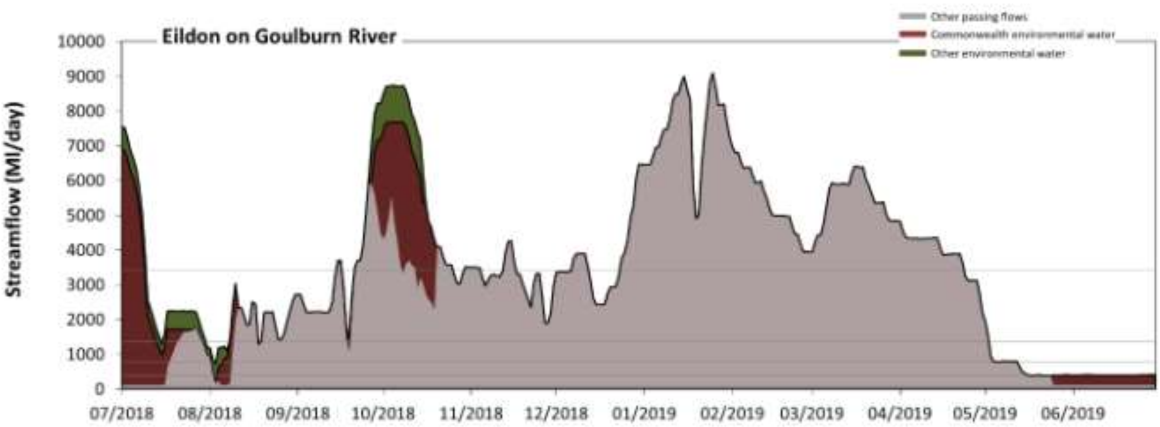


Figure 36 *Contribution of environmental water delivery at Eildon from lowest to highest on the horizontal axis (Red: Commonwealth environmental water, grey: other passing flows, green: other environmental water) (Stewardson et al. 2020)*

Similarly for the same water year, environmental water delivery from Hume Dam into the Murray River contributed 10% of the streamflow volume at Doctors Point, affecting flows on 41% of days (Figure 37). These contributions were able to translate to 10% of total flow at Barmah, importantly impacting 100% of the days of the year (Figure 38).

Figure 37 *Contribution of environmental water delivery at Doctors Point from lowest to highest on the horizontal axis (Red: Commonwealth environmental water, grey: other passing flows, green: other environmental water) (Stewardson et al. 2020)*

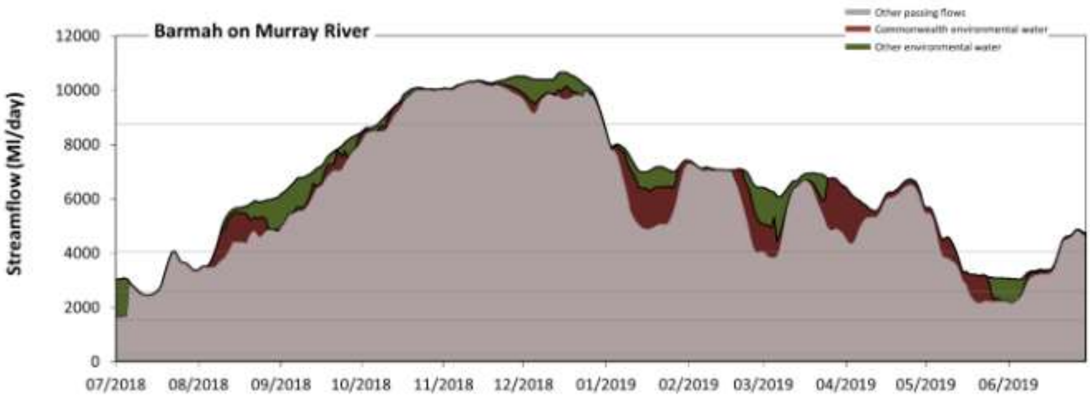


Figure 38 *Contribution of environmental water delivery at Barmah from lowest to highest on the horizontal axis (Red: Commonwealth environmental water, grey: other passing flows, green: other environmental water) (Stewardson et al. 2020)*

The two systems were able to combine to clearly demonstrate the capacity for environmental water to connect releases to downstream reaches, particularly in higher flows that are important for nutrient delivery. The environmental water deliveries from the Murray River and Goulburn River that come together upstream of Echuca are able to combine to contribute 17% of the total flow at Wakool and into the downstream reaches of the Murray River, contributing to every day of the 2018/19 water year (Figure 39).

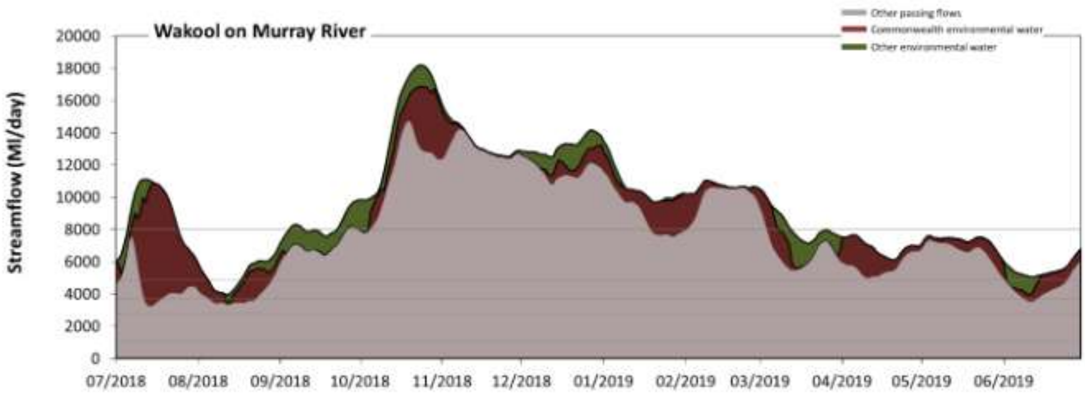


Figure 39 *Contributions of environmental water delivery at Wakool from lowest to highest on the horizontal axis (Red: Commonwealth environmental water, grey: other passing flows, green: other environmental water) (Stewardson et al. 2020)*

The relaxation of constraints provides opportunity to improve connectivity in the reaches, particularly in the winter/spring targets delivery periods. By overlaying the periods that exceed 10,000 ML/day at Molesworth and Shepparton, the changes in connectivity to the downstream reaches becomes visible (as is shown in Figure 40, Figure 41, Figure 42, and Figure 43. All of these figures developed for the feasibility study based on the project hydrology results and provided by HARC), particularly in the priority delivery periods of late winter and early spring as shown in Figure 13. Note that in the displays of the flow distributions in Figure 40, Figure 41, Figure 42, and Figure 43 the current flows are shown in their entirety, with only the additional flow periods for the compared constraint shown.

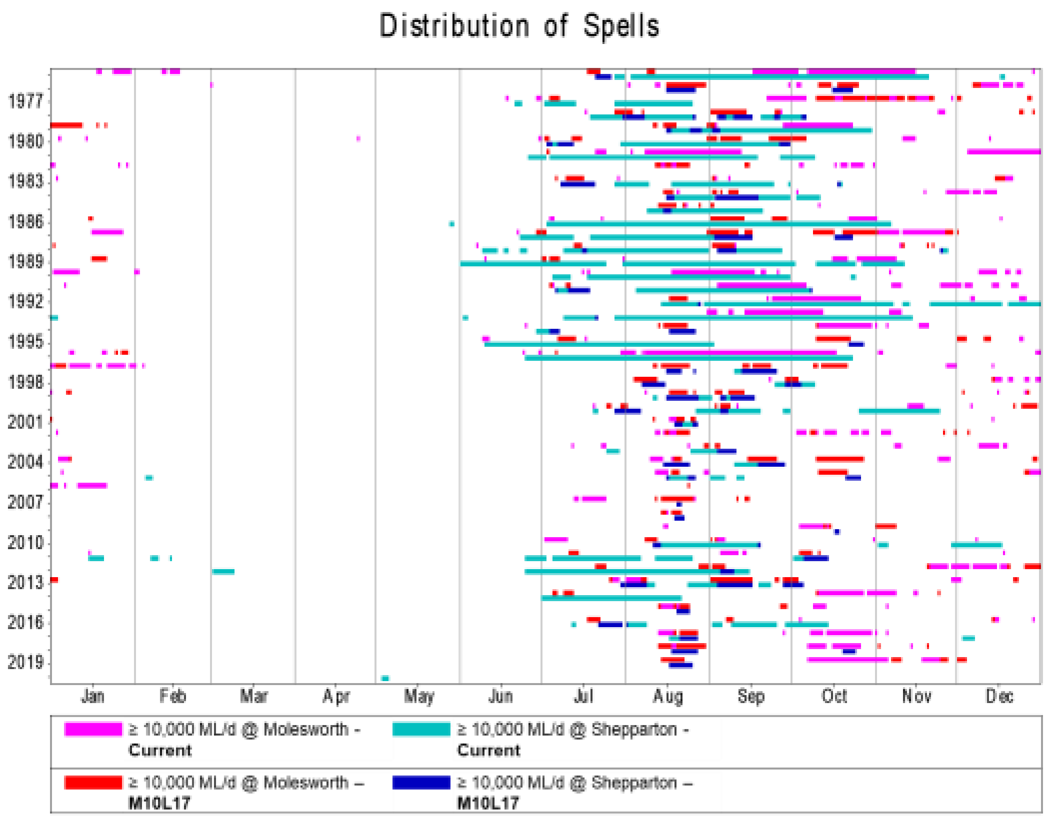


Figure 40 *Distribution of flows at Molesworth and Shepparton (Current vs M10L17)*

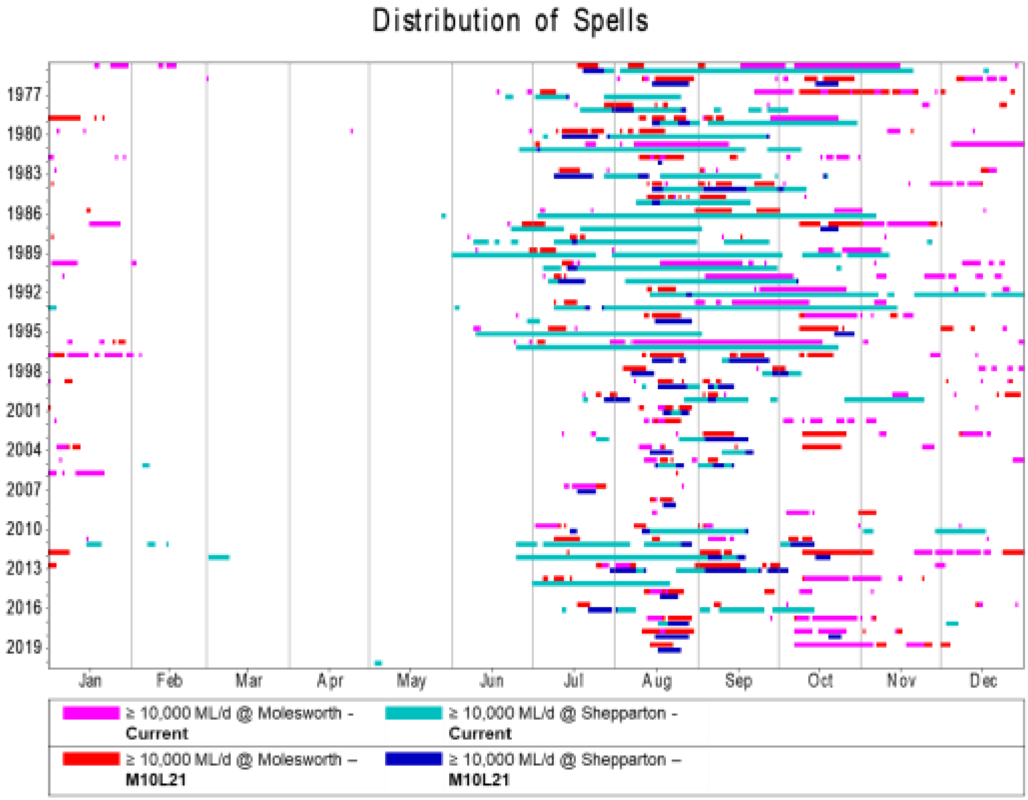


Figure 41 *Distribution of flows at Molesworth and Shepparton (Current vs M10L21)*

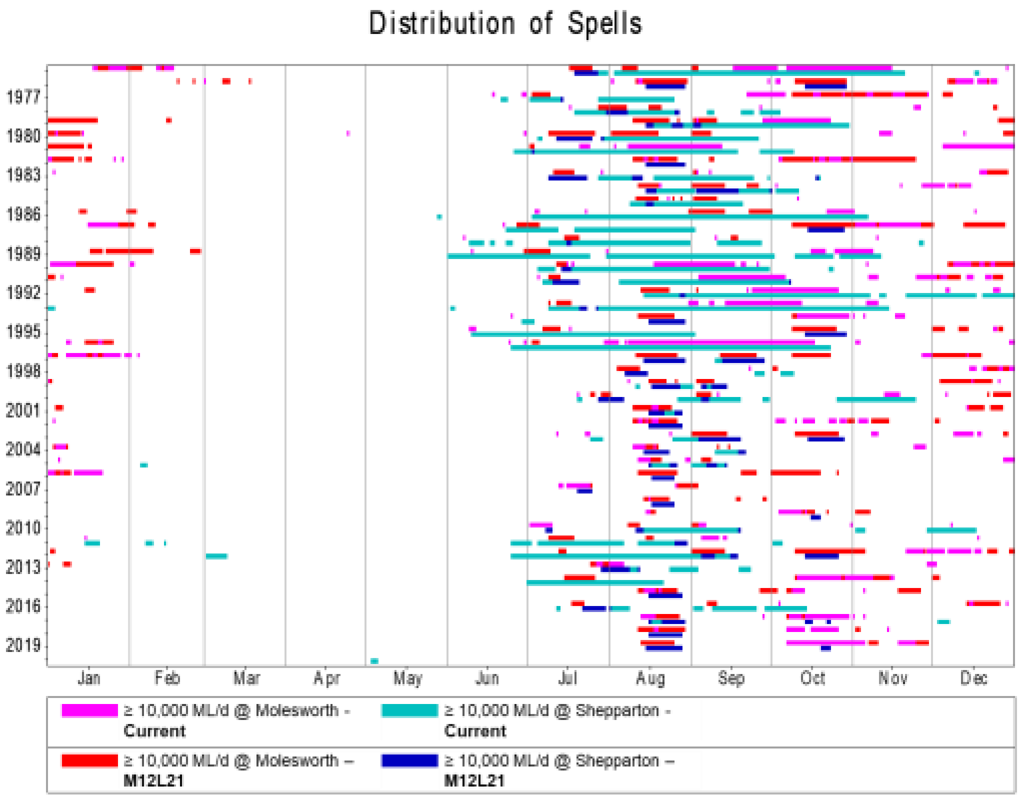


Figure 42 *Distribution of flows at Molesworth and Shepparton (Current vs M12L21)*

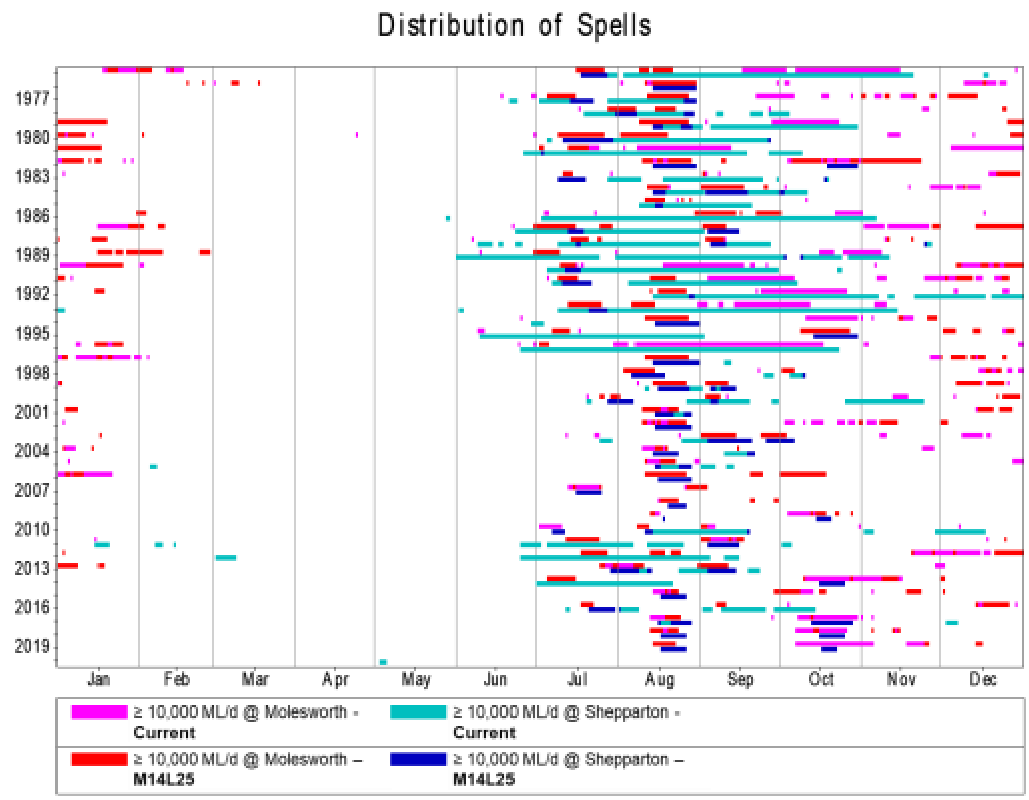


Figure 43 *Distribution of flows at Molesworth and Shepparton (Current vs M14L25)*

As the volumes of environmental water is finite, the overall volumes should not be expected to change, however when special attention is paid to the priority window of late winter to spring, the relaxation of constraints shows the potential for an increased linking to the broader system. Using the hydrologic modelling conducted on the two rivers, the changes to flows at the downstream locations (in this case Shepparton and Wakool) demonstrate the potential to provide important flows and nutrients to the broader system, while ensuring the flows required for native fauna lifecycles and the flushing of the upstream reaches.

The results of Table 13 show the potential increase in connected flows under the various constraints relaxation scenarios, showing increases in flows in the vital early spring periods, and a linked reduction of flow in other months due to the finite environmental water availability.

A key item noted in the connectivity assessment is that despite the increased connection with the floodplain, there is little to no loss in downstream connectivity.

Table 13 *Overview of connectivity changes*

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Flow change (average ML per month)	Flow change (%)	Flow change (average ML per month)	Flow change (%)	Flow change (average ML per month)	Flow change (%)	Flow change (average ML per month)	Flow change (%)
Goulburn River at Shepparton								
July	-10,360	-4.7%	-6,029	-2.7%	-5,442	-2.5%	8,346	3.8%
August	11,665	3.3%	9,824	2.8%	17,533	4.9%	31,456	8.9%
September	2248	0.7%	-1,931	-0.6%	-374	-0.1%	-2,511	0.8%
October	15795	5.8%	10,186	3.7%	6,169	2.2%	-10,412	3.8%
Murray River at Wakool								
July	11,254	0.06%	11,703	0.06%	11,823	0.06%	13,489	0.07%
August	2,731	0.01%	9,398	0.06%	-733	0.00%	-4	0.00%
September	8,856	0.02%	17,252	0.05%	11,309	0.03%	9,927	0.03%
October	19,981	0.05%	24,812	0.06%	40,125	0.10%	51,556	0.13%

Vegetation quality analysis

The vegetation quality analysis has been based on Latrobe University's state transition modelling and on University of Melbourne's Stochastic Goulburn Environmental Flow Model (Goulburn River only).

The environmental benefits and risks assessment and the preceding NSW RRC project are the first known application of state and transition models to floodplain vegetation in the Murray valley although they are widely used in other systems. The models consider a single driver of change, inundation, and the subsequent change in condition given the condition of the tree at the time of inundation. Floodplain trees have been found to utilise rainfall, groundwater and floodwater, however, for this initial assessment, consideration of inundation was believed to be appropriate (McPhan et al. 2022). The results of the Victorian side of the Murray River have been clipped and used from the RRCP model results.

Given the data rich outputs associated with the model outcomes, (multiple constraint scenarios, vegetation types, condition classes in a 123-year time series) the data has been presented in two main ways: as time series of each condition class of the main vegetation types under constraint scenarios, and as the total distribution of proportions of time in a state. Comments accompany figures to compare the scenarios and vegetation condition.

As described in Section 5, the state transition model uses five states of vegetation living health, plus dead state, to show the potential condition of vegetation in response to the various constraints relaxation scenarios. The modelling uses periods of wet or dry to allow the vegetation to transition to another state. Only inundation events of 30 days or more will improve the condition (state) of black box woodland and river red gum forests and woodlands (Figure 20). However, inundation of any duration will prevent a decline in condition of black box woodlands and river red gum forests and woodlands to the next state.

However, it is important to note that the 30-day duration of events necessary to improve condition is longer than the target length of constraints relaxation flow events. As a result, based on the state transition modelling undertaken, the flow events proposed under the constraints relaxation scenarios assessed will be effective at reducing a decline in condition (state) but will have limited role in improving the condition of the vegetation communities. Based on the model assumptions and the proposed flow scenarios, improvements in condition will largely rely on unregulated events.

An additional note in the results is the initial drop in condition seen in all of the models. This decline is a result of the drought in the early period of the 20th century, known as the Federation Drought, causing an extended dry period that causes the decline in condition. The model runs use the historic climate sequence commencing in 1896, around the time of the drought. While this has a noticeable impact on results, it is not considered to create bias for two main reasons:

1. The Federation Drought is not the only severe drought in the model period, and a similar response could be expected if the model were started just prior to the dry periods of the 1940s or the more recent Millennium Drought
2. The large decline in condition is directly countered by the assumption that all of the vegetation begins in a good condition, providing the areas the best opportunity for survival, and displaying the best possible outcome of each scenario.

The timing of the Federation Drought prompts questions around the drought's influence, given it occurs in what may be considered the 'burn-in' period of the modelling. While this may be the case, the results show potential responses to drought where constraints are or are not relaxed, even if all vegetation is in the best possible condition when the drought begins.

Goulburn River – State and transition modelling

In both modelled reaches of the Goulburn, the vegetation community was dominated by the area of river red gum forests (RRG) and black box woodlands (BBW) (Figure 44). In the Lower Goulburn reaches, the area of floodplain supporting black box woodland increased with increased inundation threshold (ML/day).

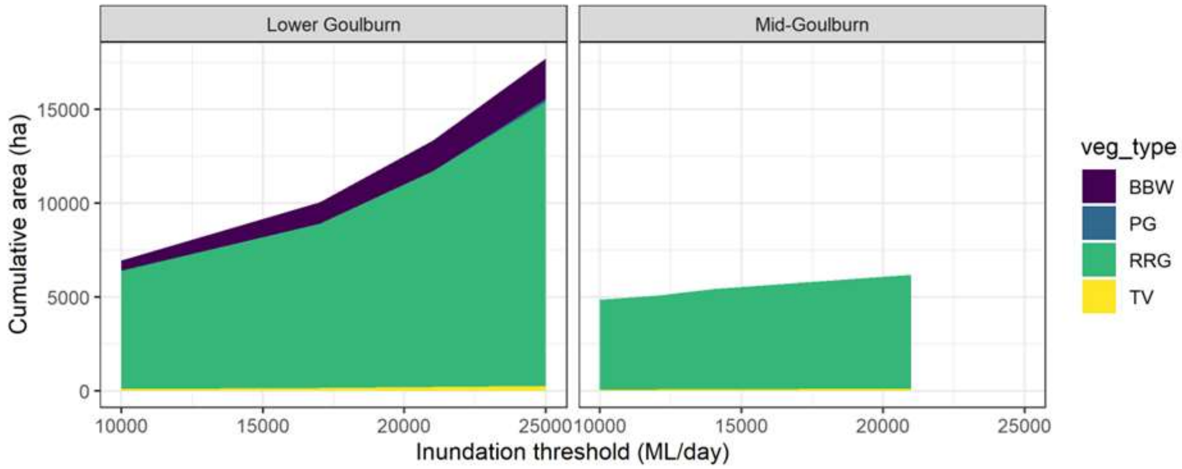


Figure 44 *Cumulative distribution by area (ha) of vegetation on the floodplain within the areas of inundation (ML/day) being modelled. Vegetation types modelled by the FVCM are each coloured separately for each region being modelled.*

For black box woodland in the Lower Goulburn, initial sharp declines in the area of good condition vegetation and sharp increases in the area in critical condition indicate that the inundation sequences were not appropriate to support good condition for the majority of the black box woodland stands. While this did not cause large areas to die back, vegetation remained in a critical state. For the base case, there is an area of good condition black box woodlands (around 500 ha) that improves in condition during the relatively wet conditions of the 1970-90's prior to a decline during the Millennium drought.

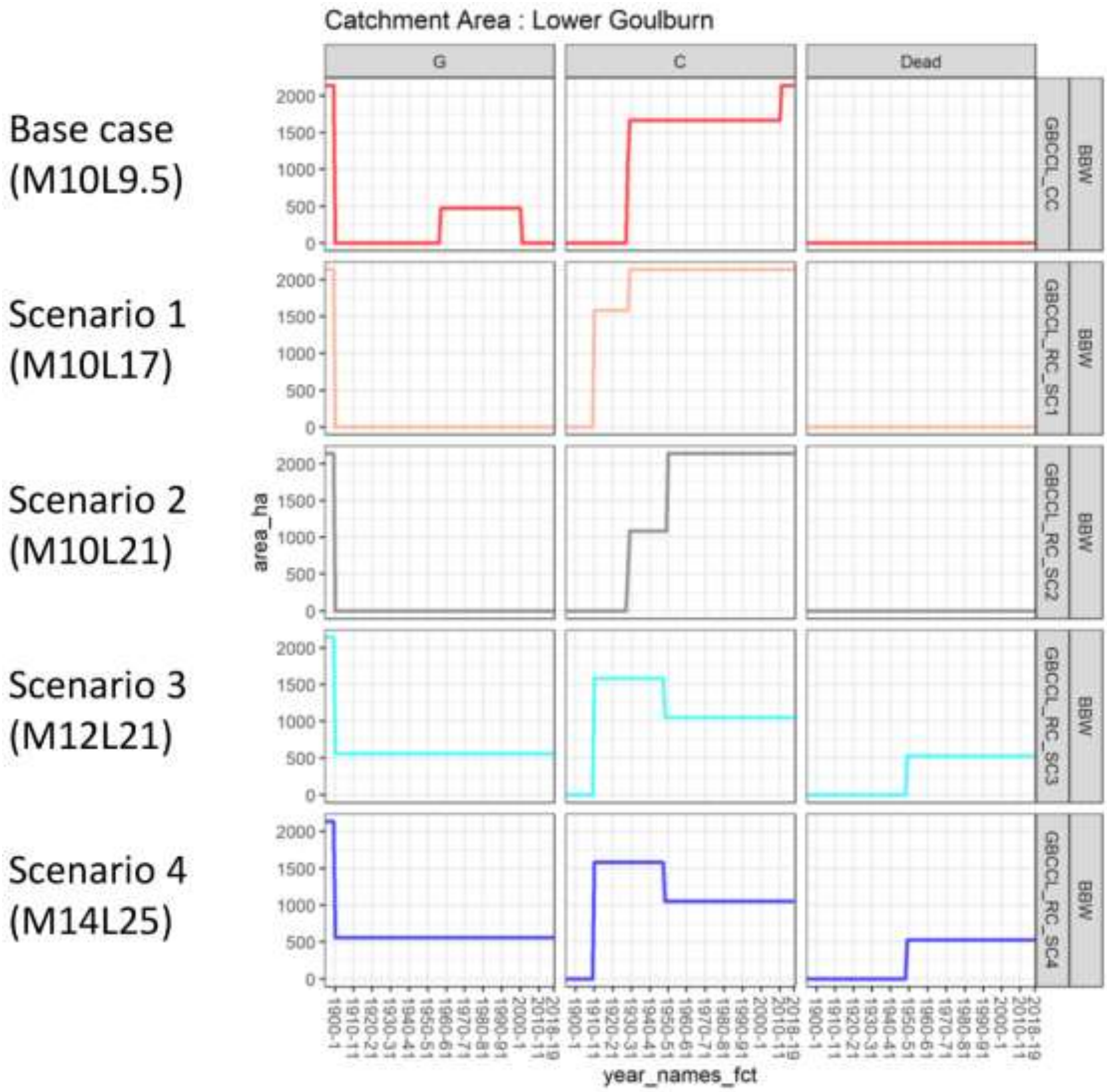


Figure 45 *Modelled area and condition of Black-box woodland (BBW) in the Lower Goulburn River. Time series of the area of the modelled conditions (Good = G > Critical = C > Dead) of black box woodland (BBW) for the following constraint scenarios as labelled.*

With respect to final community structure of black box woodlands, the base case, and Scenario 1 and Scenario 2 resulted in the entire stand in a critical condition (Figure 45) and no loss. In the higher flow scenarios (Scenario 3 and Scenario 4) an obvious trade off becomes apparent. By enabling higher volumes of water to flow more regularly there is an area (around 500 ha) of black box woodlands that remains in good condition. However, this comes at a cost of the loss of around 500ha of black box woodland.

The observed trends for good condition river red gum in the Lower Goulburn are similar to those for the black box woodland stands (Figure 46). That is, there was a fixed area (6000 ha) that could be supported in good condition under Scenarios 3 and 4. For the base case and Scenario 2, large areas of vegetation were in critical condition prior to droughts resulting in complete losses of vegetation. For the base case the Millennium drought appears to have caused this decline, while for Scenario 2, there was a decline that first occurred in the drought conditions of 1937-45, then subsequently lost in the millennium drought.

For both vegetation types, scenarios 2, 3 and 4 reduced the time vegetation is in a critical state when compared to the base case, while for the most improvement in the portion of the time series spent in good condition were seen in Scenario 3 and 4 (Figure 45 and Figure 46).

The highest constraint scenarios (i.e., Scenarios 3 and 4) for the Lower Goulburn appear to have the most positive impact on vegetation communities that are “within reach” of inundation events facilitated by the relaxation of constraints, while having the opposite effect for vegetation that is lies outside of this area of inundation. Under the lower constraint scenarios (base case, Scenario 1 and 2), the vegetation community suffers less irreversible across most of the time series, though this comes at the cost of large areas of vegetation in critical condition being susceptible to irreversible damage by droughts.

For the Mid Goulburn River, woody vegetation areas of the floodplain that were assessed only included river red gum woodlands and forests (Figure 47) and did not include black box woodlands. Additionally, the main differences that occurred between the scenarios of the Mid Goulburn and the Lower Goulburn were within the good condition states of the river red gum community, where there were no irreversible declines to the vegetation in any Mid Goulburn scenario (Figure 47).

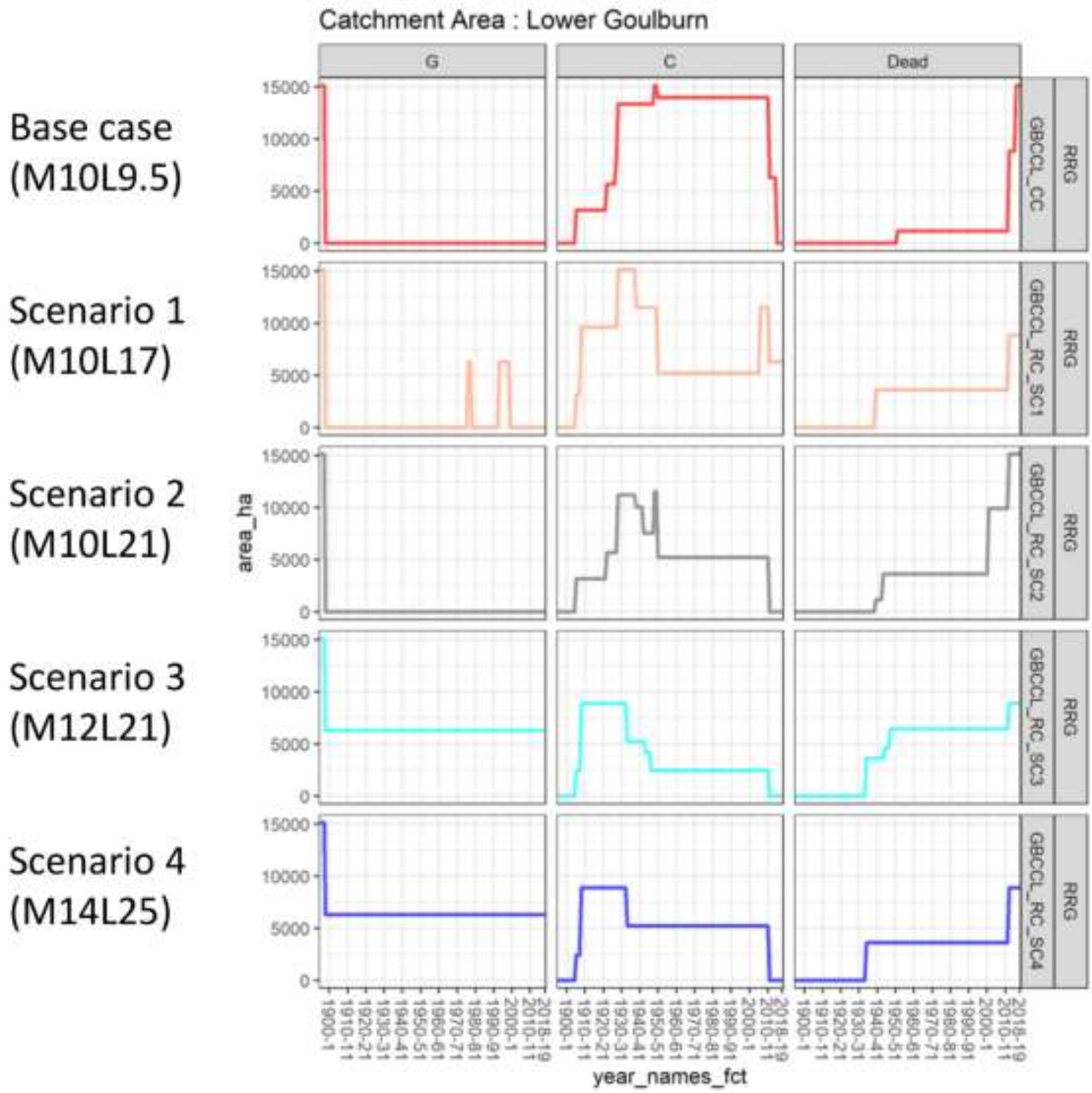


Figure 46 *Modelled area and condition of river red gum (RRG) in the Lower Goulburn River. Time series of the area of the modelled conditions for (Good = G > Critical = C > Dead) RRG in the Lower Goulburn for the base case and four constraint scenarios, as labelled.*

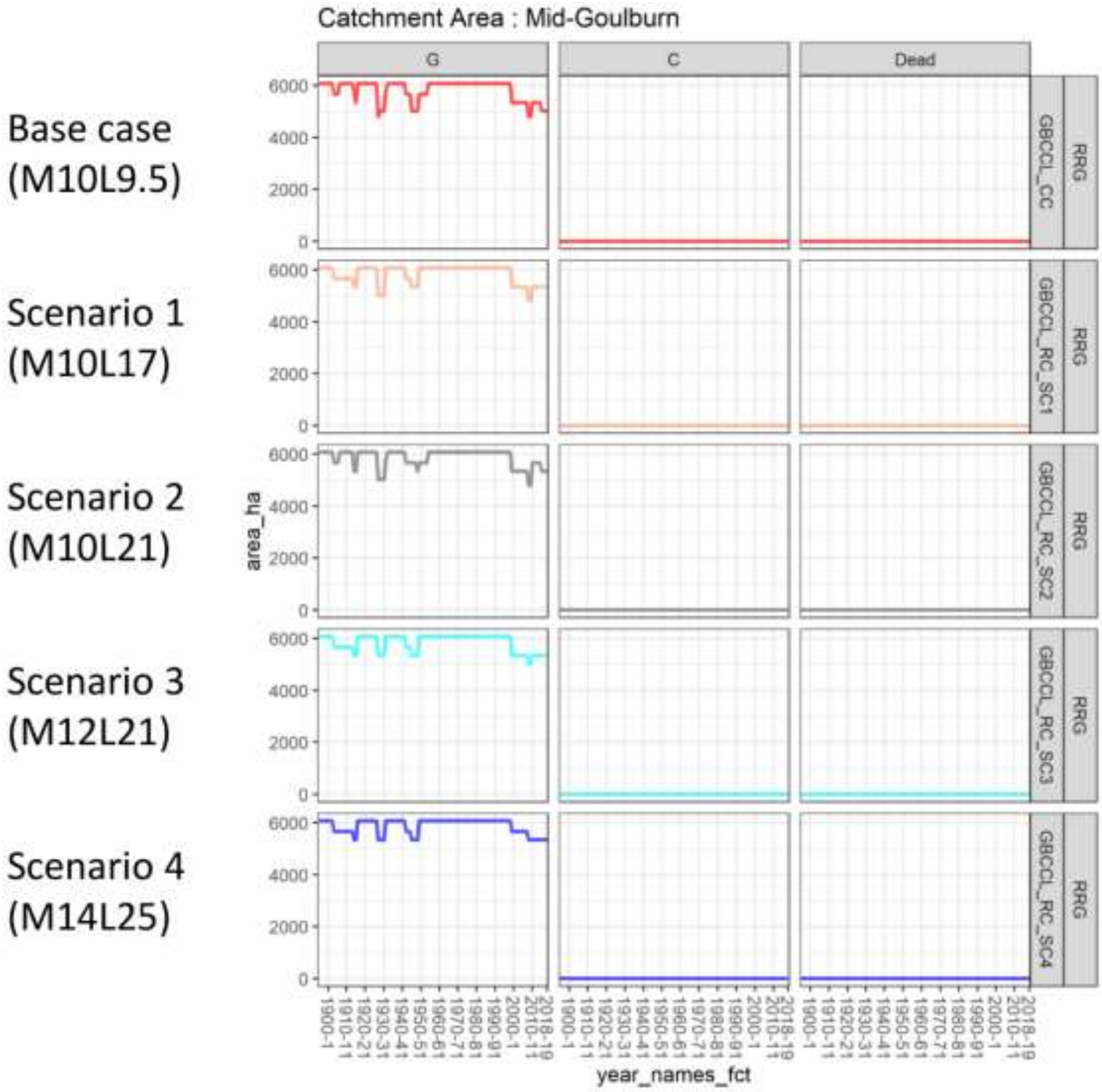


Figure 47 *Time series of the area of the modelled conditions (Good = G > Critical = C > Dead) of river red gum (RRG) for the base case and four constraints scenarios, as labelled. Note, in the Mid Goulburn, no vegetation was modelled to transition into a critical or dead state.*

Given the minor changes to cumulative vegetated area that occur as inundation threshold increases in the Mid Goulburn reaches, the majority of the community appears to be at lower inundation thresholds that are readily "within reach" of flow scenarios regardless of constraint relaxation. The minor declines that are seen in the proportion of time in good state are exceeded by the improvements meaning that all constraint relaxation scenarios in the Mid Goulburn have minor influence on the proportion of time the river red gum community is in a good condition.

It appears that relaxation of constraints will not yield significant vegetation quality outcomes for existing vegetation communities in the Mid Goulburn River. However, based on the modelling results and comparing the results for Scenarios 2 and 3 for the Mid and Lower Goulburn Rivers, the relaxation of constraints in the Mid Goulburn will be required to protect vegetation in the Lower Goulburn River.

The results can be expressed in terms of areas of vegetation held in good or average condition over the period of the model runs. As is shown in Figure 48 the change in the Mid Goulburn is negligible, however the Lower Goulburn shows improvements from relaxed constraints. The initial relaxations of M10L17 and M10L21 results in a slight improvement in the condition of vegetation, with some of the watering able to pull river red gum areas out of critical condition, if only temporarily. This ultimately reduces the risk to river red gum communities, providing more opportunities for the vegetation to recover, as is shown in the M10M17. Some areas in the

M10L17 scenario were able to move out of critical for periods, one of which then aligned with inundation from multiple spills, causing areas to improve to moderate and good condition. This was not replicated under the current constraints where areas will have died prior to the spills, nor in the M10L21 scenario where higher deliveries reduce the frequency of spills without further improving condition.

The most significant improvements in river red gum in the Goulburn River system occur in the M12L21 and M12L25 scenarios. These scenarios create an 80% increase in the area of river red gum in good and moderate condition. i.e. significant improvements in river red gum outcomes in the Goulburn River system can only be achieved with the relaxation of constraints in both the Mid and Lower Goulburn Rivers.

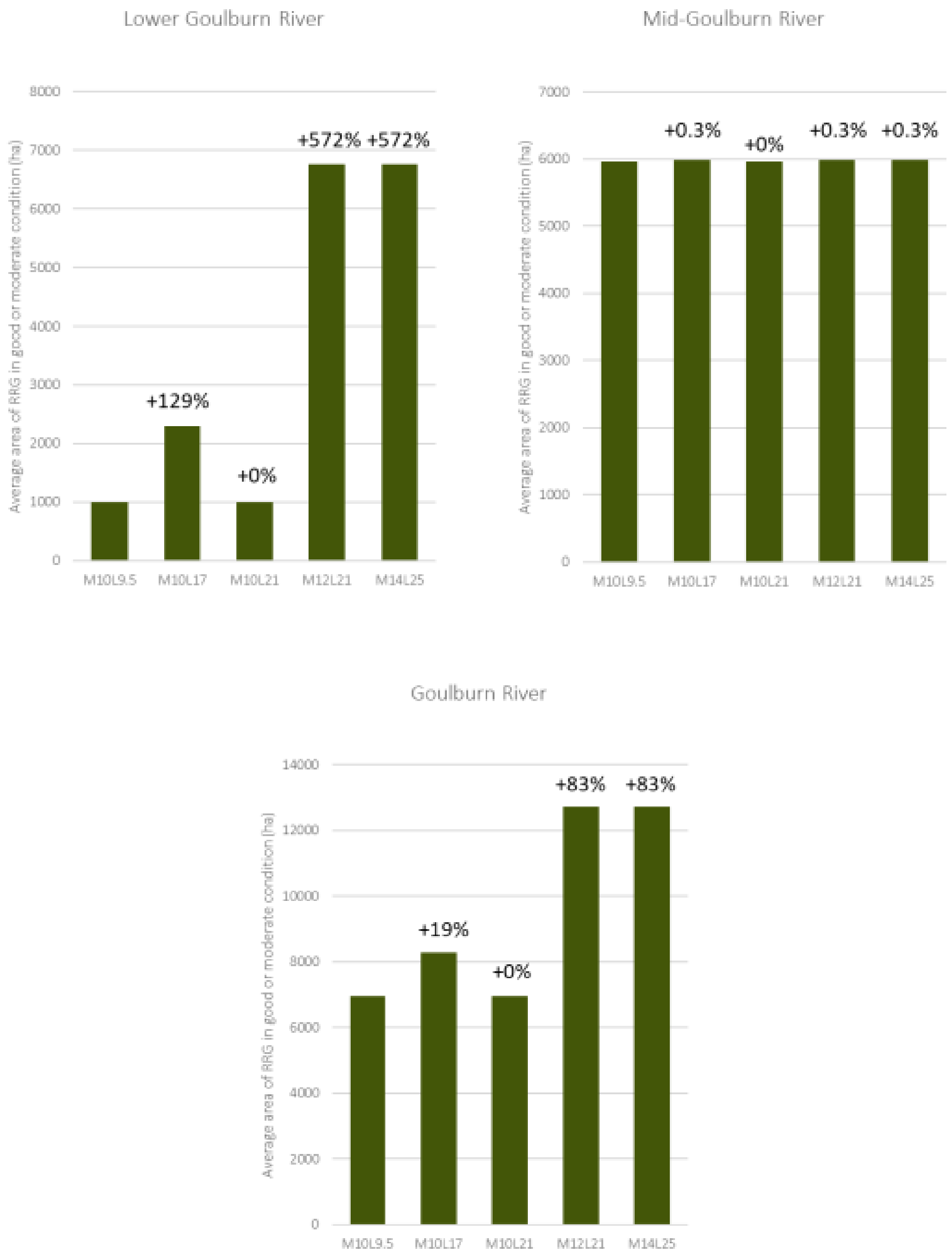


Figure 48 *Average area or RRG in good or moderate condition in the Mid and Lower Goulburn River and the combined average*

The responses in black box woodland show similar responses to the river red gum responses with the most significant benefits associated with the greatest level of constrain relaxation, However the results show a decline in areas with good and average black box condition under the M10L17 and M10L21 scenarios. In these scenarios, the loss of spills has led to a decline in condition. A relaxation of constraints in both the mid and lower Goulburn River system is needed to achieve significant benefits. There is a risk of a decline in condition associated with relaxation of constraints in the lower Goulburn River without a complementary relaxation of constraints in the mid Goulburn.

