Environmental Benefits and Risks Report - Attachments

Stage 1A of the Victorian Constraints Measures Program

FINAL DRAFT

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alluvium

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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.

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Attachment 1: Detailed Assessment Methods

Connectivity, productivity, macroinvertebrates, waterbirds, platypus and turtle assessments

Full methods for these themes are presented in the main document. No extended assessment methods are included in this attachment.

Vegetation quality assessment

To model the benefits and risks to vegetation quality, the modelling approach originally prepared for the RRC project was applied to the Victorian areas of the Murray River and recreated for the Goulburn River. This modelling utilised 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 identified the areas, frequency and duration of vegetation inundated when flows reach the threshold required to commence the filling of the vegetated area (Figure 1). The environmental response method was the same for the two river systems however the inputs were developed using slightly different inputs.

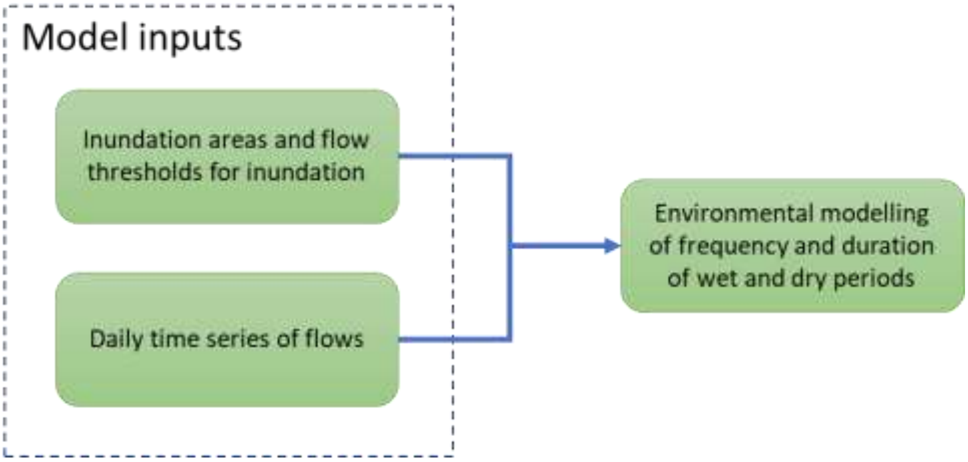

Figure 1 *Vegetation quality assessment*

Murray River inputs

The Murray River modelling was initially conducted as part of NSW RRC and has been interpreted to estimate a Victorian vegetation response.

Hydrological modelling (Floodplain vegetation)

Multiple hydrological scenarios were assessed to determine the influence of different constraint relaxations on various ecological outcomes. For the responses of vegetation, these flows scenarios were processed into spells of inundation on the floodplain through combination with inundation mapping. To generate these flow scenarios, flows were modelled using 'Source Murray Model' software (version 5.10) for each flow scenario.

For each scenario, simulated flows at corresponding gauges for the inundation areas were generated for a 124-year period from the 1/07/1895 to 30/06/2020. These hydrological time series were analysed using the hydrostats package (v0.2.8 N. Bond (2021)) to separate the entre time series into individual hydrological years. This resulted in a 123-year time series (and 1 initial state, n = 124).

Within each hydrological year, a spells analysis was used to determine the durations of inundation and drying spells at all unique levels of inundation on the floodplain for each of the inundation maps. To parameterise these spell durations, we consulted with vegetation experts external to the project and the steering committee for the RRC project.

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The inundation mapping used is based on commence to-fill volumes rather than correlations of observed inundation extents on the floodplain and antecedent flow in the river. This means that water on the floodplain will rapidly rise and fall on the floodplain in sync with flow changes in the main channel (or wherever the gauge point for that inundation map is located). To incorporate some aspect of water residence time on the floodplain, we included a tuning parameter in the spells analysis. A similar approach is included in the hydrostats package (N. Bond, 2021) to allows short, concurrent spells to be counted as the same spell and their durations of inundation added together. As mentioned, when describing the averaging of our inundation maps, a previous sensitivity analysis assessed the validity of values suggested by expert elicitation via workshops.

Flow limits modelled

The modelling framework considers the joint effects of antecedent vegetation state, and antecedent inundation conditions for each annual time-step. We largely followed the methodology of N. R. Bond et al. (2018). The model is informed by the following data sources, detailed in the following sections:

- Inundation maps of the floodplain area (RiM-FIM; IC Overton, McEwan, Gabrovsek, and Sherrah (2006), EW-FIM; Sims et al. (2014))
- Daily timeseries of flows for the duration of model projections that are from gauges representative of inundation within each inundation map
- Map of 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.

Floodplain inundation maps of the Murray River were used between the outlet of Hume dam at the furthest upstream extent of the Murray to the Lock 8 weir beyond the junction of the Murray and Darling systems. In total, projections were completed for 11 zones of the Murray catchment that were drawn from the Edward-Kolety-Wakool Floodplain inundation model (EW-FIM, Sims et al. (2014)) and the River Murray floodplain inundation model (RiM-FIM, Overton et al. (2006)).

Both the RiM-FIM and EWFIM layers are based on commence-to-fill flow volumes at a gauge in the main river channel, and as data sources were raster files with a resolution of 5m x 5m up to 15m x 15m pixels. Pixels were aggregated into 125m x 125 m pixels to represent the changes at a vegetation community scale and the modal value of all aggregated cells was used as the new value for the larger pixel. This was based on a sensitivity analysis of various averaging techniques as an earlier part of this project. Additionally, the inundation volumes of these maps were binned to 1,000 ML/day increments between 0 and 308,000 ML/day. Due to some inaccuracies across the inundation maps of the RiM-FIM, some rasters were updated or modified from the original. For every inundation map the highest flow value was removed from the modelling procedure as these highest flow pixels represent a fill of the space between the observed/satellite imagery highest flow and the bounding box of the RiM-FIM zone set out in Overton et al. (2006). Finally, some rasters were ‘clipped’ to allow the use of the more recently developed EW-FIM model where both models existed.

There are two important notes in relation to the inundation modelling approach. First, RiM-FIM and EW-FIM were used in preference to more detailed hydrodynamic models that exist for some areas so as to align with the hydrologic input scenarios provided, which lacked important operational details of local infrastructure needed when running the hydrodynamic models for flows in the range of 3,000-15,000 ML/day. Second, we modelled vegetation outcomes across the entire floodplain, not just the areas affected by ‘operational’ flows, to assess whether improvements in the areas affected by operating rules and releases caused any declines in areas above the operational range of flow releases (such as changes in operational flows influencing the frequency of uncontrolled spills from storage, which could then affect other parts of the floodplain).

Goulburn River inputs

Hydrological modelling (Floodplain Vegetation)

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.

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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/d for the Mid Goulburn, and 9,500 ML/d for the Lower Goulburn. Constraints were then relaxed in the same way as described earlier.

Flow limits modelled (Floodplain vegetation)

Modelling scenarios were considered for inundating two regions (Upstream and Downstream) for the Goulburn catchment. The floodplain inundation areas were based on the hydraulic modelling outputs previously developed by Water Technology using TUFLOW 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.

Environmental modelling

The environmental modelling process was the same for both the Murray River and the Goulburn River.

To model the dynamic ecological response of vegetation communities to the variable hydrologic conditions we refined the vegetation condition state-and-transition models developed for the SDLAM ecological elements method (N. R. Bond et al., 2018; I. Overton et al., 2014). 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) through expert elicitation to develop 'rules' describing the response of multiple vegetation types to inundation spells (Figure 2). In their most basic form, state-and-transition models (STMs) assume transition probabilities adhere to a constant first-order Markov process (Figure 2) 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.

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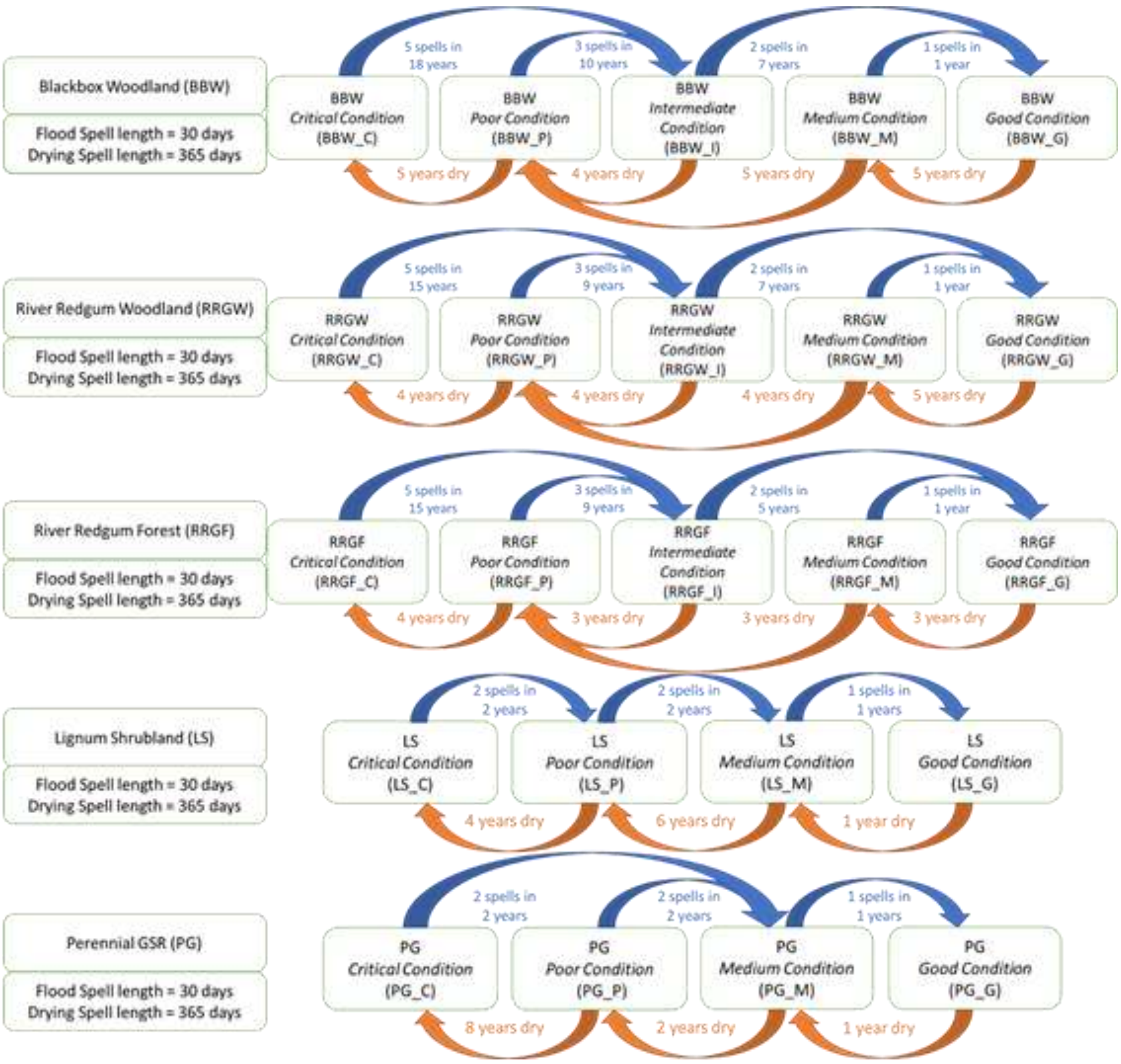

Figure 2 *Visual representation of a subset of transition rules for inundation frequency of broad vegetation categories. (Based on rules from N. R. Bond et al. (2018)*

However, this assumption can easily be relaxed to consider higher-order lag effects or the influence of exogenous variables such as disturbances that alter transition probabilities over time (Baker, 1989; Daniel, Frid, Sleeter, & Fortin, 2016). The FVCM framework is currently fully deterministic, with respect to the relationship between a transition parameter (spell rule) and the state change, though it incorporates very high-order lags e.g., 30 years of 365-day dry spells for the decline from Blackbox woodland in a “good” state to a “dead” state. This creates a significant amount of model “memory” for individual units of simulation. In simulating many millions of pixels across the Murray floodplain, these models can be very powerful with respect to antecedent conditions. This antecedent memory is generated when the spells analysis is used to cross reference which rules occur within a year.