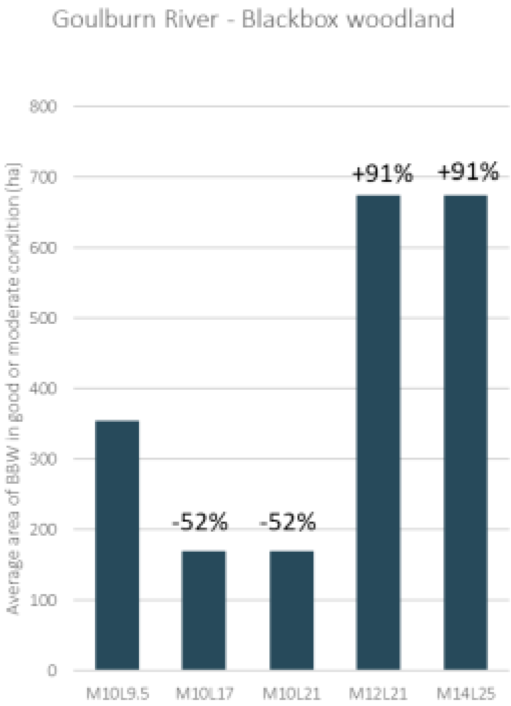


Figure 49 *Average area of BBW in good or moderate condition in the Goulburn River*

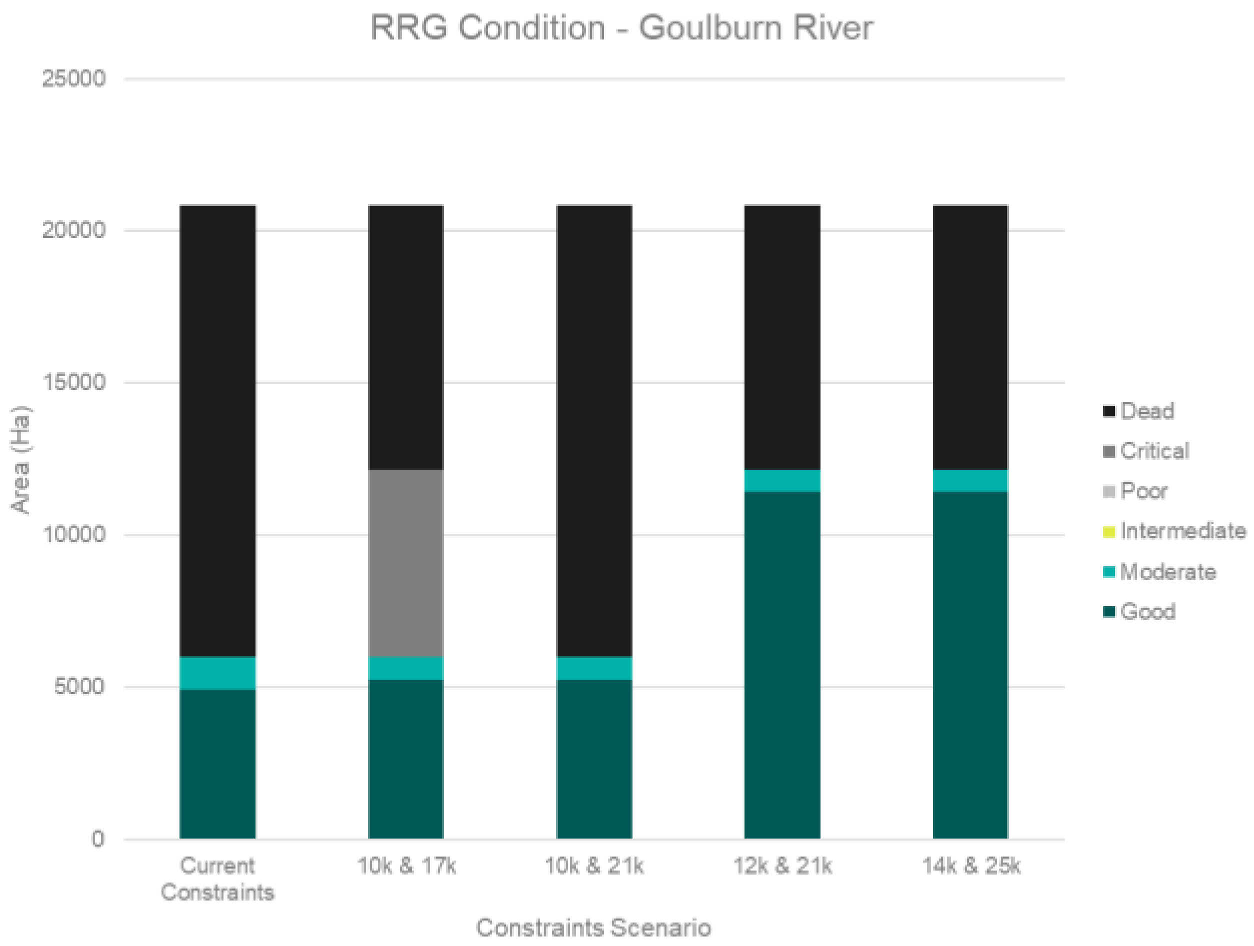


Figure 50 End state condition for Goulburn River river red gum communities

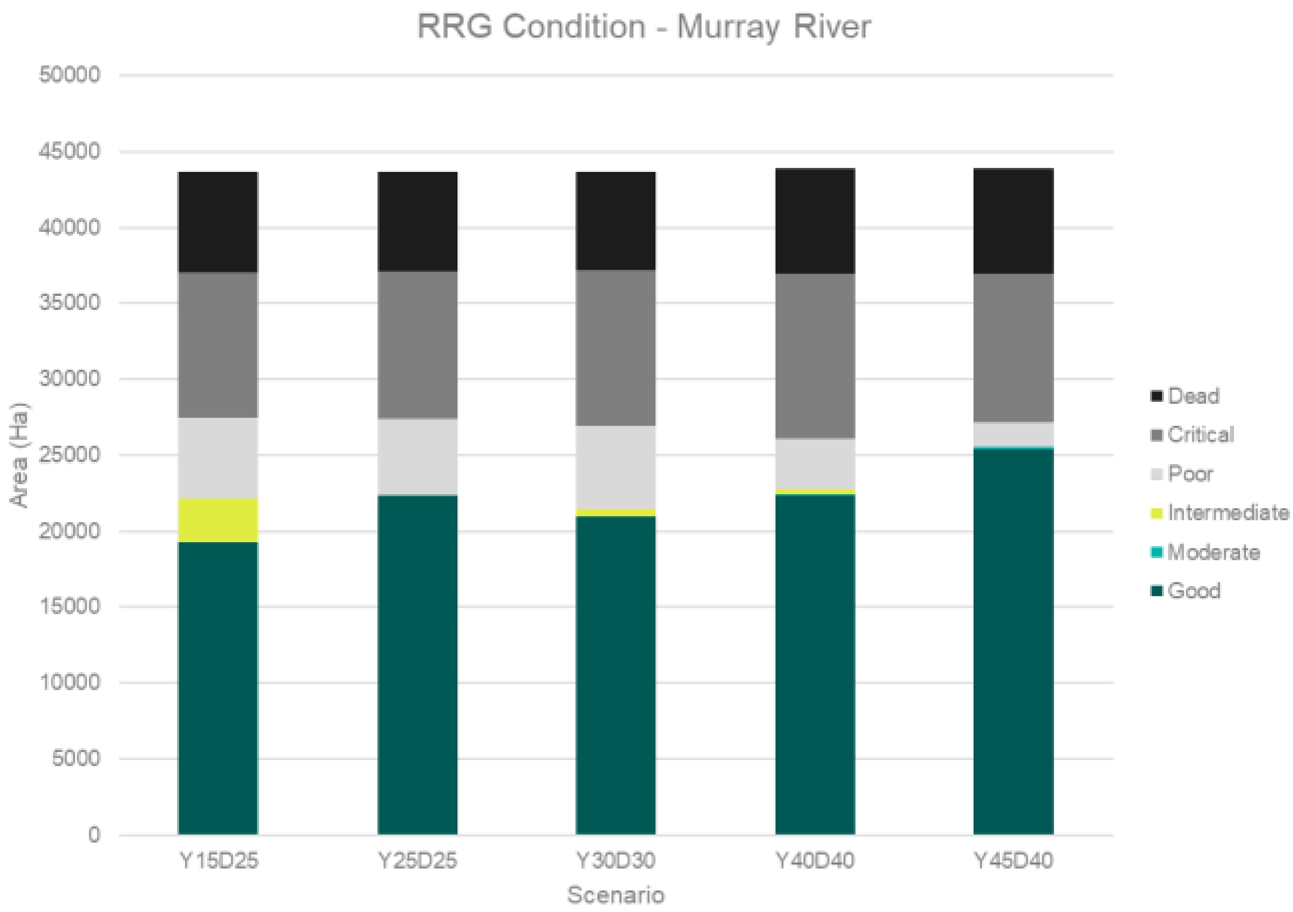


Figure 51 End state condition for Murray River *river red gum* communities

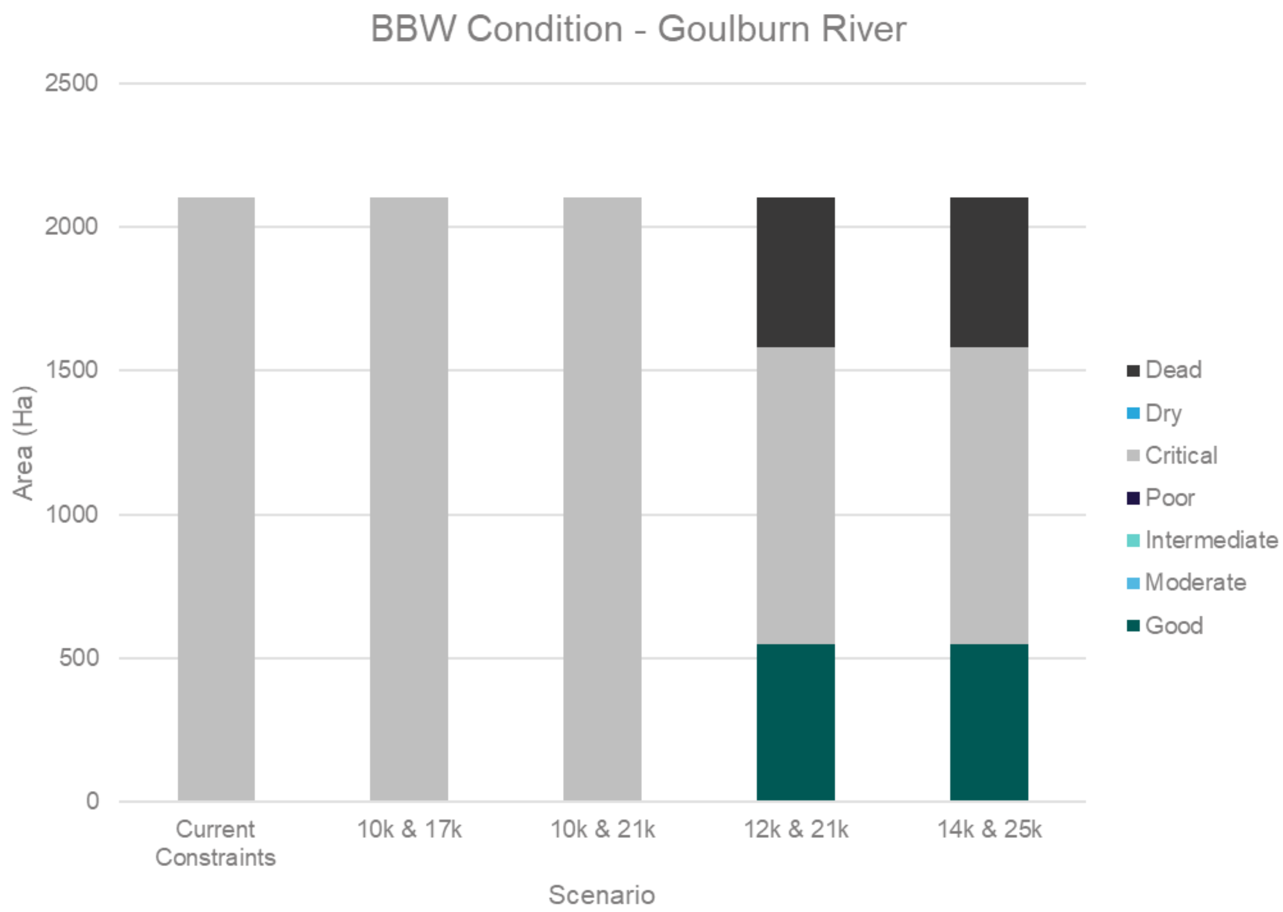


Figure 52 End state condition for Goulburn River *black box* communities

Goulburn River – Bayesian modelling

Bayesian modelling of vegetation dynamics conducted by the University of Melbourne for the Goulburn River assessed three indicators: floodplain vegetation, littoral (water's edge) and mid-bank (riparian) vegetation. The floodplain conceptual model included effects of logging, fire, and rainfall, with the major flow influence being on tree recruitment (refer to Figure 21) rather than adult condition used in the state and transition modelling.

The floodplain vegetation assessment found no improvement until Lower Goulburn flows exceeded 20,000 ML/day, which was the value used in the modelling for bank full (Figure 53). Above bank full, there were minor improvements in floodplain vegetation which would be as expected given floodplain trees require inundation to create suitable habitat, transport seeds and support germination and recruitment. The results complement those of the state and transition modelling by revealing loss of existing trees, and limited recruitment under a 'do-nothing more' scenario, with adverse impacts on tree populations and floodplain ecosystems.

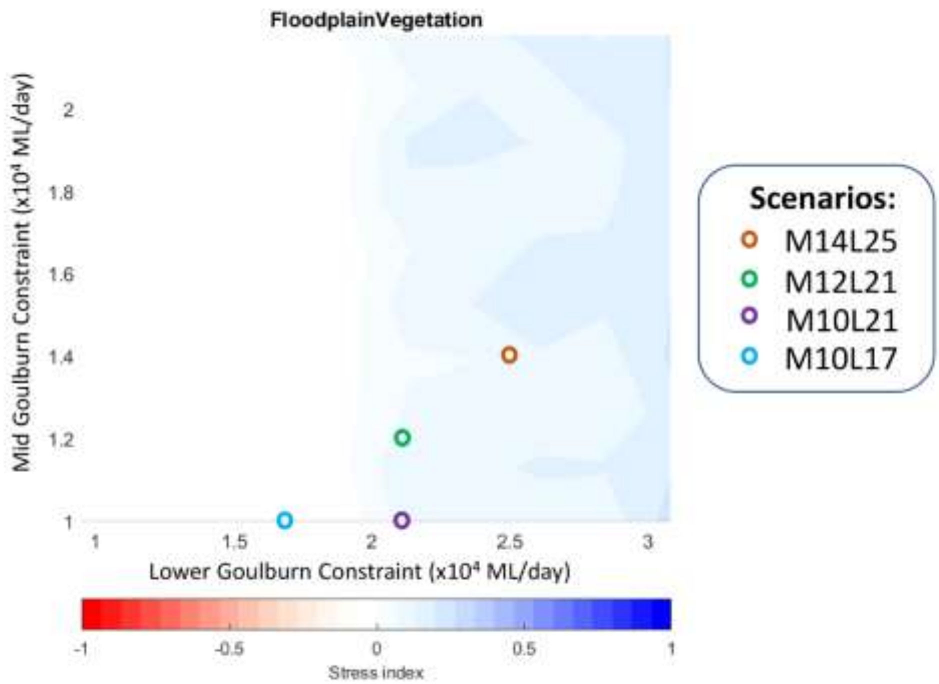


Figure 53 *Results of the Bayesian analysis of constraints relaxation in the Mid and Lower Goulburn River on Floodplain vegetation*.

The Bayesian assessment also examined littoral and mid-bank vegetation responses to constraints relaxation.

There were some negative impacts identified for littoral vegetation associated with the relaxation of constraints in the Mid Goulburn while in the Lower Goulburn there were only minor impacts (Figure 54). Littoral habitats are sensitive to changes in flow as they influence the disturbance regime and hydraulic conditions. The littoral vegetation conceptual model linked littoral vegetation to freshes and in-channel high flows, with floods only delivering seeds. The modelling indicates that replacing freshes with overbank flow has potential to impact on this community. The results suggest that for littoral vegetation, the Mid Goulburn may be more sensitive to a change in flow than the Lower Goulburn. The outcome for littoral vegetation suggests that further investigation is warranted for this vegetation community, particularly in light of the reduced erosion risk identified in the geomorphic assessments undertaken for this investigation.

The results for mid-bank vegetation reflect the same underlying conceptual model where overbank flows only function is seed delivery. A more positive response was identified for the mid-bank vegetation. Further investigations and development of the modelling may assist to reduce the level of uncertainty in the bank vegetation outcomes. This could include more explicit linkages to a geomorphic (bank erosion) response model.

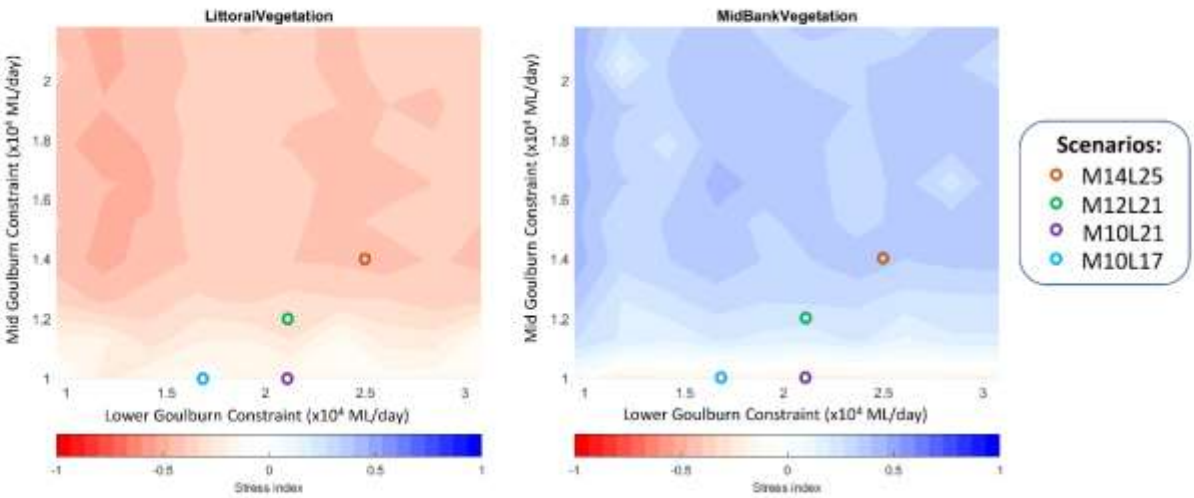


Figure 54 *Results of the Bayesian analysis of constraints relaxation in the Mid and Lower Goulburn River on Littoral (water's edge, left panel) and mid-bank vegetation (right panel). Constraints scenarios are shown.*

Murray River – Hume to Yarrawonga

A 'Without Development' scenario (WOD) was included in the Murray River analysis. This has been included in the results for information but don't represent a scenario for assessment purposes. It is also worth noting that the areas of black box woodland and river red gum are relatively small in the Hume to Yarrawonga Reach. As such the vegetation outcomes in the reach are not likely to be as significant as those in the Yarrawonga to Wakool Reach.

Both black box woodland (BBW; Figure 55) and river red gum forests/woodlands (RRG; Figure 56), within the Hume to Yarrawonga Reach were found to be responsive to the alteration of flow constraints. Broad benefits of constraint relaxation to higher flow scenarios (e.g., Y45D40) were representative of greater areas of woody species in good condition and reduced areas in critical (C) condition. The relaxation of constraints also resulted in increased period of time that the red gum and black box woodland were in good condition over the period of the model runs. This should increase the robustness of these communities to drought conditions.

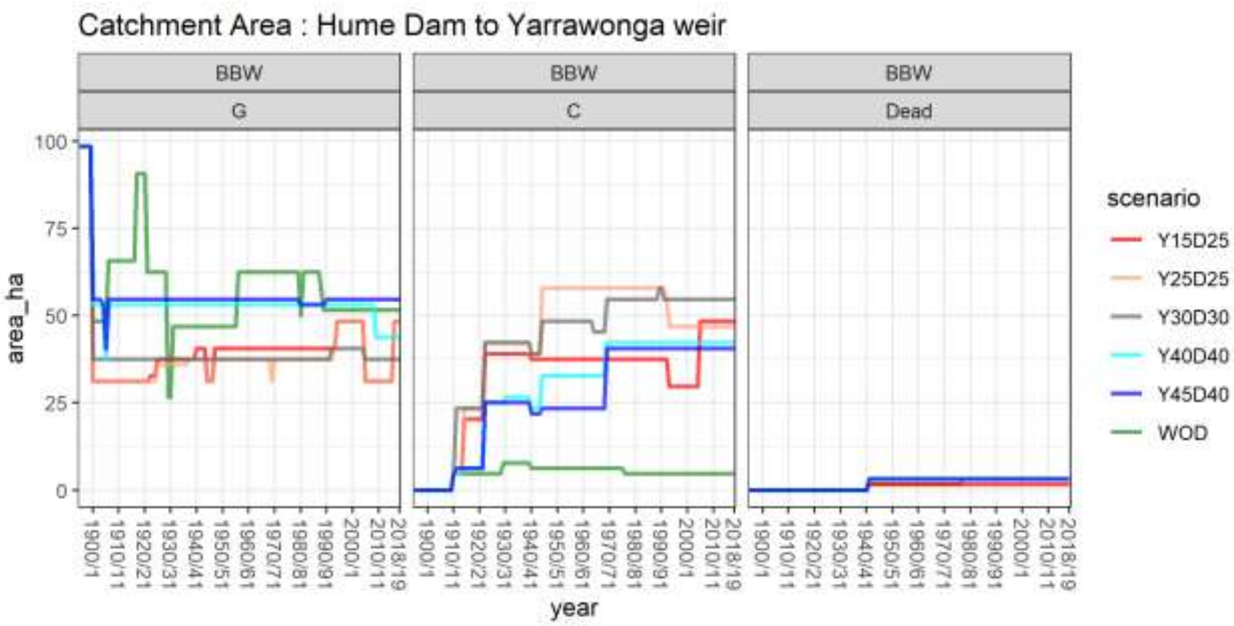


Figure 55 *Time series of the area of the modelled conditions (Good and Critical) of black box woodland (BBW) for the constraint scenarios and a without development (WOD) scenario. Note, the base case is denoted as 'Y15D25'*

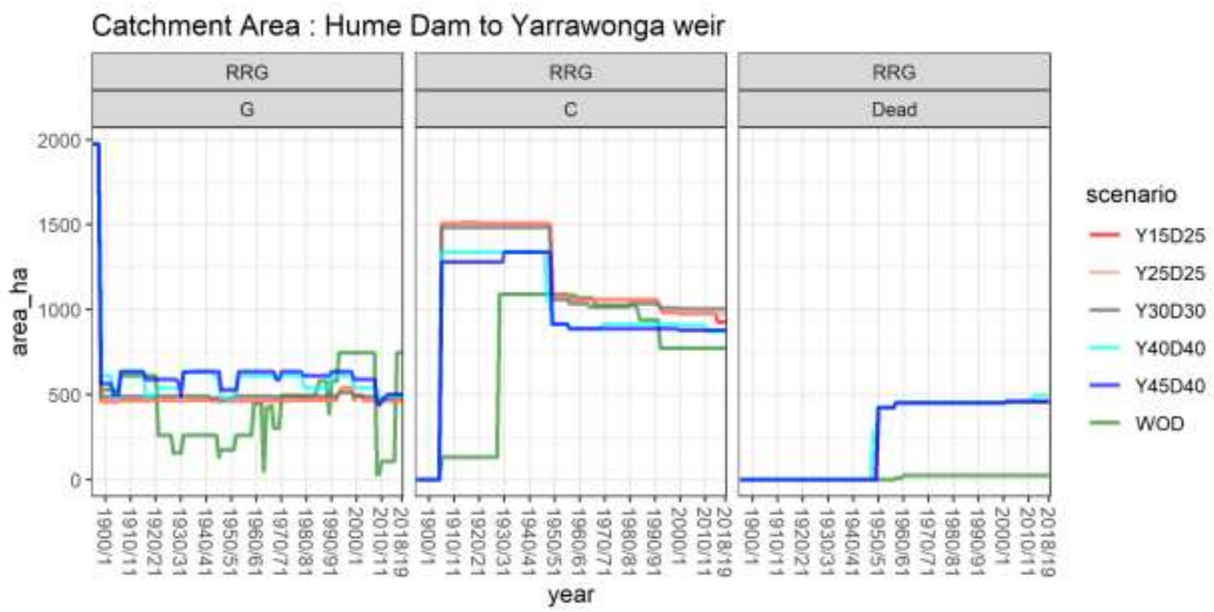


Figure 56 *Time series of the area of the modelled conditions (Good = G > Critical = C > Dead) of river red gum (RRG) for the constraint scenarios and a without development (WOD) scenario. Note, the base case is denoted as 'Y15D25'*

The results can be expressed in terms of areas of vegetation held in good or average condition over the period of the model runs (Figure 57). The average area of river red gum in good or moderate condition shows a slight improvement in the initial relaxation of constraints, however in the larger relaxation of Y40D40 and Y45D40 the areas show more substantial improvement. The black box woodland shows a similar trend, with an initial decline in the average area potentially due to a minimal increase in area from controlled delivery but the lower volumes held upstream reducing uncontrolled spills producing a decline. Again, once the relaxation increases to Y40D40 and Y45D40, significant increases are seen.

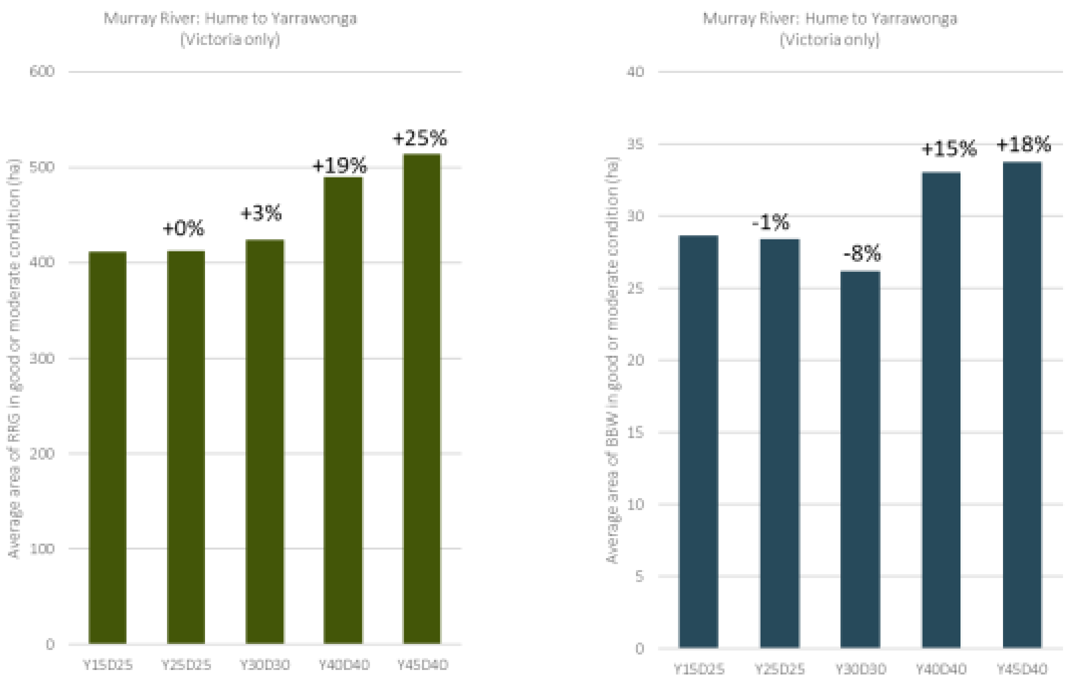


Figure 57 *Average area of RRG and BBW in good or moderate condition - Hume to Yarrawonga*

More detail on the vegetation modelling results can be found in Attachment 7.

Murray River – Yarrawonga to Wakool Junction
The Yarrawonga to Wakool reach has a significantly larger (between one and two orders of magnitude) area of vegetation assessed than the Hume to Yarrawonga Reach. Vegetation in the reach was found to responded strongly to changing constraint relaxation limits.

There was no clear trend across the critical state for both black box woodland and river red gum vegetation, with each having a unique response to flow constraint relaxation (Figure 58, Figure 59).

As with the Hume to Yarrawonga reach, higher constraint scenarios (such as Y40D40 and Y45D40) were associated with larger areas and time spent in periods of good condition woody vegetation.

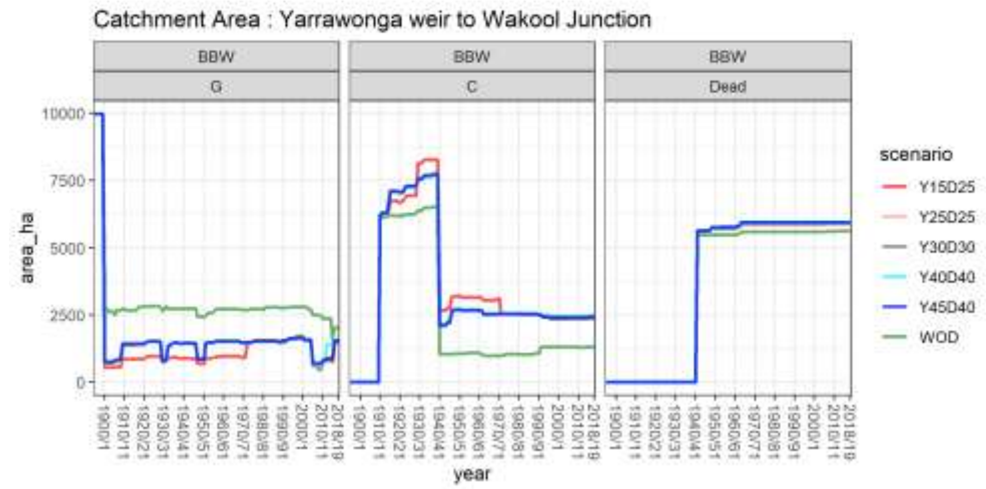


Figure 58 *Time series of the area (ha) of the modelled conditions (G>C>Dead) of perennial black box woodlands (BBW) for the constraint scenarios and a without development (WOD) scenario. Note, the base case is denoted as 'Y15D25'.*

The modelling revealed the area that was able to be supported through drought periods increased from the base case up through the scenarios to the Y45D40 scenario (refer Attachment 7)

More detail on the vegetation modelling results is provided in Attachment 7.

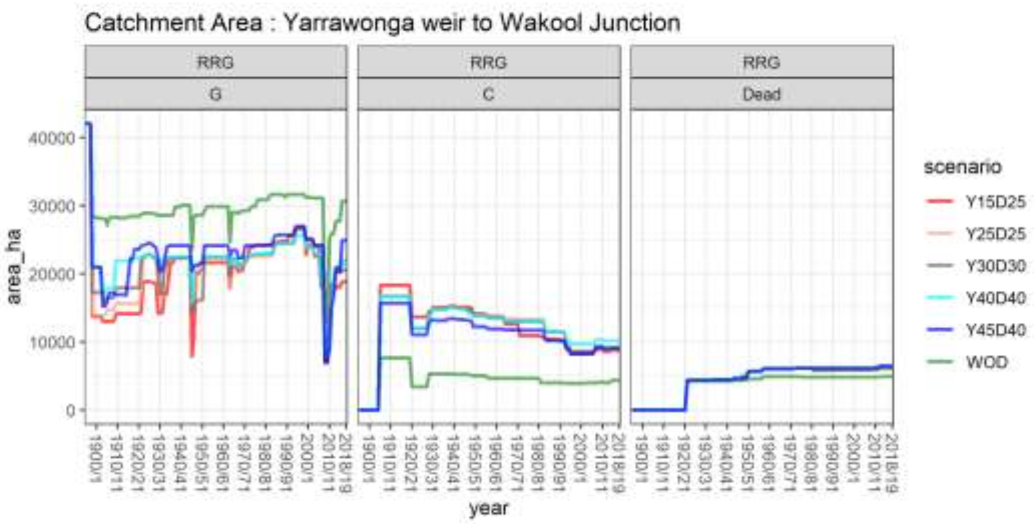


Figure 59 *Time series of the area (ha) of the modelled conditions (Good Critical) of river red gum (RRG) for the constraint scenarios and a without development (WOD) scenario.*

In a similar trend to the Hume to Yarrawonga results, the average area in good or moderate condition shows a strong response to constraints relaxation. The black box woodland response is even more pronounced, with an initial jump that only declines lightly with reduced likelihood of spills. River red gum shows a strong step increase in areas however, with each increase in constraints relaxation resulting in an increase in good or moderate areas (Figure 60).

Figure 60 *Average area of RRG and BBW in good or moderate condition – Yarrawonga to Wakool*

Summary

Across the Lower Goulburn and two Murray River reaches, the progressive relaxation of constraints was consistently found to be associated with improvements in the condition of trees influenced by the flows. This was offset to some extent by declines in the condition of trees outside the influence of constraint relaxation. The do nothing more scenario was associated with widespread declines in condition. The declines in condition under the do nothing more scenario are associated with some uncertainty given the model only considered the influence of a specified inundation regime. It is likely that shorter inundation periods provide some value and that access to rainfall and groundwater will both influence tree condition. It is important to recall that the trees are being used as indicators of the vegetation community and that the understory species will not have access to groundwater and are thus more dependent on floodwaters. This is an area where model improvements would help reduce uncertainty. The model outputs do confirm the importance of inundation on tree condition and given their role in the ecosystem, this is a particularly important finding. These results that the constraints relaxation would primarily play a role in avoiding the degradation of vegetation quality, improving resilience across the reaches. This is prominently displayed in the Goulburn River reaches, where even as vegetation is lost to the extreme dry conditions in the Millennium Drought, the area in good condition remains unchanged.

The impact across the Murray River reaches in good or medium condition vegetation shows a good response in river red gum and black box woodland. Black box woodland shows a vast improvement that does dip slightly as spills reduce, but once constraints are relaxed to Y40D40 and Y45D40 the areas jump again. River red gum responses are both strong and consistent, with a step increase in areas of good or moderate condition with each step in relaxation (Figure 61).

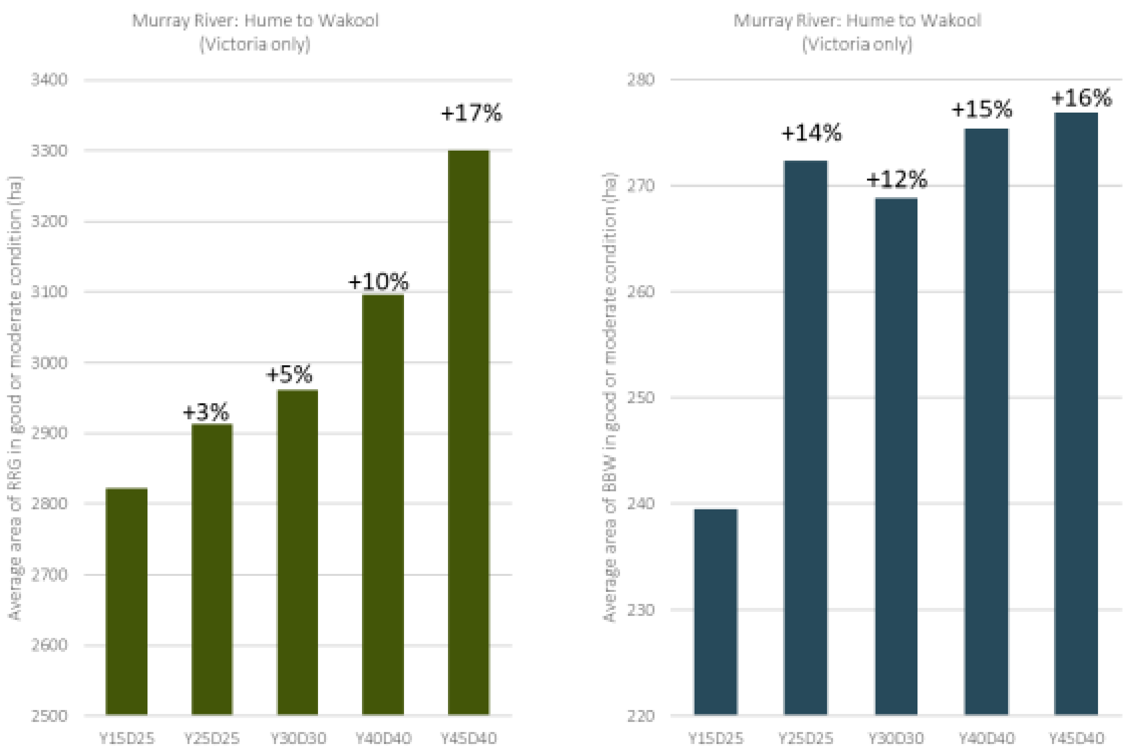


Figure 61 *Average area of RRG and BBW in good or moderate condition - Hume to Wakool*

The complementary Bayesian modelling of tree populations found that relaxing constraints would be important to the germination and recruitment of trees to the adult population, a process not considered in the state and transition modelling. The findings suggest that in the long term, sustaining red gum and black box communities will depend on constraint relaxation.

Assessments of littoral and bank vegetation produced mixed outcomes. This is to be expected given the dynamic nature of this community and its capacity to exploit habitat as it becomes available. This means that a fixed point on a riverbank may provide suitable habitat some years but not others. This is an area where model adaptation may improve the assessment.

Overall, the modelling strongly suggests that relaxing constraints is beneficial and necessary for the floodplain and wetland vegetation communities of the three river reaches assessed.

Vegetation quantity analysis

Vegetation quantity analysis has been conducted using the inundation mapping for each of the scenarios.

Overall, the areas of mapped native vegetation in Victoria, in the subject study reaches, that could be inundated via the maximum flows under the constraints relaxation scenarios assessed, are vegetation types that may benefit from inundation (see sub-sections below). All scenarios that offer an increase in flow rates above the base case offer potential benefits to flood dependent vegetation. Disbenefits, defined as inundation of areas of mapped native terrestrial vegetation that is considered not flood-adapted, are negligible in extent. It is noted again that the areas being considered are the maximum extents of the hydraulic modelling. This does not incorporate the intended flow regime and it is not expected that the maximum area would be inundated from controlled flows regularly. This investigation incorporates the range of possible benefits under each of the relaxed constraints scenarios.

It is plausible that additional inundation due to relaxed constraints may favour inundation tolerant weeds where they are present, suggesting a potential disbenefit. Where terrestrial weeds are a problem, these may be disadvantaged by any additional inundation due to relaxed constraints, suggesting a possible benefit. Such interactions are difficult to predict and are beyond the scope of these analyses.

Our findings are consistent with previous data for the Goulburn River (Water Technology 2016) which found increasing areas of wetland and native vegetation being inundated with increasing flow volumes, although only flow rates of 25,000 ML/day and above were modelled in that study.

Goulburn River

The area of mapped vegetation in each category intersected by modelled inundation layers for each constraints scenario is presented in hectares (see Table 14 - Table 16 and Figure 62 - Figure 64 below).

Unsurprisingly, preliminary analysis suggests that benefits of constraints relaxation for vegetation in the Mid Goulburn are only possible under the two highest flow scenarios, where flows above the base case. The areas that are inundated as constraints are relaxed show important trends about the vegetation that would receive increased watering. The ‘not flood-adapted’ vegetation and areas with no vegetation present show little to no change in inundation area. The increases in area, particularly in the Lower Goulburn, are in flood-adapted terrestrial vegetation present on the floodplain having adapted and grown in the natural conditions that provided semi-regular inundation. While the breakdown of specific types of vegetation (EVCs) have not been assessed, the result provides confidence in the feasibility of overbank flows targeting the vegetation communities that respond to overbank inundation. The most significant benefits were associated with the greatest level of constraint relaxation with only limited outcomes for the lower levels of constraint relaxation.

Overall, potential disbenefits that may occur via terrestrial vegetation (not flood-adapted) being inundated are negligible with relatively small areas of this vegetation category potentially inundated.

The types of mapped floodplain vegetation intersected by the inundation scenarios varies among the reaches and the two rivers. In the Mid Goulburn primarily terrestrial (flood-adapted) vegetation is likely to be inundated, whereas in the Lower Goulburn substantial areas of terrestrial (flood-adapted) to semi-aquatic vegetation are also inundated.