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) we have developed a set of functions within the R for statistical computing software (R Development Core Team, 2020) environment 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

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the 123-year time series of flows. Due to model initialisation, the years prior to 1900-01 were not considered in the interpretation.

Vegetation quantity

This analysis provides a preliminary assessment of potential benefits of relaxed river flow constraints to native vegetation, including riparian, wetland and floodplain vegetation. It is semi-quantitative and considers inundation mapping for the flow scenarios described overlaid on available vegetation mapping [2005 modelled Ecological Vegetation Class (EVC) mapping] to consider potential changes to area of various vegetation types potentially receiving inundation.

Vegetation groupings

EVCs have been allocated to one of five broad vegetation categories across a gradient of water requirements from fully aquatic through to fully terrestrial (Table 1). Further details of which EVCs and combinations of EVCs have been allocated to the categories is provided in Attachment 2 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 1 *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 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. This analysis compares areas of vegetation potentially receiving inundation under the scenarios and considers, at a high level, what benefits and risk may result from the relaxation of constraints. We assume that the timing of inundation would be between July to October (winter and spring), which is the natural season of

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inundation for many flood-dependent vegetation types. We also assume inundation in the order of 1 to several weeks[1].

We assume 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 method. 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.

[1] Based on a target of 5 days at peak flow, with around a 6 day rise and 11 days fall this could result in inundation for 1 – 3 weeks.

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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 have been identified (McInerney et al., 2022; Department of Planning and Environment, in prep):

- 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.

Due to differences in modelling capacity, resources and timing the approach taken to determine the impact of relaxed constraints differed between water quality constituents and river reaches. In some cases, we were only able to make generalised conclusions.

Hypoxic blackwater – Murray River (Hume to Wakool)

When water floods a previously dry area (e.g., a river bench, dry channel or floodplain) carbon is rapidly leached from accumulated plant litter in the previously dry area (Baldwin 2021). Carbon is a basal energy source for aquatic food webs, and hence is important for riverine productivity. Indeed, the case has been prosecuted that one of the roles of environmental flows should be the delivery of carbon, specifically DOC, from floodplains to the main stem of rivers to improve in-stream productivity (Baldwin et al. 2016). For example, carbon export from selected floodplain environments to the Murray River is now an objective for the Victorian Murray Floodplain Restoration Project (VMFRP, undated).

The carbon enters the food web through microbial metabolism. In the process of consuming the carbon, the bacteria also consume oxygen from the water (Howitt et al. 2007). If the rate of oxygen depletion is greater than the rate that oxygen can be supplied from the atmosphere (re-aeration), then the oxygen concentration in the water column will begin to fall. Under the right conditions, this can lead to hypoxia, which is typically defined in waterways of the Murray-Darling Basin as an oxygen concertation of less than 2 mg/L - which is putatively the level below which large-bodied native fish begin to die (e.g., Gehrke, 1988).

A number of factors determine the oxygen concertation in the waters downstream of a floodplain (Figure 3). These include the area inundated and the type and amount of litter present, which combined determine how much carbon is available for microbial consumption. The more carbon, the higher the likelihood of hypoxia.

Temperature is also important. As water temperature increases, so does the rate of microbial respiration, which increases the rate that dissolved oxygen is depleted from the water column (Whitworth et al., 2014).

Furthermore, both the rate and amount of carbon that can be leached from litter increases with increasing temperature (Whitworth et al., 2014). Finally, the warmer the temperature, the less oxygen that can physically be dissolved in water, meaning that less oxygen needs to be consumed at higher temperatures to fall to below the critical 2 mg/L concentration.

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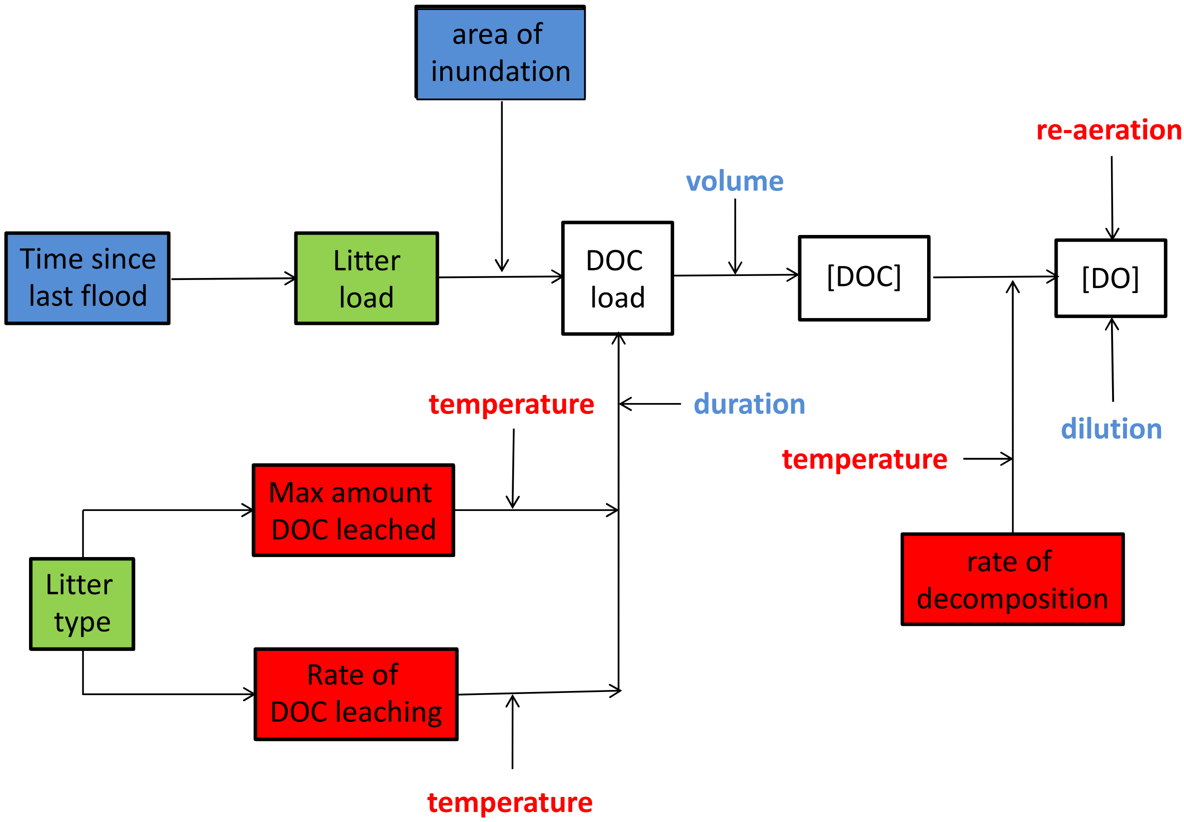

Figure 3 *Factors influencing dissolved organic carbon concentration ([DOC]) and dissolved oxygen concentration ([DO]) (modified from Whitworth and Baldwin, 2016).*

Figure 3 shows a schematic representation of the factors that influence dissolved organic carbon concentration ([DOC]) and dissolved oxygen concentration ([DO]) following the inundation of a forested floodplain. Boxes with red fill are temperature dependent; boxes with blue fill are flow/volume dependent; and boxes with green fill are vegetation type dependent; (modified from Whitworth and Baldwin, 2016).

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

Broad scale hypoxic blackwater predictive modelling has not been widely attempted and typically uses mechanistic models. Such models calculate dissolved organic carbon, and the resulting concentration of dissolved oxygen, using known temperature-dependent rate-constants for leaching, dilution, respiration, and reaeration, and operate across a floodplain of known hydrological properties. In the Murray River, The Blackwater Risk Assessment Tool (BRAT) was used. The BRAT (Whitworth KL, Baldwin DS, 2016) was developed to predict the likelihood of hypoxia resulting from discrete inundation events of a single floodplain. 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, it would not be useful to simply interface BRAT algorithms to the five 123-year time series. 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 4).