Table 14 *Mid Goulburn River - Mapped vegetation areas in Victoria under inundation scenarios rounded to 2 significant figures*

Vegetation group	Base case M10L9.5 (ha)	Scenario 1 M10L17 (ha)	Scenario 2 M10L21 (ha)	Scenario 3 M12L21 (ha)	Scenario 4 M14L25 (ha)
Aquatic	0.0	0.0	0.0	2.6	4.3
Semi-aquatic	0.0	0.0	0.0	0.0	0.0
Terrestrial, flood-adapted/semi-aquatic	0.0	0.0	0.0	0.0	0.0
Terrestrial, flood-adapted	556	556	556	793	1,071
Terrestrial, not flood-adapted	3.4	3.4	3.4	7.9	11.8
Bare rock/ground/beach	0.0	0.0	0.0	0.0	0.0
Water body	0.1	0.1	0.1	0.1	0.1
No native vegetation mapped	0.0	0.0	0.0	0.0	0.0
TOTAL	**560**	**560**	**560**	**803**	**1087**

Table 15 *Lower Goulburn River - Mapped vegetation areas in Victoria under inundation scenarios (ha) rounded to 2 significant figures*

Vegetation group	Base case M10L9.5 (ha)	Scenario 1 M10L17 (ha)	Scenario 2 M10L21 (ha)	Scenario 3 M12L21 (ha)	Scenario 4 M14L25 (ha)
Aquatic	0.0	0.0	0.0	0.0	105.5
Semi-aquatic	73.2	329.9	462.4	462.4	682.8
Terrestrial, flood-adapted/semi-aquatic	8.3	233.3	533.2	533.2	1202.9
Terrestrial, flood-adapted	429.9	1038.6	2138.5	2138.5	3819.7
Terrestrial, not flood-adapted	0.7	2.4	6.7	6.7	14.2
Bare rock/ground/beach	2.8	2.8	2.8	2.8	2.9
Water body	211.8	259.3	269.3	269.3	274.8
No native vegetation mapped	0.0	0.0	0.0	0.0	0.0
TOTAL	**726**	**1,866**	**3,413**	**3,413**	**6,103**

Table 16 *Mid and Lower Goulburn River - Mapped vegetation areas in Victoria under inundation scenarios (ha)*

Vegetation group	Base case M10L9.5 (ha)	Scenario 1 M10L17 (ha)	Scenario 2 M10L21 (ha)	Scenario 3 M12L21 (ha)	Scenario 4 M14L25 (ha)
Aquatic	0.0	0.0	0.0	2.6	109.8
Semi-aquatic	73.2	329.9	462.4	462.4	682.8
Terrestrial, flood-adapted/semi-aquatic	8.3	233.3	533.2	533.2	1202.9
Terrestrial, flood-adapted	986.1	1594.7	2694.6	2931.0	4890.6
Terrestrial, not flood-adapted	4.1	5.8	10.1	14.6	26.0
Bare rock/ground/ beach	2.8	2.8	2.8	2.8	2.9
Water body	211.9	259.3	269.3	269.3	274.9
No native vegetation mapped	0.0	0.0	0.0	0.0	0.0
TOTAL	1,268	2,426	3,972	4,216	7,189

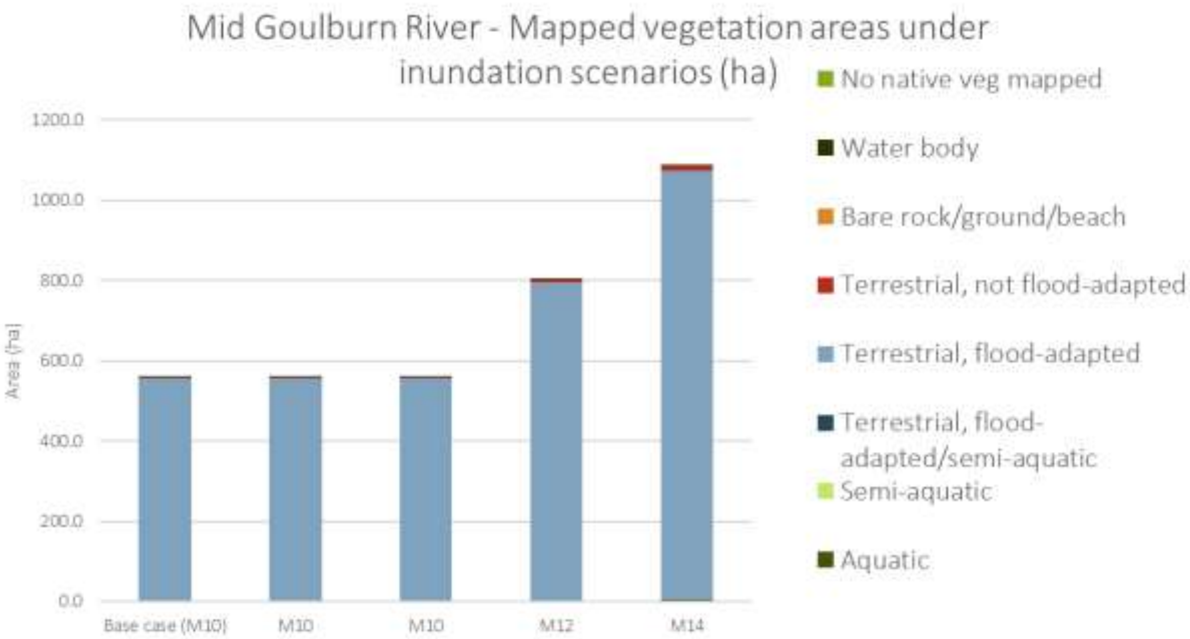


Figure 62 *Areas of mapped vegetation intersected by modelled inundation extents (ha) in the Mid Goulburn River.*

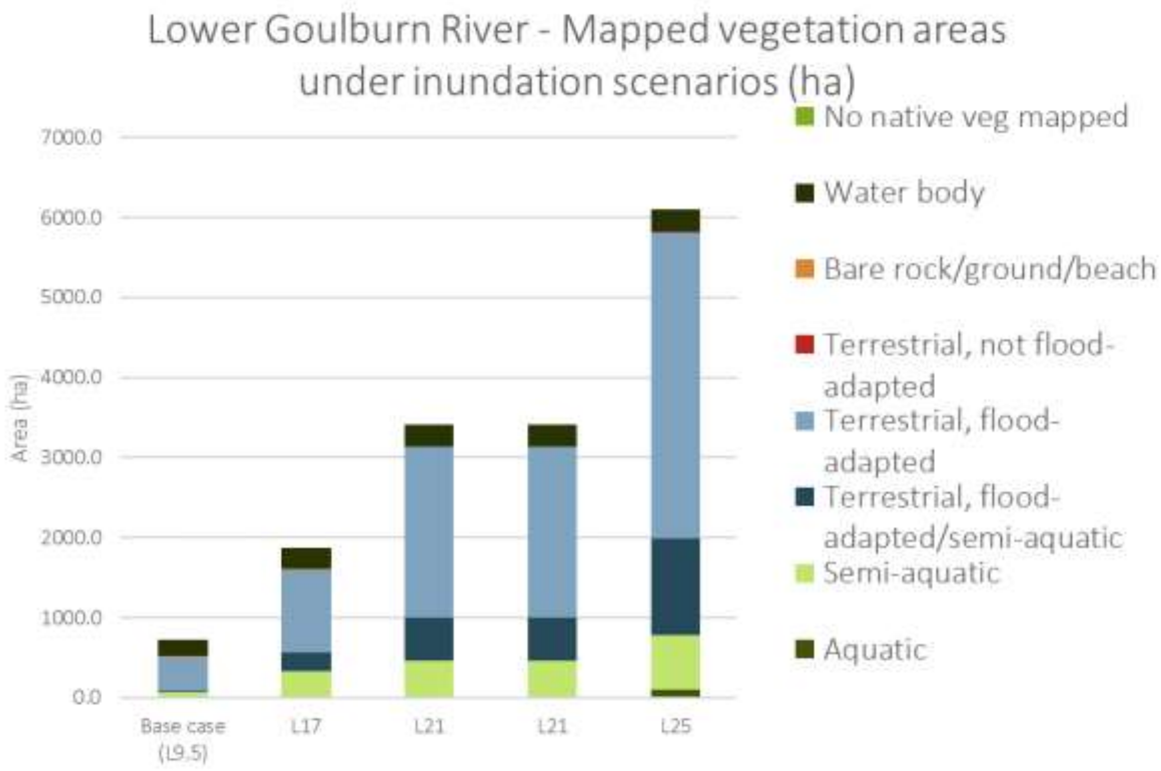


Figure 63 *Areas of mapped vegetation intersected by modelled inundation extents (ha) in the Lower Goulburn River.*

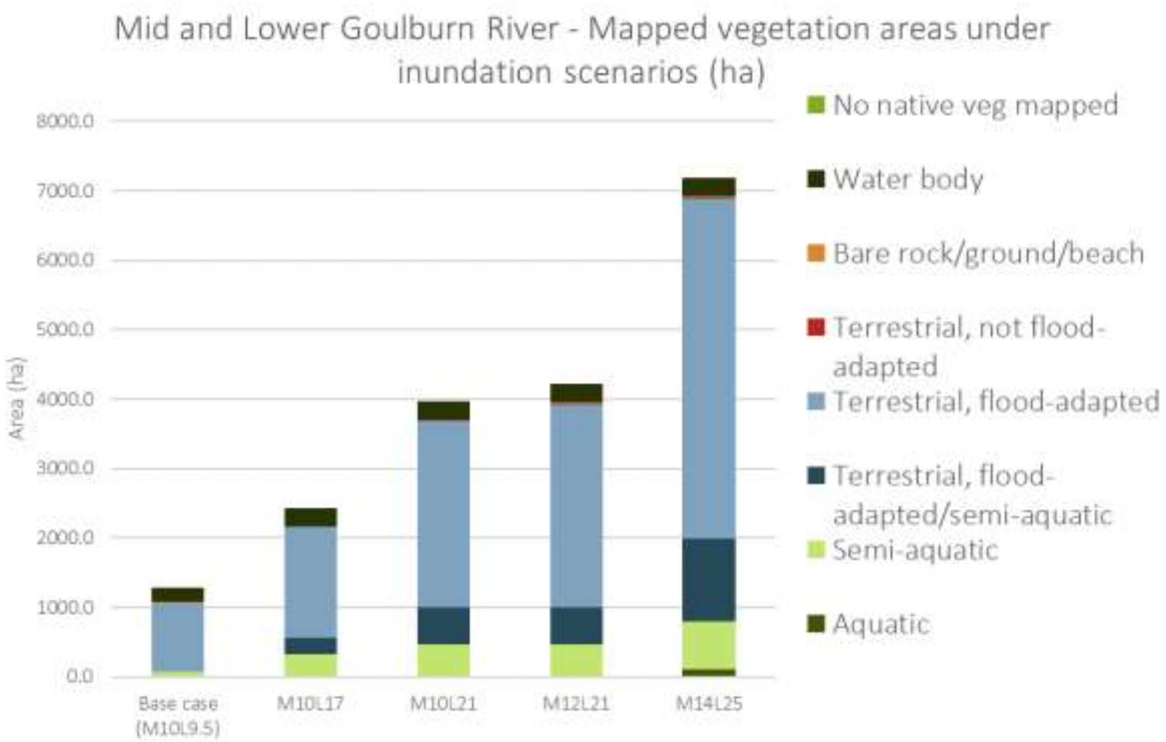


Figure 64 *Areas of mapped vegetation intersected by modelled inundation extents (ha) in the Mid and Lower Goulburn River.*

Murray River

The Murray River assessment was undertaken using the hydraulic modelling results for the 2 reaches of river. The Murray Rivers was divided into 9 zones for hydraulic modelling. The zones relevant to the environmental benefits and risk assessment (this report) are shown in Figure 65. All categories of flood-adapted, semi-aquatic and aquatic vegetation are likely to benefit in both Murray River reaches (Table 17, Figure 66).

Figure 65 *Zones used for the vegetation quantity assessment*

Negligible disbenefits arising from inundation of terrestrial (not flood-adapted) vegetation are expected. Similar to the results of the Goulburn assessment, the Murray River showed staged increases in the areas of flood-dependant vegetation with little to no change in the non-flood dependant or no vegetation areas.

Table 17 *Murray River (Hume to Wakool Junction, Victorian zones only) – Mapped vegetation areas in Victoria under inundation scenarios (ha). See Attachment 8 showing all zones downstream of Yarrawonga represented separately.*

Vegetation group	Base case Y12D25 (ha)	Scenario 1 Y25D25 (ha)	Scenario 2 Y30D30 (ha)	Scenario 3 Y40D40(ha)
Aquatic	189	218	219	281
Semi-aquatic	2,077	3,070	3,427	3,839
Terrestrial, flood-adapted/semi-aquatic	4,690	15,210	17,693	20,929
Terrestrial, flood-adapted	3,083	7,940	12,026	17,549
Terrestrial, not flood-adapted	4.2	12	17	23
Bare rock/ground/beach	68	100	125	138
Water body	1306	1360	1399	1458
No native vegetation mapped	0.0	0.0	0.0	0.0
TOTAL	**11,420**	**27,910**	**34,910**	**44,218**

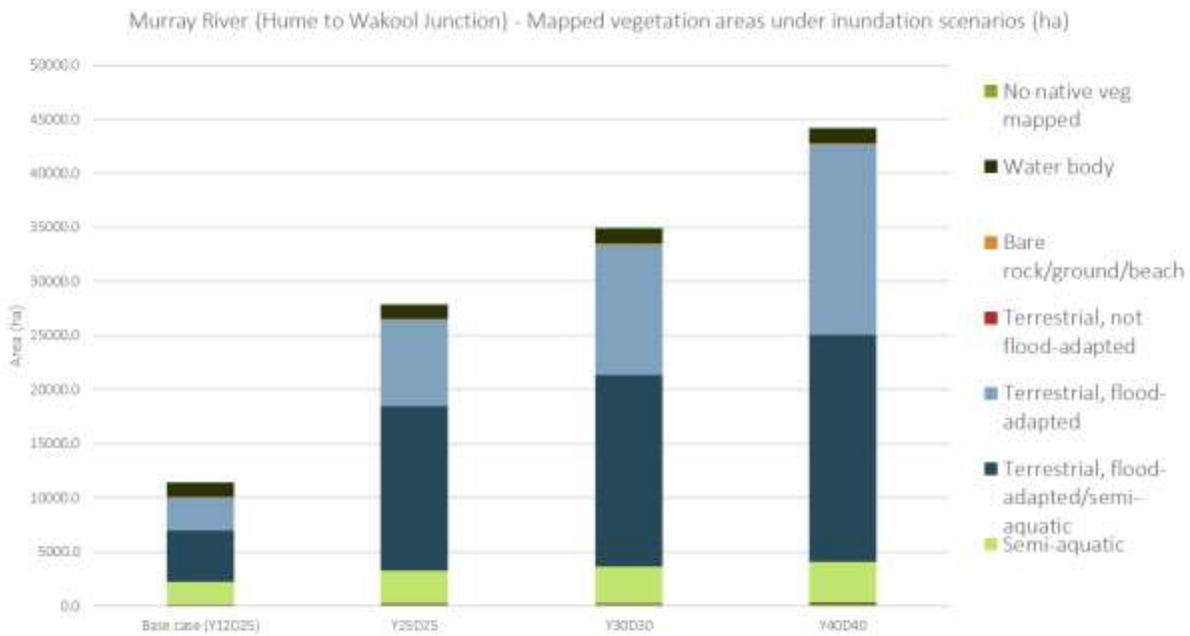


Figure 66 *Areas of mapped vegetation intersected by modelled inundation extents (ha) on the Victorian side of the Murray River (Hume to Wakool Junction). See Attachment 8 showing all zones downstream of Yarrawonga separately.*

Hume to Yarrawonga
Scenario 1 is not expected to differ from the base case assuming the inundation areas would be unchanged in this reach. Under scenario 2, additional areas of flood-dependent/adapted vegetation would be inundated and potentially benefit, with further increases under scenario 3.

Vegetation types potentially benefiting in this reach include a variety of aquatic and semi-aquatic wetlands, as well as floodplain vegetation (Table 18, Figure 67). Very small areas of terrestrial (not flood-adapted) vegetation are expected to be inundated and potentially be negatively impacted.

Note that in this reach there is no flow change between Scenario 3 and Scenario 4.

Table 18 *Murray River (Hume Dam to Yarrawonga). Mapped vegetation areas in Victoria under inundation scenarios (hectares).*

Vegetation group	Base case Y12D25 (ha)	Scenario 1 Y25D25 (ha)	Scenario 2 Y30D30 (ha)	Scenario 3 Y40D40 (ha)	Scenario 4 Y45D40 (ha)
Aquatic	7.1	7.1	7.1	7.1	7.1
Semi-aquatic	374	374	475	627	627
Terrestrial, flood-adapted/semi-aquatic	579	579	763	1027	1027
Terrestrial, flood-adapted	1015	1015	1514	2577	2577
Terrestrial, not flood-adapted	0.2	0.2	0.6	1.0	1.0
Bare rock/ground/beach	0.0	0.0	0.0	0.0	0.0
Water body	866	866	880	892	892
No native vegetation mapped	0.0	0.0	0.0	0.0	0.0
TOTAL	**2842**	**2842**	**3640**	**5131**	**5131**

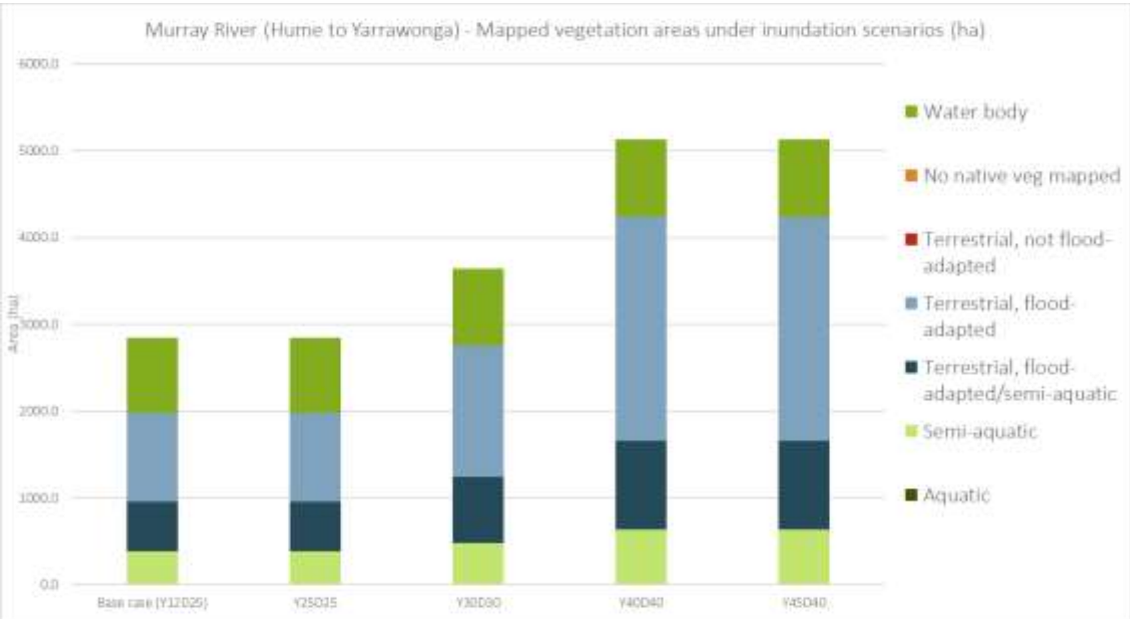


Figure 67 *Areas of mapped vegetation intersected by modelled inundation extents (ha) on the Victorian side of the Murray River (Hume to Yarrawonga)*

Yarrawonga to Wakool Junction

Although inundated areas were not available for all scenarios and zones in this Murray River reach, comparisons of the base case and scenarios 1 to 3 were possible for all zones except zone 3 (see Table 19 and Figure 68 below).

Potential benefits to native vegetation in terms of area inundated steadily increases with increasingly relaxed constraints across the scenarios. Primarily terrestrial (flood-adapted) to semi-aquatic vegetation types are likely to receive inundation throughout this reach. The proportion of terrestrial (flood-adapted) vegetation inundated also increases with flow rate, likely due to the higher flow rates reaching further out on the floodplain where this vegetation is more common.

Table 19 *Murray River (Yarrawonga to Wakool Junction). Mapped vegetation areas in Victoria under inundation scenarios (hectares). Scenario 4 not shown as this data was missing for Zones 1, 2 and 9. See Attachment 8 for all zones separately, including scenario 4 where available.*

Vegetation group	Base case Y12D25 (ha)	Scenario 1 Y25D25 (ha)	Scenario 2 Y30D30 (ha)	Scenario 3 Y40D40 (ha)
Aquatic	181.9	210.7	211.8	274
Semi-aquatic	1,703	2,696	2,952	3,211
Terrestrial, flood-adapted/semi-aquatic	4,110	14,630	16,930	19,902
Terrestrial, flood-adapted	2,068	6,925	10,512	14,971
Terrestrial, not flood-adapted	3.9	11.5	16.2	22.5
Bare rock/ground/beach	68.2	99.6	125.1	138.6
Water body	440.9	494.4	518.6	566
No native vegetation mapped	0.0	0.0	0.0	0.0
TOTAL	8,576	25,068	31,267	39,087

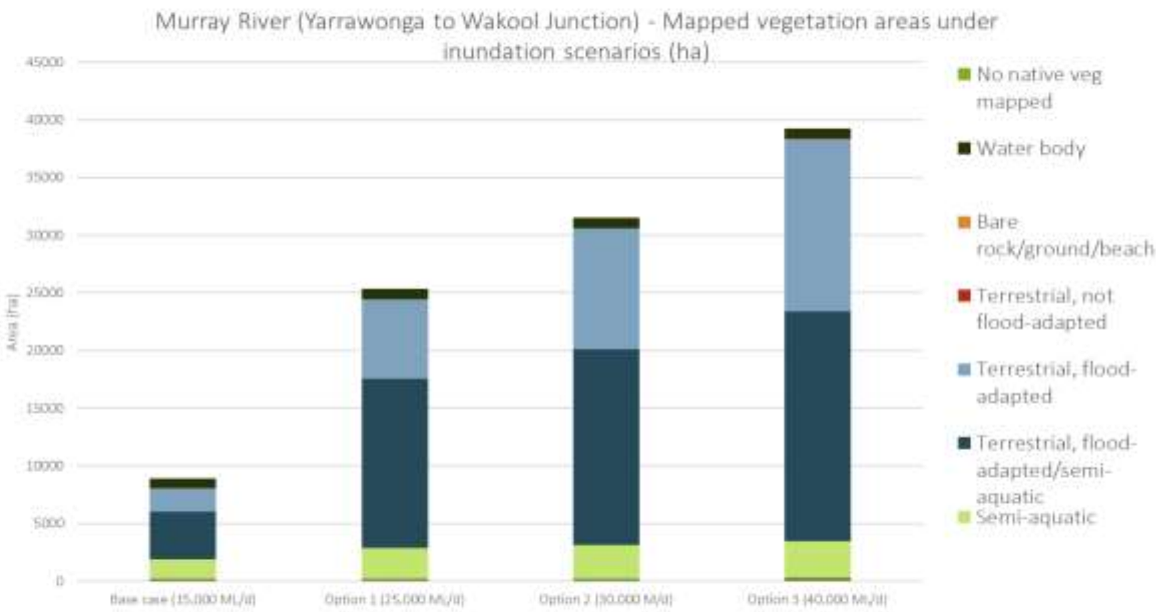


Figure 68 *Areas of mapped vegetation intersected by modelled inundation extents (ha) on the Victorian side of the Murray River (Yarrawonga to Wakool Junction, zone 3 excluded). Scenario 4 not shown (see* ***Error! Reference source not found.*** *for a comparison of scenarios 3 and 4 for zones with data available).*

The inundation areas clearly show step increases of flood-adapted vegetation with each increase, along with the semi-aquatic areas. No increases in the areas 'not flood-adapted' or with 'no vegetation present' suggest minimal adverse environmental impacts through these releases. Although the inundation extent mapping availability for the higher relaxation scenario was limited (Scenario 4), the zones where this was available showed a continuation of this trend.

Summary

The assessment consistently found that progressive constraints relaxation was associated with increases in the areas of wetland vegetation influenced, with the mid-Goulburn having only a slight increase. The dominant vegetation type influenced was terrestrial-flood adapted, particularly in the Goulburn. In the Murray, significant areas of terrestrial-flood adapted-semi-aquatic vegetation was also influenced. There remains some uncertainty around weeds, however, understanding of the inundation tolerances of key weed species will provide water managers with strategies to manage these risks.

The assessment finds that progressive constraint relaxation will increase both the area of healthy floodplain habitat but also the diversity of vegetation types.

Production

Goulburn River

In the modelling study conducted for the Goulburn River (Horne et al. 2020) it was noted that overbank flows had 'almost no impact' on predicted instream production. This outcome is likely to be a reflection of the modelling approach and the multiple nodes between the overbank flow and production nodes in the Bayesian Network.

The study by Horne et al. 2020 was extended, predicting impacts of relaxing constraints across a range of flows in the Mid Goulburn and Lower Goulburn River.

Under the baseline climate, the ecological model predicts poor instream productivity outcomes unless constraints are relaxed beyond 20,000 ML/day in the Lower Goulburn River (Figure 69). This outcome reflects the need for overbank flows to achieve floodplain inundation and flush organic matter back into the channel.

The modelling also revealed that outcomes (magnitude of the stress index) depend on whether constraints are relaxed in the Mid Goulburn River. Instream production decreases as constraints are relaxed in the Mid Goulburn River. This outcome is counter intuitive and warrants further investigation.

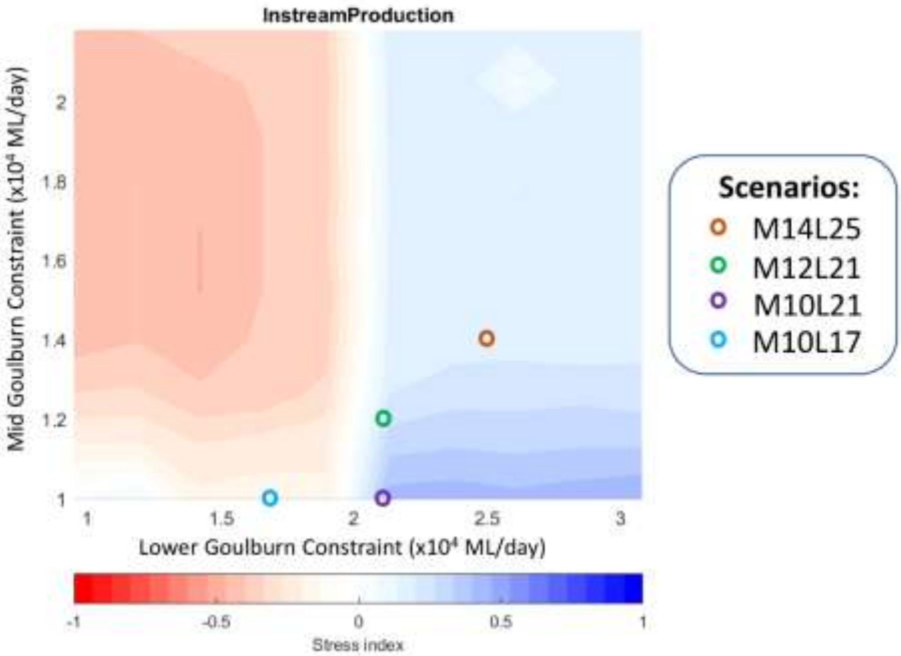
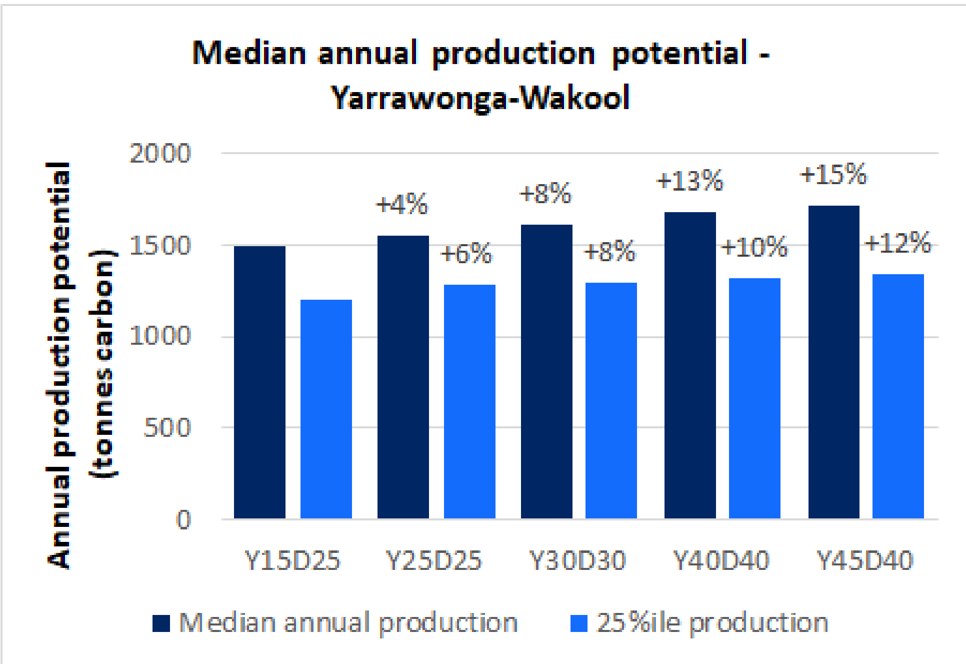


Figure 69 *Modelled instream production in the Lower Goulburn and Mid Goulburn River (John et al. 2022). Goulburn River constraints flow scenarios are indicated with coloured circles. Stress index values are indicated by shading. A stress index value >0 indicates a good outcome at the given constraints, compared with the base case. A stress index value <0 indicates a poor outcome at the given constraints compared with the base case. A stress index = 0 indicates no difference in outcome between modelled flow scenario and the base case.*

Murray River

Siebers et al. 2022 modelled the impacts of relaxing constraints on the production of large-bodied fish (a measurement of secondary productivity that reflect the transfer of energy through food webs). The Y30D30, Y40D40 and Y45D40 relaxation scenarios generally had higher median predicted productivity estimates than the



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base case. Production benefits appeared to be largely restricted to the Yarrawonga to Wakool Junction reach where modelled productivity with relaxed constraints was up to 15% above base case (Figure 70).

Figure 70 *Median total annual production potential for large bodied native fish (tonnes carbon) for the Yarrawonga - Wakool reach of the Murray River. Data are the median and 25th percentile production potential calculated using all water years (n= 123 years) (Source: DPE 2022)*

Only a two percent production increase was predicted for the Hume to Yarrawonga reach over the base case at the highest flow scenario (Figure 71), which the authors hypothesised was due to relatively high productivity influences from Lake Mulwala and small floodplain-productivity in that reach.

The results of the Murray River indicate that the productivity of the system is likely to benefit from constraints relaxation, with benefits increasing more with higher relaxation. As primary productivity is the key link between food sources accessed by floodplain inundation and the broader food web it is likely that the entire ecosystem would benefit as a result of productivity increases.

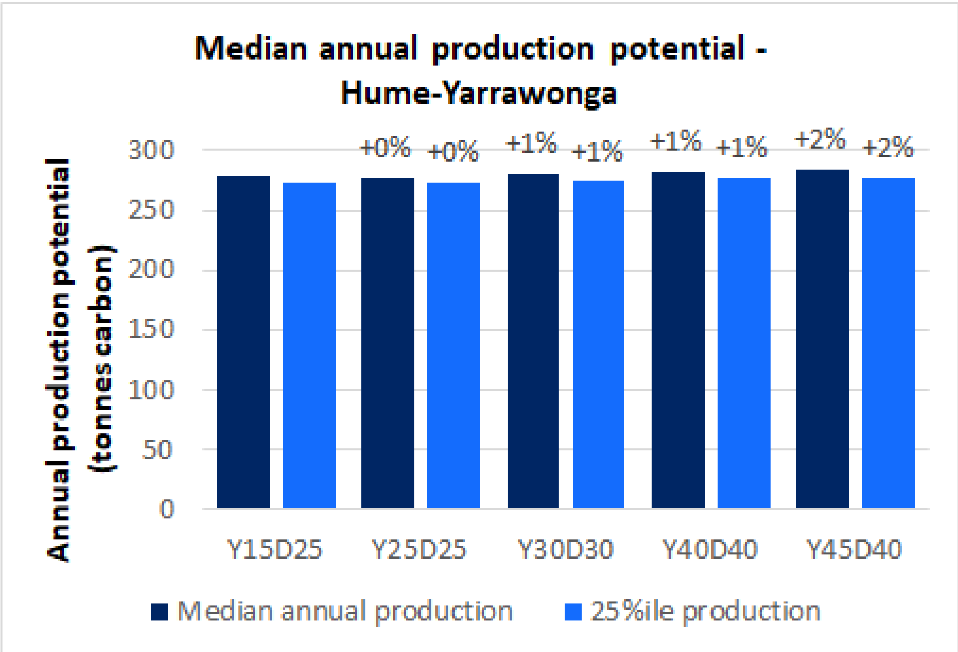

Figure 71 *Median total annual production potential for large bodied native fish (tonnes carbon) for the Hume - Yarrawonga reach of the Murray River. Data are presented as the median and 25th percentile production potential, calculated using all water years n= 123 years) (Source: DPE 2022)*

In low production years (where total annual production is below the 25th percentile), the modelling predicted an improvement in production of up to +12% in the Yarrawonga to Wakool reach, and +2% from Hume to Yarrawonga (Figure 70 and , light blue bars).

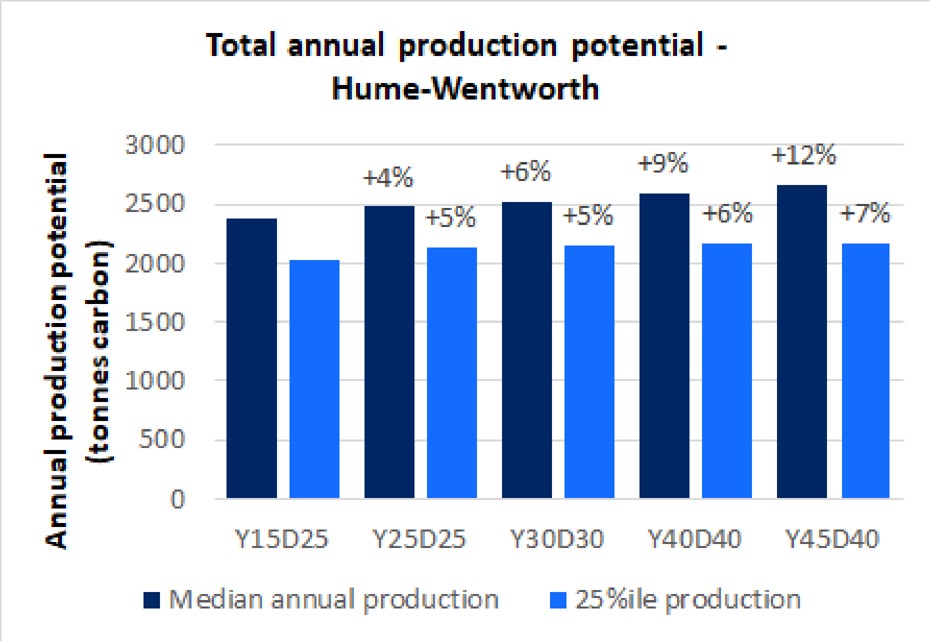

Figure 72 *Total production median and 25th percentile production for the Murray River from Hume dam to Wentworth. (Source: DPE 2022)*

Siebers et al. (2022) also modelled productivity from Hume Dam to Wentworth (length of Murray River in NSW), predicting up to a 12% increase in native fish production potential under the Y45D40 flow scenario (Figure 72). We note that this model was not formally tested for quality against empirical productivity datasets. For additional information on the model, its assumptions and limitations, refer to Siebers et al. (2022).

Summary

Forecasts for all reaches suggest that in-channel productivity will increase with floodplain engagement. These findings are consistent with the flood-pulse concept. The models both focus on outcomes within the main channel, excluding floodplain productivity outcomes which are important for some species of fish and waterbirds. While productivity may not be the primary or only limiting factor impacting on ecosystem condition, it is a common element of all contemporary conceptualisations of floodplain-river ecosystems. In terms of this assessment, the relaxation of constraints is expected to have beneficial outcomes for productivity, both within the region and as part of the broader system due to its influence on downstream assets and mobile fish and waterbirds.

Water quality

Goulburn River – Mid Goulburn

Hypoxic blackwater

Spot measurements of dissolved oxygen concentrations have been measured monthly in the Goulburn River at Seymour (Site 405202) between 1976 and 1990. Notwithstanding the significant limitations of monthly sampling for a constituent that changes diurnally, none of the dissolved oxygen concentration measured at this site was less than 4 mg/L. There are three dissolved oxygen probes in the waterbody created by the Goulburn Weir, at or immediately upstream of Lake Nagambie. The most upstream of these is at Tahbilk Winery which is in a free-flowing zone immediately upstream of the lake (Site 405323; installed in 2008), one in the middle of the lake at Kirwans Bridge (Site 405282; also installed in 2008), and one at the weir wall (Site 405259; installed in 2005).

Even though flows into Lake Nagambie have exceeded 100,000 ML/day at times (although usually not in the warmer months), the dissolved oxygen concentration at both Tahbilk Winery and at Kirwan Bridge have not fallen below 2 mg/L (note that the dissolved oxygen has fallen below 2 mg/L at the weir site at times; however, comparing DO simultaneously at the three logger sites suggest the source of dissolved oxygen concentration sag at the weir wall site is caused by processes occurring within the lake itself (Baldwin, 2017).

Taken together, the Seymour, Tahbilk Winery and Kirwans Bridge dissolved oxygen data suggests the generation of hypoxic blackwater has not been an issue in this Mid Goulburn River reach in the past and, it is highly unlikely that relaxing constraints will adversely impact on oxygen concentrations in this reach.

Blue-green algal blooms and eutrophication

As has been noted, it is unlikely that a blue-green algal bloom will form in flowing waters. Usually, as is the case in the Murray River (for example (Baldwin DS W. J., 2010), (Bowling L, 2018), blooms form in an upstream storage and then are released to downstream reaches if the outlet from the upstream storage is open and the water level in the storage is sufficiently low that the mixed surface layer (where algae accumulate) can be entrained in the outlet water. Therefore, any issues with constraints relaxation relating to blue-green algae is the quality of the water released from upstream to meet environmental watering requirements, rather than the likelihood of the release causing a bloom in the reach downstream.

Blue-green algal blooms are relatively rare in Lake Eildon, with blue-green algal warnings having only been issued on 4 occasions since 2004: November to December 2004, January to June 2011, December 2011 to January 2012 and July 2020 to October 2021. Given that the outlet from Lake Eildon is at the base of the dam wall, unless the level in the dam is unusually low, it is unlikely that environmental water releases from Lake Eildon will impact on blue-green algal levels in the mid reach of the Goulburn River. However, it is recommended that the algal status and water levels in Lake Eildon are determined immediately prior to, and during, environmental water releases from this structure.

Salinity

Monthly spot samples for electric conductivity are taken in the Goulburn River at Eildon (Site 405203), located immediately downstream of Lake Eildon (MDBA, 2011). Sampling commenced in 1990. Electrical conductivity is measured continuously in the Goulburn River at Tahbilk Winery immediately upstream of Lake Nagambie. The electrical conductivity (the measurement used for salinity) is significantly higher (t-test; $p < 0.001$)[3] at Tahbilk Winery (72 ± 3.7 µS/cm; mean ± 95% CI) than at Eildon (54 ± 1.3 µS/cm) indicating that this reach is a net source of salt to the Goulburn River. It is not surprising that the reach is a net source of salinity. There are three salinity provinces identified in sub-catchments that directly feed into this reach; Broadford (with 373 ha of salt impacted land), Majors Creek (357 ha) and Whiteheads Creek (137 ha) (Victorian Resources Online, undated). Therefore, as was the case with salinity assessment in the Murray River reaches, while there is a clear mechanistic relationship between flow and increased mobilisation of salt, there isn't sufficient knowledge available to disentangle increased salinity in this reach that may arise from relaxation of constraints, from other sources of salinity.

Turbidity

Like salinity, this reach of the Goulburn River is a net source of suspended solids (measured as turbidity). The turbidity at Tahbilk Winery is significantly higher (t-test; $p < 0.001$; 37 ± 7.3 NTU) than at Eildon, immediately downstream of Lake Eildon (4.7 ± 0.7). This is not unexpected as Lake Eildon would serve as a sediment deposition zone, collecting most of the sediment derived from upstream of the dam. Furthermore, the stretch of the Goulburn River between Lake Eildon and Lake Nagambie has seen extensive land clearing since European settlement. Therefore, as was the case with salinity, while there is a clear mechanistic relationship between flow and increased mobilisation of salt, there isn't sufficient knowledge available to disentangle increased turbidity in this reach that may arise from relaxation of constraints, from other sources of turbidity.

Stratification/destratification

The only constructed impoundment in this reach of the river is Lake Nagambie. While parts of the lake, particularly in the old river channel can be up to 10 m deep, most of the lake is extremely shallow - typically 1 - 2

[3] Based on mean monthly data calculated from the continuous data; a similar result is achieved if daily average conductivity is used instead.

metres. Persistent stratification (stretching to multiple weeks) generally does not form in shallow water bodies, nor in water bodies where there is continual flow above a critical threshold, which is usually quite low (Bormans M, 1997). Therefore, it isn't surprising that there has been little evidence of stratification in Lake Nagambie (Zampatti et al. 1996; McGuckin 2002; Swingler and Lake, 2003). Due to this lack of persistent stratification in Lake Nagambie, it is unlikely that lifting constraints would have any material effect on stratification and destratification in this reach.

Acid sulfate soils
As has been noted above, the long-term average salinity in this reach of the Goulburn River is quite low (less than 100 µS/cm) and has never exceeded 400 µS/cm. This is at least an order of magnitude lower than the chronic salinities necessary to produce acid sulfate soils (Baldwin DS H. K., 2007). Therefore, it highly unlikely that acid sulfate soils would be present either in the main channel or riverine wetlands that would be inundated following a lifting of constraints.

Thermal pollution
Lake Eildon is a large, deep storage at the upstream end of this reach. Releases from the dam are from the bottom of the storage, therefore the dam can be a source of thermal pollution to this reach, much as the case of Lake Hume on the Murray River. When considering the impact of raising constraints levels on thermal pollution below Lake Hume, RRCP investigations concluded that lifting the maximum volumes or durations of managed flows by the proposed amounts are unlikely to extend cold water pollution distance above current levels" (McInerney P, 2022).