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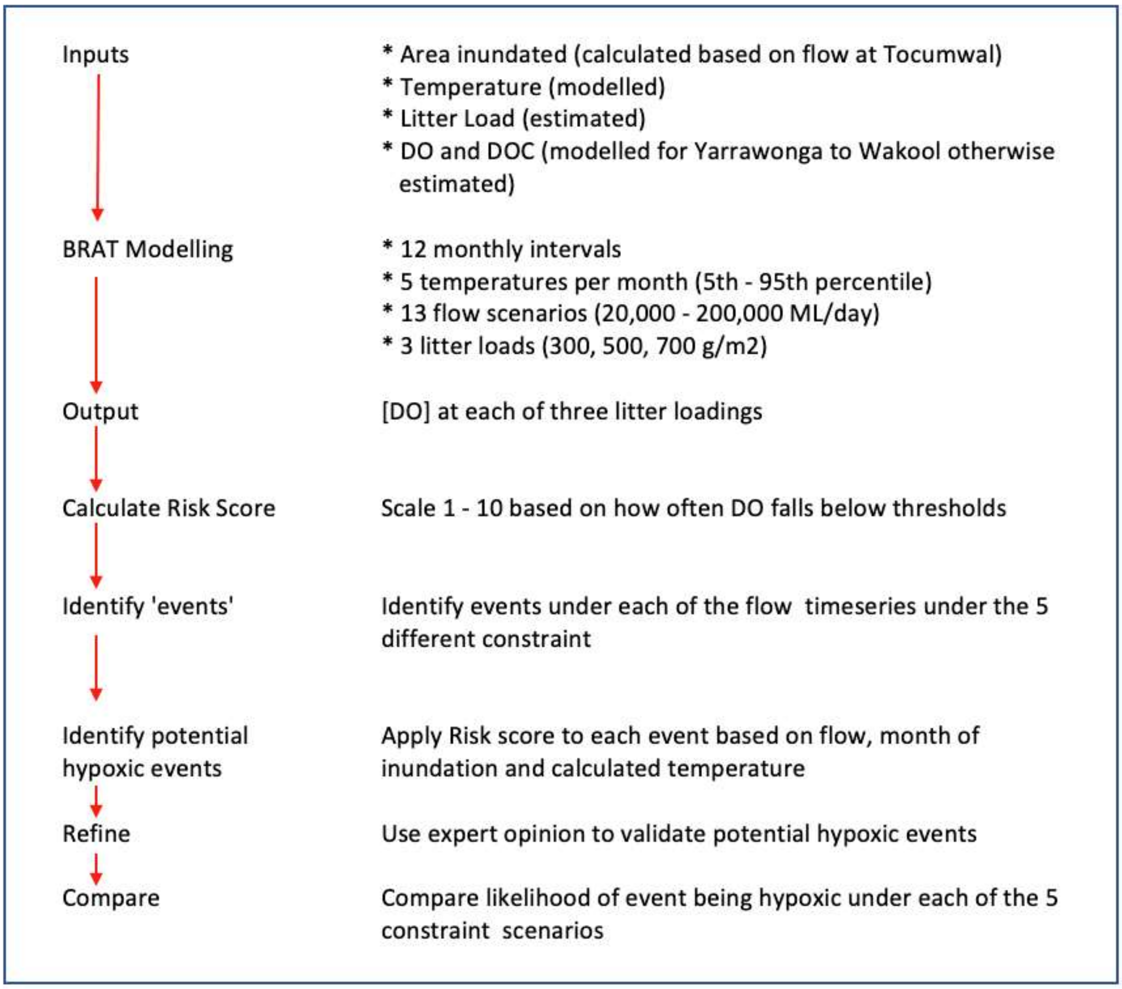

Figure 4 *Schematic representation of the steps undertaken to determine the risk of hypoxia in the Murray River following raising of constraints* (Department of Planning and Environment, in prep)

BRAT was scripted in the R coding environment (R Core Team , 2021) to allow multiple scenarios to be run within a sensible time period. Then, the area of floodplain/riparian zone inundated in each of the two reaches of interest (Hume to Yarrawonga and Barmah-Millewa Forest) was estimated based on the flow at Tocumwal. For the Hume-to Yarrawonga Reach, the flow at Corowa was estimated from the flow at Tocumwal using the Flow Peak Tracking Tool and then the area inundated was estimated using RiM-FiM output rasters based on the flow at Corowa. For Barmah-Millewa Forest the maximum inundated area was calculated using the hydrodynamic model for Barmah-Millewa Forest for flows at Tocumwal. Then, for each reach, a total of 2340 BRAT runs were undertaken based on:

- 13 different flow peaks at Tocumwal (20,000 - 200,000 ML/day);
- 12 different months (peak flow was assumed to be in the middle of the month);
- 5 different temperatures (calculated from the 5^{th}, 25^{th}, 50^{th}, 75^{th} and 90^{th} percentiles for each month for the period from 10/6/2010 until 5/2/2021); and
- 3 different leaf litter loadings (300, 500 and 700 g/m^2).

The DOC and DO concentration in the output for each scenario for the Hume to Yarrawonga reach was used as an input into the corresponding BRAT run for the Barmah-Millewa reach and used to calculate the DO concentration following the return of the flood water to the main channel. A risk score (with a value between 1-10) was assigned to each combination of flow peak/month/temperature based on how many of the three different litter loading runs produced a final DO concentration of less than 2 or less than 4 mg/L. For example, if all three runs at the different litter loads produced concentrations of less than 2 mg/L, then that scenario

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scored 10 (hypoxia was highly likely); if all three produced dissolved oxygen concentrations greater than 4, that scenario was scored 1. In all, a matrix of 780 different risk scores was produced for each reach, depending on the size of the peak flow, the month of the peak flow and temperature.

For the Hume to Yarrawonga reach, of the 780 different scenarios run:

- none produced a risk score of 10
- 3 produced a risk score of 9
- none produced a risk score of 8.

Of the three that produced scores of 9, all were at the 95th percentile of temperature and only occurred in January (2) or February (1) when it was highly unlikely that, given current knowledge, an environmental flow would be authorised. Therefore, the next step in the analysis was limited to the Yarrawonga to Wakool Junction reach.

The five 123-year-long time series (corresponding to the base case as well as the 4 relaxed constraints scenarios) were then broken down into "events":

- Events begin when flows first exceed 10,000 ML/d at Tocumwal
- Event 'peaks' occur where the discharge rate for a single day is greater than the maximum discharge rate for 7 days before and after
- Events cease after return flows from Barmah and Millewa forests are expected to have ceased (as indicated by Source model return flows for Barmah Forest)
- The overall event peak is the highest magnitude individual peak within each event.

Each hydrological event was described in terms of its maximum peak discharge, the timing (month) of that peak and median modelled water temperature. These three parameters were used to match each event to one of the scored event scenarios, rounding up or down to the nearest scenario for each parameter (peak height, timing, and temperature). For events with clustered flow peaks, the hypoxia likelihood assessment was applied to the largest individual peak in the series. The percentile temperature range for each hydrological event was determined by matching the median modelled water temperature (using a gradient tree boosting algorithm) for the event with the median observed water temperature for the same period.

Finally, 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.

Other water quality parameters – Murray River (Hume to Wakool)

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. (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.

Blackwater - Goulburn River

Mid Goulburn River Reach: BRAT modelling is based around the leaching of DOC from plant litter - especially litter from river redgums. 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 TA, 2008); (Liu XY, 2020)],

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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 Lower Goulburn River reach is dominated by river redgums - 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 – Goulburn

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.

Eutrophication

There are several definitions of eutrophication but a common feature is an increase in the biomass of photosynthetic organisms (in particular phytoplankton) in response to an increase in nutrient concentrations or loads (usually phosphorus and/or nitrogen). If the system is currently depauperate in primary production as a consequence of human interventions, then the increase in productivity can be seen as a benefit. However, from a water quality perspective, it is when excessive growth that occurs, that issues arise. Excessive algal growth can lead to substantial shifts in DO concentrations throughout any 24-hour period. During the day excessive production of oxygen during photosynthesis can lead to supersaturation of oxygen in the water column. Supersaturation of oxygen can promote gas bubble disease in fish - potentially resulting in fish mortality (Pleizer et al. 2020). At night the phytoplankton use oxygen for respiration. If the rate of respiration is high, it can lead to the point where oxygen concentrations fall below levels which are lethal to aquatic organisms such as fish.

There are several links between flow magnitude and eutrophication. Nutrients are released from floodplain soils and plant litter following inundation. Both phosphorus (Baldwin, 1999) and nitrogen (Harris et al. 2016) are leached from plant litter in an analogous way to carbon. This additional nutrient load can be exported directly back to the river or alternatively, can promote the growth of phytoplankton on the floodplain, which returns to the river channel. For example, Rees et al. (2020) recorded a net yield of total nitrogen and chlorophyll a (a surrogate for phytoplankton) peaking at about 5 and 0.1 tonnes/day respectively following an environmental flow into Barmah-Millewa Forest.

Alternatively, the increased flows can disrupt algal bloom formation (e.g., Maier et al, 2001). This is important specifically for blue-green algal bloom formation.

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

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Blue-green algal blooms

In essence blue-green algal (cyanobacteria) blooms are just a subset of the overall issue of eutrophication. Excessive growth (blooms) of blue-green algae can have the same impact on DO as excessive growth of other photosynthetic organisms, but in addition have other attributes that make excessive growth of these organisms undesirable in aquatic systems. Cyanobacteria can have impact human health through exposure to the variety of cyanotoxins (Funari and Testai, 2008; Merel et al. 2013). These toxins can cause liver, dermatological, digestive, and neurological diseases when ingested by humans and other mammals (Carmichael 2001). Recently, the amino acid BMAA, which is associated with increased incidence of neurodegenerative disease, has been identified in eight genera of cyanobacteria found in eastern Australian freshwater systems (Violi et al., 2019).

From an ecological perspective, excessive growth of blue-green algae (rather than other types of phytoplankton) can disrupt riverine food webs. In particular, fish require specific omega fatty acids for growth which they get from their food, with algae being the ultimate source of the fatty acids. Cyanobacteria lack a number of the essential fatty acids necessary for the growth of higher organisms (Müller-Navarra et al., 2000) and zooplankton feeding on cyanobacteria therefore become depleted in poly-unsaturated fatty acids and sterols (Demott and Müller-Navarra, 1997). If these zooplankton are a major component of the diet of higher consumers such as fish (e.g., King, 2005), then the consumers in turn will be depleted in those fatty acids.

For a bloom to form, blue-green algae generally require warm, still, nutrient rich water. Many blue-green algal species can regulate their position in the water column. In still water, heavier phytoplankton (e.g., diatoms) will sink. Depending on depth and turbidity, they can sink to depths where there is insufficient light for photosynthesis. At higher flows, the ability to float is negated, minimising the likelihood of a bloom forming (see Davis and Koop, 2006 for a review). If blooms do form, increased flows can be used to disrupt the bloom (e.g., Maier et al, 2001).

Salinity

Salinity is a major problem in the Murray-Darling Basin. Land-use changes (particularly the removal of large native trees and their replacement with annual crops and grasses as well as the introduction of irrigated agriculture in the arid and semi-arid parts of the basin) have resulted in the raising of saline water tables, which, in places, are high enough to impact on the root zones of plants and/or be intercepted by wetlands and creeks.

Increased flows have the potential to increase the export of salt from floodplains (Jolly et al, 2012), through leaching of surface deposits of salt, mobilisation of salt that has accumulated in low lying areas of the floodplain (e.g., wetlands and creek channels) and, through exchange with salt in shallow aquifers.

Turbidity

Turbidity is a surrogate measure of how much material is suspended in the water column. The main impacts of high turbidity levels include:

- Lower light penetration through the water column, decreasing overall riverine productivity
- A shift towards blue-green algae as the dominant source of primary production
- Smothering of benthic organisms, include submerged macrophytes
- A decrease in benthic habit diversity through the infilling of cracks and crevices.

High levels of turbidity in the southern Murray-Darling Basin are related to European settlement (Rutherfurd et al. 2020). These activities include land clearing, sediment mobilisation through mining activities (especially in the mid to late 1800's - Davies et al. 2018) and delivery of irrigation water. Furthermore, the introduction of carp into Australian waterways has also led to localised increases in turbidity. One mode of feeding of carp is mumbling, where the carp forage in the sediments looking for food.

Environmental water in the southern Basin is usually delivered from headwater or mid-level water-storage reservoirs. Because the water retention times in these reservoirs are relatively long, sediments are deposited in the reservoir rather than exported downstream. For example, the turbidity immediately below Lake Hume (Site 409016 - Murray River at Heywoods Bridge) rarely exceeds 10 NTU. Even following substantial inflows of sediment into Lake Hume following the Black Summer bushfires (Baldwin, 2022) hasn't exceeded 20 NTU, except on one occasion in mid-May 2020 when it peaked at 36 NTU. There is a possibility that the

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environmental water will increase bank erosion downstream, but not to the same extent as the delivery of irrigation water (McInerney et al., 2022).

Weir Pool stratification/destratification

Under no- or very low-flow conditions, waterbodies can stratify. The surface water heats up at a faster rate than deeper water leading to a state where these is less dense (warmer) water sitting above more-dense (cooler) water. If this condition persists for any extended period of time (days or weeks) the DO concentration begins to decline because the oxygen is consumed through respiration (mostly microbial respiration in the underlying sediment). Because of lack of mixing between the two layers, DO is not replenished from the atmosphere and eventually reaches a point where there the bottom layer become anoxic. Once oxygen is consumed in the bottom layer, nutrients begin to be released from the sediments to the overlying water column.

The strength of the stratification will depend to a large extent on the thermal energy supplied to the surface water from the atmosphere. However, under the right condition the stratification can break-down (e.g. Bormans and Webster, 1997). This can occur if there is a sudden drop in air temperature, cooling the surface water, because of strong winds and/or flow increases. When this happens the two bodies of water mix quite quickly causing the DO concentration throughout the water column to fall. How low it falls depends on both the relative volumes of the surface and deeper pools of water and, the DO concentration in both layers. Recently, destratification events have been linked to fish kills in the both the Murrumbidgee River (Baldwin 2019) and the Darling Rivers (Baldwin 2020). Persistent higher flows should limit the formation of stratification, but if the flow is increased following a period of stratification, it can lead to a destratification event.

Acid sulfate soils

Acid sulfate soils is the generic name given to soils or sediments that contain either sulfide minerals or sulfide minerals that have subsequently oxidised (EP&HC and NRMMC, 2011). Until recently, it was believed that acid sulfate soils did not occur in inland environments, but such soils have now been identified throughout inland Australia (EP&HC and NRMMC 2011), including the Murray-Darling Basin (MDBMC, 2011). Acid sulfate soils are formed under waterlogged (anaerobic) conditions, when a group of bacteria converts sulfate associated with inland salt deposits to sulfide. The sulfide can then react with metals, particularly iron, to form sulfide minerals and when these mineral sulfides are exposed to oxygen, they oxidise and produce acid (pH levels of less than 2 have been recorded in wetlands associated with the lower River Murray (McCarthy et al., 2006; MDBMC. 2011)). The ultimate source of the sulfate is usually from salt, so that salinisation of a waterbody and the formation of acid sulfate soils are usually linked.

The principal risk of higher flows inundating acid sulfate is the mobilisation of acid from the acid sulfate soils to the overlying water. However, it can also lead to deoxygenation and the mobilisation of heavy metals as well (EP&HC and NRMMC, 2011).

Thermal pollution

Unless a dam has a multi-level offtake, water releases from water storages tend to be from offtakes at the bottom of the dam. Large dams tend to thermally stratify for extended periods over the summer months. Therefore, the water released from the bottom of the dam in summer can be substantially colder than it would have been if the dam didn't exist. The plume of cold water can persist for hundreds of kilometers downstream of the dam.

Native Fish

Murray River

As previously outlined, the assessment of potential benefits to native fish from the relaxing of constraints was based on work completed for the NSW RRC Program (Todd et al. 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.

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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 work has been 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 below.

Ecological response modelling

Ecological response models were developed by Horne et al. (2020). These models were developed to have sufficient detail to show relative outcomes to different flow scenarios, and included the following key components:

- Ecological models were developed during stakeholder workshop, and then documented and refined with technical experts
- Conceptual models were translated into conditional probability networks using a formal expert elicitation process
- Surveys with technical experts were used to elicit predictions of the effects of environmental flows on fish (and a wider range of ecological objectives not considered in this assessment), and to identify potentially relevant datasets
- Aggregated predictions from experts became the prior probability distribution to parameterise the models
- Bayesian modelling was used to incorporate monitoring data into the models, creating a posterior modelled output driven by expert knowledge and data. Models were documented within the software package Netica.

An external flow scenario tool was developed to predict fish responses across a range of constraints relaxation scenarios in the Mid Goulburn and Lower Goulburn River (John et al. 2022). Outputs of this model are presented in the form of a stress index, where a positive stress index value indicates better performance of the relaxed constraints scenario compared to the base case. A negative stress index value indicates a predicted poorer ecological response from relaxing constraints, compared to the base case.

VEFMAP monitoring and stochastic population modelling

VEFMAP is a large-scale monitoring and research program exploring responses of fish (and vegetation) to changes in hydrology in general and environmental flows more specifically in systems across Victoria (Tonkin et al. 2020). Three components of VEFMAP are relevant here.

The first component of VEFMAP used here is stochastic population modelling to predict long-term trends and risk to Murray Cod and Silver Perch in the Goulburn River (and Campaspe River) under a range of managed flow scenarios. Broadly speaking, the methods for these models follow those described for the RRCP NSW project (Todd et al. 2022) and involved the following steps:

- developing and updating conceptual models of how the two species respond to changes in hydrology via several workshops with expert fish ecologists and managers
- applying this knowledge to adapt the population models to each reach and hydrological scenario
- incorporating responses of the two species to changes in flow and water temperature
- including the effects of flow on riverine productivity and anoxic blackwater events (for Murray Cod)
- defining and reporting ecological benefits of modelled hydrological scenarios

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- model sensitivity analysis to explore how different assumptions might influence predicted outcomes

Murray Cod were modelled as existing in a single population, whereas Silver Perch were modelled as existing in a metapopulation with connections to the lower connected Murray River with immigration and emigration to and from the Goulburn and Campaspe Rivers as well as other reaches of the Murray and Lower Darling.

The models compared population trends and risk in each population from 2004-2019 under the following scenarios:

- current flow and stocking as they have occurred (Actual)
- current flow without environmental water allocation - EWA (No EWA)
- current flow recommendations, had they been implemented each year (Current EWA Recs)
- current flow with the recent levels of summer inter-valley trade - IVT - observed: 9 in 15 years of summer IVT and 13 in 15 years of high summer IVT
- current flow and no stocking (No Stocking)

The second components of the VEFMAP program used was a study (Tonkin et al. 2021) undertaken to assess the annual recruitment strength (measured as the relative abundance of fish belonging to a year class) of Murray Cod in five rivers in the south-eastern Murray-Darling Basin (the Goulburn River, along with the Murray, Ovens, King and Broken Rivers) between 1999 and 2019. Monitoring data were used to test various hypotheses linking recruitment strength with key attributes of the flow regime.

The third component of the VEFMAP program was a study (Tonkin et al. 2020) undertaken to examine the movement of Silver Perch between the Murray River and two tributaries, the Goulburn and Campaspe River. Fish were collected ascending the Torrumbarry fishway on the Murray River between February 2017 and February-April 2019 and tagged. Acoustic listening stations were deployed and fish movement characterised. Generalised additive mixed effects models (GAMMs) were then used to explore the influence of environmental variables (including river discharge) on the probability of tagged Silver Perch moving in the Murray River and entering a tributary and the time spent in a tributary.

Long-term monitoring programs
Monitoring has been undertaken in the Lower Goulburn River since 2003, initially funded (2003-2006) through the Recreational Fishing Licence (RFL) fund, the Goulburn Broken Catchment Management Authority (2006-2013), and subsequently through the Long-Term Intervention (LTIM) and Flow MER (Webb et al. 2021) programs. This monitoring has involved annual population surveys (using electrofishing and netting) and surveys of eggs and larvae (using drift nets).

Geomorphology

A detailed analysis of erosion likelihood and mechanism along the Goulburn and Murray Rivers was beyond the scope of this study. Instead, changes in erosion potential have been assessed using the concept of total effective geomorphic work. Total effective geomorphic work can be thought of as the energy the river applies to the bed and banks (which drives erosion). Effective work is undertaken when the erosion forces of the flow are larger than the inherent resistance forces of the channel. Flow is considered ineffective below this threshold as sediment is not mobilised, erosion does not occur, and the channel remains unchanged. The overall steps in our 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.

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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 5). 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 (Figure 6).

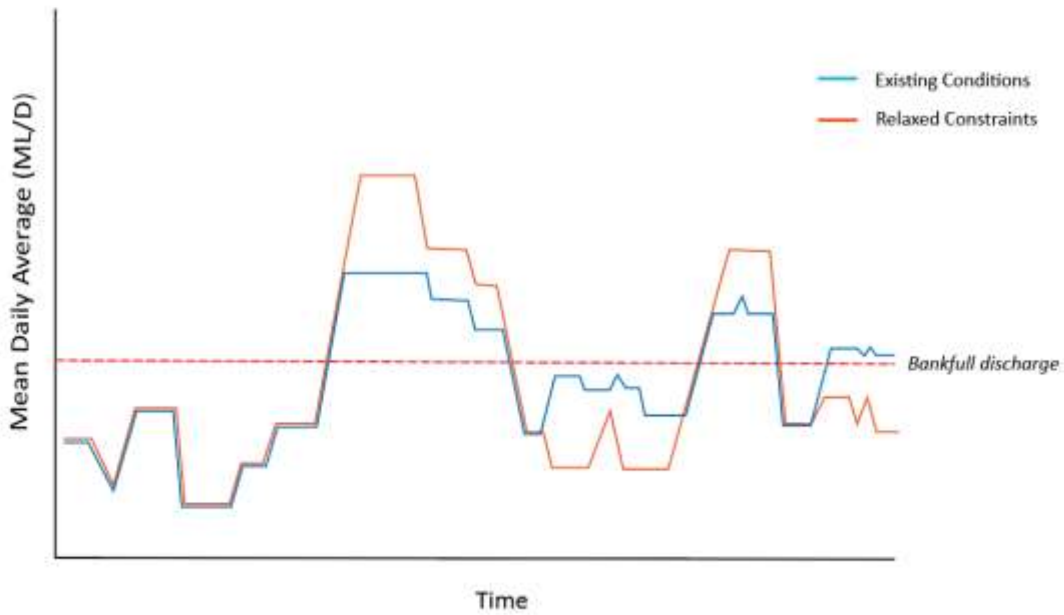

Figure 5 *Example flow conditions*

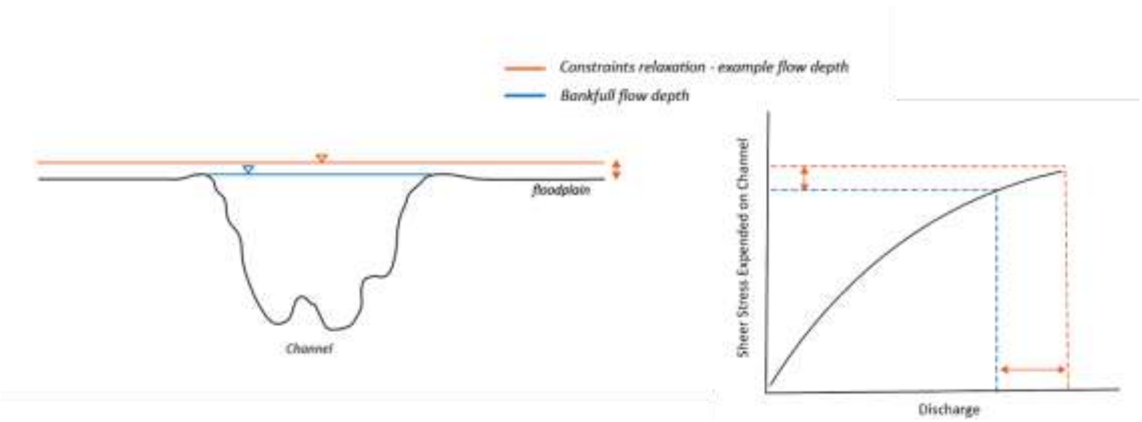

Figure 6 *Example shear stress scenario*

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 7).