Goulburn River – Lower Goulburn River

Hypoxic blackwater
There have been documented instances of hypoxia in this reach of the Goulburn River in 2010/11 (Whitworth et al. 2010, 2012, Whitworth and Baldwin, 2012), and 2016/17 (Baldwin, 2017). Unlike hypoxic events in the Murray River, these events tended to have a quick onset, and were of very short duration. For example, Figure 73 shows the dissolved oxygen concentration sags in the Goulburn River at McCoys Bridge (Site 405232; which is located towards the downstream end of this reach) at the end of 2010 and beginning of 2011. The period of hypoxia (≤ 2 mg/L) only lasted for about 10 days. This compares with the approximately 6 months that hypoxia persisted in the Murray River during the same event (Whitworth et al. 2012).

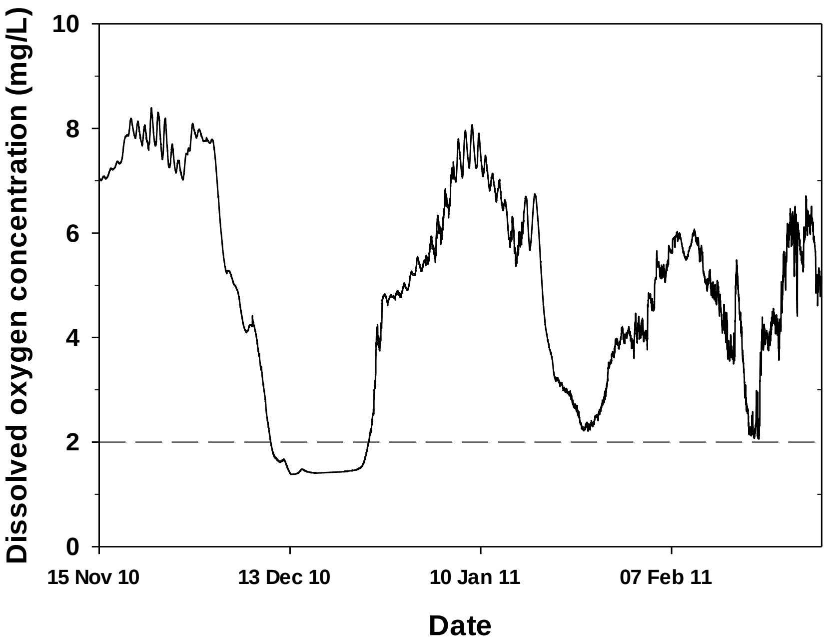

Figure 73 *Dissolved oxygen concentration at McCoys Bridge at the end of 2010 and beginning of 2011. The dashed line indicates the putative concertation below which large-bodied native fish die.*

Earlier assessments of the 2010 and 2012 hypoxic events suggested that the hypoxia may have been driven by inundation of the narrow floodplain between Murchison and the Murray River confluence (e.g., Whitworth and Baldwin, 2012). However, a more detailed investigation of the factors contributing to the 2016/17 event (Baldwin, 2017) produced strong evidence to indicate that hypoxia in this reach is driven by periods of intense rainfall in the upland regions of the catchment during the warmer months. Specifically, hypoxia in the Goulburn River downstream of Shepparton is strongly influenced by hypoxic inflows from the unregulated, intermittent creeks to the east of the catchment, as well as from the Broken River (Baldwin 2017).

The three main creek systems that feed directly into the Goulburn River between Murchison and Shepparton are in the Pranjip Creek Catchment (about 280 km of creek line), Castle Creek catchment (60 km of creeks) and Sevens Creek catchment (about 250 km of creeks). In addition, the Broken River, which also has a relatively large catchment area, flows into the Goulburn River at Shepparton. The creeks tend to be dry during the warmer months, accumulating dead plant litter, before summer storm events generate large flows across the three creeks (above 10,000 ML /day). This leaches dissolved organic carbon from litter that had accumulated in the creek beds and adjacent riparian zones during the dry period, producing a pulse of high carbon/low dissolved oxygen water which enters the Goulburn River, and then progresses downstream. As the flows in the upstream catchments are quite flashy, the hypoxic inflows are usually only of quite short duration, restricted to hours or days. All three recent hypoxic events in the lower reach of the Goulburn River (2010, 2012 and 2016/17) included significant inflows from the intermittent creeks.

A scoping exercise was undertaken to determine if lifting constraints in this reach could lead to a greater risk of hypoxic blackwater. Firstly, the area inundated under the constraint-relaxation flow scenarios was estimated. Then, indicative risk scores, based on a similar area of inundated forest in the Yarrawonga to Wakool reach of the Murray River, were developed.

The highest flow rate under relaxed constraints in the Lower Goulburn Reach is 25,000 ML/day which corresponds to an inundated area of just under 10,400 ha. For the Yarrawonga to Wakool reach in the Murray River, the lowest flow considered was 20,000 ML/day which could inundate nearly as twice as much floodplain (20,700 ha) than in the Goulburn River. Hypoxic blackwater risk scores (on a scale of 1 = no hypoxic blackwater, to 10 = certain hypoxic blackwater) across five temperature ranges and all months of the year for the Murray River downstream of Yarrawonga with 20,700 ha of inundated floodplain is presented in Table 20. The highest risk score was 4 (out of a possible 10), meaning that a hypoxic blackwater event inundating this amount of floodplain, at any time of the year, is unlikely. This is for an inundated area approximately twice as large as that which would be inundated in the Goulburn River under a lifting of constraints, therefore, lifting constraints in the Lower Goulburn River to 25,000 ML/day is unlikely to produce a hypoxic blackwater event.

Relaxing constraints in this reach may have positive outcomes for in-stream productivity. Depending on litter loading, the total amount of dissolved organic carbon (the largest pool of carbon in the return water (e.g., Rees 2020) is between about 20 and 70 g/m^2 which is equivalent to between 0.2 and 0.7 tonnes/ha. Therefore, inundating the floodplain in the lower reach of the Goulburn River should yield between about 2 to 7 tonnes of dissolved organic carbon to the river.

Table 20 *Risk scores for the Murray River downstream of Yarrawonga (source: Department of Planning and Environment, in preparation)*

Area inundated (ha)	Temperature Percentile	January	February	March	April	May	June	July	August	September	October	November	December
20,700	5th	4	4	3	1	1	1	1	1	1	3	4	4
20,700	25th	4	4	4	2	1	1	1	1	1	3	4	4
20,700	50th	4	4	4	2	1	1	1	1	1	3	4	4

20,700	75th	4	4	4	2	1	1	1	1	1	3	4	4
20,700	95th	4	4	4	2	1	1	1	1	1	3	4	4

Blue-green algal blooms and eutrophication

As has been noted, the issue of constraints and blue-green algae is the risk of delivering high levels of blue-green algae to a downstream reach during an environmental water release. Environmental water releases for the lower reach of the Goulburn River are most likely to have to come through Lake Nagambie. While blue-green algal blooms do occur in the lake, they are generally confined to backwaters and blue-green algal blooms at the outlet are rare. The National Health and Medical Research Council (2008) define a red alert when the total biovolume of blue green algae is greater than 10mm^3/L, or 4 mm^3/L where toxic blue-green algae are present. The biovolume of blue-green algae at the outlet at Nagambie in the period from 1998-2020 never reached red alert levels (Figure 74). It is therefore unlikely that environmental water releases from Lake Nagambie will impact on the blue-green algal status in the lower reach of the Goulburn River. However, it is recommended that the algal status the lake is determined immediately prior to, and during, environmental water releases from this structure. As the lake is quite shallow, unlike Lake Eildon, any releases from the lake will entrain any blue-green algae present at the outlet.

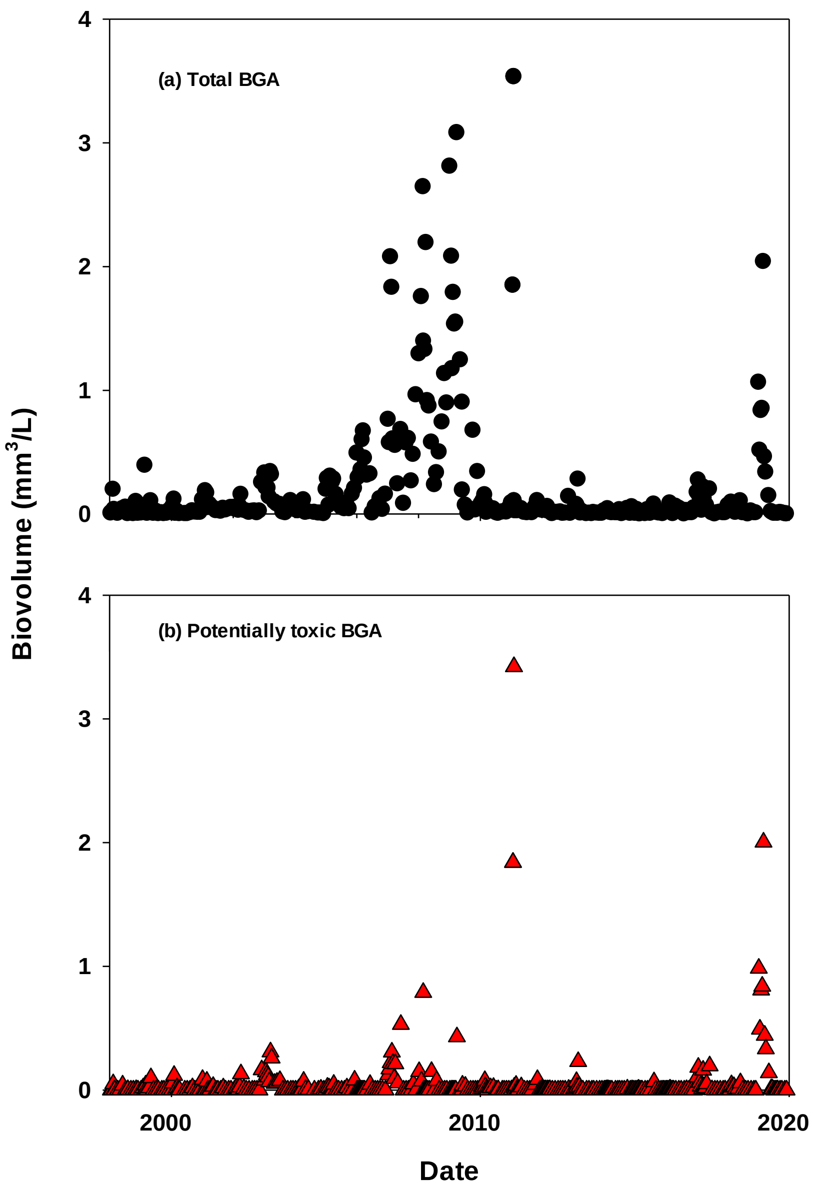

Figure 74 *Total blue-green algal biovolume (top panel) and potentially toxic blue-green algae (bottom panel) at the outlet of Lake Nagambie from 1998 to 2020 (source: Goulburn Murray Water). BGA: blue green algae.*

Salinity

Estimation of the difference in salt loads between Murchison (Site Number 405200), below the Goulburn Weir, and McCoys Bridge suggest that, while quite variable, on average about 110 tonnes of salt per day is exported from this reach into the Murray River. It has been well documented that there are areas of highly saline, shallow groundwater in this region (Victorian Resources Online, undated) which is intercepted by both natural and constructed drainage lines, some of which flow directly into the Goulburn River. Therefore, as was the case with the Murray River reaches, while there is a clear mechanistic relationship between flow and increased mobilisation of salt, there isn't sufficient knowledge available to disentangle increased salinity that may arise from constraints relaxation from increased salinity from other sources, especially dryland salinity.

Turbidity

As with the upstream reach, this reach of the Goulburn River is a net source of suspended solids (measured as turbidity). The long-term average turbidity at Murchison (17.5 ± 1.7) is significantly lower ($p < 0.001$; one-way ANOVA with Holm-Sidak pairwise comparison) than at Shepparton (Site Number 405204; 31.2 ± 2.0) which is, in turn is significantly lower ($p < 0.001$) than at McCoys Bridge (41.8 ± 1.1); that is turbidity increases as one travels downstream. This is not unexpected as there has been substantial land clearing in this part of the catchment since European settlement. As was the case with salinity, while there is a clear mechanistic relationship between flow and increased mobilisation of sediment, there isn't sufficient knowledge available to disentangle increased turbidity that may be generated in this reach from constraints relaxation from increased turbidity from other sources.

Acid sulfate soils
Although there have been occasions when salinity spiked above 500 µS/cm, at McCoys Bridge, salinity in the main channel has, for the most part, remained below 250 µS/cm.[4] This is about an order of magnitude below the chronic levels associated with the formation of acid sulfate soils (Baldwin et al. 2007), suggesting it is unlikely that acid sulfate soils would form in the river channel or adjacent riparian wetlands.

This has been borne out by an assessment of wetlands in this reach (MDBMC, 2011). Four wetlands were surveyed for acid sulfate risk and all presented negligible risk. This is not to say that acid sulfate soils are not an issue in the adjacent catchment, particularly the drains and shallow saturated soils, just that these sites will not be affected by changes to constraints.

Thermal pollution
When considering thermal (cold-water) pollution in the Murray River reaches McInerney et al. (2022) suggested that Lake Mulwala would temper potential cold-water pollution coming from Lake Hume because of the shallow water depth in Lake Mulwala coupled with the residence time, allowing the water to heat up. A similar argument can be made for the role of Lake Nagambie mitigating cold-water pollution from Lake Eildon. Figure 75 shows the difference in the mean daily temperature at Eildon, directly downstream of Lake Eildon and at Murchison downstream of Lake Nagambie. The water temperature during most of the year is consistently higher at Murchison than at Eildon; by up to 15°C in summer when the impact of cold-water pollution would be expected to be greatest.

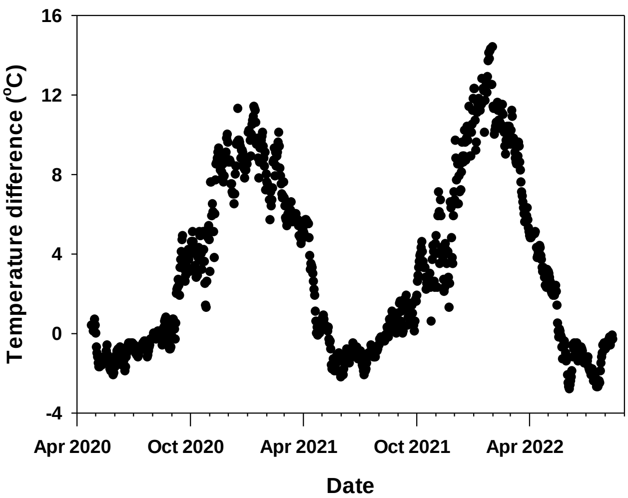

Figure 75 *Difference in water temperature between a site downstream of Lake Nagambie and one immediately downstream of Lake Eildon*

[4] And has been consistently falling from about 2000, initially because of lack of irrigation water during the millennium drought, but more recently through water efficiencies lowering the saline water table.

Murray River - Hume to Yarrawonga

Hypoxic blackwater
In preliminary modelling to determine hypoxic risk scores based on flow, time of year, water temperature and litter loads, the modelling predicted that hypoxic blackwater events in this reach were so rare as to be non-existent. Of the 780 scenarios tested, none of the runs indicated that hypoxia was certain, and only 3 predicted that it would be probable. This would require extremely high temperatures (95th percentile for the month), extremely high litter loads (average 700 g/m^2) and would only occur in January or February, when, given current knowledge and practice, would be highly unlikely.

The absence of hypoxic blackwater events is consistent with field observations. Dissolved oxygen concentration records in the Hume to Yarrawonga reach are relatively sparse, given the importance of the reach. However, monitoring activity in the Murray River upstream of Barmah Forest, was increased during the 2010 and 2012 blackwater events. The dissolved oxygen concentration upstream of Barmah Forest remained above 6 mg/L during both events (Whitworth et al. 2012, Whitworth and Baldwin, 2012). Furthermore, Joehnk et al. (2020) report that the 2016 hypoxic black water event in the Murray River began downstream of Barmah Forest, which implies the upstream reach was not impacted.

The reason for the lack of hypoxic events in this reach of the Murray River is because, for a given flow, the area of floodplain inundated in this reach is relatively small compared to Barmah Forest, and other lowland river floodplains downstream of Yarrawonga (Figure 76). Based on inundation modelling, increasing the constraint in this reach from 25,000 ML/day to 40,000 ML/day would only inundate an additional 4000 ha.

Therefore, it is highly unlikely that relaxing constraints in this reach would increase the incidence of hypoxic blackwater events.

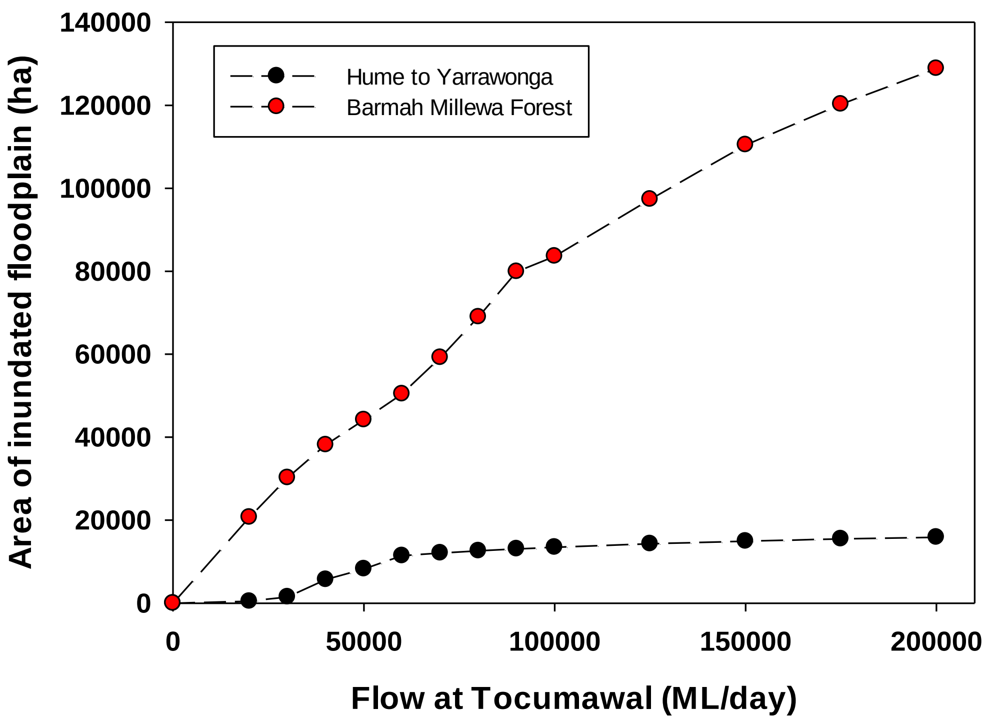

Figure 76 *Area of inundated floodplain in the Hume to Yarrawonga Reach (black circles) and in Barmah Forest (red circles) at different flows (source: DPE, in preparation)*

Eutrophication
Investigations have suggested that there wasn't a mechanistic relationship between flow and eutrophication, and therefore didn't specifically explore how constraints would impact on eutrophication in this reach

(McInerney et al. (2022)). While the overall assertion that there isn't a mechanistic relationship between flow magnitude and eutrophication has been debated (for example Rees et al. 2020), for this particular reach, based on the analogous relationship between flow and blackwater discussed in the previous paragraphs, it is unlikely that relaxing constraints would have a material difference on eutrophication in this reach. As noted above, the increase in area of floodplain inundated when going from a flow of 25,000 ML/day to 40,000 ML/day is small (4,000 ha) compared to the area flooded in the downstream reach. This suggests that the corresponding increase in the load of nutrients would also be small.

Blue-green algae
Investigations identified a mechanistic link between blue-green algal blooms and flow (McInerney et al. (2022)), however following a more detailed qualitative analysis on how the risks would change under the proposed flow scenarios, it was concluded that there was "insufficient of knowledge on the response of [blue-green algal blooms] to be able to differentiate between flow scenarios".

Salinity
Like blue-green algal blooms, McInerney et al. (2022) identified a mechanistic relationship between flows and salinity but were unable to differentiate impacts of different flow regimes. They do caution however that while the likelihood of salinity issues arising from relaxed constraints is unlikely, the consequences of an increase would be significant in this reach because of the salt sensitivity of some of the organisms living in this reach.

Turbidity
While a mechanistic relationship between turbidity and increased flows was established, it was concluded that the risk posed by increasing flows was no greater than that that currently exist (McInerney et al. (2022))

Weir pool stratification/destratification
While a mechanistic relationship between stratification/destratification and increased flows was established, it was concluded that the risk posed by increasing flows was no greater than that that currently (McInerney et al. (2022)).

Acid sulfate soils
Investigations on this reach soils could not establish a relationship between increased flow and water quality issues caused by the disturbance of acid sulfate soils (McInerney et al. (2022)), and if this is not the case any relationship in this reach is likely to be minimal. The Murray-Darling Basin Authority undertook a comprehensive assessment of acid sulfate soils in wetlands and channels in the Murray-Darling Basin, including in the reach from Hume to Yarrawonga (MDBMC, 2011) and none of the wetlands surveyed in this reach posed a risk to acidification. The wetlands in this reach could cause deoxygenation, but the impact would be minimal because the volume of deoxygenated water generated in the wetland would be relatively small compared to the volume in the main channel. Similarly, metal mobilisation was identified as a potential hazard in one wetland but would only marginally elevate metals in the main channel.

Thermal pollution
While a mechanistic relationship between thermal pollution and increased flows was established, on further analysis concluded that the risk posed by relaxed constraints was no greater than that that currently exists (McInerney et al. 2022).

Murray River Yarrawonga to the Wakool Junction

Blackwater
Out of 123 years assessed across all flow scenarios, the initial assessment identified 17 potential flow events in this reach that could cause hypoxic blackwater events. The expert assessment revised the number of years down to 6 likely hypoxic blackwater events in this reach (Department of Planning and environment, in preparation). In each of these 6 events, hypoxia would have occurred irrespective of constraints. Furthermore, the time series assessment found no evidence that the constraints relaxation flow scenarios would create new hypoxic events.

Eutrophication
Investigations have suggested that there isn't a mechanistic relationship between flow and eutrophication, and therefore didn't specifically explore how constraints would impact on eutrophication in this (McInerney et al. 2022). While the overall assertion that there isn't a mechanistic relationship between flow magnitude and eutrophication is often unclear, for this reach, based on the analogous relationship between flow and blackwater discussed previously, it is unlikely that relaxing constraints would have a material difference on eutrophication in this reach.

Acid sulfate soils
Investigations could not establish a relationship between increased flow and water quality issues caused by the disturbance of acid sulfate soils (McInerney et al. 2022). Even if this assertion is not accurate it is likely that the impacts of increased flow on acid sulfate soils in this reach is also minimal if the Edward-Wakool River system is excluded from the analysis[5]. Additionally, none of the wetlands examined in the Murray-Darling Basin Ministerial Council's survey (2011) along the main channel of the Murray River in this reach posed significant risk to water quality through disturbance of acid sulfate soils.

Blue-green algal blooms, salinity, turbidity, stratification, and thermal pollution
The assessment for these constituents in this reach were that no greater risks than that that currently exists, consistent with the Hume to Yarrawonga reach.

Summary
There are a range of existing water quality risks in each of the reaches. The relationship between flow and water quality is often difficult to quantify, although blue-green algae, anoxic blackwater and suspended sediments have well understood links with flow. The assessment found that constraint relaxation would not increase the risk for any of them. Increasing the occurrence of overbank inundation may reduce the occurrence of adverse water quality events arising from unregulated out of season (Summer and early Autumn) floodplain inundation.

A summary of the water quality results is provided in Table 21.

Table 21 *Summary of water quality outcomes across the reaches assessed.*

Water Quality	Murray Hume to Yarrawonga	Murray Yarrawonga to Wakool	Goulburn Eildon to Goulburn Wier	Goulburn Goulburn Weir to Murray River
Blackwater	No additional risk	No additional risk	No additional risk	No additional risk
Eutrophication	No additional risk	No additional risk	No additional risk	No additional risk
Blue-green algae	Insufficient data	No additional risk	No additional risk	No additional risk
Salinity	Insufficient data but unlikely	Insufficient data but unlikely	Insufficient data but unlikely	Insufficient data but unlikely
Turbidity	No additional risk	No additional risk	Insufficient data but unlikely	Insufficient data but unlikely
Weir pool stratification/ destratification	No additional risk	No additional risk	No additional risk	No additional risk
Acid Sulfate soils	Insufficient data but unlikely	Insufficient data but unlikely	No additional risk	No additional risk
Thermal pollution	No additional risk	No additional risk	No additional risk	No additional risk

[5] The western part of the Edward-Wakool River system was identified as a hot spot for acid sulfate soils in the Murray-Darling Basin, with much of the material in channels, and therefore mobilised by flows (MDBMC 2011; Bush et al. 2010).

Macroinvertebrates

Response to the relaxation of constraints has only been conducted for the the main channel of the Goulburn River through the work conducted by Horne et al. 2020 and John et al. 2022. As a result, the assessment of benefits to macroinvertebrates was focused on the Goulburn River. The macroinvertebrate model included consideration of the inchannel macro invertebrate outcomes arising from freshes and base flows (not overbank flows).

The baseline climate, constraint relaxation model scenarios predict small beneficial outcomes for macro biomass-diversity (Figure 77). The Bayesian model captures several flow drivers, including seasonal freshes, number of freshes as well as yearly baseflow. Additional drivers include instream production and instream vegetation which are accounted for through other conditional probability network models within this project. In interpreting the outputs of the model, it appears that relaxation of constraints will be associated with minor improvements in macroinvertebrates within the main channel, potentially driven by the improvements to instream productivity.

However as indicated above, the model was not designed to consider macroinvertebrate responses in direct response to over bank flows. Significant increased floodplain macroinvertebrate productivity should be expected to occur in response to increased occurrence of floodplain inundation. It is also likely that within the channel, over bank flows will leave a legacy (Paul et al. 2018, Le et al. 2020), beyond the flow event. However, these relationships are not incorporated into the model.

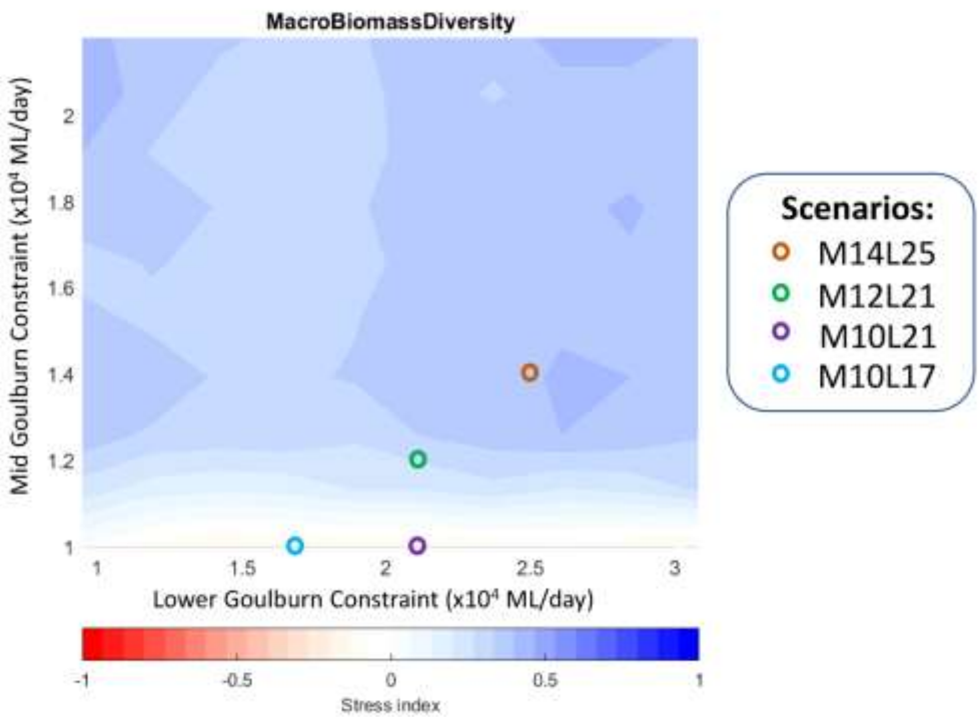

Figure 77 *Result from modelling of macroinvertebrate biomass and diversity response to constraint relaxation (John et al. 2022). Stress index values are indicated by shading. A stress index value >0 indicates a good outcome at the given constraint flows, compared with the base case (blue). A stress index value <0 indicates a poor outcome at the given constraint flows compared with the base case (red). A stress index = 0 indicates no difference in outcome between modelled flow scenario and the base case. Constraints scenarios are shown.*

Summary

The model forecasts that relaxing constraints in the Goulburn River will benefit the in channel macroinvertebrate community. However, this is only part of the story, as the largest response is likely to be on the floodplain and associated wetlands that have not been assessed via the ecological response modelling.

There also remains considerable uncertainty about the causal pathways by which flows influence macroinvertebrate communities in river channels. The assessment therefore provides an extremely conservative picture of the likely benefits of relaxing constraints for a key link in the food chain that would link increased productivity to outcomes for fish and birds.

Given the productivity and vegetation benefits that have been predicted in the Murray River, it is considered likely that increased secondary productivity for macroinvertebrates will occur in the Murray River with relaxation of constraints, particularly with constraints scenarios that permit overbank flows.

Native fish

Goulburn River

Native fish assessments in the Goulburn River focussed on the responses of fish from three different life history groups: equilibrium, periodic and opportunistic fish. Responses to a range of different flows combinations in the Mid Goulburn and Lower Goulburn were modelled (Figure 78).

The University of Melbourne, Bayesian modelling found minor benefits for equilibrium and opportunistic species could be achieved once flows exceeded 15,000 ML/day on the Lower Goulburn. The benefits of relaxing constraints were greater in Opportunistic species compared to equilibrium species. Benefits for periodic species also occur with relaxation of constraints, with improvements starting at flows below 15,000 ML/day and continuing until flows are just over 20,000 ML/day (Figure 78). Maximal benefits occur for fish of all three life histories when Lower Goulburn River flows exceed 20,000 ML/day. Together these data suggest that benefits can be achieved by relaxing constraints, particularly under higher flow scenarios, accompanying inundation of the floodplain.

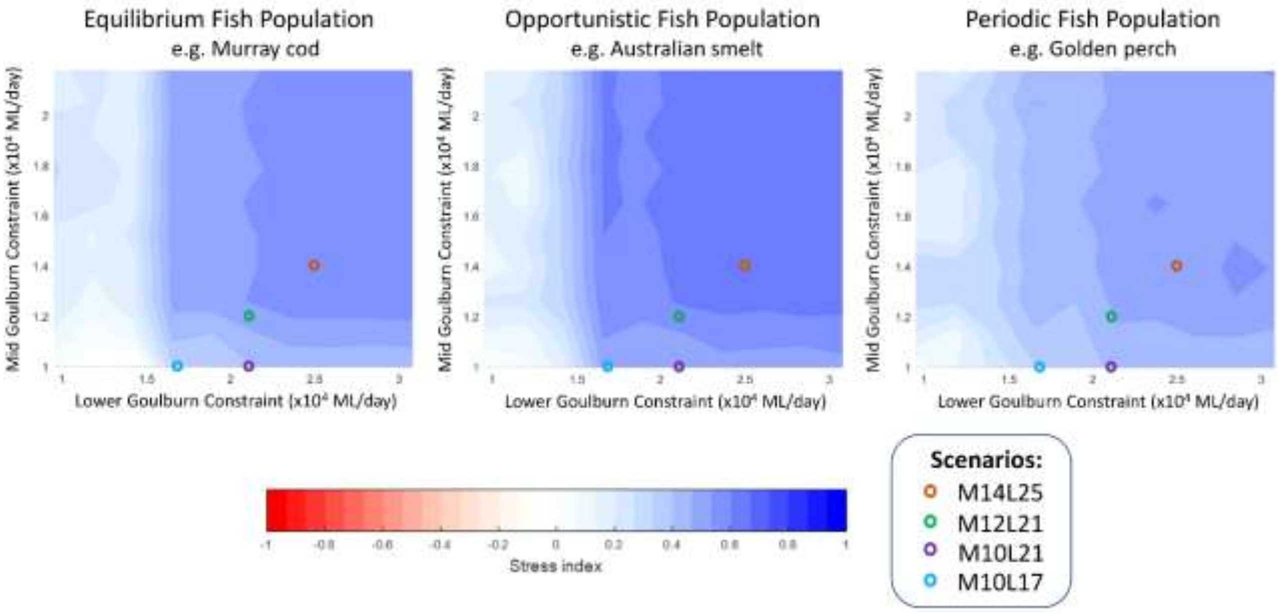

Figure 78 *Modelled outcomes for equilibrium, opportunistic and periodic fish populations (John et al. 2022). Stress index values are indicated by shading. Stress index values >0 indicates a good outcome at the given constraints flows in the Mid and Lower Goulburn River, compared with the base case (blue). Stress index values <0 indicate a poor outcome at the given constraints flows compared with the base case (red). Stress index = 0 indicates no difference in outcome between modelled flow scenario and the base case. Constraints scenarios are shown.*

Murray River - Hume to Yarrawonga

Results in this section are summarised from (Todd et al. 2022) and presented as the predicted benefit of each hydrological scenario relative to the base case.

The predicted benefits for Golden Perch in the Hume to Yarrawonga reach increased from the base case across the four scenarios (Figure 79). The largest predicted benefit was observed for Scenario 4 (Y45D40), with adult population size predicted to be 39% higher than the base case.

The largest predicted benefit for Murray Cod in the Hume to Yarrawonga reach was an 11% increase in population size under scenario 2 relative to the base case (Figure 80). Predicted benefits were more variable also across the scenarios i.e., an 11% increase predicted for scenario two (Y30D30), a 1% decrease predicted for scenario 3 (Y40D40) and a 4% increase predicted for scenario 4 (Y45D40). These results highlight that the modelled responses to relaxation of constraints are not always uniform. This reach can be severely affected by cold water pollution and the timing of cold-water releases affect Murray Cod responses to flow.

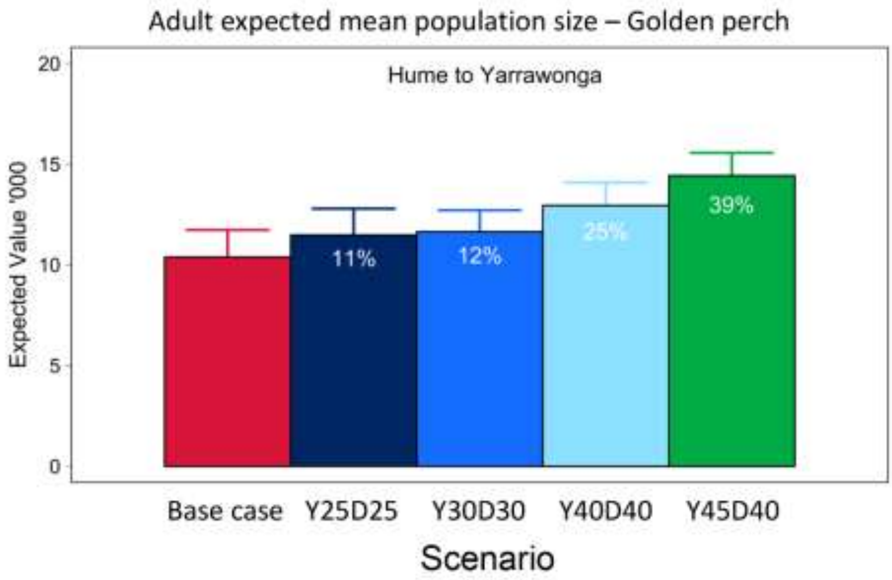

Figure 79 *Modelled Golden Perch in the reach Hume to Yarrawonga for the base case and four constraints flow scenarios. Expected mean population size with % change from Base case shown in each bar. Error bars are one standard deviation (Todd et al. 2022)*

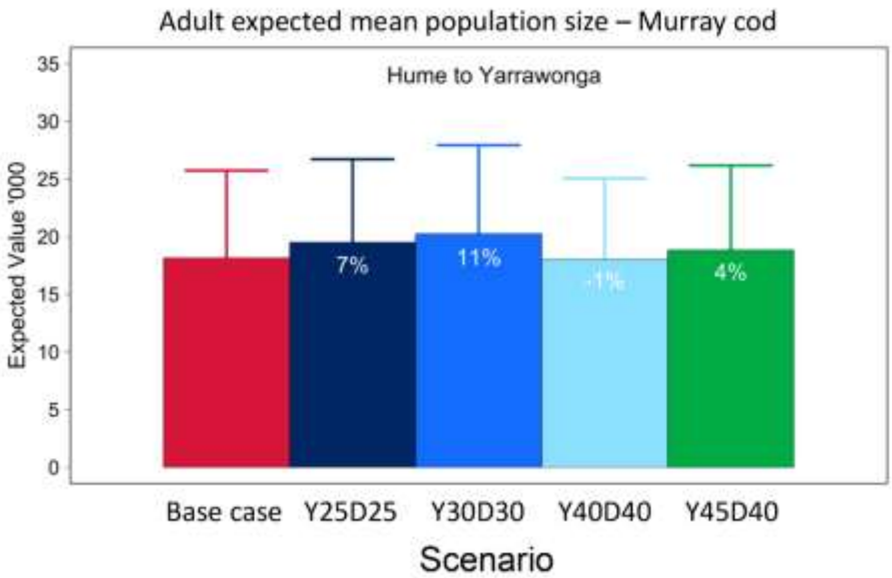

Figure 80 *Modelled Murray Cod in the reach Hume to Yarrawonga for the base case and four constraints flow scenarios. Expected mean population size with % change from Base case shown in each bar. Error bars are one standard deviation. (Todd et al. 2022)*

Murray River - Yarrawonga to Wakool Junction

Results in this section are summarised from (Todd et al. 2022) and are presented as the predicted benefit of each hydrological scenario modelled, relative to the Base case.

The largest predicted benefits for Golden Perch in the Murray River between Yarrawonga and Wakool junction were observed under scenario 4 (Y45D40). The adult population size was predicted to be 39% higher for scenario 4 (Y45D40) than the base case in the Yarrawonga to Torrumbarry reach (Figure 81), and 28% higher for the Torrumbarry to Lock 10 reach (Figure 82). Like the Hume to Yarrawonga results, the predicted benefit for Golden Perch increased across hydrological scenarios.

The Victorian constraints environmental benefit assessment is considering Yarrawonga to Wakool junction as one single reach, whereas the ecology of the species required that this was split into the two reaches for the NSW RRCP modelling, with differences between the two reaches indicating they are not the same (Figure 81 and Figure 82). The results were relatively consistent across the two reaches, with largest predicted benefits observed under scenario 4 (Y45D40) for Golden Perch in both, and no predicted benefits observed for Murray Cod. There was no difference in the predicted population sizes of Murray Cod in either the Yarrawonga to Torrumbarry or Torrumbarry to Lock 10 reaches (Figure 83 and Figure 84). However, these results focussed on the direct responses to flow changes, as opposed to the broader interactions of the Goulburn River modelling that expects an improvement for Murray Cod.