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In this way, over time, geomorphic work is re-distributed from the channel to the floodplain. It is this re-distribution that has the potential to lead to a decrease in bed and bank erosion.

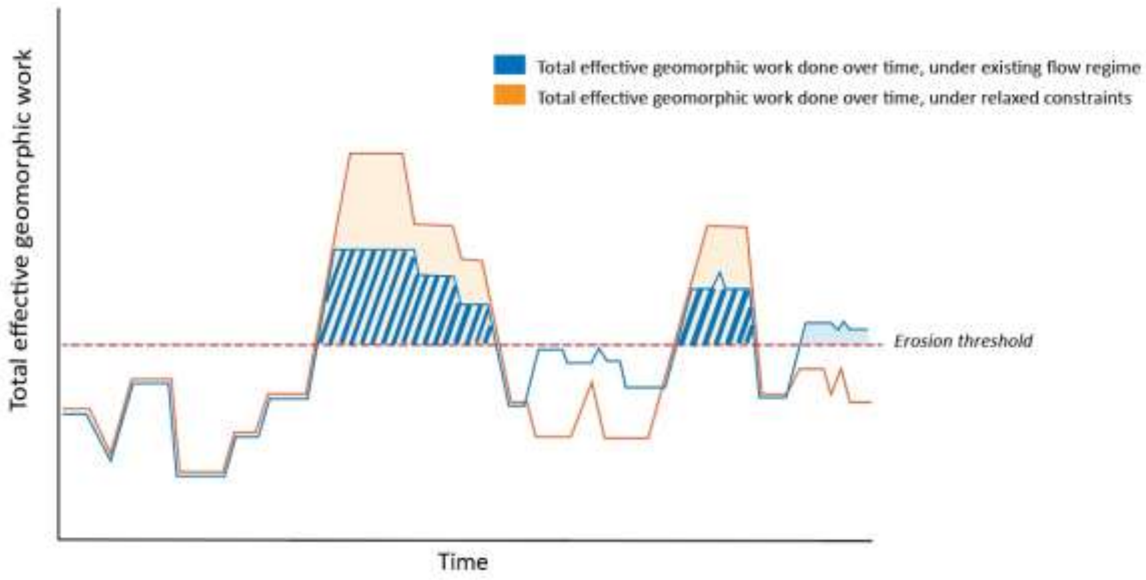

Figure 7 *Example geomorphic work scenario*

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

We quantified total effective geomorphic work (the area under the curve in Figure 7) by calculating an Erosion Potential Index (EPI) for each scenario for the Lower Goulburn River only. We used the four scenarios of the Lower Goulburn River 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. We also calculate simple flow statistics for the Lower Goulburn River, so that the proportion of flow delivered over bank and in-channel under each scenario can be compared to the relevant EPI value. By establishing the link between these simple flow statistics and the calculated EPI values, we are then able to apply the same statistical analysis 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 are normalised so that the natural (pre-development) flow regime has an EPI value of 1.0. An EPI of greater than one indicates an increase in total effective work compared to natural (without development) conditions, and an EPI of less than one indicates a decrease in total effective work compared to natural (without development) conditions.

The EPI approach requires three main inputs:

- A continuous simulation hydrologic model that provides a flow series for each study reach at a daily timestep, for natural (without development), current and each constraints relaxation scenario.
- A one-dimensional hydraulic model for a representative segment of the study reach, that converts flow magnitudes into shear stress values at each cross section within each reach.
- A critical shear stress threshold below which significant sediment transport does not occur.

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For this assessment, we calculated a single EPI value for each scenario, using modelled daily timestep flow data for the 123-year period data was available. The steps in our analysis are:

1. A one-dimensional hydraulic model was developed for a segment of the Lower Goulburn River, downstream form the McCoys Bridge gauge site.
2. A series of flows at magnitudes that range between baseflow and overbank flows at least as large as the largest constraints relaxation scenario were input to the hydraulic model. The cross-section averaged shear stress was extracted for each cross-section, for each flow and then averaged to produce a single shear stress value for each modelled flow rate. Shear stress has units of N/m^2 and is a measure of the forces imparted by flowing water against the channel bed and banks.
3. Flow magnitude was plotted against the corresponding shear stress values and a linear rating curve fit to the series. The equation of this line (e.g., $0.0264x^{0.759}$ in Figure 8) can then be used to derive a shear stress value for any given flow rate.
4. The flow-shear stress rating curve was applied to the daily flow data, to calculate a single shear stress value for each day of the time series.
5. Finally, a constant shear resistance threshold of 10 N/m^2 (which corresponds to the shear stress required to mobilise cohesive sediment on the channel bed and banks) was assumed for all cross-sections for all timesteps. Daily shear stress values that fell below this threshold were filtered from the data series. The remaining daily shear stress values were then summed to produce a single measure of total effective geomorphic work (also units of N/m^2) for each scenario.

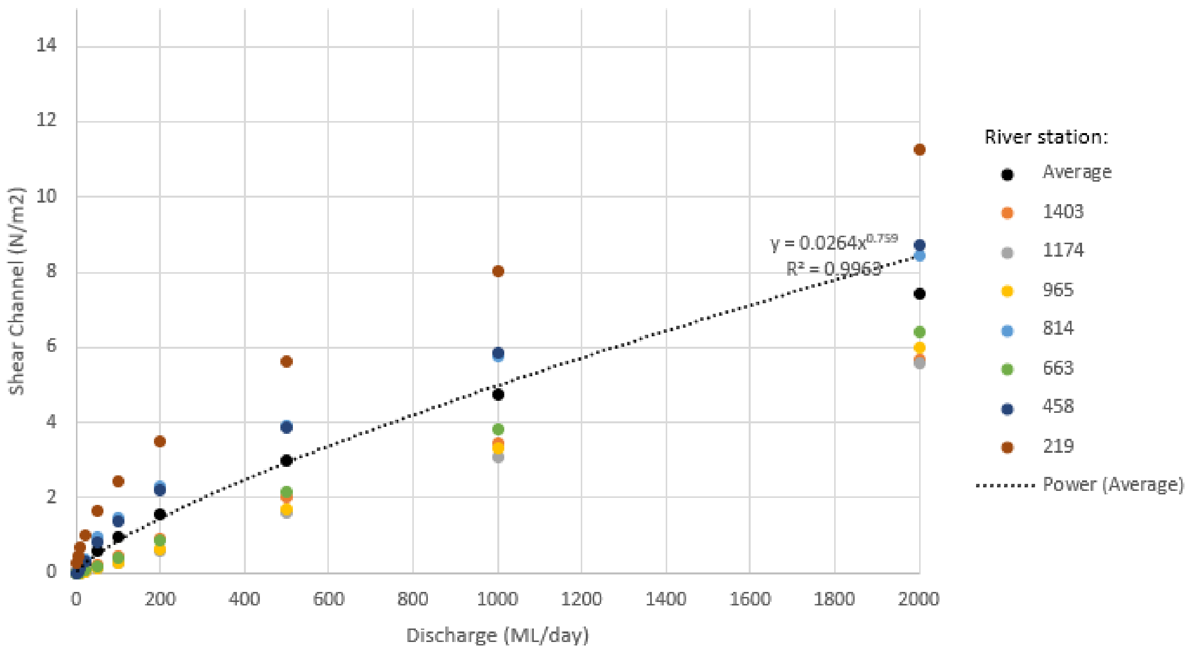

Figure 8. *Shear stress values for given flow magnitudes, resulting from hydraulic model with trendline.*

The ratio between this erosion potential for the natural flow series versus the current, or scenario flow series provides the Erosion Potential Index.

$$EPI = \frac{EP_{natural}}{EP_{scenario}}$$

Where:

- *EPI* is erosion potential index
- $EP_{natural}$ is erosion potential under natural flow conditions
- $EP_{scenario}$ is erosion under scenario flow series (or current flow series)

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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 EPI is greater than one the analysis indicates erosion is likely to occur.

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Attachment 2: 'Do nothing more' scenario

The assessment has focused on the potential effects of relaxing constraints using current conditions as the base case. The current condition represents the outcomes of implementation of The Living Murray and some elements of the Basin Plan. This 'do nothing more' paper provides a discussion on the current condition of the systems, and how things would change over time should the Victorian Constraints Measures Project not proceed.

Regulation of the Goulburn and the subject reaches of the Murray River have led to a decrease in the occurrence of overbank events. The rivers are now used to deliver consumptive (and more recently, environmental water) via the river channel, below bankfull. The use of the river for the supply of consumptive water supply and delivery of environmental water has increased the erosive 'work' done by available water on the riverbed and banks. Rather than a portion of the energy contained in over bank events being expended on the floodplain, those flow events are now contained in the river channel and the energy associated with that water contained and retained in the river channel. The process of regulation of the Murray and Goulburn Rivers has effectively increased the 'work' on the riverbank (Tilleard and Ford, 2016). In gravel bed rivers such as the Murray and Goulburn Rivers, this has led to increases in channel erosion. Under the base case and in the absence of management intervention, bank erosion will continue at accelerated rates. Accelerated rates of bank erosion will have implications for populations of species dependent on bank habitat including aquatic plant, fish, and platypus.

On the floodplain, changes to flooding regimes will influence patterns of sedimentation and habitat that will lead to the terrestrialisation of floodplains. In some instances, this will take hundreds of years as long-lived trees will persist, however, understory species will change more rapidly as they are outcompeted by terrestrial species and also as the lack of flooding means that fewer seeds in the seedbank will respond to inundation. Many of the species of flood dependent, amphibious or flood tolerant species provide important habitat (foraging and breeding) and food resources, with several species of water bird such as Spoonbills and Ibis relying on reeds to build their nests, while swans and many ducks are dependent on aquatic plants for their food.

There are also several species of fish dependent on floodplain habitats to either complete their life cycle or as a supplementary source of food. As an example of a species that would benefit from floodplain inundation, Eel-tailed catfish have a complex life cycle in which individuals move into wetlands to breed, but then young catfish move back to the river to feed and disperse (Stoffels et al. 2013). Small native fish such as carp gudgeons have been found to move into wetlands and breed in response to increases in flow and that this may be associated with the abundant food available in the wetland (Jarod et al. 2010; Beesley et al. 2014). Reducing or eliminating flooding will deprive these fish species of critical habitat leading to population declines. Species that rely on floodplain habitats to complete their lifecycle will also decline over time. Species who complete their lifecycle within the channel may also experience declines due to reductions in the quantity or quality of food. This severing of a food source impacts the larger food web, from the macroinvertebrates at the base of the food web through small fish and crustaceans up to the birds and platypus that feed on the fish and smaller invertebrate species.

In many ways some of the changes forecast appear manageable from a risk perspective. However, this perception is created by gradual changes and consideration of averages. Climate change is forecast to lead to greater extremes and so the capacity of the system to respond to more intense and longer droughts, larger but shorter floods and increases in fire need to be considered.

The impacts of the millennium drought provide important insights into some of the risks. One example of the impacts of changes in climate is the number of native fish species at Gunbower (Figure 9), where 2011 (the end of the millennium drought) was associated with a dramatic decline in native species abundance (Brown and Whiterod, 2021). An examination of floodplain bird responses to the return of wet conditions revealed that of 67 species, 55% declined during the drought. Of these, 37% showed no recovery with the return of wet conditions and 10% continued to decline (Selwood et al. 2015a). Before regulation and climate change, waterbirds could capitalize on opportunities anywhere in Australia (Roshier et al. 2001; Arthur et al. 2012), however, large scale changes now mean that effective conservation of waterbirds will depend on every region doing what it can, when it can to provide the breeding and foraging habitats that they and other species need to

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survive (Reid et al. 2013). Within this context, floodplains may be particularly important, not just for water birds but for terrestrial species as well by providing refuge (Selwood et al. 2015).

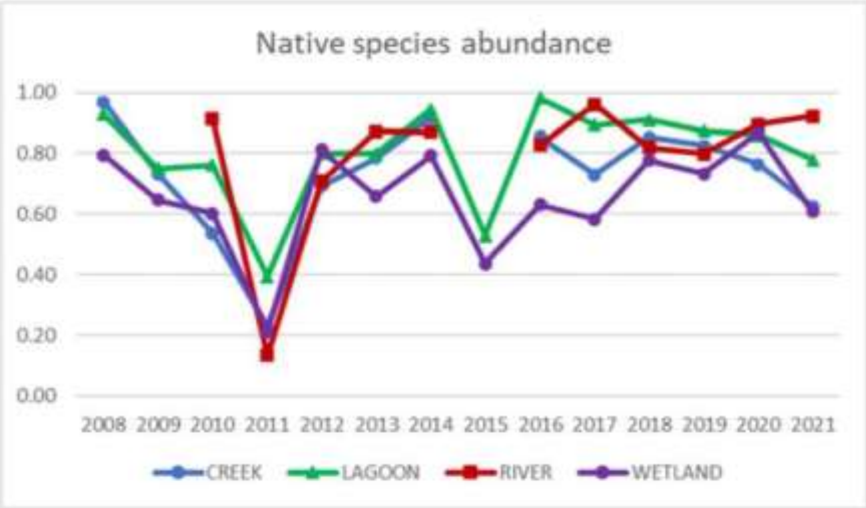

Figure 9 *Mean Native species abundance scores in Gunbower TLM Icon site by macrohabitat. Sampling only started at RIVER sites in 2010 and there were no CREEK or RIVER samples in 2015. (Source: Brown and Whiterod 2021)*

If the millennium drought was merely a harbinger, then these results suggest that every drought will undermine the conservation status of species in a cycle that would ultimately leave only a small number of hardy, adaptable species, potentially favouring introduced species. It is likely that severe events like the Millennium drought would be associated with major declines in native species and that there would be limited recovery afterward, as has been identified in the assessments of bush birds at Barmah and waterbirds in the Goulburn River. Environmental flows will be critical to sustaining biodiversity through a range of pathways, including ensuring that ecosystems are event ready to capitalise on booms associated with naturally occurring floods, maintaining habitats and connections to enable species to complete their life cycle and protecting refuges to ensure species endure extreme events and that their recovery is subsequently supported.

The do-nothing scenario would see environmental flows confined to the main channel of major tributaries. Given that most of the species that the environmental delivery would be seeking to protect are resident on the floodplain, and that all but a few of the species resident in the main channel are also either dependent on or heavily influenced by connections to the floodplain, it leaves the water delivery powerless to counter the feedback loop of severe decline that currently exists in both river systems and cross the basin.

Continued delivery of environmental water in the river channel will contribute to ongoing accelerated channel erosion, while potentially increasing the occurrence of unplanned spills due to reduced availability of dam capacity, including overbank events in summer. These late season spills floodplains can increase carbon load to rivers creating an increased threat of water quality issues and create flooding of platypus and turtle breeding sites.

Any potential buybacks are likely to be stored behind Hume or Eildon Dams. Higher volumes of environmental water held behind the dams would then need to be released, either to ensure airspace in the lakes to aid in flood mitigation, or to allow the environmental water to achieve the benefits in the downstream reaches. The need to release stored water combined with the inability to spill these flows overbank will lead to an increase in the frequency and/or duration of flows that are large enough to trigger erosion, but small enough to remain in-channel. The results are a potential increase in erosion potential, which would exacerbate existing erosion issues within the Murray and Goulburn Rivers.

Environmental flows have demonstrated that they have effectively protected ecosystems where they have been delivered. What they have not achieved to date is to restore some of the species lost through the combined effects of river regulation, land use, introduced species and drought. What they will never do is achieve

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outcomes in ecosystems to which they are never allocated. The intrinsic interconnected nature of freshwater systems means that the failure to protect, let alone restore, important ecosystems will have repercussions for the rest of the system, in this case, the main channel of the Goulburn and Murray Rivers and downstream floodplain-river ecosystems.

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Attachment 3: Panel based reach assessment

The environmental benefits and risks assessment team and an expert panel met on July 12, 2022 to discuss predicted environmental benefits and negative impacts of relaxing constraints within the designated study reaches.

Attendees at the workshop included:

- Ben Gawne (Alluvium)
- Ross Hardie (Alluvium)
- Alex Sims (Alluvium)
- Kate Brandis (UNSW)
- Gilad Bino (UNSW)
- Josh Griffiths (envirodna)
- Darren Baldwin (Rivers and Wetlands)
- Andrew John (University of Melbourne)
- Luke McPhan (La Trobe University)
- Rob Hale (Arthur Rylah Institute)

As part of this workshop, the panel were invited to add content (sticky notes) to a mural board indicating the magnitude of expected benefits and adverse impacts to environmental values for each flow scenario. Experts generally commented within their field of expertise. Expert 'confidence' in their assessments were also recorded. Mural board responses were then discussed as a group, where experts could further clarify their sticky notes and share the broader context of their responses.

Expert assessments from the Workshop 1 mural board are summarised for each study area reach in Table 2 - Table 5. Blue shading indicates a system/value benefit. Red shading indicates a negative impact. The depth of colour reflects the magnitude of predicted benefit/impact. White shading indicates no change from current scenario. Grey shading indicates that no assessment was provided. The experts' level of confidence in their assessment is indicated by the number of plus symbols (+ low, ++medium, +++ high).

Table 2. *Murray River benefits/impacts between Hume Dam and Yarrawonga identified in Workshop 1*

Theme	Value	Constraint Scenario			
		Y25D25	Y30D30	Y40D40	Y45D40
Water Quality	Hypoxic Blackwater				+
Fish	Murray Cod	++	++	++	++
	Trout Cod	++			
	Golden Perch	++	++	+++	++
Vegetation	General	++	++	++	++
	Colonial Waterbirds			+++	
	Waterbirds (Gunbower KP)				++
	Waterbirds (Barmah-Millewa)				+++
	Waterbirds (other)				++
Geomorphology	Anabranches			+	+
	Bank Erosion	+++	+	+	+

Colour coding: Adverse Impact Benefit Grey = N/A
Confidence in assessment: + low, ++ medium, +++ high

Table 3. *River Murray Benefits/Impacts from Yarrawonga to Wakool Junction identified in Workshop 1*

Theme	Value	Constraint Scenario			
		Y25D25	Y30D30	Y40D40	Y45D40
Vegetation	General	++	++	++	++

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Theme	Value	Constraint Scenario			
		Y25D25	Y30D30	Y40D40	Y45D40
	Trees	+++		+++	+++
Water Quality	Hypoxic blackwater	++	++	++	++
Geomorphology	Bank Erosion		++		
Birds	General		++		+++
Productivity	Gross Productivity				++

Colour coding: Adverse Impact Benefit Grey = N/A

Confidence in assessment: + low, ++ medium, +++ high

Table 4. *Environmental Benefits/Impacts in the Mid Goulburn Identified in Workshop 1*

Theme	Value	Constraint Scenario			
		M10L17	M10L21	M12L21	M14L25
Platypus	Platypus	+			+
Hydrology	Flow Regime	+++			
Geomorphology	Bank Erosion	+++	+++	+	+
Fish	Carp (invasive)		+++	+++	+++
Birds	Waterbirds		+++		
Vegetation	Floodplain			++	

Colour coding: Adverse Impact Benefit Grey = N/A

Confidence in assessment: + low, ++ medium, +++ high

Note: An adverse impact for carp reflects an increase in carp breeding in the Barmah-Millewa Forest, which is an adverse impact at a system level. A negative impact on erosion indicates that erosion is worsening.

Table 5. *Environmental Benefits/Impacts in the Lower Goulburn Identified in Workshop 1*

Theme	Value	Constraint Scenario			
		M10L17	M10L21	M12L21	M14L25
Geomorphology	Bank Erosion	+	+	+	+
Vegetation	General	+++			
	Floodplain		+	+	++
Hydrology	Flow Regime	++	++		
Fish	General		++		
Turtles	General		+		
Platypus	Platypus				+
Macroinvertebrates	Macroinvertebrates				+
System	System				+

Colour coding: Adverse Impact Benefit Grey = N/A

Confidence in assessment: + low, ++ medium, +++ high

Summary of discussions from Workshop 1:

River Murray

Waterbirds: Empirical data used in modelling suggested strong positive association between waterbird parameters (abundance, species diversity, breeding behaviours) and inundation in the Barmah-Millewa Forest, generally related to the quality of bird habitat. Although the upper quartiles of modelled bird parameters were not influence by relaxing constraints, the lower quartiles were improved. This suggests that constraint relaxation may increase the minimum capacity of the reach to support waterbird populations.

Floodplain vegetation: Discussions centred around the construction of the model based on expert elicitation and available literature. Mural board responses suggested substantial benefits to vegetation in both Murray River study reaches, particularly in drier times.