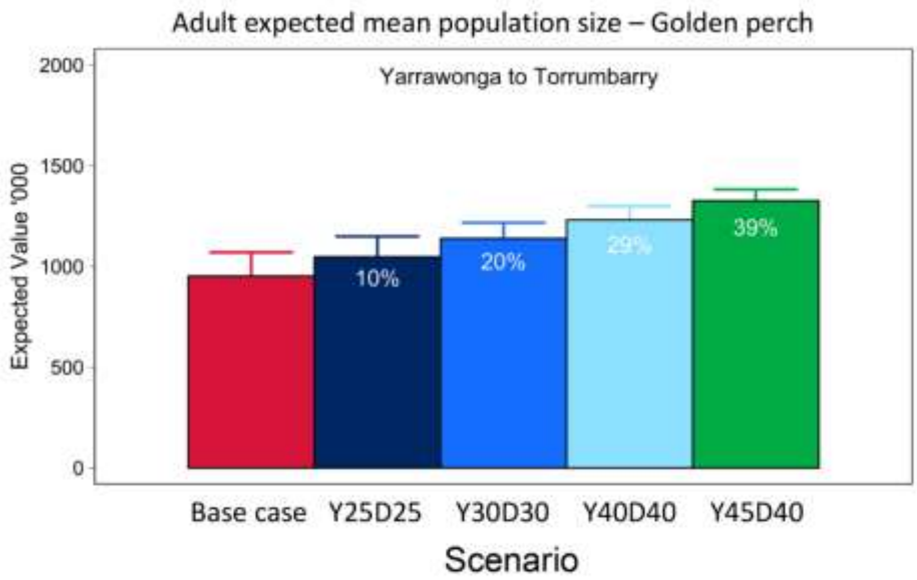

Figure 81 *Modelled Golden Perch in the reach Yarrawonga to Torrumbarry for the base case and four constraints flow scenarios. Expected mean population size with % change from Base case shown in each bar. Error bars are one standard deviation. (Todd et al. 2022)*

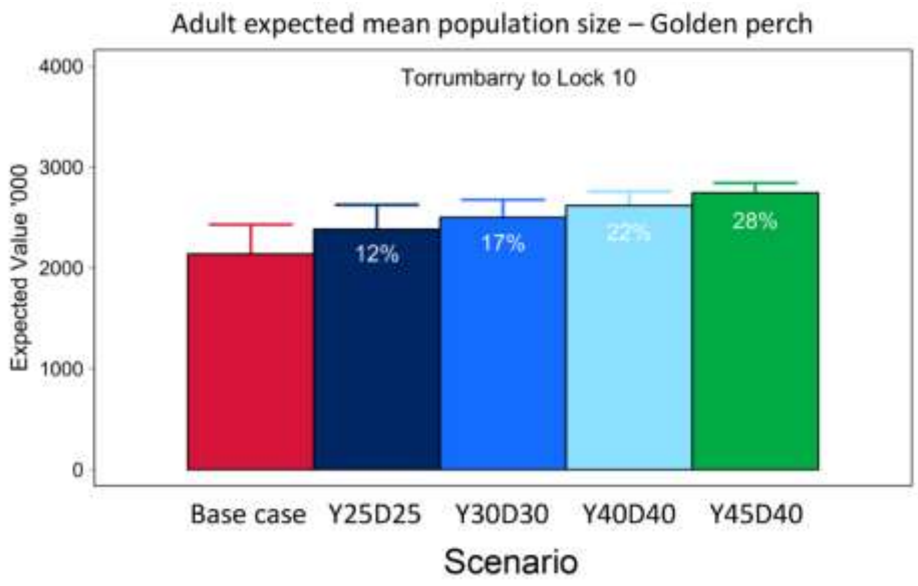

Figure 82 *Modelled Golden Perch in the reach Torrumbarry to Wentworth (Lock 10) for the base case and four constraints flow scenarios. Expected mean population size with % change from Base case shown in each bar. Error bars are one standard deviation. (Todd et al. 2022)*

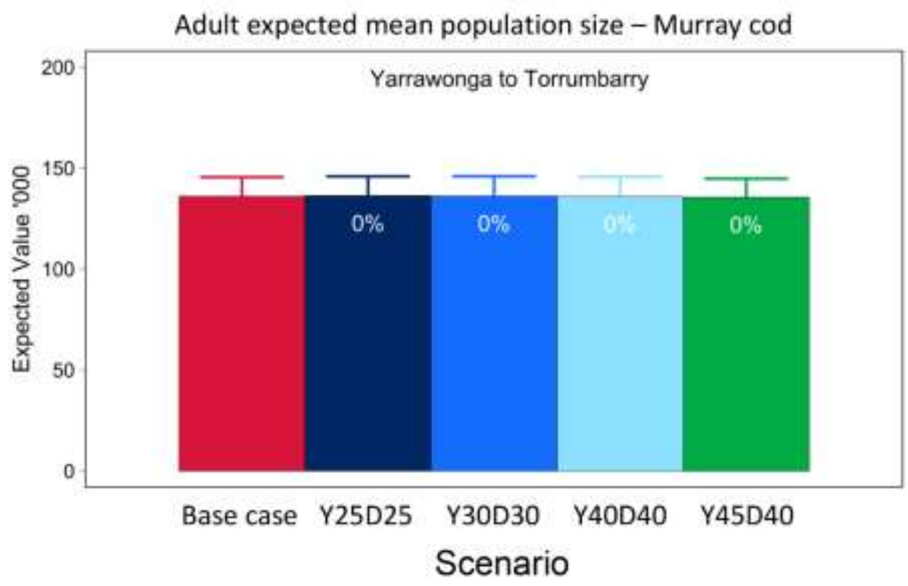

Figure 83 *Modelled Murray Cod in the reach Yarrawonga to Torrumbarry for the base case and four constraints flow scenarios. Expected mean population size with % change from Base case shown in each bar. Error bars are one standard deviation. (Todd et al. 2022)*

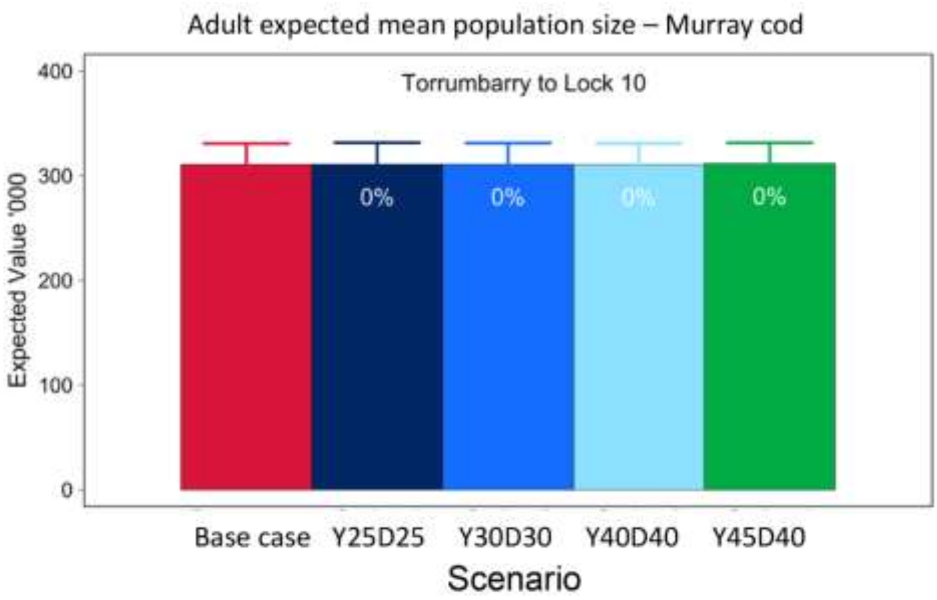

Figure 84 *Modelled Murray Cod in the reach Torrumbarry to Wentworth (Lock 10) for the base case and four constraints flow scenarios. Expected mean population size with % change from Base case shown in each bar. Error bars are one standard deviation (Todd et al. 2022)*

The predicted population sizes of Murray Cod in this project reach were found to have no difference between the four hydrological scenarios. Contrary to this result, the Goulburn fish modelling assessment found responses to constraints by equilibrium species including Murray Cod (see above). The differences in the modelling results, despite being assessed in different river systems, illustrates the complexity behind modelling the responses of Murray Cod to different flow regime and the level of uncertainty of these modelling results around the links between flow and Murray Cod recruitment.

Recent work has identified five causal pathways by which flow may be expected to influence Murray Cod recruitment (Tonkin et al. 2020). Subsequent assessment found evidence to support the hypotheses, but that the relationships were variable through time and between rivers. This suggests a complex, multi-factor relationship between flow and recruitment which may not have been captured in the Murray River assessment models. In the future, it may be possible to refine the modelling to predict benefits between Yarrawonga to Wakool Junction, but this would involve making some large assumptions, especially that fish are evenly distributed along the river length.

Summary

The assessment in the Goulburn River found that relaxation of constraints above 15,000 ML/day would lead to improvements in equilibrium, opportunistic and periodic guilds of fish. The assessment in the two Murray River reaches did not identify a threshold, but did find that Golden perch populations would be improve with the progressive relaxation of constraints. The assessment in the Goulburn and Murray Rivers differed in that the Murray River modelling found that Murray cod would not benefit, while the Goulburn assessment found that the periodic guild (including Murray cod) would benefit. It is not clear whether the differing predictions are due to the inclusion of multiple species in the Goulburn River assessment or whether the Murray R assessment's use of statistical relationships affected the overall relationship between flow and fish populations. This is a issue that should be explored in the next stage of the project.

The Goulburn River assessment found that all guilds of fish benefited, while the Murray River assessment found that species dependent on flood-plain inundation would benefit from constraints relaxation. The Murray River assessment for Golden perch can broadly be applied to a range of other species including catfish and small native species (e.g. Carp gudgeon) known to move into floodplain habitats during high flows.

Waterbirds

Goulburn River

Waterbirds rely on flooding to provide foraging habitat and breeding opportunities. We used available aerial survey data (1983-2021) to model waterbird responses (species richness, abundance, and colonial waterbird breeding activity) to river flows and inundated area in the Goulburn River selected area. Waterbird breeding in Goulburn River was strongly associated with cumulative river flows 90 days prior to the waterbird survey, most noticeably with the likelihood of breeding occurring in the area (see Figure 27 and Figure 28).

Maximum area of inundation, mapped using the Water Observations from Space (WOfS) dataset, was highly associated with cumulative river flows as well as with waterbird breeding. We used modelled waterbird responses to predicted hydrological responses under each of four constraint scenarios. Relaxing constraints were expected to improve the likelihood of breeding events, expressed with an increase of the median probability of breeding by 5% and the overall average by 12%. In contrast, however, waterbird breeding occurrences were predicted to decrease under relaxed constraints, lowering support for large breeding events (90^{th} percentile) by 11% (Scenario 4) while increasing small breeding events (25^{th} percentile) by 11% (Scenario 4), with an overall reduction in the average long-term breeding likelihood of 3%. Declines in waterbird abundances to relaxed constraints was noticeable in large waders, displaying similar responses, with a predicted decline of 13% in the 90th percentile of large wader abundances while increasing the 25th percentile by 14% with an overall decline of 4% in the long-term average. Existing climate change projections of discharge predicted a decline in the average probability of breeding of 24 – 58%, depending on the climate scenario (dry, medium, or wet future) while overall breeding abundance was predicted to decline between 11 – 36%, depending on the climate scenario.

Relationships between observed data

The assessment analysed observed waterbird data collected as part of annual aerial surveys. It looked at patterns in total abundance, probability of breeding, breeding abundances (and abundance of each functional response group (ducks, herbivores, large waders, piscivores) (in response to cumulative river flows and inundated area between August and October corresponding with annual aerial surveys using Generalized Linear Models. We used a QuasiPoisson distribution with a log link function for abundance models and binomial for probabilistic models of breeding events (R Development Core Team 2022).

We calculated cumulative flows at 90 days prior to the aerial survey (Oct-Nov) for each year using data from river gauge at the Goulburn River flow gauge at Shepparton (405204) to investigate flow predictors of waterbird responses. We also used estimated area of inundation from Water Observations from Space (WOfS) imagery to calculate maximum inundation area for three months preceding the aerial surveys.

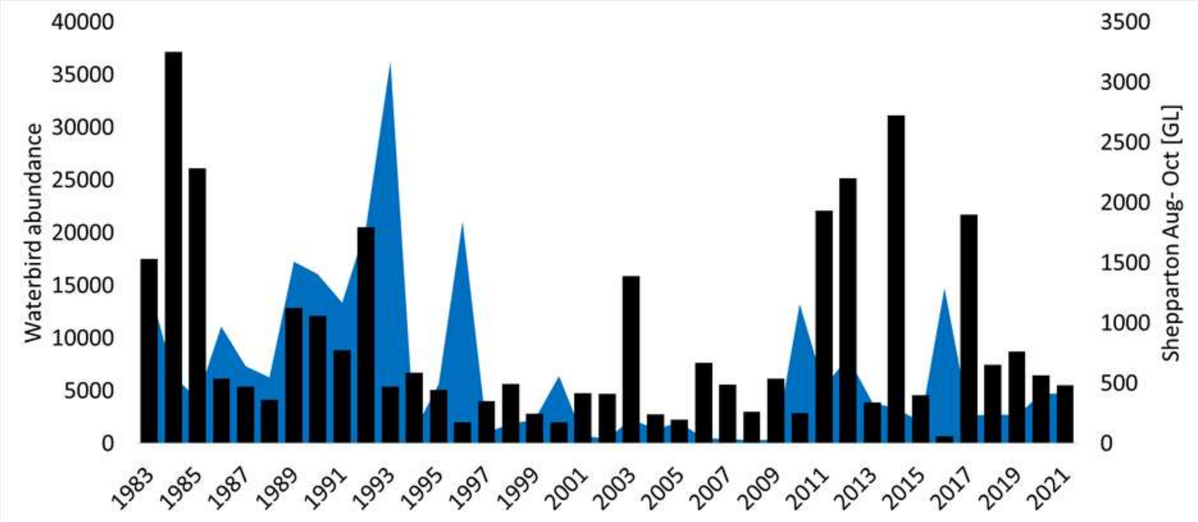

Figure 85 *Waterbird abundances in the selected Goulburn River region counted during the Eastern Australian Aerial Waterbird Survey 1983-2021. Black columns are the number of waterbirds counted, while the blue represents discharge at Shepparton in August-September in GL.*

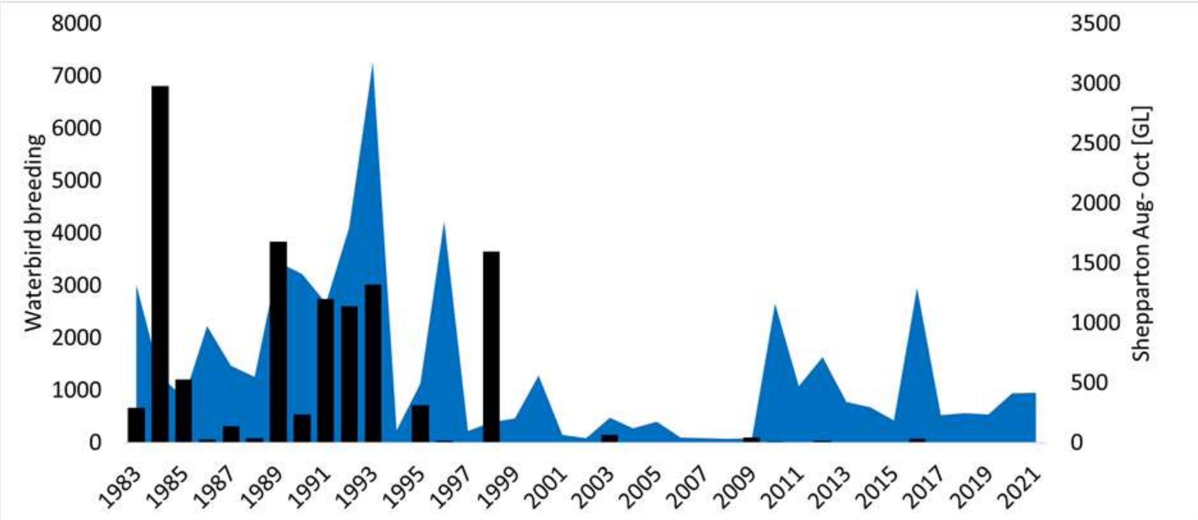

Figure 86 *Waterbird breeding abundances in the selected Goulburn River region counted during the Eastern Australian Aerial Waterbird Survey 1983-2021. Black columns are the number of waterbird nests counted, while the blue represents discharge at Shepparton in August-September in GL*

Murray River

The waterbird assessment focussed on the Yarrawonga-Wakool reach as this reach contains several significant waterbird areas, including the Ramsar listed Barmah-Millewa Forest and Gunbower-Koondrook-Perricoota forests.

Modelled river flow and modelled inundation data were examined to assess changes to the availability of waterbird habitat in Barmah-Millewa and Gunbower-Koondrook-Perricoota forests under different relaxed constraints scenarios. The number of days when small overbank events were recorded, which would inundate greater areas of the forests, increased for all the relaxed constraints scenarios compared to current constraints. This included events that would be of suitable duration and magnitude to initiate small-scale colonial waterbird breeding.

The relaxation of constraints in the Murray River is likely to provide cumulative benefits to waterbird populations by inundating these important wetland areas more frequently. This would maintain and improve the condition of the feeding and breeding waterbird habitat, and in turn, support improvements in waterbird populations, a key objective of the Basin Plan.

Barmah-Millewa Forest

The best predictors of waterbird responses in Barmah-Millewa Forest were maximum inundated area and cumulative river flows 180 days prior to spring (Figure 87). The modelled inundated and flow data for each constraint was linked to predicted waterbird responses in Barmah-Millewa Forest. Compared to current constraints there were small increases in median waterbird species richness (4-5%) and waterbird density (10-13%) in Barmah-Millewa Forest for the highest relaxed constraint scenarios of 40,000 and 45,000 ML/day downstream of Yarrawonga Weir.

The probability of colonial waterbird breeding in Barmah-Millewa Forest also increased for all relaxed constraint scenarios compared to current constraints from a 6% increase for the lowest scenario (25,000 ML/day) to a 11% increase for the highest scenario (45,000 ML/day downstream of Yarrawonga).

Gunbower-Koondrook-Perricoota

The best predictors for waterbird responses in Gunbower-Koondrook-Perricoota Forest were cumulative river flows 180 days prior to spring aerial surveys and inundated area at the time of the surveys (Figure 88). Small increases were observed in the median number of species (1-4% compared to current constraints) and median waterbird abundance (8-48% compared to current constraints) in Gunbower-Koondrook-Perricoota Forest with increased relaxation of constraints. The largest predicted benefits were for the highest relaxed constraint scenarios of 45,000 ML/day downstream of Yarrawonga (which equates to 35,000 ML/day downstream of Torrumbarry Weir the nearest river gauge to the forest).

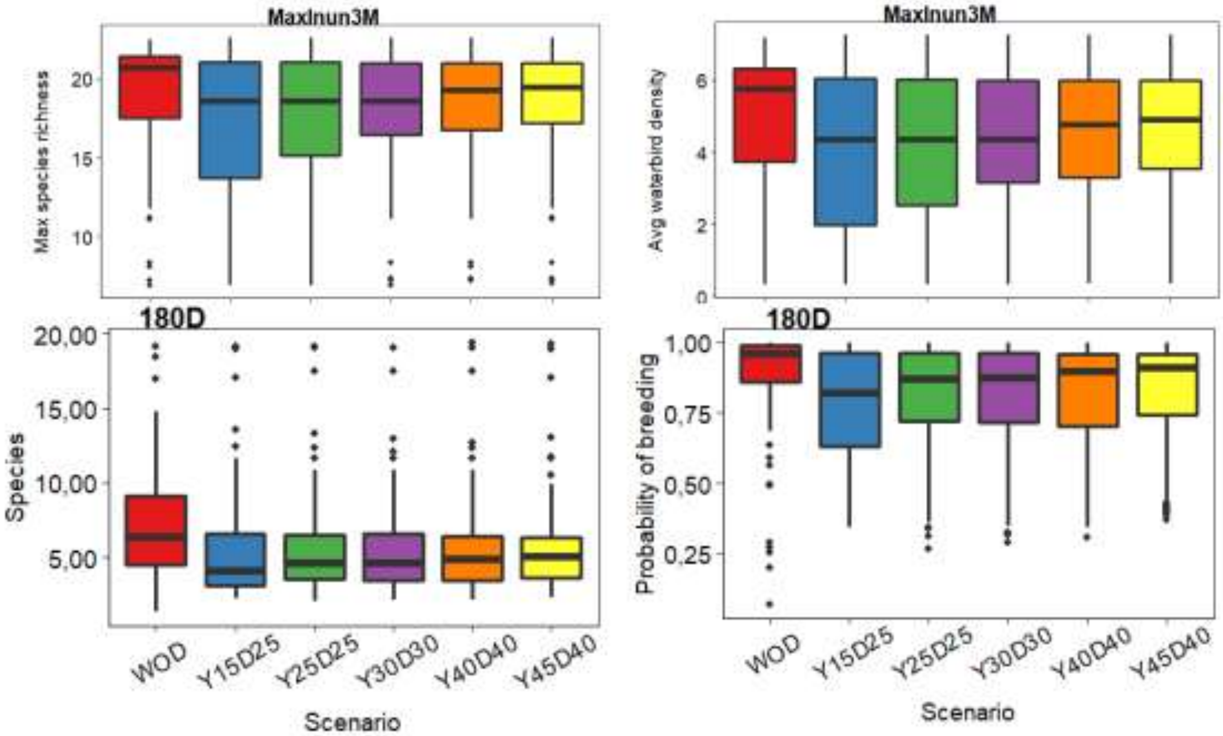

Figure 87 *Summary of predicted number of species (top left), waterbird density (top right) and number of breeding species (lower left) probability of colonial waterbird breeding (lower right) in Barmah-Millewa Forest under the flow scenarios. Inundated area in the 3 months prior to spring ground surveys was used as the predictor for species richness and waterbird density. Cumulative river flows in the 180 days prior the start of the breeding season was used as the main predictor for the probability of breeding and number of breeding species. The Box plots represent the distribution of the data. The line in the middle of the box is the median (middle point), the bottom of the box is the first quartile (Q1) (greater than 25% of values) while the top of the box is the third quartile (Q3) (greater than 75% of values). The whiskers extend to the furthest data point on either side of the box that is within 1.5 times the difference between Quartile one and three. Data points that lie outside this range are represented by dots and are considered outliers.*

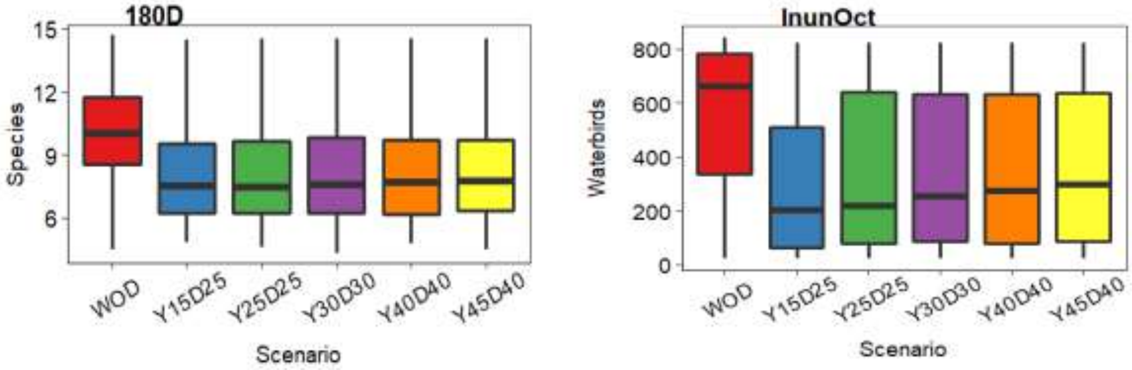

Figure 88 *Summary of predicted number of waterbird species (left) and total waterbird abundance (right) in Gunbower-Koondrook-Perricoota Forest under the flow scenarios. Cumulative river flows in the 180 days prior to the spring aerial surveys was used as the main predictor species of richness. Inundated area at the time of the aerial surveys in October was used as the main predictor for waterbird abundance. The line in the middle of the box is the median (middle point), the bottom of the box is the first quartile (Q1) (greater than 25% of values) while the top of the box is the third quartile (Q3) (greater than 75% of values). The whiskers extend to the furthest data point on either side of the box that is within 1.5 times the difference between Quartile one and three. Data points that lie outside this range are represented by dots and are considered outliers.*

It is important to note that relaxing constraints will not greatly influence flows over the 180-day period that informs waterbird outcomes and so the model does not predict any effect of relaxing constraints on the number of waterbird species. Relaxing constraints will influence the area of inundation with small increases in the median as constraints are progressively relaxed. The change in median across the October inundation results shows the key output for the waterbird benefits. As waterbirds rely on an array of locations for breeding, habitat and food sources, the decline of one is unlikely to have an extreme impact, however the improvement of the locations within the study areas creates better opportunities for water birds, and as a result the probability of positive outcomes for water bird species improves.

Summary

The assessment confirmed that maximum inundated area and cumulative river flows are the two key influences on waterbird communities and within this context, relaxing constraints to increase the area inundated will have beneficial impacts. There remains some uncertainty around the response of the number of species as constraints will not influence flows for 180 days. Importantly however, the relaxation of constraints will be important during dry periods help to maintain populations. This will be an important influence on waterbird resilience and their capacity to respond to floods when they occur. Within this context constraint relaxation is both feasible and important to achievement of Basin Plan objectives.

Platypus

As with many sub-catchment areas across their range, no quantitative data on the current status of platypus populations in the Goulburn and Murray Rivers is available due to a lack of systematic surveys. This assessment is based on the conditional probability network and flow scenario modelling studies by Horne et al. 2020 and John et al. 2022.

Modelling suggests low level benefits for platypus outcomes until flows in the Lower Goulburn reach 22,000 ML/day (Figure 89). Above this flow rate, slightly negative outcomes were predicted. 22,000 ML/day represents bankfull and overbank flows, which if delivered between October-January would inundate breeding burrows and drown or displace dependent young. A key flow/stress threshold was not predicted in the Mid Goulburn as the ecological modelling was only conducted for the Lower Goulburn. Indeed, increasing flows above 12,000 ML/day in the Mid Goulburn are predicted to improve platypus outcomes as long as the Lower Goulburn flows remain below 22,000 ML/day during critical nesting periods. No modelling was undertaken for Murray River reaches although similar outcomes as for the Goulburn River are expected.

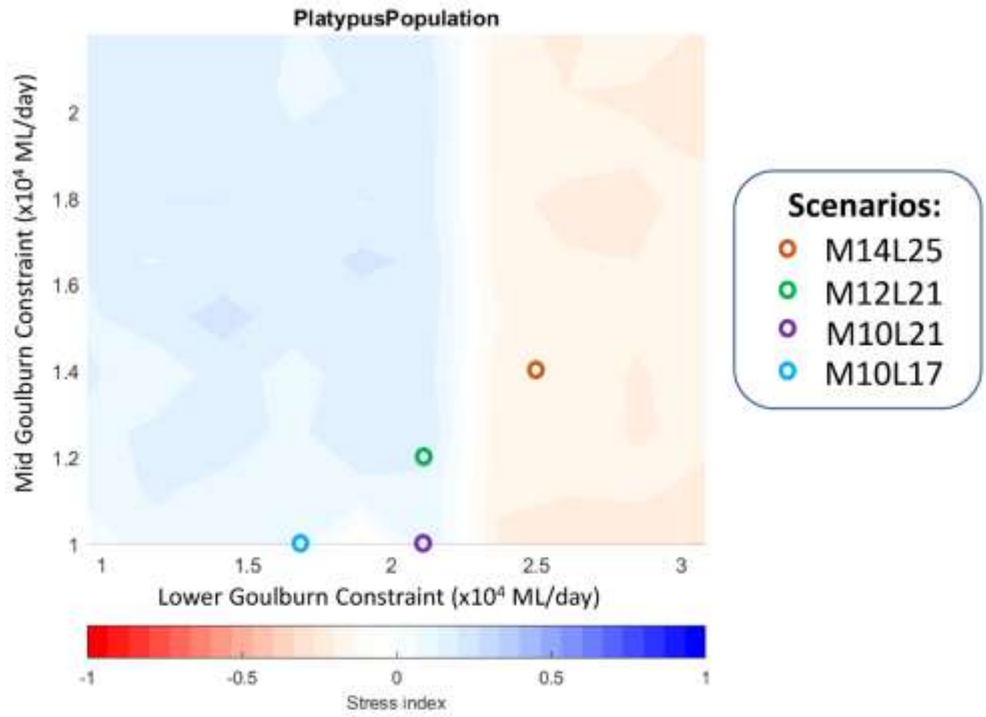

Figure 89 *Modelled Platypus population stress index under different flows in the Lower and Mid Goulburn River (John et al. 2022). Stress index values are indicated by shading. A stress index value >0 indicates a good outcome at the given constraint flows, compared with the base case (blue). A stress index value <0 indicates a poor outcome at the given constraint flows compared with the base case (red). A stress index = 0 indicates no difference in outcome between modelled flow scenario and the base case. Constraints scenarios are shown.*

This model should be interpreted with caution due to considerable uncertainty and the lack of quantitative analyses of the relationship between platypus population dynamics data and environmental factors. In this model, the seasonality of high flows is of critical importance for the platypus population. Several studies have reported a negative correlation between juvenile recruitment and summer high (bankfull or overbank) flows (Bino et al. 2015; Serena et al. 2014) that can presumably drown nestlings within maternal burrows. Sensitivity analysis of the model revealed that the antecedent platypus population had the greatest influence on the size of the final platypus population with other factors being reproduction, body condition and then macroinvertebrate abundance. In a recent review of platypus biology the key threats identified were connectivity, habitat loss, bycatch and feral predators (Bino et al. 2019). Without consideration of the relative risk posed by all these threats compared to that of nest inundation, any estimate of the effects of flows on platypus will be highly uncertain. It is unfortunate that the model did not include habitat given that environmental flows are likely to enhance riparian vegetation and geomorphological processes, both of which would be associated with improvements in habitat.

Summary

Despite the lack of quantitative data and uncertainty of the modelling parameters, the predicted outcomes are consistent with what one might reasonably expect from the expected hydrological changes and knowledge of the species' biology. None of the study reaches suffer from extensive cease to flow events or extreme flow variability, therefore impacts of relaxed flow constraints on platypus are likely to be subtle and indirect.

An increase in flows within these reaches may be associated with risk to platypus breeding, however, this risk needs to be considered within the broader documented declines over the last 30 years associated with increased river regulation. Over the long-term, further work is required to improve our understanding of the relationship between flow regimes and platypus. Overall, relaxing constraints, including occasional overbank flows (provided these are not delivered during Oct-Jan) that mimic relatively natural flow patterns are expected to enhance conditions for platypus through improved riparian vegetation, foraging habitat, water quality, and macroinvertebrate communities.

Turtles

The modelling to turtle responses to relaxation of constraints in the Goulburn River was performed by Horne et al. 2020 and John et al. 2022. Although three different turtle species, with different breeding and habitat preferences, exist in the Goulburn and Murray Rivers, the model combines the three turtle species into a single turtle population.

The baseline climate - ecological model outputs indicate poorer outcomes for turtle populations under relaxed constraints in lower reaches of the Goulburn River, with a sharp decline once flows increase above around 14,000 ML/day (Figure 90). It is important to note that an equivalent assessment was not undertaken in the Murray River reaches. Flow rates that begin to negatively impact turtle populations in the Murray River would need to be determined via Murray River reach-specific assessments.

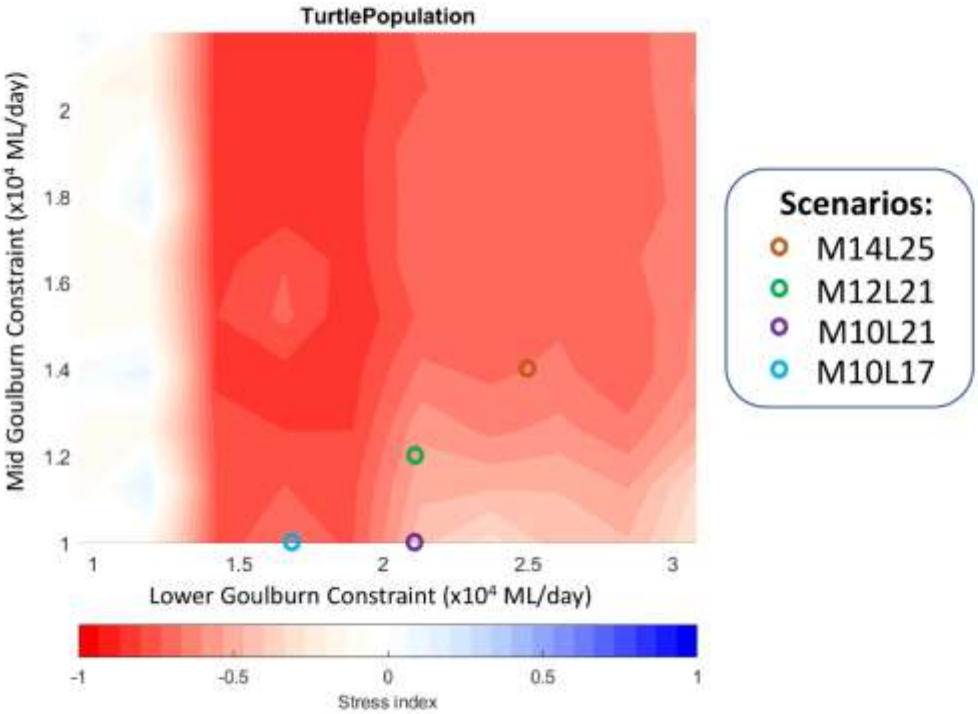

Figure 90 *Result from modelling of turtle population responses to constraint relaxation (John et al. 2022). Stress index values are indicated by shading. A stress index value >0 indicates a good outcome at the given constraint flows, compared with the base case (blue). A stress index value <0 indicates a poor outcome at the given constraint flows compared with the base case (red). A stress index = 0 indicates no difference in outcome between modelled flow scenario and the base case. Constraints scenarios are shown.*

These outcomes likely relate to the influence of high flows between October and January and the risk they pose to turtle nests, in turn, impacting on recruitment. While this risk may affect all three species, the risk would appear greatest for Macquarie River turtles which nests 30m from the river's edge. Of course, the water's edge is not static, and it may well be that higher flows in the lead up to November would encourage mothers to seek higher nest sites. This was certainly what was found for *E. albagula* in Queensland when trials of higher flows reduced inundation to less than 11% of nests over three years (Espinoza et al. 2022). This suggests that the risk to inundation may be managed within constraint relaxation measures, although further investigation would be warranted. It is noted that TLM intervention monitoring is currently investigating turtle populations in Barmah that may provide additional information on turtle water requirements and vulnerabilities.

The risk is not seasonally dependent for the broad shelled tortoise due to their long incubation. The risk is also reduced as they have the potential to utilise wetlands as breeding habitats that would not be as affected by high flows. Finally, eastern long-neck turtles would appear to be least vulnerable to riverine high flows given their habitat preferences (wetlands) and they nest in early summer.

The forecast decline may not represent a significant risk as populations of the three species in the Lower Murrumbidgee River were found to be impacted by decreased flooding frequencies and duration and that maintaining key habitat areas with environmental water was found to be critical for the survival of these species. This is echoed by Chessman (2011) who outlined drought-induced loss of floodplain habitat as a key factor in the decline of *C. longicollis* and *E. macquarii* turtles in the Murray-Darling Basin. Thus, restoring floodplain habitats would provide direct benefits to eastern long-necked and Macquarie River turtles in both the Murray and Goulburn Rivers.

Summary

In findings similar to those of platypus, the modelling identified a risk to turtle breeding, however, within the broader context of the effects of river regulation on habitat and the effects of fox predation on nests, the risk should be noted, and further work undertaken to improve our understanding of turtle population dynamics. Importantly, turtles are long-lived and may only need to breed successfully in a few years to sustain populations. Therefore, ensuring that there is suitable habitat to support them through their lives is a more critical issue than whether relaxing constraints will affect breeding in some years. For turtle populations, relaxation of constraints is feasible and necessary to protect populations, although this is an area where flow management may be necessary but insufficient given the impact of non-flow threats.

Geomorphology

This section summarises the outcomes of the Erosion Potential Index modelling for the Lower Goulburn River, and the results of the statistical analysis of flows above and below bank full for all other reaches. As outlined in Section 0, a complete EPI analysis for all four study reaches was beyond the scope of this project.

Goulburn River – Goulburn Weir to the Murray River

A complete Erosion Potential Index analysis was undertaken for the Lower Goulburn River. Relative to natural, pre-development conditions, the current flow regime has an increased potential for erosion (4% greater, see Figure 91). However, relaxed constraints scenarios have lower EPI values than both the natural baseline and current conditions (Figure 91). The same pattern in EPI values is mirrored in the total number of days (over the entire modelled period of 123 years) that the threshold for erosion (a constant 15 N/m^2) was exceeded (right hand side of Figure 91) The key outcome from the EPI analysis is that as the degree of constraints relaxation increases (larger flows are delivered overbank) the erosion potential and the number of days that the erosion threshold is exceed both steadily decrease.

Constraints relaxation scenario	EPI value
Natural	1.00
Current conditions (M10L9.5)	1.04
Scenario 1 (M10L17)	0.97
Scenario 2 (M10L21)	0.94
Scenario 3 (M12L21)	0.93
Scenario 4 (M14L25)	0.92

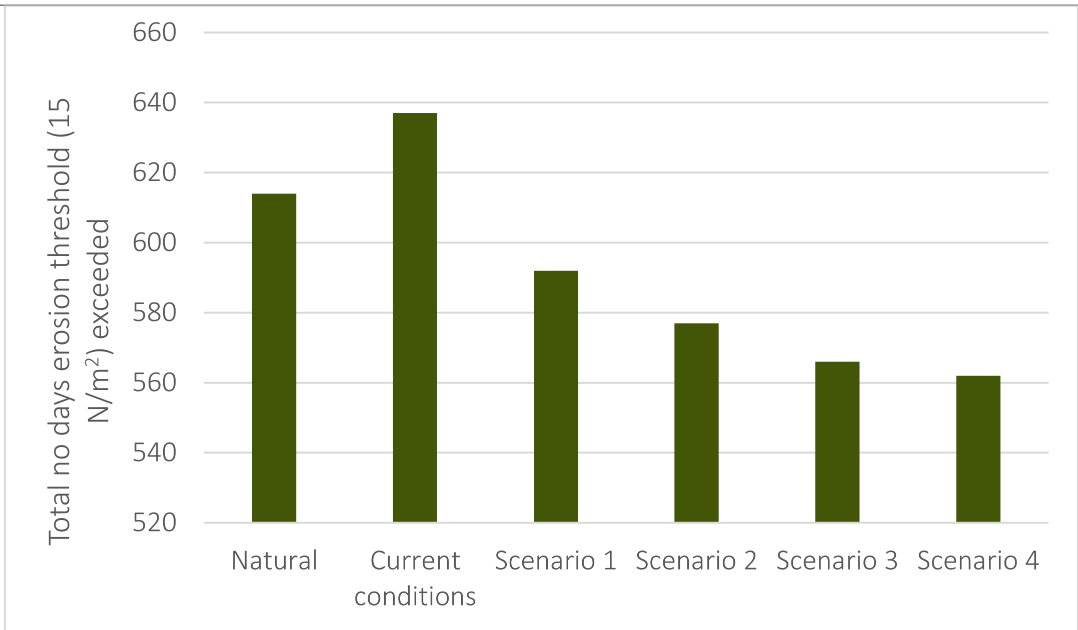

Figure 91 *Left - EPI values for natural (pre-development), current and the four relaxed constraints scenarios, right - total number of days flow exceeds the threshold for erosion of 15 N/m^2.*

All scenarios deliver a lower total volume of flow, and therefore less total energy, than under natural (pre-development) conditions (Figure 92). Note that despite the decrease in total flow energy available under post-development scenarios, erosion potential *increases* (Figure 91). While this result may seem counter-intuitive, it indicates that the pattern of flow delivery (in-channel vs overbank) plays a greater role in determining erosion potential than the total volume of flow delivered to the reach.

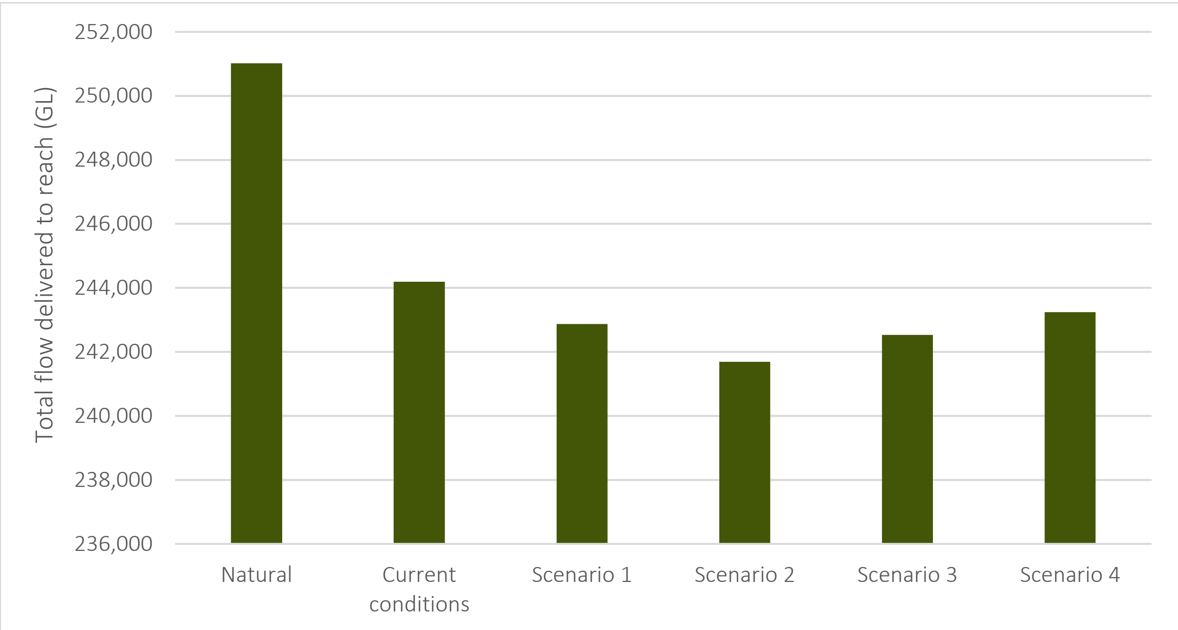

Figure 92 *The total volume of flow (Gigalitres) delivered to the Lower Goulburn over the 123 years of modelled data for each scenario.*

Finally, a comparison was made between the total number of days that flow remains in-channel with the total number of days flow spills over bank, for each constraints relaxation scenario in the Lower Goulburn. A clear trend emerges. As the degree of constraints relaxation increases (moving from scenario one to four), the total number of days flows spills overbank increases and the total number of days flow remains in-channel decreases (Figure 93). Taken together, the results of the EPI analysis, total flow delivery and the number of overbanks and in-channel flows illustrate an inverse relationship between the number of days flows spills overbank and erosion potential. We have used the in-channel/overbank distribution of flows as a proxy for erosion potential in the remining reaches of the Goulburn and Murray Rivers.

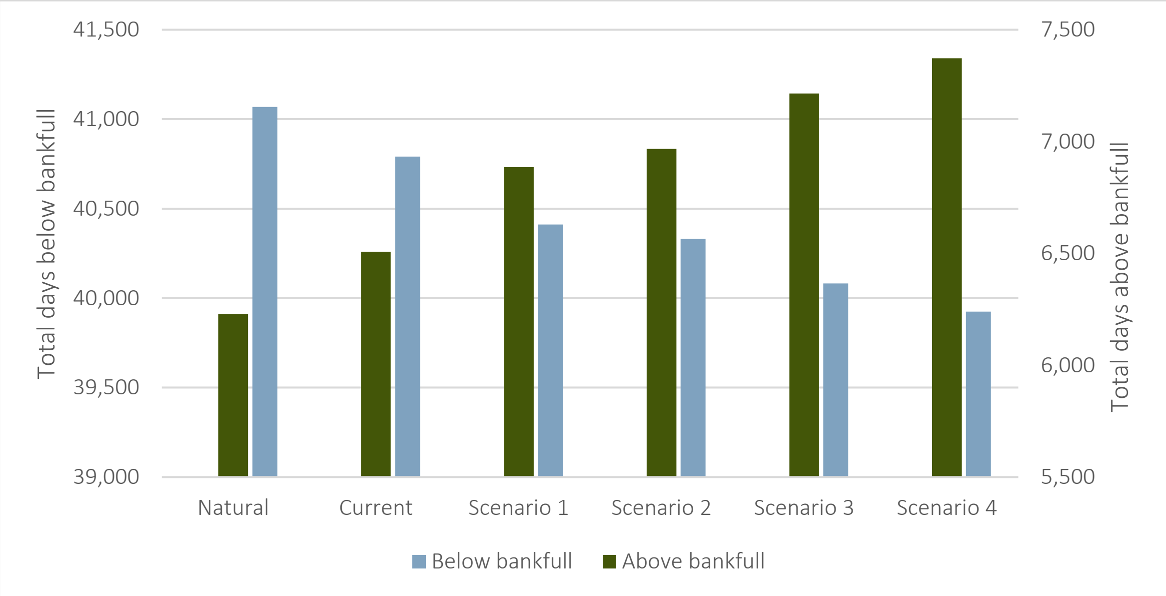

Figure 93 *The total number of days over the 120 years of modelled data that flow spills overbank and the total number of days flow remains in-channel in the Lower Goulburn. Note the change in scale of the left and right axis.*

Goulburn River – Mid Goulburn

Compared with current conditions[6], constraints relaxation scenarios one and two show only a slight increase in the total number of days flow is above bank full, and a slight decrease in the number of days flow remains in-channel (Figure 94). However, scenarios three and four generate a much larger decrease in the total duration of in-channel flows and increase in overbank flows compared to the combined grouping of the current and scenarios one and two (Figure 94).

Relying on the assumption developed in the Lower Goulburn (see above), this implies that only scenarios three (12,000 ML/day) and four (14,000 ML/day) that create overbank inundation have the potential to decrease erosion potential relative to current conditions. Scenarios one and two (10,000 ML/day) are unlikely to have a significant impact on erosion potential in the Mid Goulburn reach.