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Native Fish: Stochastic population models were used to predict fish responses. Modelling suggested that Murray Cod populations would remain unchanged if constraints were relaxed. Golden Perch are more mobile than Murray Cod and are flow-responsive, hence constraint relaxation was expected to provide moderate benefits to Golden Perch metapopulations.

Erosion: Erosion impacts are greater when flows remain in channel. Conceptually, if constraints are relaxed water flows onto the floodplain and decreases 'work' done by water on the channel itself.

Platypus: Quantitative platypus assessments have been hampered by a lack of quantitative models and data. Platypus impacts can perhaps be inferred qualitatively, through assessed impacts on erosion, fish and macroinvertebrates.

Expert confidence: The preponderance of 'medium confidence' assessments was due to (1) limitations regarding spatial resolution and processing power, which may affect interpretation of data at fine scale (2) limitations in applying the 'commenced to fill' inundation layer across all vegetation, when only a small proportion of vegetation may inundated (3) The use of BRAT model for blackwater risk analysis, which had a sub-optimal hydrograph and is complicated by a flow mismatch, where constraints flows are considerably lower than those usually associated with blackwater events. It was noted that some experts had high confidence in between-scenario comparisons.

Goulburn River

A Goulburn River model (SGEFM) developed for a 2018-2022 linkage project was used to assess benefits/risks across a range of flows in the Mid and Lower Goulburn. The flow scenarios were linked to Bayesian Networks that had been developed for 12 ecological values, and the model outputs were in the form of a stress index, that reflected performance of relaxed flow scenarios relative to current constraints.

Modelled results and flow recommendations highlighted >20,000 ML/day as delivering benefits across multiple values, although these individual benefits were not represented on the mural board.

Periodic fish (such as Golden Perch) saw benefits. Other values had mixed outcomes, depending on the combination of flows in the Mid Goulburn and Lower Goulburn River.

The modelling predicted that bank stability and littoral vegetation could see worse outcomes with relaxed constraints. Negative outcomes were also predicted for turtles, although the combining of three turtle species into a single assessment category when each with different habitat requirements was overly simplistic. There is a need to understand the requirements of each turtle species, and to consider the impacts of flow timing and foxes, if the project is to proceed to a business case. It was also noted that the timing of flows impacted the predicted ecological responses, for example inundation of turtle and platypus nesting sites during nesting seasons would negatively impact populations. The Goulburn assessment team stated that it was difficult to find a flow schedule that would benefit all themes/values. For example, flow regime timing that benefits fish may negatively impact platypus populations. System-wide benefits/impacts of relaxing constraints will be dependent on hydraulics and floodplain residence time, which should be modelled if the project was to proceed to business case.

Overall Assessment:

A summary of participant overall perceptions of benefits / impacts generated in workshop 1 are shown in Figure 10. Overall, relaxing constraints would mostly provide benefits in the Murray and Goulburn Rivers, with differing degrees of likelihood and significance. Responses suggested a low likelihood of adverse impacts on Hydrology in the River Murray and to Birds and some freshwater ecosystems in the Goulburn River.

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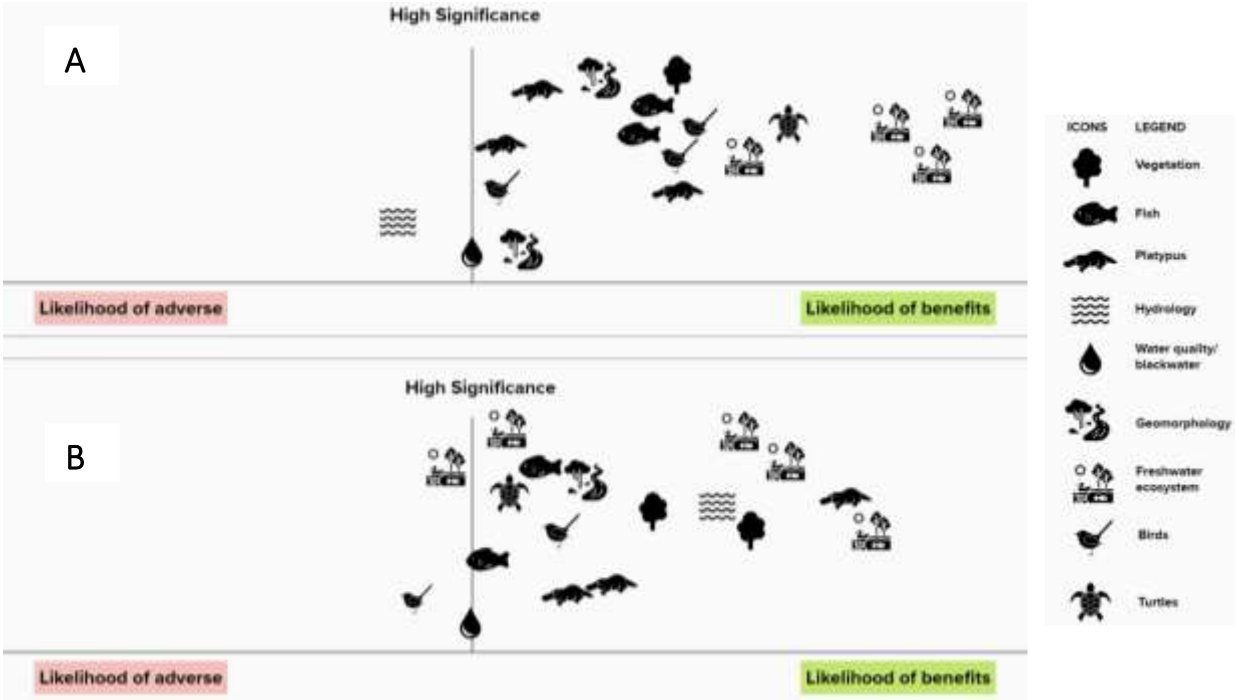

Figure 10 *Participant overall perceptions of environmental benefits, recorded at the end of workshop 1. Participants were invited to record responses of the likelihood of benefits/adverse impacts and how significant benefits/adverse impacts may be in (A) the Murray River and (B) the Goulburn River.*

Further investigations identified from the expert panel workshops

The following comments and suggestions were made in the second expert workshop regarding how confidence in system-wide and downstream assessments could be improved if proceeding to a business case.

Water quality

- Assessments could include carbon export as a benefit to productivity
- Assessments need to consider inputs from the Murrumbidgee

Birds

- Identification of suitable waterbird habitat downstream, and who uses it and how, would help inform likely waterbird responses
- More information is required on relationships between downstream flows and waterbird responses.

Native fish

- Understanding fish movement across the integrated Murray-Darling Basin is important

Riparian vegetation

- A spatial assessment of predicted inundation areas overlaid on vegetation mapping in the lower Murray should be conducted.
- A risk assessment of riparian weeds is required, including a review of how applicable the Griffith University study is to the lower Murray
- Vegetation diversity across catchments will be variable across floodplain inundation thresholds (e.g., black box more representative in downstream locations) and should be kept in mind when considering "vegetation response" in future assessments
- Modelling of vegetation responses to constraints relaxation scenarios downstream of the study area should be performed.

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Wetland and floodplain vegetation

- Largely the influence of attenuation. For sites downstream will mean the variation in response to constraint options downstream of the reaches Hume-Yarrawonga & Yarrawonga-Wakool will be negligible without additional allocated flows.
- Currently the influence of rainfall and groundwater are not captured in the models, nor is an assessment of water residence time on the floodplain. Our findings are more certain for vegetation that is flood dependent, meaning responses of vegetation at lower thresholds are likely more accurate.
- Vegetation diversity across catchments will be variable across floodplain inundation thresholds (e.g., black box more representative in downstream locations) and should be kept in mind when considering "vegetation response"
- Scenarios where coordinating and combining flows from additional systems could achieve inundation of the floodplain (e.g., Murrumbidgee) should be modelled
- Modelling of vegetation responses to constraints relaxation scenarios downstream is recommended
- Determination of how applicable the weed risk assessment done by Griffith University is to the lower Murray is recommended
- There may well be thresholds such as where some areas of floodplain fill and then retain water for a period, or where certain vegetation types associated with mid floodplain elevations get inundated. It is unclear to what degree this has been studied in the lower Murray

Geomorphology

- Hydrologic modelling and hydraulic modelling should be extended downstream of the Wakool and then analysis techniques such as EPI should be applied
- Improved confidence in assessment will rely on improved understanding of how EEWD will coordinate delivery of environmental flows

Platypus

- Delivery of environmental flows during winter and spring are likely to be beneficial, however, using the additional channel capacity to deliver consumptive water over summer would be detrimental to platypus breeding. The risk of out of season high flows should be investigated further.
- A long-term monitoring program for platypuses should be established

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Attachment 4: Implications from updated hydrologic modelling

The hydrologic modelling used to inform the ecological modelling and assessments included in the environmental risks and benefits assessment comprised daily time step Source water balance models for the Goulburn and Murray Rivers. Details of the modelling can be found in Section **Error! Reference source not found.** of the report and associated references.

The modelling included only preliminary model results for the Goulburn River. Subsequent to the ecological response modelling undertaken for this assessment, final hydrologic model runs were undertaken for the Goulburn River. It has not been possible within the time constraints for this feasibility assessment to re-run the ecological response modelling with the updated hydrologic modelling results for the Goulburn River.

Following the completion of the hydrologic modelling, the results have been able to show only one major change from the targets that were used in the previous version of the model. In previous modelling the yearly target for delivery was two winter/spring fresh event, where the updated version reduced that target to one. It is important to note that the updated results have not been used in the modelling that has been completed for this investigation, however it may be possible to make assumptions about what the change may cause.

For instance, the vegetation response modelling that has been completes had a minimum time step of drop in phase (degraded quality) of one year without watering, and a minimum time step of increase in quality of one year. If it can be assumed that the change in delivery target from twice a year to once a year does not result in an increase of missed years, the difference is likely to be small. The single delivery may result in the fixed window of a year passing briefly before delivery, resulting in a potential drop in phase in some areas before returning to the original phase, appearing in the results as an increase in variability. Overall, this change is unlikely due to the changes in model targets being limited to winter/spring fresh deliveries.

The main change likely to be seen is a reduced watering of littoral vegetation. This will have an impact on this vegetation, most likely through a decline in vegetation quality, as well as to the rest of the food web for which this interaction is able to provide. It is expected that this change is relatively minor, however there would be value in modelling the change to quantify the difference. The assumption of minor change is in part as there is a remaining winter/spring fresh, and the contribution of second event would be offset by the increased floodplain interaction through constraints relaxation.

It was also noted however that the model results indicated that the target peak flows in the constraints relaxed scenarios, those that are able to engage the floodplain and provide vital connection to the ecological process that come with that connection were not met as often as are likely to be beneficial for environmental outcomes. While the assessments here show that the benefits to the environment are feasible and very much needed, these hydrological model results show the need for further investigation into how those results can be achieved.