[6] Natural (pre-development) model outputs were not available for the Mid Goulburn system.

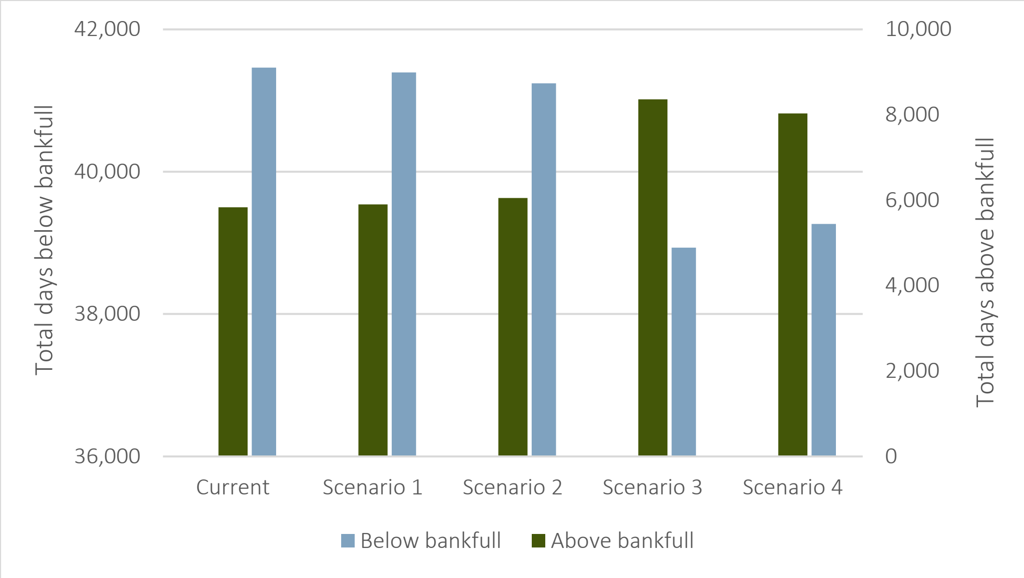

Figure 94 *The total number of days over the 120 years of modelled data that flow spills overbank and the total number of days flow remains in-channel in the Mid Goulburn. Note the change in scale of the left and right axis.*

Murray River - Hume to Yarrawonga

Regulation of the Murray River has dramatically reduced the total number of days that flow spills overbank and at the same time, increased the total number of days flow remains in-channel (Figure 95).

None of the constraints relaxation scenarios return total number of days of overbank spills to natural (pre-development) levels. Compared to current conditions, the Y25D25 scenario makes little difference to the total number of days flow is overbank or in-channel. However, the remaining three scenarios (Y30D30, Y40D40 and Y45D40) all have a greater impact on total days flow is overbank and in-channel than the Y25D25 scenario.

The grouping of the three scenarios (Y30D30, Y40D40 and Y45D40) have a similar totals of overbank spill and in-channel flow to one-another. These flow results indicate that the greatest decrease in erosion potential would be delivered using the three largest constraints relaxation scenarios, but that none of those three scenarios is markedly better at reducing erosion potential than the others.

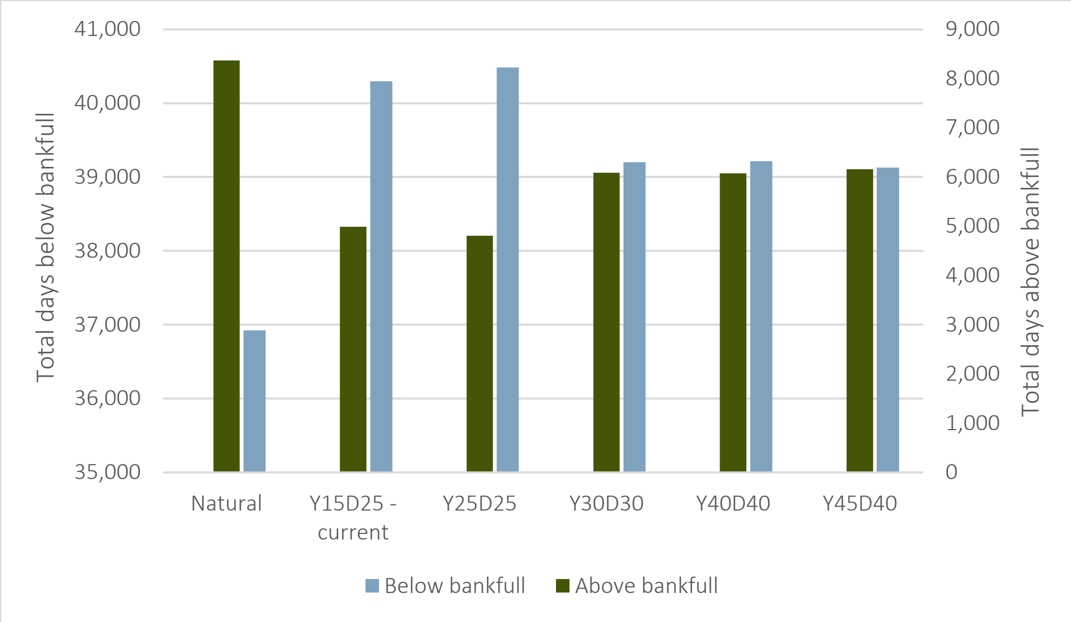

Figure 95 *The total number of days over the 120 years of modelled data that flow spills overbank and the total number of days flow remains in-channel in the Murray River – Hume to Yarrawonga. Note the change in scale of the left and right axis.*

Murray River - Yarrawonga to Wakool Junction

The impact of regulation on the number of days flows spills overbank and remains in-channel is also felt in the Yarrawonga to Wakool Junction reach (Figure 96). As in the Hume to Yarrawonga reach, the greatest change in overbank and in-channel flows is between natural (pre-development) conditions and current conditions. The progressive relaxation of constraints (moving from left to right, Y25D25 -Y45D40 in Figure 96), is accompanied by only a subtle change in both the total days of overbank spill and in-channel flows. This subtle difference corresponds to a 0.03% decrease in the number of days flow are in-channel and a 3 % increase in the total number of days flows spill overbank. Overall, the flow statistics presented in Figure 96 suggest that constraints relaxation will lead to a minor decrease in erosion potential, if at all.

Importantly the investigation has not revealed potential for increased bank erosion arising from the relaxation of constraints.

However, the scope of the erosion risk assessments has been limited, further investigation should be undertaken to confirm the results of the effective work approach applied to the Goulburn River and the inferred results for the other reaches. Further the risks associated with anabranch development, particularly in the Hume to Yarrawonga Reach warrant attention.

Stock access to waterways impact on the quality of riparian vegetation and erosion potential. Boat wake also plays a significant role in streambank vegetation. Significant reductions in streambank erosion, accompanying any relaxation of constraints is unlikely to be realised in reaches with either of these factors at work. Complementary efforts will be required to address these drivers, to realise erosion reduction benefits accruing from the relaxation of constraints.

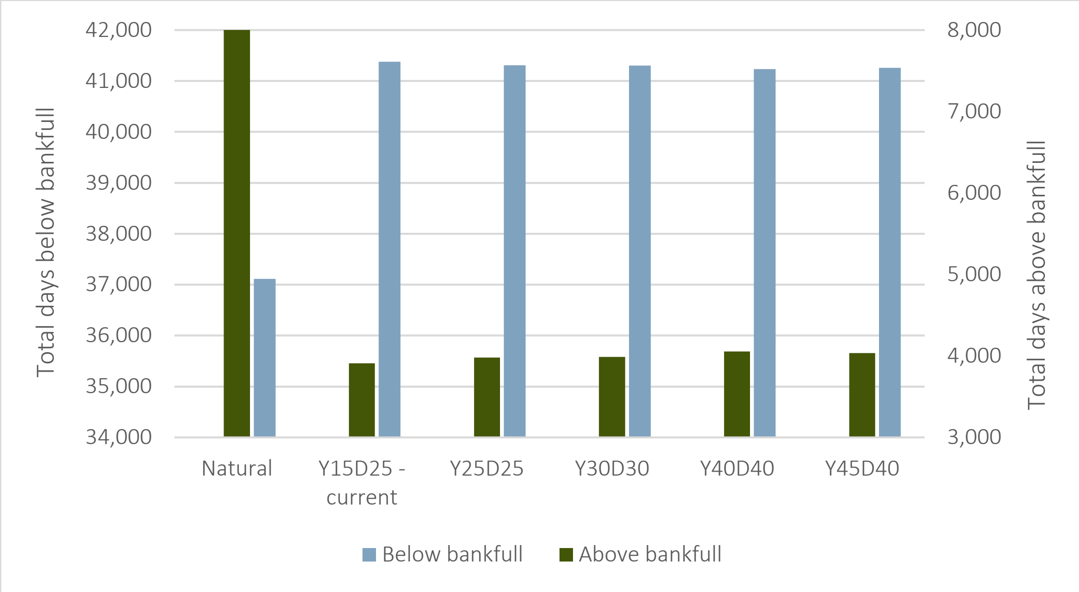

Figure 96 *The total number of days over the 120 years of modelled data that flow spills overbank and the total number of days flow remains in-channel in the Murray River - Yarrawonga to Wakool. Note the change in scale of the left and right axis.*

7 Climate change

The Murray-Darling Basin is experiencing the impacts of climate change and is projected to continue to change into the future. It is predicted that the Basin's climate is becoming drier and more variable with increased likelihood of extreme droughts and floods (BOM 2020, MDBA 2021, Figure 97 and Figure 98).

Changes to the climate pose an ongoing threat to the Basin's water availability, increased pressure on water resources, delivery of environmental water and associated ecological outcomes. This section draws upon the recent literature on the impacts of climate change on the Murray River and Goulburn River focus area and discuss on the role of relaxing constraints under the context of climate change.

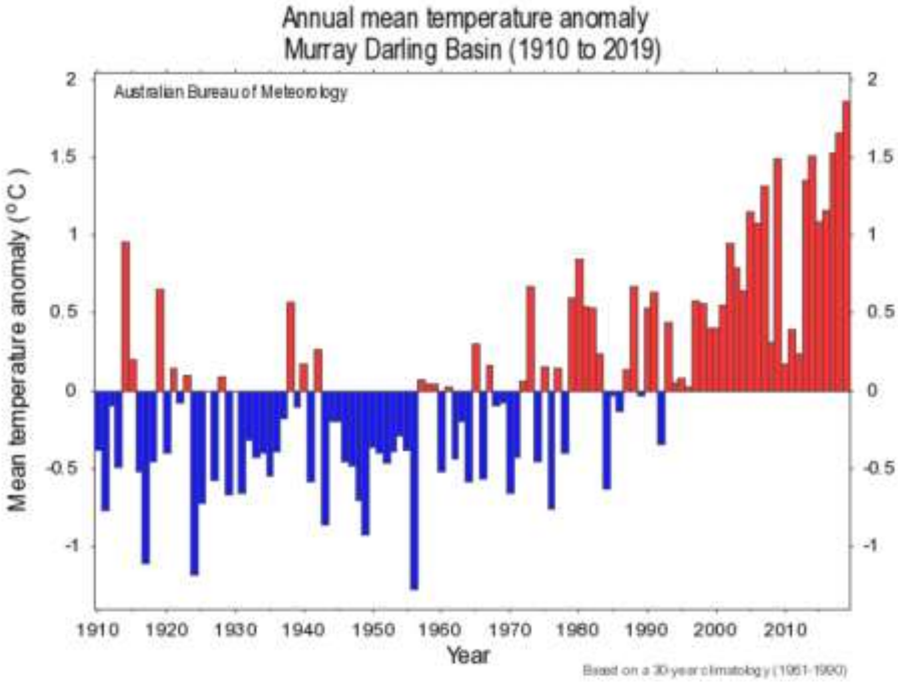

Figure 97 *Annual mean temperature anomaly across the Basin based on a 30-year climatology (1961 – 1990) (BOM. 2020).*

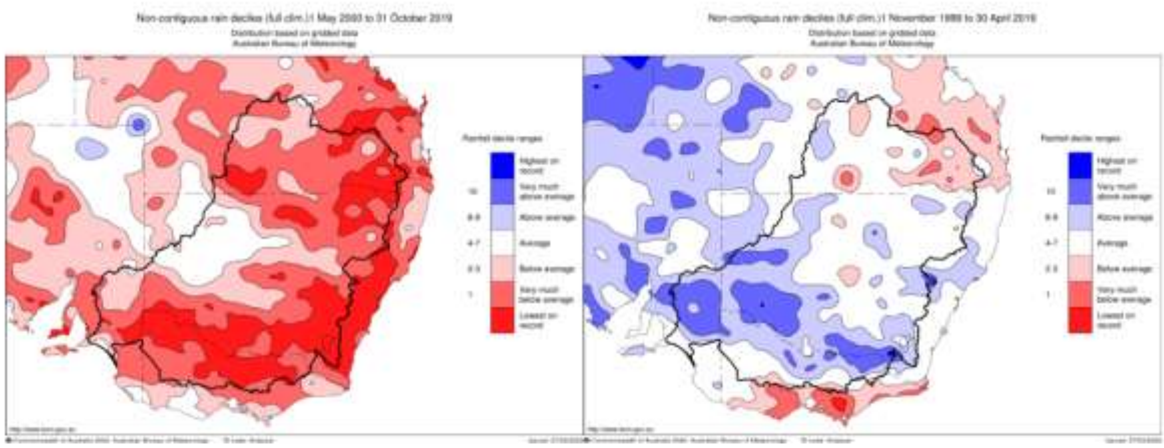

Figure 98 *Rainfall deciles for the last 20 years (2000 – 2019) where rainfall is above average, average or below average compared to the entire rainfall record from 1900. Left panel shows the rainfall deciles from May to October and right panel shows November to April rainfall deciles* (BOM, 2020)

Murray River

The Murray River is experiencing high temperatures and decreasing rainfall in winter which are expected to continue into the future (BOM 2020; Figure 97 and Figure 98). The hydroclimatic storylines study completed by CSIRO found that the range of climatic scenarios lead to a variable response in the flow regime (Zhang et al. 2020).

At Yarrawonga, a warmer and wetter climate depicted in Scenario A (Table 22) will lead to a positive outcome for the river regime where mean annual flows, overbank and freshes are likely to increase by 26% – 32% and baseflow increase by 15%. A warmer and drier climate depicted in Scenario B and C however is likely to decrease mean annual flows by 35 – 58% and similar decreases are predicted for overbank flows and freshes. Likewise, low flow metrics such as baseflows will also be negatively impacted by up to 46% while number of cease-to-flow days will increase by 21 days. Such observations are even more pronounced under multi-year drought scenarios with reduction of high flows by up to 50%.

Table 22 *Summary of changes in hydrological metrics in the Murray River (at Yarrawonga) under different climate scenarios (1895 – 2018) (BOM 2020).*

Scenario	Mean Annual Rainfall (%∆)	Potential Evaporation (%∆)	Mean Annual Flow (%∆)	Soil Moisture Index (%∆)	Over-bank Flows (%∆)	Freshes (%∆)	Replenish-ment (%∆)	Base flows (%∆)	Cease-to-flow (# days)	Max dry spell (days)
A	10	3	27	6	26	32	20	15	-2	-32
B	-10	3	-35	-13	-33	-41	-28	-25	6	79
C	-20	3	-58	-23	-57	-65	-48	-46	21	160

%∆ = percentage change in metric relative to delivery under a historic climate.

Scenario A: warmer and wetter climate – daily temperature increased by 2°C and daily rainfall increased by 10% compared to historic climate. Scenario B: warmer and drier climate – daily temperature increased by 2°C and daily rainfall decreased by 10% compared to historic climate. Scenario C: warmer and much drier climate – daily temperature increased by 2°C and daily rainfall decreased by 20% compared to historic climate. Extracted from Zhang et al. (2020)

Ecological vulnerability

Changes in the hydrological metrics as indicated from the CSIRO hydroclimatic storylines (Zhang et al. 2020) would have a profound impact on the ecological values and ecosystems in the Murray. As part of the 2020 evaluation, the MDBA assessment of ecological vulnerabilities under climate change found that climate change can impact on the ecosystem in two processes: gradual shift in climates over time and high impact climatic events such as bushfires, flooding and drought. These two processes can happen in conjunction with each other, therefore compounding the impacts further.

Gradual shifts in climate such as changes in temperature and rainfall could test species viability that are pushed to function beyond their optimal environmental conditions. High impact climate induced events such as bushfires, flooding and drought could test species and ecosystem resilience and recovery. The combination of both processes compromises healthy functioning of ecosystem and reduces ecosystem resilience in major climatic events. Climate change will add to the stressors that the ecosystem is already experiencing from river regulation and over-extraction in the Basin, therefore there is a greater risk of reaching tipping points for ecosystems within the Basin (MDBA 2020b).

The prediction of less inflows and longer dry spells are likely to decrease the number and magnitude of flushing events that are critical in flushing the salts and organic matter from the river system. Extreme events (e.g., increased temperature) are also likely to increase instances of water bodies being thermally stratified and frequency of low dissolved oxygen events.

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.

Goulburn River

Several climate modelling outputs suggest the future climate of the Goulburn is expected to be hotter and drier than it is today (DELWP 2021; GBCMA 2012). The hydroclimatic storylines study completed by CSIRO found that the range of climatic scenarios lead to a variable response to the flow regime (Zhang et al. 2020). At Shepparton, a warmer and wetter climate depicted in Scenario A (Table 23) will lead to a positive outcome for the river flow regime where mean annual flows, overbank and freshes are likely to increase by 17-19% and baseflows increase by 8%. In contrast, a warmer and drier climate depicted in Scenario B and C is likely to decrease mean annual flows by 29 – 50%, and similar decreases are predicted to occur with overbank flows and freshes. Low flow metrics such as baseflows will also be impacted by up to 25% while the number of cease-to-flow days will increase by 13 days. Such observations are even more pronounced under multi-year drought scenarios with high flows being the most impacted.

Table 23 *Summary of changes in hydrological metrics in the Goulburn River (at Shepparton) under different climate scenarios (1895 – 2018).*

Scenario	Mean Annual Rainfall (%Δ)	Potential Evaporation (%Δ)	Mean Annual Flow (%Δ)	Soil Moisture Index (%Δ)	Over-bank Flows (%Δ)	Freshes (%Δ)	Replenish-ment (%Δ)	Base flows (%Δ)	Cease-to-flow (# days)	Max dry spell (days)
A	10	4	19	5	18	17	14	8	-1	-23
B	-10	4	-29	-14	-27	-31	-24	-14	5	2
C	-20	4	-50	-23	-48	-52	-40	-25	13	37

%Δ = percentage change in metric relative to delivery under a historic climate.

Scenario A: warmer and wetter climate – daily temperature increased by 2°C and daily rainfall increased by 10% compared to historic climate. Scenario B: warmer and drier climate – daily temperature increased by 2°C and daily rainfall decreased by 10% compared to historic climate. Scenario C: warmer and much drier climate – daily temperature increased by 2°C and daily rainfall decreased by 20% compared to historic climate. Extracted from Zhang et al. (2020)

The stochastic modelling completed by University of Melbourne using the SGEFM water resource model provided another level of granularity to assess climate change vulnerability on the Goulburn River system. This study identified the benefits of relaxing constraints across a range of future climate change scenarios. Figure 99 illustrates the range of CMIP6 climate model projections for annual rainfall and temperature for the Goulburn River for the emission scenarios of SSP5 – 8.5. It suggests that there is a significant uncertainty in future climate projections in predicting how it may influence on the river regime.

The stochastic climate change modelling was simulated to determine how allocation reliability, environmental water shortfall and constrained delivery volumes vary with climate change. It found that the Goulburn system is highly sensitive to changes in climate. An increasingly drying climate is predicted to increase environmental water shortfall volumes when tributaries inflow and entitlements decrease. Table 24 summarises the benefits of relaxing constraints on environmental water metrics.

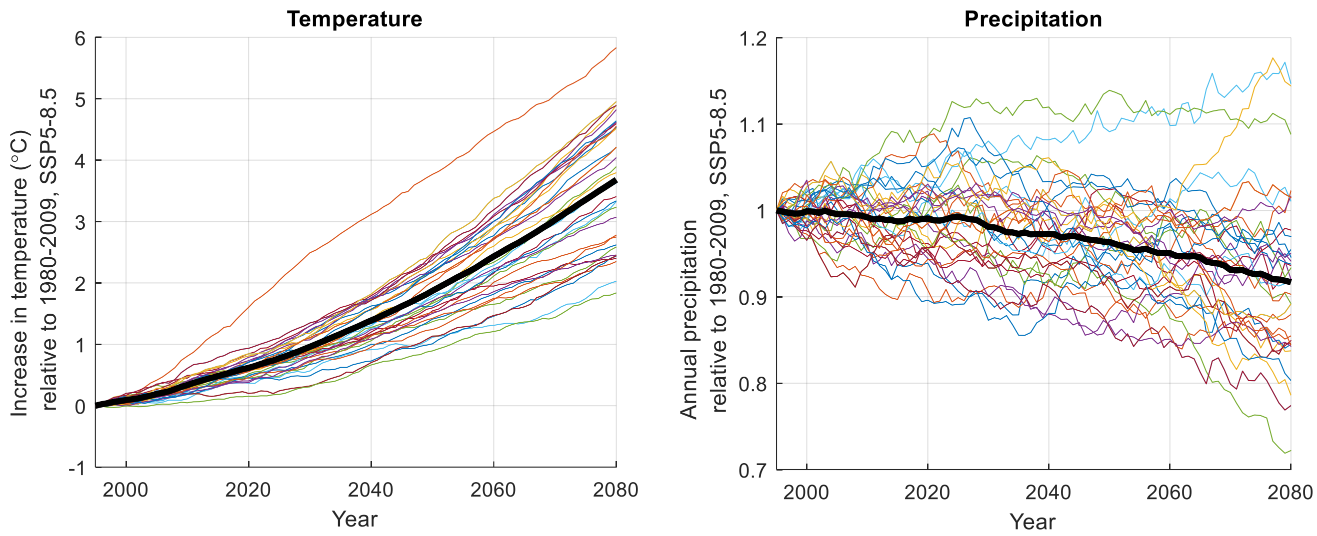

Figure 99 *Climate model projections for annual precipitation and temperature for the Goulburn River basin for SSP5-8.5. Each coloured line is a CMIP6 model projection. The bold black line is the multi-model-mean projection.*

Table 24 *Commentary on the benefits of relaxing constraints on allocation reliability, environmental water shortfall and constrained delivery volumes (John et al. 2022). Further details are provided in Attachment 9.*

Constraint scenarios	Commentary on environmental water metrics
Mid Goulburn: 10,000 ML/day Lower Goulburn 17,000 ML/day	Consistent benefits across future climates. Provides greater benefits under a drier future climate though total environmental water shortfall remain high
Mid Goulburn: 10,000 ML/day Lower Goulburn: 21,000 ML/day	Similar but slightly better benefits under future climates especially improving constrained delivery volumes. Diminishing returns in reducing environmental water shortfalls
Mid Goulburn: 12,000 ML/day Lower Goulburn: 21,000 ML/day	Consistent benefits under future climates but notable benefits to reduce environmental water shortfalls. Under current climate, residual constrained delivery is small.
Mid Goulburn: 14,000 ML/day Lower Goulburn: 25,000 ML/day	Largest benefits in hydrologic metrics across future climates, but under very dry future climates (e.g., <20% in rainfall), relaxing constraints lead to less benefits. Different river operating environment is required in such dry conditions instead.

The impacts of climate change are significant for the ecosystems in the Goulburn system. The stochastic modelling completed by University of Melbourne using the SGEFM water resource model identified large changes to the stress index arising from climate change in most ecological models (John et al. 2022). Whilst the ecological responses are poor under the drying climates, relaxing constraints would help to ease the effect of climate change for several ecological values and processes such as platypus, littoral vegetation, and instream productivity.

John et al. (2022) further investigated potential long-term effects to ecological outcomes for small and large bodied fish, in-channel vegetation and floodplain vegetation that could occur as a result of different hydroclimatic changes, including long-term average rainfall and temperature, seasonality of rainfall and the rainfall-runoff relationship. They found that reduced average rainfall and the amount rainfall that reaches the river were the two most important factors in predicting poorer ecological outcomes for native fish and vegetation. Notably, these impacts were predicted to be considerably dampened in the Lower Goulburn reach regulated with environmental water compared to the Seven Creeks reach which is unregulated and reliant on natural rainfall and run-off events.

8 System scale assessment

A workshop was held involving the project team and expert panel on August 25, 2022 to explore environmental benefits/risks that may occur beyond the study reaches. No modelling was performed beyond the study area and assessments were instead based on trends that had been identified in the 'within study area assessments' from workshop 1. Beyond-study-area assessments were therefore qualitative in nature. Environmental benefits/impacts across seven themes were discussed. The Mural board outputs from the workshop for each theme are included in Attachment 10, and a summary of predicted impacts included in Table 25 and Attachment 3.

Overall, largely positive outcomes were predicted for the system with relaxed flow limits across all workshop themes (Table 25). Relaxing constraints is predicted to increase resilience of the system particularly when conditions are dry. Population increases in birds and fish within the study area will contribute to wider populations in the system, provided that suitable habitat is available.

It was noted however, that erosion from increased in-channel flows may negatively impact water quality. Negative system impacts on platypus populations could occur if the largest flows are delivered between September to January due to inundation of nesting burrows. Constraints relaxation without the delivery of extra water to floodplains may reduce the extent of natural flow events in floodplain and wetland vegetation, which would decrease the inundation of (and therefore negatively impact) vegetation at higher elevations.

Table 25 *System-wide and downstream benefits/impacts of relaxing constraints*

Theme	System wide / downstream benefits/ impact of relaxing constraints		
	Positive	Negative	Negligible
Water quality	Increase lateral and longitudinal connectivity with relaxed constraints will improve ecosystem functions with moderate benefits downstream		Relaxed constraints unlikely to cause blackwater events
Native birds	Impacts downstream depend on habitat for roosting and foraging. Responses depend on waterbird guild Increases in birds achieved in Barmah-Millewa Forest will contribute to wider populations, including in Murrumbidgee and Lachlan catchments. Use of system will be influenced by system habitat availability		
Native fish	NSW RRCP modelling for Golden Perch looked at benefits for mid-Murray, highest populations were predicted under highest flow scenario.		
Riparian vegetation	Inputs of nutrients and plant propagules flowing downstream i.e., landscape scale connectivity Riparian woody vegetation was greatly benefited by the relaxation of constraints in the Murray, particularly in years that were relatively dry Assuming easing of constraints results in minor flooding/overbank flows during the natural high flows season, then riparian vegetation is likely to receive flows and benefit from inundation.	Downstream riparian habitats appear to have proportionally less benefit when relaxing constraints than upstream sites	Similar responses to watering, but riparian condition upstream has no mechanism to influence downstream condition.
Wetland and floodplain vegetation	Influence on sediment and nutrient cycling during floods Generation of seeds to maintain downstream communities. Environmental responses that are seen along the river channel are significantly benefited by relaxed constraint limits that are within reach of inundation events.	Without the addition of water under relaxed constraints relaxation of constraints tends to reduce the extent of "natural flow" events, impacting veg at higher elevations.	Large areas of the floodplain remain unaffected by constraint scenarios when compared to the base case. This is predominantly on the floodplain > 40,000 ML Commence To Fill inundation Large proportion of the floodplain at higher elevations not inundated under constraints scenarios, so floodplain veg communities there are unlikely to benefit e.g., shrublands

Theme	System wide / downstream benefits/ impact of relaxing constraints		
	Positive	Negative	Negligible
Geomorphology	Less bank erosion will lead to less fine sediment production and improved water quality downstream. Geomorphic implications downstream will depend on the relaxed constraints producing overbank events downstream...if yes they create overbank events, then yes expect reduced erosion ...however if relaxed constraints upstream don't create overbank downstream them expect to see increased erosion downstream.	Increased erosion associated with relaxed constraints that do not create overbank inundation will have a negative impact on downstream water quality.	
Platypus	Positive benefits can be achieved by avoiding cease to flow events as well as supporting refugia during dry periods	Negative impacts may occur if increased discharge inundated platypus nests during the breeding season ~Sep-Jan	

9 Synthesis of findings

Goulburn River

Summary

The modelling and information gathered for the Goulburn River shows clear benefits to the environment under the relaxation of constraints. The ‘do nothing’ scenario shows an ongoing decline and to the ecological values of the Goulburn River system, with floodplain vegetation such as black box woodland and river red gum communities placed at risk. The limited floodplain engagement poses significant risk to instream communities, and the focused delivery of flow to bank level is expected continue to contribute to erosion issues.

The decline of the system under the ‘do nothing more’ scenario is expected to be mitigated with the relaxation of constraints proportionate to the level of relaxation, with the larger relaxation scenarios of Scenario 3 (M12L21) and Scenario 4 (M14L25) showing the greatest benefit to the river system. The benefits associated with these scenarios is directly related to the inundation of floodplain ecosystems.

The modelling revealed the ‘do nothing more’ scenario and lower relaxation scenarios, to have increased potential for unregulated spills. These unregulated spills if occurring later in the season (e.g., late spring and summer) have potential to cause adverse water quality, platypus and turtle outcomes.

Some potential risks have also been identified with the relaxation of constraints. These include carp breeding events and platypus and turtle nests. Carp breeding is considered as part of the environmental flow risk management while the risks to platypus and turtles remain uncertain. Other disbenefits include the potential decline in vegetation communities not serviced by (beyond the reach of) the relaxed constraint inundation.

However, based on the information available the benefits of relaxed constraints in the Goulburn River have been identified to far outweigh the disbenefits. The relaxation of constraints in the Goulburn River is feasible from the environmental perspective.

Assessment

A summary of the Goulburn River results is provided in Table 26.

Major vegetation quality benefits can be gained from constraint relaxation in the Goulburn catchment associated with Scenario 3 (M12L21) and 4 (M14L25). These scenarios can improve the health of the floodplain vegetation inundated. There were comparatively minor benefits seen in the Mid Goulburn, with no modelled declines in vegetation health. There is a tradeoff to be made with respect to conserving floodplain vegetation. The trade-off is that relaxing constraints will support a smaller area in better condition compared to a slightly larger area in poorer condition. Given the importance of vegetation as habitat and food for animals, keeping relaxing constraints is more likely to protect and restore the ecosystem’s biodiversity. The extent and value of the benefiting vegetation is more substantial than that which may be lost at the fringe.

The vegetation quantity assessment showed that increases in flow rates above the base case offer potential benefits to flood dependent vegetation. Disbenefits, defined as inundation of areas of mapped native terrestrial vegetation that is considered not flood-adapted, are expected to be negligible.

The investigations revealed no adverse water quality impacts arising from relaxed constraints and improvements in instream production.

Quantitative modelling undertaken to date predicts small but significant fish population level responses with the greatest benefits being among floodplain dependent fish species. Relative condition of fish populations is predicted to be lowest under ‘do nothing’ scenario (no constraint relaxation) and higher in other flow scenarios. These results align with our understanding of the ecology of the species modelled but should be considered as conservative for the native fish community given high uncertainty around wetland dependent species water requirements.

Table 26 *Summary of outcomes - Goulburn River*

Theme	Summary of outcomes of relaxing constraints, compared to base case
Hydrologic connectivity	Improved longitudinal connectivity with up to 9% increase in August flows at Shepparton. Up to 4% increase in flows in July and October. Changes in lateral connectivity assessed via themes below
Vegetation quality	Relaxation of constraint to low levels (less than 22,000ML/day) likely to provide some support to native vegetation but likely to remain vulnerable. High relaxation will allow targeted vegetation to be held in good condition, though some sacrifice of fringe areas as a result of reduced spills. Significant improvements in black box and river red gum will require relaxation of constraints in both the mid and lower Goulburn
Vegetation quantity	Increased inundation of semi-aquatic, terrestrial flood-adapted/semi-aquatic, and terrestrial flood-adapted ecological vegetation classes in the Mid Goulburn and Lower Goulburn River. Negligible inundation of terrestrial (not flood-adapted) vegetation.
Production	Negative impacts on production (compared to base case) if constraints are relaxed below 22,000 ML/day. Increased production (compared to base case) above 22,000 ML/day, as floodplains are engaged.
Water quality	Relaxation of constraints as proposed and assessed is unlikely to adversely impact on any water quality parameters in this reach
Macroinvertebrates	Benefits to macroinvertebrate biomass and diversity are predicted if constraints in Mid Goulburn are relaxed above 11,000 ML/day and Lower Goulburn constraints are relaxed above 21,000 ML/day
Native fish	Benefits for equilibrium, periodic and opportunistic fish increase with progressive relaxation of constraints up to ~20,000 ML/day in the Lower Goulburn River and ~12,000 ML/day in the Mid Goulburn River. Sustained benefits above these flows. Benefits to large fish such as Murray Cod are limited, however floodplain specialists are expected to significantly benefit from relaxed constraints that enable proposed frequency of floodplain inundation.
Waterbirds	Mixed outcomes are predicted for waterbirds. Increased median probability of waterbird breeding (up to +5%), +12% overall probability of waterbird breeding with relaxation of constraints. Decreased chance of large breeding events by up to 11%, but an increased chance of small breeding events by 11%. Overall reduction of long-term breeding likelihood by 3% with relaxation of constraints. Declines in long-term average waterbird abundances with relaxation of constraints, particularly for Large Waders (13% decline in 90th percentile, increased 25th percentile by 14%)
Platypus	Disbenefits have been identified if Lower Goulburn constraints are relaxed above 22,000 ML/day during nesting periods. Platypus have evolved and adapted to winter and spring overbank inundation. Potential disbenefits are unlikely if events occur outside nesting season. The timing of environmental flow delivery is important. Nesting is expected to improve with reduced bank erosion.
Turtles	Negative impacts on turtle populations are predicted if overbank events occur during critical nesting periods. The timing of environmental flow delivery is important.
Geomorphology	Decreased erosion is predicted as constraints are relaxed in the Lower Goulburn. Relaxation of constraints at above 12,000 ML/day (creating overbank flows) in the Mid Goulburn is also expected to decrease erosion potential

Complementary literature on bird responses found that large waders are noticeably declining in abundance post drought under current constraint conditions, suggesting that there is a lack of food resources, including fish, in locations where waterbirds frequent (i.e., floodplains). This further emphasises the role of floodplain inundation in increasing the recruitment of native fish and return of organic matter that allows native fish populations to increase, thereby further highlighting the benefits of relaxation of constraints in improving native fish population in the Goulburn system.

Ecological model outputs suggest there is a risk for the turtle populations under relaxed constraints in the lower reaches of the Goulburn River and is more significant if flows are above 14,000 ML/day. The identified risk is associated with high flows in spring/summer periods where inundation to turtle nests is likely to occur and thereby impact turtle breeding. This risk remains uncertain and needs to be viewed within the broader context that river regulation has impacted turtles through loss of habitat and the greatest threat to turtle breeding is fox nest predation. Given turtles are long-lived, ensuring they have habitat available every year is more important than ensuring they successfully breed every year.

The relaxation of constraints in the Goulburn River has the capacity to provide benefits across a range of environmental outcomes while reducing the risks posed by the current trends of degradation. This would notably include a potential decrease in erosion, particularly in the Lower Goulburn River. The greater the peak magnitude of overbank flows the greater the reduction in erosion potential. Overall, Scenario 4 (M14L25), the largest overbank flows, has the potential to have the greatest reduction in erosion potential.

Murray River - Hume to Yarrawonga Reach

Summary

The Hume to Yarrawonga reach comprises the main river channel and its anabranches between Hume Dam and Yarrawonga Weir. Fluvial geomorphic processes have led to the development and movement of anabranches across the floodplain creating channels and billabongs. The reach is highly regulated with flow dominated by releases from Hume Reservoir. The ecology of the reach is dominated by the flow and water quality controlled by Hume Dam. The fish community has been rated as being in poor condition while the riparian vegetation has been rated as being in good condition despite widespread clearing and large numbers of willows.

Assessment

A summary of the Hume to Yarrawonga reach assessment is provided in Table 27

Last surveyed in the Sustainable River Audit 2 (2012), vegetation was found to be in a good condition where riparian vegetation is highlighted as close to the reference condition in all zones within the Central Murray Valley (that extends from Lake Hume to Lock 9). Likewise, the recent Basin Plan evaluation plan (2020) found that environmental watering has improved the diversity of plant and vegetation communities since 2012.

Both black box woodland and river red gum forests/woodlands within the Hume to Yarrawonga reach showed positive responses to relaxation of constraints with higher flow scenarios (e.g., Y45D40) leading to larger areas in good condition and reduced areas in critical (C) condition. Vegetation condition improvements are predicted to increase the resilience of vegetation communities in drier years, improve their capacity to act as refugia, and subsequently support the vegetation community’s ability to respond when climate conditions are favourable.

Water quality in the reach is dominated by the operation of Lake Hume which can be associated with decreased dissolved oxygen and temperatures and elevated blue-green algal counts. While some of these are influenced by climate, the risks in the reach were not found to be influenced by changes to environmental flow delivery. An assessment of the risk of anoxic blackwater due to floodwater returning to the main channel found that this was a very low risk in the reach.

Relaxing constraints is expected to contribute a minor increase to the overall production with benefits increasing with higher flow limit scenarios. Scenario 4 (Y45D40) was associated with a 2% median increase in production potential for native fish which was attributed to the relatively minor lateral connectivity in the reach. Over time, the annual production potential is dominated by production during large, unregulated flow events.

Table 27 *Summary of outcomes for the Murray River - Hume to Yarrawonga*

Theme	Summary of outcomes of relaxing constraints, compared to base case
Hydrologic connectivity	No adverse impacts to longitudinal connectivity. Lateral connectivity assessed through the themes below.
Vegetation quality	Both black box woodland and river red gum forests/woodlands were responsive to the relaxation of flow constraints. Broad benefits of constraint relaxation to higher flow scenarios were representative of greater areas of woody species in good condition and reduced areas in critical condition
Vegetation quantity	Over 2,289 ha of additional vegetation (81% increase) inundated through relaxation of constraints compared to base case, including 1562 ha terrestrial flood-adapted vegetation (154% increase), and 447 ha terrestrial flood-adapted semi-aquatic vegetation (77% increase). A negligible (1ha) of terrestrial not flood-adapted vegetation inundated at the highest constraint relaxation scenario.
Production	Up to 2% increase in mean annual production
Water quality	Relaxation of constraints as proposed and modelled is unlikely to adversely impact on any water quality parameters in this reach
Macroinvertebrates	Not assessed.
Native fish	Up to 39% increase in expected mean population of Golden Perch. No change to Murray Cod population size with relaxation of constraints. Floodplain specialists are expected to significantly benefit from relaxed constraints that enable the proposed frequency of floodplain inundation.
Waterbirds	Not assessed – significant waterbird sites in Murray River are located downstream of Yarrawonga.
Platypus	Not assessed
Turtles	Not assessed
Geomorphology	Decreased erosion potential expected when constraints are relaxed to 30,000 ML/day and higher.

The Sustainable River Audit 2 (2012) rated the condition of fish community in Central Murray Valley as 'very poor', with a substantial decline of native fish species relative to the reference condition. Small-bodied native fish species such as gudgeon, Australian smelt and unspecked hardyhead dominated the total native fish biomass. The more recent Basin Plan evaluation (2020c) found that the number of native fish species are largely maintained surveyed between 2014-2019, but there is an increase in Murray Cod adult fish population suggesting there is successful breeding and recruitment since 2012. This increase may be due to completion of fishways along the Murray River and extensive re-snagging, highlighting the importance of complementary management. In contrast, there was a decline in Golden Perch population since 2012 and given there was no juveniles detected during the fish surveys, its population is thought to be ageing (MDBA, 2020c)

Golden Perch populations in the Hume to Yarrawonga are predicted to progressively increase with relaxation of constraints. The largest improvement was observed for Scenario 4 (Y45D40), with a 39% increase in adult abundance compared to the base case. The forecast improvement in Golden Perch contrasts with its actual population in the reach which has declined over the last 30 years. In contrast, Murray Cod responses were more variable with the largest being an 11% increase under scenario 2 (Y30D30) and a 4% increase predicted for scenario 4 (Y45D40). This variability was attributed to the potential effects of other threats such as cold-water pollution and seasonal reversal of flows. The 'do nothing more' scenario is likely to exacerbate this decline if no intervention is carried out. Though no benefits are predicted for Murray Cod in this reach it is noted that the assessment did not find any disbenefits for Murray Cod populations, and there is potential for benefits through the support and promotion of the complex food web that Murray Cod sit within.

There was no assessment of wetlands, waterbirds, turtles or platypus in this reach. It is noted that this reach has a large number of wetlands that may provide habitat for waterbirds and turtles, however, many of the wetlands are isolated from the main channel and affected by surrounding land use. The risks identified for platypus and turtles in the Goulburn River may also apply to this reach, however, seasonal reversal of flows and extended periods of bankfull flows are likely more important risks than overbank flows in spring. Improvements in productivity, macroinvertebrates and vegetation condition could conceivably support waterbirds, platypus and turtles.

Regulation of the Murray River has reduced the duration of overbank flows, increasing the time flows are in-channel. Scenario 1 (Y25D25) was found to make little difference to the duration of overbank flows. The remaining three scenarios (Y30D30, Y40D40 and Y45D40) all provide similar increases in the days of overbank flow compared to current and the Y25D25 scenario. These flow results indicate that the greatest decrease in erosion potential would be delivered using the three larger scenarios, noting that none of them will come close to restoring natural durations.

Ultimately the assessments were consistent with the finding that the more flows can interact with the floodplain through the movement of environmental water out of the channel and over bank, the more the reach will benefit, although this needs to be viewed within the context of the fish community being in poor condition and limited extent of floodplain vegetation.

Murray River - Yarrawonga to Wakool

Summary

The Yarrawonga to Wakool reach extends from Yarrawonga Weir to the Wakool Junction with the Murray River. This covers a region that includes broad flat floodplain interconnected through a network of flood runners and creeks supporting multiple wetlands and forests of state, national and international significance. Within the reach the Ramsar wetlands of Barmah-Millewa forest and Gunbower forest are both dependent on floodplain inundation to sustain their condition and character.

Assessment

A summary of the Murray River Yarrawonga to Wakool reach assessment is provided in Table 28.

Productivity in the Yarrawonga to Wakool reach is predicted to increase by up to 15% under scenario 4 (Y45D40). Once again, the pattern of total annual production potential is dominated by production during large, unregulated flow events. The vast areas of vegetated floodplain and wetland within the reach provide the opportunity for the return of nutrients and carbon to the river system, providing the inputs for the primary production that underpins the foodweb within the reach and downstream.

The current vegetation condition for the Hume to Yarrawonga reach is similar to the Yarrawonga to Wakool reach given the assessment was completed at a larger scale (Hume to Lock 9). Vegetation is found to be in good condition while newer evidence from the Basin Plan evaluation (2020) found that plant and vegetation communities benefited from environmental watering since 2012.

The Yarrawonga to Wakool reach has between one and two orders of magnitude greater area of vegetation than the Hume to Yarrawonga Reach. Relaxing constraints were associated with larger areas of good condition woody vegetation in addition to smaller areas of critical condition vegetation. For black box woodland relaxing constraints was associated with an increase in the area that could be supported during droughts. For river red gum woodlands the differences between scenarios were greatest during periods of more frequent drought, suggesting that relaxing constraints will be critical to supporting the resilience of these woodlands.

Table 28 *Summary of outcomes for the Murray River - Yarrawonga to Wakool*

Theme	Summary of outcomes of relaxing constraints, compared to base case
Hydrologic connectivity	No adverse impacts to longitudinal connectivity. Lateral connectivity assessed through the themes below.
Vegetation quality	Similar results as seen in the Goulburn, however the rate of decline may not be as rapid due to tributary flows supporting vegetation communities
Vegetation quantity	An additional 18,000 ha (approx.) of vegetation will benefit, including 12,000 ha (approx.) of terrestrial flood-adapted/semi-aquatic vegetation and 11,000 ha (approx.) terrestrial flood-adapted vegetation. A potential disbenefit of a relatively negligible 19ha of additional not flood-adapted terrestrial vegetation may be inundated.
Production	Up to 15% increased mean annual production potential.
Water quality	Relaxation of constraints as proposed and assessed is unlikely to adversely impact on any water quality parameters in this reach
Macroinvertebrates	Not directly assessed. Macroinvertebrate production is expected increase in response to constraint relaxation.
Native fish	Up to 39% increase in expected mean population size of Golden Perch from Yarrawonga to Torrumbarry. Up to 28% increase Golden Perch population between Torrumbarry to Lock 10. No change to Murray Cod population size with relaxation of constraints. Floodplain specialists are expected to significantly benefit from relaxed constraints that enable the proposed frequency of floodplain inundation.
Waterbirds	4-5% increases in median waterbird species richness and 10-13% increase in waterbird density in Barmah-Millewa Forest. Up to 11% increase in probability of colonial waterbird breeding in Barmah-Millewa Forest with relaxation of constraints. 1-4% increase in the median number of species, and 8-48% increase in median waterbird abundance in Gunbower Koondrook-Perricoota Forest with relaxation of constraints.
Platypus	Not assessed
Turtles	Not assessed
Geomorphology	Decreases in erosion potential are expected as constraints are progressively relaxed beyond 25,000 ML/day.

As with the Hume to Yarrawonga reach, the areas of good condition were higher, and areas of critical condition were lower under WOD scenario. The WOD benchmark again illustrating that not all current woodlands will be protected.

Similar to Hume to Yarrawonga, the native fish condition rating is very poor under the Sustainable River Audit 2 (2012). There is recent breeding and recruitment observed for Murray Cod but condition for Golden Perch declines. However, Golden Perch are expected to benefit from the relaxing of constraints, slowing or potentially, reversing this decline. The response was much greater with the Y45D40 scenario being associated with a 39% increase in the Yarrawonga to Torrumbarry reach and 28% increase in the Torrumbarry to Lock 10 reach. Increasing flows is believed to facilitate Golden Perch movements which increases spawning and recruitment. Murray Cod population condition did not change with scenario in either the Yarrawonga to Torrumbarry or Torrumbarry to Lock 10 reaches. Murray Cod responses have been modelled as being consistent across all scenarios yet as has been noted, the interaction with the floodplains would spark a food web response that could be expected to benefit Murray Cod across the system.

Increases in floodplain inundation would increase productivity, creating food resources available to waterbirds. At Barmah-Millewa relaxing constraints was associated with small increases in median waterbird species richness (4-5%) and waterbird density (10-13%) for the highest relaxed constraint scenarios of 40,000 and 45,000 ML/day downstream of Yarrawonga Weir. There was a similar, but smaller increase in waterbird species at Gunbower, Koondrook and Perricoota, but a much larger increase in median abundance 8-48%.

The probability of colonial waterbird breeding in Barmah-Millewa Forest also increased for all relaxed constraint scenarios compared to current constraints from a 6% increase for the lowest scenario (25,000 ML/day) to a 11% increase for the highest scenario (45,000 ML/day downstream of Yarrawonga).

The improvements were attributed to increases in the area of inundated habitat. The number of days when small overbank events, which would inundate greater areas of the forests, increased for all the relaxed constraints scenarios compared to current constraints. The relaxation of constraints in the mid-Murray is likely to provide cumulative benefits to waterbird populations by inundating these important wetland areas more frequently. This would maintain and improve vegetation condition that is a key determinant of feeding and breeding waterbird habitat, and in turn, support improvements in waterbird populations, a key objective of the Basin Plan.

While there was no assessment of platypus, turtles or macroinvertebrates in this reach, the benefits and risks identified for platypus and turtles in the Goulburn River are likely to apply to this reach. Seasonal reversal of flows and extended periods of bank-full flows are likely more important risks than overbank flows in spring. For macroinvertebrates, the response to overbank flows on the floodplain is likely to be greater in this reach due to the extensive forests and macrophyte beds that will be inundated. The response within the channel may be affected by the sand slug that is reducing habitat heterogeneity and represents poor macroinvertebrate habitat.

As with the Hume to Yarrawonga reach, regulation of the Murray River has dramatically reduced the duration of overbank flows, increasing the time flows are in-channel. The progressive relaxation of constraints is associated with only a 3% increase in days of overbank flow. This means that the change in erosion potential would be insignificant and not measurable.

System scale assessment

Conceptual Model

The Basin Plan establishes Basin scale objectives and targets that provide context for the development of long-term watering plans. The long-term watering plans include identification of key ecosystem assets and functions that are critical to achieve healthy and resilient ecosystems with rivers and creeks regularly connected to their floodplains and, ultimately, the ocean. The Basin Plan's hierarchical structure was applied in the assessment of the environmental benefits and risks of relaxing constraints, reflecting both the contribution of environmental assets within an area but also dependencies that occur between areas. Achieving Basin Plan objectives therefore requires management of both key environmental assets within areas but also the connections among areas. This section provides an overview of the assessment, starting with the expected outcomes of restoring lateral connectivity on key environmental assets within an area and then the outcomes at the system scale that include restoration of connectivity between areas.

Area outcomes

The assessments in the three reaches used slightly different suites of indicators and different methods for common indicators. In this section we consider common indicators under the headings consistent methodology responses and contrasting methodology responses. We also discuss 'areas of uncertainty'.

Consistent methodology responses

In all three reaches, river regulation has reduced the total number of days of overbank flows and, at the same time, increased the total number of days flow remains in-channel. While some smaller constraints relaxation scenarios made little difference to the duration of overbank flows, there was a consistent trend of increasing days of overbank flow with increased constraints relaxation, noting that none of the scenarios restored durations to those prior to river regulation. The area of inundation also increased with greater levels of constraint relaxation leading to larger areas being inundated. The largest improvement was in the Lower Goulburn where the area inundated increased from 2,010 ha to 10,379 ha under M14L25. This large proportional increase was, in part, due to the relatively small area currently inundated in the Lower Goulburn. In the Murray River, the Hume to Yarrawonga reach only has a small area of floodplain inundated (2,482 ha) under current conditions compared to Yarrawonga to Wakool (9,040 ha).

Across all three reaches, relaxation of constraints was associated with improvements in the areas of woodland in good condition and declines in areas of trees that would be expected to be lost (die). Trees have been widely used as indicators in the development and implementation of the Basin Plan as they provide habitat and food for a wide variety of animals and plants over the course of their lives and for decades after their death. The assessment found that for the greatest levels of constraint relaxation assessed there would be 84,000 ha vegetation that would benefit from the delivery of environmental flows with relaxed constraints.

The relationship between waterbirds and environmental flows is more complex, but there were consistent responses across reaches. As with any environmental change, the assessment found improvements in some species while other species declined. Overall, there were no improvements in abundance which may be due to the limited effects constraints relaxation had on waterbird breeding in the assessment. The important finding across reaches was that relaxing constraints increased waterbird abundance during dry times. This is important finding with increased flows reducing the impacts of dry conditions on waterbird populations. Relaxation of constraints will contribute the establishment of waterbird populations that are more resilient to climate change and other threats.

Native fish also have a complex relationship with environmental flows with environmental water requirements varying among species. The assessment found consistent improvements in populations of opportunistic species of which Golden Perch were an indicator in the Murray River assessments. Further, contrasting responses on the native fish assessments are discussed below.

We found no adverse water quality outcomes arising from the implementation of constraint relaxation, consistent with the scenarios assessed. This beneficial outcome can occur despite the substantial quantities of carbon and nutrients that would return to the waterway through floodplain inundation. Under the constraint relaxation scenarios assessed and the associated hydrologic regimes, such inundation would support carbon transfers for the benefit of instream production, macro invertebrates and the broader beneficial food web rather than detrimental outcomes such as blackwater or blue-green algae.

Contrasting approach responses

The approaches to the fish assessment varied across the two rivers with the Goulburn River assessment including the University of Melbourne Bayesian modelling. The University of Melbourne modelling approach divided fish into three guilds Equilibrium, Periodic and Opportunistic based on their breeding strategies. The Murray assessment examined one equilibrium species (Murray Cod) and one periodic species (Golden Perch). The Goulburn River assessment found responses to constraints relaxation by equilibrium species while the Murray River assessment found no response. This is likely due to the way the models in the two assessments were developed rather than differences in responses to flows in the two rivers. There is ongoing uncertainty around the links between flow and Murray Cod recruitment. Recent work has identified five causal pathways by which flow may be expected to influence Murray Cod recruitment (Tonkin et al. 2020). Subsequent assessment found evidence to support the hypotheses, but that the relationships were variable through time and between rivers. This suggests a complex, multi-factor relationship between flow and recruitment which may not have been captured in the Murray River assessment models and which may have been oversimplified in the Goulburn River assessment.

Tonkin et al. (2020) Murray Cod hypotheses

1. Extreme variation in river discharge during spawning and the early larval period (October – December) will negatively influence recruitment strength, by disturbing spawning behaviour and egg survival/retention of larvae within a reach.

2. Increased bank-full flows or flooding during spring will enhance recruitment by increasing availability of spawning habitat such as anabranches, or by providing additional food resources to larvae.

3. High flows and flooding in the year prior to spawning will enhance recruitment by improving growth, condition and reproductive fitness of adult fish.

4. That lower flows (below the annual average discharge) during summer and early autumn will enhance recruitment by increasing water temperature and concentrating food resources for juvenile fish.

5. Increased winter flows will increase habitat availability and reduce predation on juvenile fish

Productivity assessments also revealed some minor variation. The Murray River assessment found that progressive relaxation of constraints was associated with increasing productivity. In contrast, the Goulburn River assessment found a threshold of 20,000 ML/day (in the Lower Goulburn) above which productivity increased; although this response was modified by further relaxation in the Mid Goulburn but not the Lower Goulburn. Once again, this is likely a reflection of the different approaches taken rather than differences in responses to flows in the two rivers. The Goulburn River assessment used bank full as a threshold whereas the Murray River assessment used area inundated as an input to the model which would include a gradual increase in area inundated.

Areas of uncertainty

Due to their ability to utilise expert elicitation, the Goulburn River models were able to include Platypus, macroinvertebrates and turtles as indicators. All three indicators have complex relationships with flow regimes due to the influence of flow on habitat, food and connectivity. Turtles, like macroinvertebrates, represent multiple species that are known to have contrasting flow requirements. The assessment did identify risks associated with changing the flow regime, but the likelihood and consequences of these risks remain uncertain in both the Goulburn and Murray Rivers.

Platypus are believed to be vulnerable to high flows during the breeding season as there is a risk of inundation of nesting burrows and drowning of juvenile platypus. The first area of uncertainty is the distribution of platypus within the Goulburn valley given recent declines in populations. The second area is the timing of breeding which may start as early as August, but there are observations from Tasmania and Victorian high country of breeding starting in October (Bino et al. 2019). High flows are not just a risk at the start of the breeding season and may be detrimental to platypus through summer. The risk of high flows over the breeding season appears inconsistent with observations that flow regulation has impacted platypus and that declines have been greatest over the last 30 years. It is possible that platypus take cues from winter flows when locating and constructing their burrows in which case, platypus environmental water requirements may need to be defined in terms of a regime, rather than individual flow events. There are also a number of other threats that have been identified for platypus, some of which are directly or indirectly related to flow management including threats to dispersal and riparian habitats (Bino et al. 2019). In planning an appropriate flow regime for the Goulburn and Murray Rivers, it will be important to place the risk of high flows during breeding season within the broader context of sustaining platypus populations, in particular identifying key source populations and protecting them.

There are similar levels of uncertainty around the three species of turtle known to populate the southern connected basin. The three species all have different habitat preferences and nesting requirements. The available evidence suggests that river regulation has been associated with population declines which appears inconsistent with findings that restoring elements of the natural flow regime would lead to further degradation. Work in the Murrumbidgee River has found that Broad-shelled turtles (*Chelodina expansa*) and Macquarie River turtles (*Emydura macquarii macquarii*) distributions centred on frequently inundated wetlands close to the river, suggesting that overbank flows are critical for their survival (Ocock et al. 2018). Turtles also face multiple threats among which is nest predation by introduced predators.

Macroinvertebrates were previously considered the default indicator for rivers and streams because they provided an integrated and predictable response to threats such as eutrophication, contaminants and habitat changes such as changes in sediment or loss of snags or macrophytes. They were used in the last iteration of the Index of Stream Condition in Victoria which found that most sites in the Mid and Lower Goulburn were in moderate condition which appeared to be related to patterns of land use. Macroinvertebrates are now used a lot less commonly as an indicator due in part to their variable responses to changes in flow. More recently there is a preference to use indicators that respond more directly to changes in flow and are easier to communicate. The Goulburn River assessment was based on expertise gained from the implementation of Flow-MER that has monitored responses of macroinvertebrates to environmental flows within the main channel. The 2020-21 Flow-MER report found seasonal changes in macroinvertebrate abundance as would be expected but could not identify changes in macroinvertebrate responses to an environmental flow in spring or whether the increase in summer was influenced by the environmental flow (Treadwell et al. 2020). This type of result is common and so, given the uncertainty and the variable responses it is not clear on the value macroinvertebrates contribute to the assessment. If there is a desire to retain macroinvertebrates as an indicator, then work needs to be undertaken to identify the ways in which environmental flows are expected to influence communities and adapt the monitoring program to generate data to inform a description of the relationship. This could then form a basis for improved ecological response modelling.

System outcomes

Aggregate outcomes

One of the ways of considering system scale outcomes is to merely consider the sum of the reach scale outcomes. As noted in the previous section, relaxation to the Y40D40 in the Murray and M14L25 in the Goulburn would be associated with the inundation of an additional 55,000 ha of floodplain vegetation in Victoria alone.. It is also possible to consider increases in the number of opportunistic fish across the entire system, which according to the productivity and population modelling would range between 15 and 30% increases respectively. For the whole Murray River under scenario 4 (Y45D40) this would mean around an extra 4.4 million adult fish, with a smaller result in the Goulburn River. Relaxing constraints would also increase the area and quality of foraging habitat for waterbirds, reducing mortality during dry periods and thereby increases waterbird resilience to drought.

There are a range of outcomes that are less certain, including the response of turtles, macroinvertebrates and platypus. While it is not uncommon for changes in flow to be associated with species that benefit while others decline. This may well be the case within the macroinvertebrate community. For turtles and platypus, however, relaxing constraints is associated with positive benefits in terms of habitat, connectivity and food. However, both turtles and platypus have some potential risk arising from the timing of overbank inundation with their breeding. However, our understanding of breeding behaviour is uncertain and given their long evolutionary history of living in systems that flood, the model outputs should be treated as having identified a risk rather than a basis to halt a constraints relaxation program.

Overall, the assessment shows that the area of active floodplain and wetland habitat in each reach will increase with associated increases in the condition of key species including:

- trees critical for habitat and food
- predatory fish that are dependent on a functioning food web to complete their life cycle
- waterbirds dependent on wetlands and floodplains for food, roosting and breeding.

Ecosystem functions

Based on forecast improvements in environmental condition within each reach, we can infer ecosystem function outcomes for the system. There are a number of perspectives where the outcomes of relaxing constraints surpass the aggregate effects of within reach assessments.

Sediment dynamics are a critical determinant of channel and floodplain morphology and habitat availability. Changes in channel morphology and the composition of the riverbed of flow and sediment dynamics may change habitat availability and patterns of productivity within the river. Regulated flows exert energy on riverbanks increasing sediment inputs to rivers while reducing opportunities to export it onto floodplains where it contributes to the development of fertile soils. Overbank flows with the range of constraint relaxation scenarios assessed are likely to result in net movement of sediments onto floodplains.

Floodplain inundation plays a major role in nutrient and organic matter cycling that underpins cycles of boom and bust in Australian rivers. Floodwaters deposit sediment onto the floodplain, but dissolved organic matter and nutrients can be returned to the channel as a significant subsidy to the channel food web. Changes in the condition of the floodplain ecosystems will influence the amount and type of organic material and nutrients that enter the river, while the river condition will influence branching of the food web that processes those nutrients and organic matter. This assessment has found that relaxing constraints will lead to significant improvements in floodplain vegetation which will contribute to greater subsidies entering the river. During winter and spring this will be beneficial but is associated with risks when temperatures are warm. The way the subsidy is processed will depend on the health of the river channel, however, if the flow regime and carbon cycles are restored, then this provides a foundation for further restoration to optimize its transformation into fish.

The assessment found that relaxing constraints will be associated with improvements in waterbird abundance during dry periods. Waterbirds are known to respond to habitat availability at Basin or continental scales. Given the climate change forecasts, foraging habitat is going to become an increasingly important resource and it will be important that each water resource area contribute to sustaining waterbird populations across the Basin. Relaxing constraints will enable environmental water managers along the Murray to maintain foraging habitat under a greater range of weather conditions. The Goulburn and Murray are important for waterbirds due to their proximity to the Barmah-Millewa Forest, a key breeding site. It is also possible that wetlands along the Murray and Goulburn Rivers could be managed to enhance recruitment of chicks hatched in Barmah-Millewa as mortality rates among fledging chicks have been found to be high given their lack of experience in obtaining their own food. We are on a steep learning curve in terms of understanding waterbirds use of floodplain landscapes and, as our understanding improves, it should be possible to use floodplain inundation to ensure that they provide optimal value to breeding, recruiting or refuge seeking waterbirds.

Additional ecosystem functions

Research on Golden Perch has concluded that the Goulburn River is part of a sink population, that is, it needs fish to move into the reach if numbers are to be sustained. There has been some success using environmental flows to attract Golden Perch into the Goulburn River. Our understanding of the population dynamics and movements of other species is far less certain. It is possible that a range of native fish (Catfish, Silver Perch, River Blackfish), may all be induced to disperse. However further information is required to better understand their life cycles and behavioral cues. If this were the case, then using environmental flows to facilitate fish movement could be used to achieve Basin Plan targets of expanding the distribution of native fish populations.

Seed dispersal is another ecosystem function influenced by flow. For native plants to persist, they need to be able to disperse into new habitats as they become available. Improvements in the condition of floodplain vegetation communities may help increase the proportion of native plant seeds being dispersed by flows downstream when compared to weeds which are an enduring problem in many riparian, floodplain and wetland ecosystems.

The Basin Plan seeks to ensure that water-dependent ecosystems are resilient to climate change and other risks and threats. Relaxing constraints will improve the condition of floodplain vegetation which on its own is expected to increase resilience. More frequent inundation will also regenerate seedbanks so that the proportion of viable seeds increases, improving responses to subsequent inundation. Increased frequency and heterogeneity of inundation will help maintain a dynamic habitat mosaic. While there remains considerable uncertainty about the relationship between habitat heterogeneity, diversity and resilience, it is expected that species distributed across a diverse landscape would have improved chances of persisting over those restricted to an isolated patch in a degraded landscape.

Climate change
The investigation into the potential climate change impacts found the two most important factors in predicting poorer ecological outcomes for native fish and vegetation were reductions in average rainfall and reductions in the amount rainfall that reaches the river. Climate change impacts were predicted to be considerably dampened in regulated reaches with defined water entitlements (e.g. Goulburn River) when compared with unregulated systems such as Seven Creeks reliant on natural rainfall and run-off events.

An increasingly drying climate is predicted to increase environmental water shortfall volumes, in part and increasingly as a result of decreased inflow from tributaries. The outcomes of the modelling available for this investigation suggests environmental water entitlements will become increasingly important for floodplain inundation.

Synthesis summary

The assessment found that there will are benefits from the relaxation of constraints, spread widely across the landscape and for all values. These benefits occur both within each reach but also cumulatively across the whole system. While there are risks associated with the relaxation of constraints, these are mostly localised and able to be managed.

The findings highlight the importance of assessing environmental responses at river valley scale, rather than focusing on isolated environmental assets. This reach and system scale assessment provides some latitude for managing local impacts of relaxation without materially effecting the system scale ecological benefits of a constraint relaxation program.

The benefits of relaxed constraints are closely tied to achieving overbank inundation. While in some themes there can be some slowing of or reduced degradation through low levels of constraint relaxation, the more constraints are relaxed and overbank inundation achieved, the greater the environmental benefit. Overbank flows reach floodplain vegetation that relies on the inundation to survive and flourish, while initiating the important early stages of a river system food web by returning carbon and nutrient back to the waterway.

The scenarios with greatest constraint relaxation and floodplain inundation provided the greatest level of environmental benefit. The benefits are realised on the subject floodplains, the adjoining riparian lands and channel and downstream reaches.

Relaxing constraints will increase the proportion water-dependent vegetation communities that can be held in good condition between dry spells. This keeps the vegetation communities out of the critical condition status (i.e., ‘near death’) and increases their likelihood of surviving extended dry periods. The areas that were able to be protected increased with constraints relaxation, and the higher flows led to larger flood-adapted vegetation inundation with minimal disbenefit through inundation of vegetation vulnerable to flooding. For the lower constraint scenarios, the total area with an increase in time spent in good condition in the vegetation quality modelling was lowest. The current management scenarios (base case) can be expected to lead to ongoing decline of the system’s vegetation.

However, the benefits are tied to the winter-spring delivery periods. This is important as later season delivery has the capacity to cause adverse effects through turtle and platypus nest inundation and water quality issues. Overall, the modelling provides a cautionary message about potential risks to these two important values. This risk needs to be considered within the broader context of how these species have evolved and persisted in these systems for millennia, including the way they have adapted to late winter and spring events. The identification of the risk triggers and responses through ongoing research, monitoring and adaption of environmental water delivery programs is recommended, rather than using these risks as a basis to not proceed with the further development of relaxed constraints.

The outcomes of the hydrologic modelling made available for his assessment suggests that held environmental entitlements will become increasingly important for river and wetland health if climate change results in a net reduction in the frequency of floodplain inundation arising from streamflow inputs from tributary streams.

10 Risks and uncertainties

Out-of-season delivery

This investigation assumed that the relaxation of constraints will only be applied to environmental flows delivered in winter and spring, and that bankfull and overbank flows will only be delivered in accordance with applicable seasonal watering plans. There is a perceived risk that, if relaxed, the new constraints limits could be applied to releases delivered out of season. As has been identified, flow seasonality is important for several environmental values, and reversed seasonality through the delivery of overbank flows in summer is expected to negatively impact several ecological values. For example, high flows in summer increases the risks of inundating platypus and turtle nests and drowning young. Out of season overbank flows may restrict fish migration and recruitment and impact the condition of instream habitat (VEWH, 2022), with flow on impacts to macroinvertebrates and higher secondary consumer organism. Indeed, intervalley transfers have previously exceeded the existing environmental constraints in the Goulburn River and have damaged bank vegetation and caused erosion (VEWH, 2022). The risk of out of season delivery of overbank events is very low given the level of understanding of this issue.

To the contrary any reduction in uncontrolled spills associated with greater use of the environmental water portfolio arising from relaxed constraints, reduces the potential for, and risk of, out of season floodplain inundation.

Carp

Carp are abundant and widespread across the Murray Darling Basin (Stuart et al. 2021). Carp occupy most aquatic ecosystems from estuarine lakes through to upland streams. Their densities within these different ecosystems are, however, highly variable (Koehn et al. 2004, Stuart et al. 2021). Carp do, however, have negative impacts (Figure 100), particularly in wetlands when their abundance exceeds 80–100 kg/ha.

Freshwater ecosystems around the world are subject to a variety of threats and there is often considerable uncertainty around the most important threat or the ways that threats interact with each other (Nichols et al. 2018). This provides managers with a challenge in prioritising protection or restoration activities.

Inundation of floodplains such as the Barmah-Millewa Forest through relaxation of constraints has potential to increase the carp breeding. The Commonwealth Environmental Water Holder notes that seasonal delivery of environmental water can be used to preferentially benefit native species, though an increased risk of carp could occur through the relaxation of constraints.

While it is known that carp populations are detrimental to the river systems they invade, there are also multiple arguments to suggest the constraints project should proceed with caution despite this risk. The distribution and effects of carp vary widely, with many northern, unregulated parts of the Basin supporting the lowest carp numbers (Stuart et al. 2021). This suggests that there is a relationship between carp numbers and flow regulation. Gehrke et al. (1995) suggested that river regulation may alter the relative abundance of native and alien fish by desynchronizing environmental cycles and the reproductive cycles of native species. Driver et al. (2005) suggested that floods may enhanced recruitment, however, flow regulation provides long-term refuge from mortality associated with high flows. There remains uncertainty around this relationship, much as there remains uncertainty around the relationship between flow and Murray Cod recruitment. If there is a relationship, then flow restoration is likely to be associated with declines in the proportion of carp in fish populations in the southern Murray-Darling Basin.

The density of carp varies widely both among different ecosystems and through time. As a consequence, the effects of carp are also highly variable. There may be some areas where increases in carp numbers may outweigh the benefits of flow restoration, but for many areas, the benefits are still believed to outweigh the risks. This is particularly true of environmental watering in the southern connected basin where despite carp representing 80% of the fish biomass in regulated rivers, environmental flows have achieved positive outcomes for fish species including Golden Perch, and Silver Perch and a range of waterbird and vegetation species.

Finally, the effects of carp are not entirely negative. Young carp have become a major source of food for waterbirds (McGinness et al. 2020). So, while there may be risks of contributing additional carp recruits to regional populations, any contribution can be minimised through flow management that increases the vulnerability of young carp to waterbird predation, leading to benefits for waterbirds.

While carp populations are a real risk across the Southern Connected Basin, limiting the relaxation of constraints to protect ecosystems from increases in carp population would be counterproductive given the systems ongoing decline.

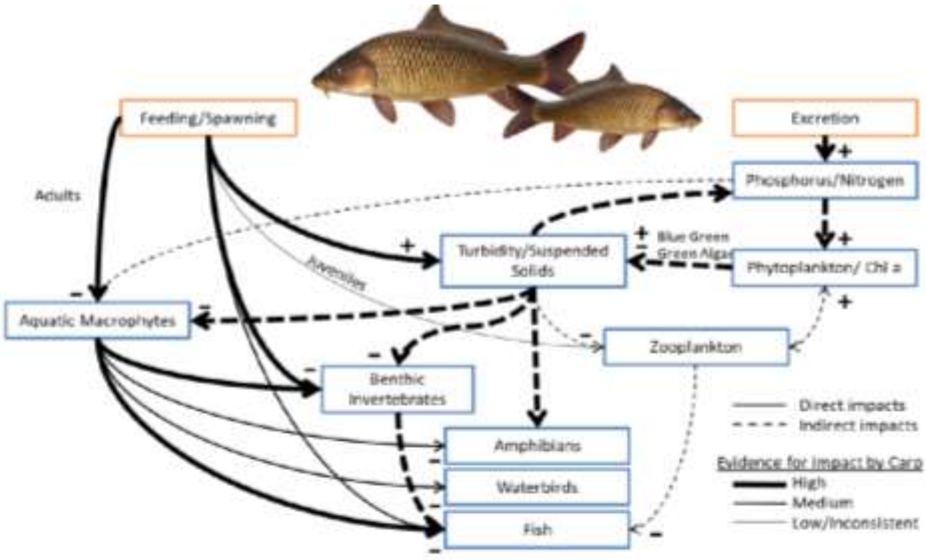

Figure 100 *Effects of Carp in freshwater systems. Source: Nichols et al. 2018, which source information from Koehn et al. 2018, Weber and Brown (2009) and Vilizzi et al. (2015).*

These impacts are relatively unknown in the context of this project, with the analysis based on existing literature. It is expected that the RRCP will release reporting that details carp response modelling for that project, however that was not available in time for this project. As such bringing the Murray River modelling, and replicating that modelling in the Goulburn River, has been included as a recommendation for future work.

Invasive vegetation

Riparian ecosystems play a crucial role in stabilising riverbanks, diversifying habitat structure and supplying energy and nutrients to aquatic ecosystems. They provide a large range of ecological functions and services especially critical in human modified landscape where riparian vegetation may be the last remnants of native vegetation. Restoring riparian vegetation is therefore critical in increasing the resilience of adaptive capacity of riparian ecosystems because of their irreplaceable ecological functions and services (Capon and Pettit, 2018).

Riparian plants communities are dependent on the flow conditions in the river system, and are often subject to anthropogenic pressures such as vegetation clearing, weed invasion, increased riverbank erosion, water quality decline and biodiversity losses (Catford et al. 2014). Invasive weed species can alter the structure and function of ecosystems that could pose a threat to native biodiversity, and could further be facilitated through flow regulations where there are increases in opportunities for species with broader environmental ranges to adapt to altered conditions.

Increasing flows through the river system could also increase propagule pressure. Flooding connects habitats across the landscape. Flow pulses can facilitate the dispersal of weed propagules within these ecosystems, leading to more propagule pressure and increased opportunities for invasive species to colonise (Thomaz et al. 2022). Despite that, flooding can also reduce abundance of weed species by washing out existing established populations. In some circumstances weed species can also co-exist with native species when their ecological niche reduces and if species fitness is increased (Thomaz et al. 2022) under the influence of flow pulses.

Managing weeds in riparian ecosystems requires a holistic approach that considers the riparian landscape and adjacent existing land uses as a whole. Land use adjacent to the riparian zones may often contribute to increased weed presence in the riparian zones if not managed well. Therefore, weed management should be considered as a complementary measure to enhance and restore ecosystem health and function of the riparian ecosystems.

Riparian grazing

Riparian areas are vulnerable to grazing pressures as they are often fertile and provide easy access to drinking water. Grazing is one of the major causes of riparian degradation and has significant impacts on riparian function and biodiversity.

Grazing stock causes reductions in vegetation cover, biodiversity loss, streambank erosion, water eutrophication and degradation of instream processes (Lunt et al. 2007). It can also contribute to increased sediment loads delivering to the waterways when livestock access the riverbanks and accelerate instream and bank erosion. Topsoil erosion is also another impact caused by grazing where trampling of soils on the adjacent floodplain could also contribute to sediment delivery to the waterways. Increased sediment delivery to waterways can worsen water quality and impact on aquatic species such as fish and aquatic macroinvertebrates.

Aquatic macrophytes or juvenile plants are most vulnerable to livestock, where they are often heavily grazed when there is clear access to riverbanks (DELWP, 2016) This disturbance prevents aquatic macrophytes and young plants from establishing within the riparian zone and could unintentionally provide opportunities for weed species to occupy the same location.

Managing flows through the system should consider riparian management interventions to further enhance the ecological outcomes of riparian ecosystems. The relaxation of constraints can provide benefits to the riparian ecosystems, but the ecological outcomes are also dependent on managing riparian zones and grazing pressure. The application of appropriate on-ground interventions to control weeds and grazing can reduce threats to riparian ecosystems and improve the conditions of the riparian ecosystems complementing a constraints relaxation program.

Boat wake

Boat wash is one of a range of anthropogenic mechanisms that contributes to fluvial scour – an erosion process in which particles are removed from the riverbank due to the application of shear stress (Alluvium 2022). Positive correlations exist between high boat use and increased erosion (NSW and MDBA, 2017). In weir pools and lakes, upper bank retreat (overcutting, with stable lower banks) is the dominant erosion process caused by boat wash. In free-flowing river reaches, boat waves may affect the full height of the riverbank and drive the formation of multiple notches and parallel bank retreat, as river levels are variable (Alluvium 2022). The rate of boat-wake erosion is dependent upon the 'nature' of the bank (composition, particle size), the peak power of the wave, the vertical extent of the wetted bank (which decreases adhesion of particles, leading to slumping), and the extent of riparian vegetation and emergent macrophyte cover that decrease erosive work done directly on the bank (Baldwin, 2008).

Engaging floodplains via overbank flows is predicted to decrease the risk of flow-based erosion. However, a residual erosion risk from boat wake will remain under relaxed constraints. Recreational boats (particularly water skiing and wake boats) are the major source of boat wash waves. These craft are used in all stretches of the Murray River constraints study area, but are most common between Yarrawonga and Torrumbarry weirs, and from Corowa to the Murray River confluence with the Ovens River. The erosive impacts of boat waves are exacerbated by consistent river levels and the water-skiing season generally coincides with consistent, high level irrigation flows delivered in Summer and early Autumn. It is unclear whether relaxation of constraints will be associated with increased speed boating activity in winter/spring, although it is noted that during the Millennium drought low water levels in lakes and high levels in rivers (due to irrigation flows) led boater/skiers to transition their boating activities from lakes to rivers (NSW and MDBA, 2017). Boating speeds on the Goulburn River between Eildon Pondage and Hughes Creek are limited to 5 knots (GBCMA, 2008), which is not conducive to speed/wake boating activities.

The relative impact of boat waves verses river flows in the Murray and Goulburn Rivers requires further investigation. Examination of riverbank profiles in relevant reaches in conjunction with assessments of riparian vegetation could be performed to assess residual boat wave risk, should the program proceed to business case. This would focus on the likely change in boats activity during the winter/spring seasons when environmental delivery would change.

11 Further investigations

The assessment of the ecological benefits and risks assessment has identified knowledge gaps that have potential to impact on the scale of beneficial outcomes sought and identified. Further investigations that would improve the confidence in the assessments and the benefits are set out below.

Invasive carp

Carp are an existing threat across the Murray Darling Basin and readily respond to overbank flows. This is an existing threat across the study reaches. Environmental water delivery programs have been found to benefit targeted native species, but can also favour carp. Limits on the duration of floodplain events may limit the benefits to carp and related risks to the river system.

While carp pose a risk to the health of the river system, this risk does not warrant a cessation in further investigation into and development of a constraints relaxation program.

It is noted here though that the potential response of carp has not been included in the modelling for this feasibility stage assessment as no functional ecological response model was available for the investigations. It is recommended that the potential carp response to relaxed constraints be further investigated including the development and application of ecological response model to enable exploration of environmental flow regimes that maximise opportunities for native species while limiting the benefits for carp.

It is expected that the NSW RRCP will develop an invasive carp model which could be applied to the Goulburn River, and the impacts on the Victorian Murray River better understood.

Platypus and turtle models

The investigations have revealed uncertainties in the platypus and turtle models. Further work is required to refine and update these ecological response models to reflect;

1. the requirements of individual species (turtles) and
2. research into platypus response to antecedent conditions and overbank inundation in winter and early spring.

Geomorphic impacts/ bank erosion

The scope of the investigation limited the extent of investigations that could be undertaken into geomorphic processes such as bed and bank erosion and anabranch development. Further investigations are required to confirm the preliminary outcomes identified in this report and to pursue issues not examined such as the potential for anabranch development e.g., in the Hume to Yarrawonga reach of the Murray River

Other assessments

Broader impacts of environmental benefits

This review has been conducted with the focus of environmental benefits and risks as they apply to the environment itself. The environmental assets that have been considered in this assessment play an important role in the broader community. It is recommended that any business case include an assessment of the secondary benefits, arising from relaxed constraints and improved riverine condition. These secondary benefits include:

- The benefits of floodplain engagement to the extent proposed by the scenarios assessed provides to farming and agriculture, through watering and carbon exchange
- The benefits of healthy environmental assets to farming and agriculture, through processes such as pollination
- Social, recreation and economic benefits that are provided by a healthy riverine and floodplain ecosystems

Consistent ecological modelling
While best efforts have been made to ensure consistency in the assessment across the reaches, the modelling across the Goulburn River and Murray holds important differences. Future stages should create consistency across the two rivers and expand the complexities included wherever possible. Although beyond the timeframe of this study a longer-term exercise could involve fish population modelling for the Goulburn River similar to work carried out by NSW. This could be done by modifying the Silver Perch model to predict Golden Perch responses and adapting underlying model rules (e.g. eco-hydrological relationships).

Case study analyses & ground truthing
Following the desktop focused assessment, future stages should incorporate case study analyses of key wetlands and location along each of the reaches to understand the extent of benefits to key environmental assets. Where possible ground-truthed mapping could be carried out to support modelled EVC mapping in order to mitigate potential inaccuracies.

Incorporation of Traditional Owner environmental knowledge
The environmental benefits and disbenefits of relaxing constraints were modelled using 'western' scientific approaches. Traditional Owners have managed Country holistically and sustainably for many thousands of years and have a wealth of expert traditional ecological knowledge of river flows, wetland and floodplain inundation, and the requirements of flora and fauna. Future environmental benefits assessments could be strengthened by the inclusion of Traditional ecological scientific knowledge on ecological responses to the watering of Country.

Groundwater assessment
The role of groundwater and its interactions with surface water has not been investigated in the current scope of work. Groundwater and surface water can be highly connected to provide flow for refuge pools for fish and other aquatic animals. Groundwater also provides essential moisture to mature river red gum communities in times when surface water is scarce. Relaxing constraints, in the long term, may be able to replenish shallow groundwater that maintains surface water in times of drier and warmer climate. Improving river health and ecosystem health of Murray River and the Goulburn River needs to consider both the management of surface water and groundwater. Further work is required to understand the role of groundwater in supporting floodplain ecosystems.

12 References

Alluvium (2022) Synthesis of current knowledge on bank condition and erosion drivers along the River Murray. Report prepared by Alluvium Consulting Australia for the Murray Darling Basin Authority, Canberra

Arthur A.D., Reid J., Kingsford R.T., McGinness H., Ward K., and Harper M. J. (2012). Breeding Flow Thresholds of Colonial Breeding Waterbirds in the Murray-Darling Basin, Australia. *Wetlands*. 32. pp 257–265.

Baldwin D.S. (1999) DOM and Dissolved P Leached from Fresh and 'Terrestrially'-Aged River Red Gum Leaves - Implications for Assessing River-Floodplain Interactions. *Freshwater Biology*. 41. pp 675-685.

Baldwin D.S. (2008) Impacts of Recreational Boating on River Bank Stability: wake Characteristics of Powered Vessels. Report for the Murray Catchment Management Authority. Murray-Darling Freshwater Research Centre, Wodonga, Victoria

Baldwin D.S. (2017) Hypoxic blackwater events in the Goulburn-Broken Catchment. A report to the Goulburn-Broken Catchment Management Authority. pp 46.

Baldwin D.S. (2019) Weir stratification and hypoxic water management - Murrumbidgee River 2019. A report to the Commonwealth Environmental Water Office.

Baldwin D.S. (2020) Assessing the response to the risk of hypoxia in the Lower Darling River: November 2019 until March 2020. A report to the Murray-Darling Basin Authority. pp 93.

Baldwin D.S. (2021) Planning for restarting rivers to minimise harm to native fish and other aquatic biota in the Murray-Darling Basin. A report to NSW Department of Primary Industries. pp 49.

Baldwin D.S., Hall K.C., Rees G.N., Richardson A. (2007) Development of a protocol for recognising sulfidic sediments (potential acid sulfate soils) in inland wetlands. *Ecological Management and Restoration*. 8. pp 56-60.

Baldwin D.S. (2022) Third interim report on the impacts of bushfires on water and sediment quality in Lake Hume and its catchment: January 2020 to May 2022. A report prepared for the Murray-Darling Basin Authority. pp 50.

Baldwin D.S., Colloff M.J., Mitrovic S.M., Bond N.R., Wolfenden B. (2016) Restoring dissolved organic carbon subsidies from floodplains to lowland river food webs: a role for environmental flows? *Marine and Freshwater Research*. 67(9). pp. 1387-1399.

Baldwin DS, Wilson J, Gigney H, Boulding A (2010) Influence of extreme drawdown on water quality downstream of a large water storage reservoir. *Rivers Research and Applications*. 26. pp 194-206.

Ballinger, A., and Lake P. S. (2006). Energy and nutrient fluxes from rivers and streams into terrestrial food webs. *Marine and Freshwater Research.* 57(1). pp 15-28.

Bartley R., and Rutherfurd I. (2005). Measuring the reach-scale geomorphic diversity of streams: application to a stream disturbed by a sediment slug. River research and Applications. 21(1). pp 39-59.Beesley, L., King, A. J., Amstaetter, F., Koehn, J. D., Gawne, B., Price, A., Meredith, S. N. (2012). Does flooding affect spatiotemporal variation of fish. *Freshwater Biology*. 57. pp 2230–2246.

Beesley, L., King, A. J., Amstaetter, F., Koehn, J. D., Gawne, B., Price, A., Nielsen D.L., Vilizzi, L. Meredith, S. N. (2012) Does flooding affect spatiotemporal variation of fish assemblages in temperate floodplain wetlands? *Freshwater Biology*, 57: 2230-2246. https://doi.org/10.1111/j.1365-2427.2012.02865.x

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Beesley, L., King, A.J., Gawne, B., Koehn, J.D., Price, A., Nielsen, D., Amtstaetter, F. and Meredith, S.N. (2014), Optimising environmental watering of floodplain wetlands for fish. *Freshwater Biology*. 59. 2024-2037. https://doi.org/10.1111/fwb.12404

Bino G., Kingsford R. T., Archer M., Connolly J. H., Day J., Dias K., Goldney D., Gongora, J., Grant, T., Griffiths, J., Hawke, T., Klamt, M., Lunney, D., Mijangos, L., Munks, S., Sherwin, W., Serena, M., Temple-Smith, P., Thomas, J., Williams, G., Whittington, C. (2019). The platypus: evolutionary history, biology, and an uncertain future. *Journal of Mammalogy*. 100(2). pp. 308–327.

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. Final report. June 2022. Prepared by University of New South Wales and NSW Department of Planning and Environment for the NSW Reconnecting River Country Program.

Bond N. R., and Lake P. S. (2003) Local habitat restoration in streams: constraints on the effectiveness of restoration for stream biota*. Ecological Management & Restoration*. 4(3). pp 193-198.

Bormans M, W. I. (1997). A mixing criterion for turbid waters. *Environmental Modelling & Software*, pp. 12: 329-333.

Bowling L, Baldwin DS, Merrick C, Brayan J, Panther J (2018). Possible drivers of a Chrysosporum ovalisporum bloom in the Murray River, Australia in 2016. *Marine and Freshwater Research*. 69. pp 1649 - 1662.

Brederveld RJ, Jähnig SC, Lorenz AW, Brunzel S, Soons MB (2011) Dispersal as a limiting factor in the colonization of restored mountain streams by plants and macroinvertebrates. Journal of Applied Ecology 48:1241-1250

Brock MA, Casanova MT (1997) Plant life at the edge of wetlands: ecological responses to wetting and drying patterns. In: Klomp N, Lunt I (eds) Frontiers in Ecology: building the links. Elsevier Science Ltd., Oxford, pp 181-192

Brown, P. and Whiterod, N. (2021) Fish Monitoring at Gunbower Island 2020-21. Draft Final report prepared in conjunction with North Central CMA by Fisheries and Wetlands Consulting and Aquasave-Nature Glenelg Trust, FWC Publication 01/2021, September

Bureau of Meteorology [BoM] (2020). Trends and historical conditions in the Murray Darling Basin: A report prepared for the Murray-Darling Basin Authority by the Bureau of Meteorology.

Bush RT, Tulau M, Coughran J, Ward NJ, Wong VNL, Cheetham M, Morand D (2010). Distribution and hazard of sulfidic sediments in a river and creek channel system of the Murray– Darling Basin: Edward–Wakool channel system case study, report to the Murray–Darling Basin Authority, Canberra.

Carmichael WW, Azevedo SM, A, JS, Molica RJ, Jochimsen EM, Lau S, Rinehart KL, Shaw, GR, Eaglesham GK (2001). Human fatalities from cyanobacteria: chemical and biological evidence for cyanotoxins. *Environmental health perspectives.* 109(7). pp 663-668.

Casanova M, Brock MA (2000) How do depth, duration and frequency of flooding influence the establishment of wetland plant communities? Plant Ecology 147:237-250

Catford, J.A, Morris, W.K., Vesk, P.A, Gippel, C.J and Downes, B.J. (2014). Species and environmental characteristics point to flow regulation and drought as drivers of riparian plant invasion. Diversity and Distributions, 20, pp. 1084 – 1096

Capon, S.J and Pettit, N.E (2018). Turquoise is the new green: Restoring and enhancing riparian function in the Anthropocene. Ecological Management and Restoration, 19 (1), pp. 44-53

Cellot B, Mouillot F, Henry CP (1998) Flood drift and propagule bank of aquatic macrophytes in a riverine wetland

Chapman, J. M., Proulx C. L., Veilleux M. A. N., Levert C., Bliss S., Andre M. E., Lapointe N. W. R., and Cooke S. J. (2014). Clear as mud: A meta-analysis on the effects of sedimentation on freshwater fish and the effectiveness of sediment-control measures. *Water Research*. 56. pp 190-202.

Chessman B. C. (2009) Climatic changes and 13-year trends in stream macroinvertebrate assemblages in New South Wales, Australia. Glob. Chang. Biol. 15 , 2791–2802.

Chessman B. C. (2011). Declines of freshwater turtles associated with climatic drying in Australia's Murray–Darling Basin. *Wildlife Research*. 38. pp 664-671.

Cook, R. A., Gawne, B., Petrie, R., Baldwin, D. S., Rees, G., Nielsen, D. L., & Ning, N. S. (2015). River metabolism and carbon dynamics in response. Marine and Freshwater Research, 66, 919-927.Davis JR, Koop K (2006) Eutrophication in Australian rivers, reservoirs and estuaries - a southern hemisphere perspective on the science and its implications. *Hydrobiology*. 559. pp 23 – 76

Davies P., Lawrence S., Turnbull J., Rutherfurd I., Grove J., Silvester E., Baldwin D. and Macklin M. (2018). Reconstruction of historical riverine sediment production on the goldfields of Victoria, Australia. *Anthropocene.* 21. pp 1-15.

Demott, W, Müller-Navarra D, (1997). The importance of highly unsaturated fatty acids in zooplankton nutrition: evidence from experiments with Daphnia, a cyanobacterium and lipid emulsions. *Freshwater Biology.* 38. pp 649-664.

DELWP (2016). Managing grazing on riparian land – Field companion. Department of Environment, Land, Water and Planning, Victoria

Department of Environment, Land, Water and Planning; Bureau of Meteorology; Commonwealth Scientific and Industrial Research Organisation; The University of Melbourne (2020). Victoria's Water in a Changing Climate.

Department of Environment, Land, Water and Planning [DELWP] (2019). Index of Stream Condition: The Third Benchmark of Victorian River Condition.

DPE (2022) Reconnecting River Country Program: Murray Environmental Benefits Analysis Synthesis Report. Report prepared by the Department of Planning and Environment, Sydney

Department of Planning and Environment. (in prep). Hypoxic blackwater time series analysis. A report for the Reconnecting River Country Program.

Department of Sustainability, Environment, Water, Population and Communities [DSEWPC]. (2012). Wetlands in Australia- Roles and responsibilities- Fact sheet

DeRose R., Prosser I., Weisse M., Hughes A. (2003). Patterns of Erosion and Sediment and Nutrient Transport in the Murray-Darling Basin. Technical Report 32/03, CSIRO Land and Water, Canberra

Driver, P.D., Harris, J.H., Closs, G.P. and Koen, T.B. (2005), Effects of flow regulation on carp (Cyprinus carpio L.) recruitment in the Murray–Darling Basin, *Australia. River Res. Applic*., 21: 327-335. https://doi.org/10.1002/rra.850

Espinoza T., Marshall S.M., Limpus D.J., Limpus C. J., McDougall A. J. (2022) Adaptive Management to Reduce Nest Inundation of a Critically Endangered Freshwater Turtle: Confirming the Win-win. *Environmental Management*. 69. pp 972–981.

Figuerola J, Green AJ (2002) Dispersal of aquatic organisms by waterbirds: a review of past research and priorities for future studies. Freshwater Biology 47:483-494 doi: 10.1046/j.1365-2427.2002.00829.x

Frood, D. and Papas, P. (2016). A guide to water regime, salinity ranges and bioregional conservation status of Victorian wetland Ecological Vegetation Classes. Arthur Rylah Institute for Environmental Research. Technical Report Series No. 266. Department of Environment, Land, Water and Planning.

Funari E, Testai E (2008). Human health risk assessment related to cyanotoxins exposure. *Critical reviews in toxicology*. 38(2). pp.97-125.

Furlan E. M., Griffiths J., Gust N., Handasyde K. A., Grant T.R., Gruber B., Weeks A.R. (2013). Dispersal patterns and population structuring among platypuses, Ornithorhynchus anatinus, throughout south-eastern Australia. *Conserv Genet*. 14. pp 837–853.

Furst, D., Ye, Q., Bice, C., McInerney, P., Biswas, T., Rees, G., & Watts, R. (2020). Zooplankton response to a multi-site environmental watering event during spring 2019 in the River Murray. A report to the Commonwealth Environmental Water Office, Canberra. Project number: CEWO- 2000007157.

Gardner, J., and M. Serena. (1995). Spatial-organization and movement patterns of adult male platypus, Ornithorhynchus anatinus (Monotremata, Ornithorhynchidae). *Australian Journal of Zoology.* 43. pp 91–103.

Gawne, B., Merrick, C., Williams, D.G., Rees, G., Oliver, R., Bowen, P.M., Treadwell, S., Beattie, G., Ellis, I., Frankenberg, J. and Lorenz, Z. (2007). Patterns of primary and heterotrophic productivity in an arid lowland river. *River Res. Application.,* 23: 1070-1087. https://doi.org/10.1002/rra.1033

Gehrke PC (1988.) Response-surface analysis of teleost cardiorespiratory responses to temperature and dissolved oxygen. *Comparative Biochemistry and Physiology A*. 89. pp 587-592.

Gehrke, P.C., Brown, P., Schiller, C.B., Moffatt, D.B. and Bruce, A.M. (1995), River regulation and fish communities in the Murray-Darling River system, Australia. Regul. Rivers: Res. Mgmt., 11: 363-375. https://doi.org/10.1002/rrr.3450110310

Geoscience Australia. (2022, 08). Earth observation from space. Retrieved from Water Observations from Space: https://www.ga.gov.au/scientific-topics/earth-obs/case-studies/water-observations-from-space

Goulburn Broken Catchment Management Authority [GBCMA] (2008). Goulburn River Boating Guide. https://docslib.org/doc/87797/goulburn-river-boating-guide

Goulburn Broken Catchment Management Authority [GBCMA] (2011). Climate Change Integration Strategy (2012-2015).Goulburn Broken Catchment Management Authority [GBCMA] (2014). Goulburn Broken Waterway Strategy (2014-2022). Part D: Implementing the Strategy.

Grant T. R. (1992) Historical and current distribution of the platypus, Ornithorhynchus anatinus, in Australia. In: Platypus and Echidnas (ed M. L. Augee) pp. 232–254 Royal Zoological Society of New South Wales.

Grant, TR and Temple-Smith PD (1998) Field biology of the platypus (Ornithorhynchus anatinus): historical and current perspectives. *Phil. Trans. R. Soc. Lond. B*. 353. pp 1081-1091.

Greet J, Webb JA, Cousens RD (2011) The importance of seasonal flow timing for riparian vegetation dynamics: a systematic review using causal criteria analysis. Freshwater Biology 56:1231-1247

Griffiths J., Kelly T. & Weeks A. (2014) Impacts of high flows on platypus movements and habitat use in an urban stream. (Report to Melbourne Water). Parkville, VIC.

Griffiths J., Maino J. & Weeks A. (2019) Identifying key flow variables and quantifying their impact on platypus populations (Report to Melbourne Water). cesar, Parkville, VIC.

Griffiths J. & Weeks A. (2015) Impact of environmental flows on platypuses in a regulated river. Report to Melbourne Water. Parkville, VIC.

Griffiths J. & Weeks A. (2018) Platypus Strategic Management Plan for Melbourne ' s Catchments (Report to Melbourne Water). cesar, Parkville, VIC.

Groves JH, Williams DG, Caley P, Norris RH, Caitcheon G (2009) Modelling of floating seed dispersal in a fluvial environment. River Research and Applications 25:582-592

Gurnell A et al. (1998) Morphological and ecological change on a meander bend: the role of hydrological processes and the application of GIS. Hydrological Processes 12:981-993

Gust N., and Handasyde K. (1995). Seasonal Variation in the Ranging Behaviour of the Platypus *(Ornithorhynchus anatinus)* on the Goulburn River, Victoria. *Aust.* J. *Zool.* 43. pp 193-208

HARC (2022a) Stage 1A of Victorian Constraints Measures Program Synthesis report - Hydraulic modelling

HARC (2022b) Stage 1A of Victorian Constraints Measures Program Hydrology Synthesis Report

Harris CW, Silvester E, Rees GN, Pengelly J, Puskar L (2016) Proteins are a major component of dissolved organic nitrogen (DON) leached from terrestrially aged Eucalyptus camadulensis leaves. *Environmental Chemistry.* 13(5). pp 877 - 887.

Hawke, T., Bino, G., Kingsford (2019). A silent demise: Historical insights into population changes of the iconic platypus (Ornithorhynchus anatinus). *Global Ecology and Conservation*, https://doi.org/10.1016/j.gecco.2019.e00720

Higginson, W., Reynolds, B., Cross, Y., Dyer, F. (2022) Seed germination requirements of an Australian semi-arid floodplain Acacia species, Acacia stenophylla. *Marine and Freshwater Research* 73(5), 615–623. doi:10.1071/MF21226

Hillman, T. J. and Quinn G. P. (2002). Temporal changes in macroinvertebrate assemblages following experimental flooding in permanent and temporary wetlands in an Australian floodplain forest. *River Research and Applications.* 18(2). pp 137-154.

Hopfensperger K, Baldwin A (2009) Spatial and temporal dynamics of floating and drift-line seeds at a tidal freshwater marsh on the Potomac River, USA. In: Herbaceous Plant Ecology. Springer, pp 313-322

Horne A., Webb A., Rumpff L., Mussehl M., Fowler K and John A. (2020) Kaiela (Lower Goulburn River) Environmental Flows Study. Report for Goulburn Broken Catchment Management Authority https://vewh.vic.gov.au/__data/assets/pdf_file/0005/539204/Kaiela-Goulburn_Eflows-Final-Report.pdf

Howitt J, Baldwin DS, Rees GN Williams J (2007) Modelling blackwater: predicting water quality during flooding of lowland river forests. *Ecological Modelling.* 203. pp 229-242.

Humphries P., Keckeis H., Finlayson B. (2014). The River Wave Concept: Integrating River Ecosystem Models, *BioScience*, 64(10). pp 870–882, https://doi.org/10.1093/biosci/biu130

Humphries P., King A., McCasker N., Keller Kopf R., Stoffels R., Zampatti B., and Price A. Riverscape recruitment: a conceptual synthesis of drivers of fish recruitment in rivers, *Canadian Journal of Fisheries and Aquatic Sciences*. 77: 213–225 (2020) dx.doi.org/10.1139/cjfas-2018-0138

Humphries P., King A., McCasker N., Kopf R. K., Stoffels R., Zampatti B., and Price A. (2020). Riverscape recruitment: a conceptual synthesis of drivers of fish recruitment in rivers Can. J. *Fish. Aquat. Sci*. 77. pp 213–225

Jacobs, APC & cesar (2016) Understanding the environmental water requirements of platypus. Report by Jacobs, Australian Platypus Conservancy and cesar for Melbourne Water.

Jansson R, Zinko U, Merritt DM, Nilsson C (2005) Hydrochory increases riparian plant species richness: a comparison between a free-flowing and a regulated river. Journal of Ecology 93:1094-1103 doi: 10.1111/j.1365-2745.2005.01057.x

Joehnk, K, Sengupta, A, Biswas, TK, Mosley, L. and Rees, G (2020). Assessment and mitigation options of blackwater risk in the River Murray system. pp 60. CSIRO Land and Water, Canberra ACT 2601, Australia.

John A., Horne A., Nathan R. (2022). Stage 1A Victorian Constraints Measures Program: SGEFM updates, Goulburn range-finding exercise, and climate change vulnerability analysis. University of Melbourne.

Jolly I, Holland K, Rassam D, Pickett T (2012). Review of Salt Mobilisation from River Murray Floodplains and wetlands: Processes and prediction tools. CSIRO: Water for a Healthy Country National Research Flagship. Available at: https://publications.csiro.au/rpr/download?pid=csiro:EP118217&dsid=DS6; accessed August 16, 2022.

Jones J., Collins A., Naden P. and Sear D. (2012a), The relationship between fine sediment and macrophytes in rivers. *River Res. Application.* 28. pp 1006-1018.

Jones, J. I., Murphy J. F., Collins A. L., Sear D. A., Naden P. S., and Armitage P. D.(2012b). The impact of fine sediment on macro-invertebrates. River Research and Applications. 28(8). pp 1055-1071.

Junk W. J. and Wantzen K. M. (2004). The flood pulse concept: new aspects, approaches and applications- an update. In R. L. Welcomme, & T. Petr (Eds.), Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries (pp. 117-149). Bangkok: Food and Agriculture Organisation and Mekong River Comission, FAO Regional Office for Asia and the Pacific.

Junk, W.,Bayley P.B., and Sparks R. E. (1989). The flood pulse concept in river-floodplain systems. In D.P. Dodge, ed. Proceedings of the International Large River Symposium (LARS). *Canadian Special Publication of Fisheries and Aquatic Sciences.* 106. pp 110-127.

Kemp, P., Sear D., Collins A., Naden P., Jones I. (2011). The impacts of fine sediment on riverine fish. Hydrological Processes. 25(11). pp 1800-182King, A. J. (2005). Comparison of larval fish drift in the Lower Goulburn and mid-Murray Rivers. *Ecological Management & Restoration*. 6. pp. 136–139.

Kerr J., Baldwin D. S., Whitworth K. (2013) Options for managing hypoxic blackwater events in river systems: a review. *Journal of Environmental Management*. 114. pp 139-147.

King A. J., (2005). Ontogenetic dietary shifts of fishes in an Australian floodplain river. *Marine and Freshwater Research.* 56. pp 215-225.

King, A. J., Crook, D. A., Koster, W. M., Mahoney, J., & Tonkin, Z. (2005). Comparison of larval fish drift in the Lower Goulburn and mid-Murray Rivers. *Ecological Management & Restoration*. 6. pp 136–139.

Kingsford R. T. Norman F. I. (2002) Australian waterbirds — products of the continent's ecology. *Emu* 102, 47-69. https://doi.org/10.1071/MU01030

Kingsford R. T., Roshier D. A., Porter J. L. (2010) Australian waterbirds – time and space travellers in dynamic desert landscapes. *Marine and Freshwater Research* 61, 875-884. https://doi.org/10.1071/MF09088

Koehn, J.D. (2004) Carp (Cyprinus carpio) as a powerful invader in Australian waterways *Freshwater Biology* 49(7) pp 882-894 DOI: 10.1111/j.1365-2427.2004.01232.x

Koehn, J.D. and Harrington, D.J. (2006). Environmental conditions and timing for the spawning of Murray cod (*Maccullochella peelii peelii*) and the endangered trout cod (*M. macquariensis*) in Southeastern Australian rivers. *River Research and Applications*. 22. pp 327–342.

Koehn J.D. and Todd C.R. (2012) Balancing conservation and recreational fishery objectives for a threatened species, the Murray Cod, *Maccullochella peelii*. *Fisheries Management and Ecology.* 19. pp 410-425.

Koehn J.D. and Nicol S.J. (2016) Comparative movements of four large fish species in a lowland river. *Journal of Fish Biology.* 88. pp 1350–1368.

Koehn, J.D., Todd, C.R., Zampatti, B.P. et al. (2018) Using a Population Model to Inform the Management of River Flows and Invasive Carp (Cyprinus carpio). Environmental Management 61, 432–442. https://doi.org/10.1007/s00267-017-0855-y

Koehn J. D., et al. (2020). A compendium of ecological knowledge for restoration of freshwater fishes in Australia's Murray-Darling Basin. *Marine and Freshwater Research.* 71. pp 1391-1463.

Koster, W. C. (2012). Status of fish populations in the lower Goulburn River (2003-2012). Unpublished Client Report for Goulburn Broken Catchment Management Authority, Department of Sustainability and Environment, Heidelberg, Victoria.

Koster, W. M. (2014). Timing, frequency and environmental conditions associated with mainstem–tributary movement by a lowland river fish, golden perch (Macquaria ambigua). *PLoS One*, 9.

Koster, W. M. (2017). Influence of streamflow on spawning-related movements of golden perch Macquaria ambigua in south-eastern Australia. *Journal of Fish Biology*. 90. pp 93–108.

Koster, W. M., Dawson, D. R., Liu, C., Moloney, P. D., Crook, D. A., & Thomson, J. R. (2017). Influence of streamflow on spawning-related movements of golden perch Macquaria ambigua in south-eastern Australia. *Journal of Fish Biology*. 90. pp 93–108.

Koster, W. M., Dawson, D. R., O'Mahony, D. J., Moloney, P. D., & Crook, D. A. (2014). Timing, frequency and environmental conditions associated with mainstem–tributary movement by a lowland river fish, golden perch (Macquaria ambigua). *PLoS One*, 9.

Koster, W., Crook, D., Dawson, D. and Moloney, P. (2012) Status of fish populations in the lower Goulburn River (2003-2012). Arthur Rylah Institute for Environmental Research Unpublished Client Report for Goulburn Broken Catchment Management Authority, Department of Sustainability and Environment, Heidelberg, Victoria.

Lake P. (2000). Disturbance, patchiness, and diversity in streams. *Journal of the North American Benthological Society*. 19(4). pp 573-592.

Laura S. Craig, Julian D. Olden, Angela H. Arthington, Sally Entrekin, Charles P. Hawkins, John J. Kelly, Theodore A. Kennedy, Bryan M. Maitland, Emma J. Rosi, Allison H. Roy, David L. Strayer, Jennifer L. Tank, Amie O. West, Matthew S. Wooten; Meeting the challenge of interacting threats in freshwater ecosystems: A call to scientists and managers. Elementa: Science of the Anthropocene 1 January 2017; 5 72. doi: https://doi.org/10.1525/elementa.256

Liu XY, Watts RJ, Howitt JA, McCasker N (2020) Carbon and nutrient release from experimental inundation of agricultural and forested floodplain soil and vegetation: influence of floodplain land use on the development of hypoxic blackwater during floods. *Marine and Freshwater research.* 71(2). pp 213 -228.

Lunt, I.D., Jansen, A., Binns, D.L. & Kenny, S.A. (2007). Long-term effects of exclusion of grazing stock on degraded herbaceous plant communities in a riparian Eucalyptus camaldulensis forest in south-eastern Australia. Austral Ecology 32, 937-949.

Lyon J., Stuart I., Ramsey D., O'Mahony J. (2010). The effect of water level on lateral movements of fish between river and off-channel habitats and implications for management. *Marine and Freshwater Research.* 61. pp 271-278. https://doi.org/10.1071/MF08246

Maier HR, Burch MD Bormans M (2001). Flow management strategies to control blooms of the cyanobacterium anabaena circinalis in the Murray River at Morgan, South Australia (2001). *Regulated rivers; Research and Management* 17(6) 637-650.

Marchant R. & Grant T. R. (2015) The productivity of the macroinvertebrate prey of the platypus in the upper Shoalhaven River, New South Wales. Mar. Freshw. Res. 66 , 1128–1137.

Martin E. H., Walsh C. J., Serena M. & Webb J. A. (2013) Urban stormwater runoff limits distribution of platypus. Austral Ecol. doi: DOI: 10.1111/aec.12083.

Martin, HS., Batty, EM., Hussin, J., Westall, P., Daish, T., Kolomyjec, S., Piazza, P., Bowden, R., Hawkins, M., Grant, T., Moritz, C., Grutzner, F., Gongora, J., Donnelly, P. (2018). Insights into Platypus Population Structure and History from Whole-Genome Sequencing. *Mol. Biol. Evol.* 35(5). pp 1238–1252

McCarthy B, Conalin A, D'Santos P, Baldwin DS (2006) Acidification, salinisation and fish kills at an inland wetland in south-eastern Australia following partial drying. *Ecological Management and Restoration.* 7. pp 218-223.

McGinness H.M, Brandis K, Robinson F, Piper M, O'Brien L, Langston A, Hodgson J, Wenger L, Martin J, Bellio M, Callaghan D, Webster E, Francis R, McCann J, Lyons M, Doerr V, Kingsford R, Mac Nally R (2019) Murray–Darling Basin Environmental Water Knowledge and Research Project — Waterbird Theme Research Report. Report prepared for the Department of the Environment and Energy, Commonwealth Environmental Water Office by CSIRO and La Trobe University, Centre for Freshwater Ecosystems, CFE Publication 225 June 2019 44p

McGinness H.M., Paton, A., Gawne B., King A.J., Kopf, R.K., Mac Nally R., McInerney P.J., (2020) Effects of fish kills on fish consumers and other water-dependent fauna: exploring the potential effect of mass mortality of carp in Australia. *Marine and Freshwater Research* 71, pp 260. https://doi.org/10.1071/MF19035_CO

McGuckin J (2002) An investigative study of the fish fauna of the Nagambie Lakes and Chateau Tahbilk Lagoon. Report for the Nagambie Angling Club. Streamline Research Pty Ltd.

McInerney P. J., Rees G, Cuddy S. M., Wahid S., 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. pp 55.

McInerney, P. J., Stoffels R. J., Shackleton M. E., Davey C. D. (2017). Flooding drives a macroinvertebrate biomass boom in ephemeral floodplain wetlands. *Freshwater Science.* 36(4). pp 726-738.

McLachlan-Troup T. A., Dickman C. R. & Grant T. R. (2010) Diet and dietary selectivity of the platypus in relation to season, sex and macroinvertebrate assemblages. J. Zool. 280 , 237–246.

Meitzen K. M., Doyle M. W., Thoms M. C., and Burns C. E. (2013). Geomorphology within the interdisciplinary science of environmental flows. *Geomorphology*. 200. pp 143-154.

Merel S, Walke, D, Chicana R, Snyder S, Baurès E, Thomas O (2013). State of knowledge and concerns on cyanobacterial blooms and cyanotoxins. *Environment international*, 59, pp.303-327.

Merritt DM, Wohl EE (2002) Processes governing hydrochory along rivers: hydraulics, hydrology, and dispersal phenology. Ecological Applications 12:1071-1087

Moggridge HL, Gurnell AM (2010) Hydrological controls on the transport and deposition of plant propagules within riparian zones. River Research and Applications 26:512-527 doi: 10.1002/rra.1273

Müller-Navarra DC, Brett MT, Liston AM, Goldman CR (2000). A highly unsaturated fatty acid predicts carbon transfer between primary producers and consumers. *Nature* 403, pp 74-77.

Murray Darling Basin Authority [MDBA] (2009). Fact sheet: The Living Murray Program

Murray Darling Basin Authority [MDBA] (2012). Sustainable Rivers Audit 2: The ecological health of rivers in the Murray–Darling Basin at the end of the Millennium Drought (2008–2010). Summary. Murray Darling Basin Authority Canberra

Murray Darling Basin Authority [MDBA] (2015). Climates and climate change. https://www.mdba.gov.au/importance-murray-darling-basin/environment/climate-change

Murray Darling Basin Authority [MDBA] (2018). River flows and connectivity. Technical Report. Basin Plan Evaluation. Murray-Darling Basin Authority Canberra

Murray Darling Basin Authority [MDBA] (2020a). 2020 Basin Plan Evaluation. https://www.mdba.gov.au/node/6189/#section4 Murray-Darling Basin Authority Canberra

Murray Darling Basin Authority [MDBA] (2020b). Basin-wide environmental watering strategy: Second edition. Murray-Darling Basin Authority Canberra

Murray Darling Basin Authority [MDBA] (2020c). The 2020 Basin Plan Evaluation: Southern Basin evidence report. Murray-Darling Basin Authority Canberra

Murray Darling Basin Authority [MDBA] (2020d). Who manages the Murray-Darling Basin, https://www.mdba.gov.au/water-management/allocations-states-mdba/managing-murray-river

Murray Darling Basin Ministerial Council (2011) Acid Sulfate Soils in the Murray-Darling Basin. pp 81. Murray-Darling Basin Commission http://www.mdba.gov.au/files/publications/Acid-sulfate-soils-in-the-MDB.pdf

Murray Regional Tourism (n.d.). Gunbower National Park. https://www.visitthemurray.com.au/places-to-go/national-parks/gunbower-national-park

National Health and Medical Research Council (2008) Guidelines for Managing risk in recreational waters. Available at https://www.nhmrc.gov.au/sites/default/files/images/guidelines-for-managing-risks-in-recreational-water.pdf, accessed September 1, 2022.

New South Wales Government and Murray-Darling Basin Authority [NSW and MDBA] (2017) Draft River Murray (Corowa to Ovens River) Erosion Management Plan – December 2017

Newson M. D., and Newson C. L. (2000). Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. *Progress in Physical Geography*. 24(2). pp 195-217.

Nichols S.J., Gawne B., Richards R., Lintermans M., and Thompson R. (2019). NCCP: The likely medium- to long-term ecological outcomes of major carp population reductions. Final Report. Prepared by the Institute for Applied Ecology, University of Canberra for Fisheries Research and Development Corporation, ACT.

Nichols S.J., Gawne B., Richards R., Lintermans M., and Thompson R. (2018). NCCP: The likely medium- to long-term ecological outcomes of major carp population reductions. Final Report. Prepared by the Institute for Applied

Ecology, University of Canberra for Fisheries Research and Development Corporation, ACT. Global Perspective, Reviews in Fisheries Science & Aquaculture, 23:3, 253-290, DOI: 10.1080/23308249.2015.1051214

Nielsen, D. L., Cook, R. A., Ning, N., Gawne, B., & Petrie, R. (2016). Carbon and nutrient subsidies to a lowland river. *Marine and Freshwater Research*, 67, pp 1302–1312.

Nilsson C, Andersson E, Merritt DM, Johansson ME (2002) Differences in riparian flora between riverbanks and river lakeshores explained by dispersal traits. Ecology 83:2878-2887

Ocock J. F., Bino G., Wassens S., Spencer J., Thomas R. F. and Kingsford R. T. (2018). Identifying Critical Habitat for Australian Freshwater Turtles in a Large Regulated Floodplain: Implications for Environmental Water Management. Environmental Management. 61 (3). pp 375-389

Pleizier NK, Algera D, Cooke SJ, Brauner CJ (2020). A meta-analysis of gas bubble trauma in fish. *Fish and Fisheries* 21, pp 1175-1194.

Poff N. L., Allan J. D., Bain M. B. et al. (1997) The natural flow regime: A paradigm for river conservation and restoration. Bioscience 47 , 769–784.

Raymond, S. Duncan, M. Tonkin, Z. and Robinson, W. (2018). Barmah-Millewa Fish Condition Monitoring: 2018. Arthur Rylah Institute for Environmental Research Unpublished Client Report for the Murray Darling Basin Authority. Department of Environment, Land, Water and Planning, Heidelberg, Victoria

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rees GN, Cook RA, Ning NSP, McInerney PJ, Petrie RT, Nielsen DL (2020). Managed floodplain inundation maintains ecological function in lowland rivers. *Science of the Total Environment* 727 138469.

Rees, G., Biswas, T., McInerney, P., Nielsen, D., Joehnk, K., Pengally, J., Ye, Q. (2020b). Monitoring productivity outcomes of the 2019 River Murray Channel multi-site water for the environment event - carbon and nutrient loads. Report prepared to the Murray Darling Basin Authority.

Reid J. R. W., Colloff M. J., Arthur A. D., and McGinness H. M. (2013) Influence of Catchment Condition and water resource development on waterbird assemblages in the Murray-Darling Basin, Australia, *Biological Conservation*. 165(2013). pp 25-34.

Roberts J, Marston F (2011) Water regime for wetland and floodplain plants: a source book for the Murray–Darling Basin. In. National Water Commission, Canberra

Rogers K, Ralph TJ (2011) Floodplain Wetland Biota in the Murray-Darling Basin: Water and Habitat Requirements. CSIRO Publishing, Melbourne

Roshier D., Robertson A. I., Kingsford R. T., and Green D. G. (2001) Continental-scale interactions with temporary resources may explain the paradox of large populations of desert waterbirds in Australia. *Landscape Ecology*. 16. pp 547–556.

Rowland S.J. (1998a). Age and growth of the Australian freshwater fish Murray cod, *Maccullochella peelii*. *Proceedings of the Linnean Society of New South Wales.* 120. pp 163–180.

Rutherfurd I.D., Kenyon C., Thoms M., Grove J., Turnbull J., Davies P. and Lawrence S. (2020). Human impacts on suspended sediment and turbidity in the River Murray, South Eastern Australia: Multiple lines of evidence. *River Research and Applications*, *36*(4), pp.522-541.

Santamaria, L. (2002) Why are most aquatic plants widely distributed? Dispersal, clonal growth and small-scale heterogeneity in a stressful environment. Acta Oecologica-International Journal of Ecology 23, 137-154

Selwood, K.E., Clarke, R.H., Cunningham, S.C., Lada, H., McGeoch, M.A. and Mac Nally, R. (2015a), A bust but no boom: responses of floodplain bird assemblages during and after prolonged drought. J Anim Ecol, 84: 1700-1710. https://doi.org/10.1111/1365-2656.12424

Selwood K.E., Thomson J.R., Clarke R.H., McGeoch M. A. and Mac Nally R. (2015), Floodplains as drought refugia. *Global Ecology and Biogeography*, 24. pp 838-848. https://doi.org/10.1111/geb.12305

Serena M. & Pettigrove V. (2005) Relationship of sediment toxicants and water quality to the distribution of platypus populations in urban streams. J. North Am. Benthol. Soc. 24 , 679–689. [online]. Available from: http://www.journals.uchicago.edu/doi/10.1899/04-024.1.

Serena, M., and G. Williams. (2012). Movements and cumulative range size of the platypus (Ornithorhynchus anatinus) inferred from mark–recapture studies. *Australian Journal of Zoology.* 60. pp 352–359.

Siebers AR, Crook D, Silvester N, Bond N (2022) Production Condition Predictive Modelling. Part 1: River Murray, Hume to Wakool Junction.

Siebers et al. (2022). Production Condition Predictive Modelling. Part 1: River Murray, Hume to Wakool Junction. Department of Planning, Industry and the Environment NSW.

Stella JC, Battles JJ, Orr BK, McBride JR (2006) Synchrony of seed dispersal, hydrology and local climate in a semi-arid river reach in California. Ecosystems 9:1200-1214

Stewardson M. J. and Guarino F. (2020) 2018–19 Basin-scale evaluation of Commonwealth environmental water. Hydrology: Annex A Valley Report Cards. Final Report prepared for the Commonwealth Environmental Water Office by La Trobe University, Publication 253.

Stewardson M. J., Walker G., and Coleman M (2020). Chapter 3: Hydrology of the Murray-Darling Basin. In Volume 1 of Ecohydrology from Catchment to Coast Murray–Darling Basin, Australia: Its Future Management. edited by Barry Hart, Neil Byron, Nick Bond, Carmel Pollino, Michael Stewardson. Elsevier, Oxford https://www.elsevier.com/books/murray-darling-basin-australia/hart/978-0-12-818152-2

Stoffels R. J., Clarke K. R., Rehwinkel R. A., and McCarthy B. J (2014). Response of a floodplain fish community to river-floodplain connectivity: natural versus managed reconnection. *Canadian Journal of Fisheries and Aquatic Sciences.* 71(2). pp 236-245.

Stuart I.G., Fanson B.G., Lyon J.P., Stocks J., Brooks S., Norris A., Thwaites L., Beitzel M., Hutchison M., Ye Q., Koehn J.D., Bennet A.F. (2021) Continental threat: How many common carp (*Cyprinus carpio*) are there in Australia? *Biological Conservation* 254: 108942

Stuart I.G. and Sharpe C.P. (2021). Ecohydraulic model for designing environmental flows supports recovery of imperilled Murray cod (*Maccullochella peelii*) in the Lower Darling–Baaka River following catastrophic fish kills. *Marine and Freshwater Research*.

Swingler K., Lake M. (2003) NLS: Temperature and stratification investigation 2002/2003. Final report to Goulburn-Murray Water. Sinclair Knight Merz, Armadale, Victoria. July 16, 2003. 16 pp.

Technical Report Series No. 316, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

The Environment Protection and Heritage Council and the Natural Resources Management Ministerial Council (2011). National Guidance on the Management of Acid Sulfate Soils in Inland Aquatic Ecosystems. Department of Environment Water Heritage and the Arts.

http://www.environment.gov.au/water/publications/quality/guidance-for-management-of-acid-sulfate-soils.html

Thiem J.D., Baumgartner L.J., Fanson B., Sadekov A., Tonkin Z. and Zampatti B.P. (2021) Contrasting natal origin and movement history informs recovery pathways for three lowland river species following a mass fish kill. *Marine and Freshwater Research*. 73. pp 237-246.

Thoms M.C., Foster J.M., and Gawne, B. (2000) Flood-plain sedimentation in a dryland river: the River Murray, Australia. The Role of Erosion and Sediment Transport in Nutrient and Contaminant Transfer (Proceedings of a symposium held at Waterloo, Canada, July 2000). IAHS Publ. no. 263.

Tilleard S. and Ford J. (2016). Adaptation readiness and adaptive capacity of transboundary river basins. *Climate Change*. 137. pp 575-591.

Todd C., and Koehn J. (2007). Modelling management scenarios for Murray cod populations in the Mullaroo Creek. Report for the Mallee Catchment Management Authority, Victoria.

Todd C., Wootton H., Koehn J., Stuart I., Hale R., Fanson B., Sharpe C., and Thiem J. (2022). Population Modelling of Native Fish Outcomes for the Reconnecting River Country Program: Golden Perch and Murray Cod. Final report for the NSW Department of Planning and Environment, Reconnecting River Country Program. Arthur Rylah Institute for Environmental Research, Technical Report Series No. 341, DELWP, Heidelberg.

Thomaz, S.M (2022). Propagule pressure and environmental filters related to non-native species success in river-floodplain ecosystems. Hydrobiologia, **849**, pp. 3679–3704

Tonkin Z., Yen J., Lyon J., Kitchingman A., Koehn J.D., Koster W.M., Lieschke J., Raymond S., Sharley J., Stuart I. and Todd C., (2021). Linking flow attributes to recruitment to inform water management for an Australian freshwater fish with an equilibrium life-history strategy. *Science of the Total Environment*. 752. 141863.

Tonkin Z., Jones C., Clunie P., Vivian L., Amtstaetter F., Jones M., Koster W., Mole B., O'Connor J., Brooks J., Caffrey L., and Lyon J. (2020). Victorian Environmental Flows Monitoring and Assessment Program. Stage 6 Synthesis Report 2016-2020. Technical Report Series No. 316, Department of Environment, Land, Water and Planning, Heidelberg, Victoria.

Treadwell S. et al. (2021). Commonwealth Environmental Water Office Monitoring, Evaluation and Research Program: Goulburn River Selected Area Summary Report 2020–21. Commonwealth of Australia

Vannote R. L., Minshall G. W., Cummins K. W., Sedell J. R., and Cushing C. E. (1980). The River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Sciences.* 37(1). pp 130-137.

Victorian Environmental Water Holder [VEWH] (2022). Seasonal Watering Plan 2022-2023. Victorian Environmental Water Holder and State Government of Victoria.

Victorian Murray Floodplain Restoration Project (n.d.) Victorian Murray Floodplain Restoration Project portal. www.caportal.com.au/vmfrp/projects, accessed August 16, 2022.

Victorian Resources online (n.d.) Salinity provinces in the Goulburn Broken Catchment Region; https://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/salinity-province-goulburn-broken accessed August 16, 2022

Vilizzi, A. S. Tarkan & G. H. Copp (2015) Experimental Evidence from Causal Criteria Analysis for the Effects of Common Carp Cyprinus carpio on Freshwater Ecosystems. *Reviews in Fisheries Science & Aquaculture* 23(3) pp 253-290 DOI: 10.1080/23308249.2015.1051214

Violi J.P., Mitrovic S.M., Colville A., Main B.J., Rogers K.J. (2019) Prevalence of beta-methylamino-L-alanine (BMAA) and its isomers in freshwater cyanobacteria isolated from eastern Australia. *Ecotoxicology and Environmental Safety*. 172. pp 72 -81.

Walker G. and Prosser I. P. (2020). Chapter 6: Water quality: Land use impacts on salinity, sediments, and nutrients. In Volume 1 of Ecohydrology from Catchment to Coast Murray–Darling Basin, Australia: Its Future Management. edited by Barry Hart, Neil Byron, Nick Bond, Carmel Pollino, Michael Stewardson. Elsevier, Oxford https://www.elsevier.com/books/murray-darling-basin-australia/hart/978-0-12-818152-2

Wallace T.A., Ganf G.G., Brookes J.D. (2008) A comparison of phosphorus and DOC leachates from different types of leaf litter in an urban environment. *Freshwater Biology.* 53(9). pp 1902 - 1913.

Walsh C. J., Fletcher T. D. & Burns M. J. (2012) Urban Stormwater Runoff: A New Class of Environmental Flow Problem. PLoS One 7.

Walsh C. J., Roy A. H., Feminella J. W., Cottingham P. D., Groffman P. M. & Morgan R. P. (2005) The urban stream syndrome: current knowledge and search for a cure. J. North Am. Benthol. Soc.

Walsh C. J., Sharpe A. K., Breen P. F. & Sonneman J. A. (2001) Effects of urbanization on streams of the Melbourne region, Victoria, Australia. I. Benthic macroinvertebrate communities. Freshw. Biol. 46 , 535–551.

Water Technology (2016), *Goulburn River Constraints Management – Environmental Flow Inundation Modelling and Mapping*. Report prepared for the Goulburn Broken CMA, January 2016.

Webb A. H. (2021) Goulburn River Selected Area Scientific Report 2020-2021. Commonwealth Environmental Water Office Monitoring, Evaluation and Research.

Webb A., Hou X., Treadwell S., Baghbanorandi P., Baker B., Bovill W., Casanelia S., Christopher N., Grace M., Greet J., Kellar C., Koster W., Lovell D., McMahon D., Morris K., Pettigrove V., Russell L., Sutton N and Vietz G. (2021) Goulburn River Selected Area Scientific Report 2020-2021. Commonwealth Environmental Water Office Monitoring, Evaluation and Research.

Weber, M. J., and Brown, M. L. (2009). Effects of common carp on aquatic ecosystems 80 years after 'carp as a dominant': ecological insights for fisheries management. Reviews in Fisheries Science 17, 524–537.

Whitworth K.L., Baldwin D.S. (2012a) Drought, floods and water quality: drivers of a severe hypoxic blackwater event in a major river system (the southern Murray-Darling Basin, Australia). *Journal of Hydrology*. 450(1), pp 190-198.

Whitworth K.L., Baldwin D.S. (2012). Blackwater in the Southern Murray-Darling Basin during 2012 flood events. A report to the Murray-Darling Basin Authority. pp 34.

Whitworth K.L., Baldwin D.S. (2014). The effect of temperature on leaching and subsequent decomposition of dissolved organic carbon from inundated floodplain litter: implications for the generation of hypoxic blackwater in lowland floodplain rivers. *Chemistry and Ecology.* 30(6). pp. 491-500.

Whitworth K.L., Baldwin D.S. (2016) Improving our capacity to manage hypoxic blackwater events in lowland rivers: the blackwater risk assessment tool. *Ecological Modelling.* 320. pp 292-298.

Whitworth K.L., Baldwin D.S., Kerr J. (2012) Drought, floods, and water quality: drivers of a severe hypoxic blackwater event in a major river system (the southern Murray-Darling Basin, Australia). *Journal of Hydrology.* 450(1), pp 190-198.

Whitworth K.L., Baldwin D.S., Kerr J. (2014) The effect of temperature on leaching and subsequent decomposition of dissolved organic carbon from inundated floodplain litter: implications for the generation of hypoxic blackwater in lowland floodplain rivers. *Chemistry and Ecology.* 30(6). pp 491-500

Woinarski J. & Burbidge A. A. (2016) Ornithorhynchus anatinus. The IUCN Red List of Threatened Species.

Woinarski J. C. Z., Burbidge A. A. & Harrison P. L. (2014) The action plan for Australian mammals 2012. CSIRO Publishing, Collingwood.

Zampatti B., Loone J., Hunter K. (1996) NLS water quality study: final report. Water Ecoscience, WES Report No. 57/96.

Zhang, L, Zheng, HX, Teng, J, Chiew, FHS, and Post DA (2020). Hydroclimate storylines for selected catchments in the Murray-Darling Basin. A report for the Murray–Darling Basin Authority, CSIRO, Australia.