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Attachment 5: Reconnecting River Country

The Reconnecting River Country Program focuses on investigating environmental benefits of relaxing flow constraints in the NSW section of the Murray and Murrumbidgee Valley. This therefore calls for consistency in the analysis and delivery of relaxed constraints in NSW and Victoria. A summary of the outcomes from the Reconnecting River Country Program with the breakdown of outcomes per theme is provided below, and in Table 6:

- There are substantial environmental benefits to provide additional water to the environment through relaxing flow constraints, especially for wetland and floodplain connectivity.
- Higher flow limit scenarios provide greatest environmental benefits across all focus areas.
- Greatest benefits of relaxing flow constraints are predicted during moderate to dry periods when contribution of environmental water to river flows is the highest.
- Greatest benefits are predicted in the Hume to Yarrawonga and Yarrawonga to Wakool reaches (NSW) and benefits decrease downstream.

Table 6. *Summary of outcomes extracted from the NSW Reconnecting to River Country Program*

Themes	Summary of outcomes
Native Fish	Up to 29% increase in long-term average abundance of Golden Perch in the Murray system (NSW) and 45% increase in abundance in dry periods. Increased breeding and recruitment opportunities for floodplain specialist fish species.
Vegetation	Up to 15% increase in healthy river red gum forest long term and woodlands and up to 50% increase during dry periods. Conditions for vegetation in higher-elevation areas may be reduced from reduced peak discharge rates during unregulated flood events
Waterbirds	Up to 13% increase and up to 80% increase in median waterbird density during moderate years and in dry years respectively in Barmah-Millewa Forest. Up to 48% increase and 34% increase in abundance during moderate years and dry years respectively in Gunbower-Koondrook-Perricoota forests.
Connectivity	Up to 190% increase in floodplain inundation, up to 97% increase in wetland watering provided by environmental water releases Between 20 – 40% increase in wetland and floodplain connectivity from Hume to Yarrawonga and Yarrawonga to Wakool Junction
Production	Up to 12% increase in production potential with more benefits in the Yarrawonga to Wakool area
Water quality	No significant increase to the risk of adverse water quality events and likely benefits to bring forward timing of high flow events to cooler months (e.g., winter/spring).
Geomorphology	Low – medium risk of accelerating current geomorphic processes. Medium risk for reinstating previously active geomorphic processes in Edward/Kolety-Wakool system. Predicted benefits for nutrient and carbon transfer into the riparian zone and enhanced geomorphic diversity
Invasive species - weeds	Decrease in weed hotspots, change in distribution of suitable habitat decreases for amphibious species and increases for terrestrial species.

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Attachment 6: EVCs allocated to vegetation groups for quantity assessment

Mapped EVC (2005 modelled EVC mapping)	Vegetation group	Comment
Bare Rock/Ground	Bare rock/ground/beach	
Billabong Wetland Aggregate	Semi-aquatic	Includes terrestrial flood-adapted, semi-aquatic and aquatic EVCs
Chenopod Grassland	Terrestrial, flood-adapted	Fringing active floodplains
Drainage-line Aggregate	Semi-aquatic	
Floodplain Grassy Wetland	Semi-aquatic	
Floodplain Grassy Wetland/Riverine Swamp Forest Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Floodplain Riparian Woodland	Terrestrial, flood-adapted	
Floodplain Riparian Woodland/Riverine Swamp Forest Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Floodplain Riparian Woodland/Sedgy Riverine Forest Mosaic	Terrestrial, flood-adapted	
Floodplain Wetland Aggregate	Semi-aquatic	
Floodway Pond Herbland	Semi-aquatic	
Floodway Pond Herbland/Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Grassy Riverine Forest	Terrestrial, flood-adapted	
Grassy Riverine Forest/Floodway Pond Herbland Complex	Terrestrial, flood-adapted/semi-aquatic	
Grassy Riverine Forest/Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Intermittent Swampy Woodland	Terrestrial, flood-adapted/semi-aquatic	
Lignum Shrubland	Terrestrial, flood-adapted	
Lignum Swamp	Semi-aquatic	
Lignum Swampy Woodland	Terrestrial, flood-adapted	
Loamy Sands Mallee	Terrestrial, not flood-adapted	Presumed not flood-adapted
Low Chenopod Shrubland	Terrestrial, flood-adapted	Occurs on alluvial terraces
No native vegetation recorded	No native veg mapped	

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Mapped EVC (2005 modelled EVC mapping)	Vegetation group	Comment
Plains Grassland	Terrestrial, not flood-adapted	Presumed not flood-adapted
Plains Woodland	Terrestrial, flood-adapted	Black box is a character species
Riverine Chenopod Woodland	Terrestrial, flood-adapted	
Riverine Grassy Woodland	Terrestrial, flood-adapted	
Riverine Grassy Woodland/Plains Woodland Complex	Terrestrial, flood-adapted	Black box is a character species in north-west, may be seasonally waterlogged
Riverine Grassy Woodland/Riverine Swampy Woodland Mosaic	Terrestrial, flood-adapted	
Riverine Grassy Woodland/Sedgy Riverine Forest Mosaic	Terrestrial, flood-adapted	
Riverine Swamp Forest	Terrestrial, flood-adapted/semi-aquatic	
Riverine Swamp Forest/Riverine Swampy Woodland Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Riverine Swamp Forest/Sedgy Riverine Forest Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Riverine Swamp Forest/Sedgy Riverine Forest-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Riverine Swampy Woodland	Terrestrial, flood-adapted/semi-aquatic	
Riverine Swampy Woodland/Sedgy Riverine Forest Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Rushy Riverine Swamp	Semi-aquatic	
Sand Ridge Woodland	Terrestrial, not flood-adapted	On rises adjacent wetlands/rivers, may be able to tolerate occasional, brief inundation
Sandy Beach	Bare rock/ground/beach	Unvegetated open water, bare soil or mud can be a wetland component
Sedgy Riverine Forest	Terrestrial, flood-adapted	
Sedgy Riverine Forest/Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Semi-arid Chenopod Woodland	Terrestrial, not flood-adapted	
Semi-arid Woodland	Terrestrial, not flood-adapted	
Shallow Freshwater Marsh	Semi-aquatic	

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Mapped EVC (2005 modelled EVC mapping)	Vegetation group	Comment
Shallow Sands Woodland	Terrestrial, not flood-adapted	Uncertain. Typically located between heavier soils of plains and deep-sand dunefields.
Shrubby Riverine Woodland	Terrestrial, flood-adapted	EVC can include river red gum and black box
Spike-sedge Wetland	Semi-aquatic	
Tall Marsh	Semi-aquatic	
Tall Marsh/Open Water Mosaic	Aquatic	
Water Body - Fresh	Water body	Unvegetated open water, bare soil or mud can be a wetland component
Wetland Formation	Aquatic	
Mosaic of Riverine Swamp Forest/Floodway Pond Herbland-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Mosaic of Grassy Riverine Forest-Riverine Swamp Forest Complex/Riverine Swamp Forest	Terrestrial, flood-adapted/semi-aquatic	
Low Rises Woodland	Terrestrial, not flood-adapted	
Grassy Riverine Forest/Riverine Swamp Forest Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Mosaic of Drainage-line Aggregate/Grassy Riverine Forest-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Aquatic Herbland/Floodplain Grassy Wetland Mosaic	Semi-aquatic	
Riverine Swamp Forest/Tall Marsh Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Mosaic of Sedgy Riverine Forest/Floodway Pond Herbland-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Mosaic of Sedgy Riverine Forest/Sedgy Riverine Forest-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Floodplain Grassy Wetland/Riverine Swampy Woodland Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Mosaic of Floodway Pond Herbland/Grassy Riverine Forest-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Mosaic of Grassy Riverine Forest/Floodway Pond Herbland-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	

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Mapped EVC (2005 modelled EVC mapping)	Vegetation group	Comment
Mosaic of Sedgy Riverine Forest-Riverine Swamp Forest Complex/Tall Marsh	Terrestrial, flood-adapted/semi-aquatic	
Aquatic Herbland	Aquatic	
Low Rises Woodland/Riverine Swampy Woodland Mosaic	Terrestrial, flood-adapted	
Mosaic of Tall Marsh/Floodway Pond Herbland-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Grassy Riverine Forest/Sedgy Riverine Forest Mosaic	Terrestrial, flood-adapted	
Mosaic of Grassy Riverine Forest/Sedgy Riverine Forest-Riverine Swamp Forest Complex	Terrestrial, flood-adapted	
Mosaic of Riverine Swampy Woodland/Sedgy Riverine Forest-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Drainage-line Aggregate/Riverine Swamp Forest Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Tall Marsh/Non-Vegetation Mosaic	Semi-aquatic	
Mosaic of Sedgy Riverine Forest-Riverine Swamp Forest Complex/Floodway Pond Herbland-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Riverine Grassland	Terrestrial, flood-adapted	
Grassy Riverine Forest/Riverine Grassy Woodland Mosaic	Terrestrial, flood-adapted	EVCs can include river red gum and black box
Grassy Riverine Forest/Plains Grassy Woodland/Grassy Woodland Mosaic	Terrestrial, flood-adapted	EVCs can include river red gum and black box
Aquatic Herbland/Tall Marsh Mosaic	Aquatic	
Riverine Swamp Forest/Spike-sedge Wetland Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Floodplain Riparian Woodland/Riverine Grassy Woodland Mosaic	Terrestrial, flood-adapted	EVC can include river red gum and black box
Riverine Grassy Woodland/Riverine Swamp Forest Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Mosaic of Floodplain Grassy Wetland/Grassy Riverine Forest-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Floodplain Grassy Wetland/Spike-sedge Wetland Mosaic	Terrestrial, flood-adapted/semi-aquatic	

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Mapped EVC (2005 modelled EVC mapping)	Vegetation group	Comment
Mosaic of Aquatic Herbland/Floodway Pond Herbland-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Drainage-line Aggregate/Sedgy Riverine Forest Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Floodplain Grassy Wetland/Tall Marsh Mosaic	Semi-aquatic	
Floodplain Riparian Woodland/Floodway Pond Herbland Mosaic	Terrestrial, flood-adapted	
Floodway Pond Herbland/Tall Marsh Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Mosaic of Floodway Pond Herbland/Sedgy Riverine Forest-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Grassy Riverine Forest/Floodway Pond Herbland Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Drainage-line Aggregate/Tall Marsh Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Aquatic Herbland/Floodway Pond Herbland Mosaic	Aquatic	
Mosaic of Aquatic Herbland/Sedgy Riverine Forest-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Tall Marsh/Riverine Swamp Forest Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Spike-sedge Wetland/Tall Marsh Mosaic	Semi-aquatic	
Mosaic of Drainage-line Aggregate/Sedgy Riverine Forest-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Aquatic Herbland/Riverine Swamp Forest Mosaic	Semi-aquatic	
Floodway Pond Herbland/Riverine Swamp Forest Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Mosaic of Floodplain Riparian Woodland/Sedgy Riverine Forest-Riverine Swamp Forest Complex	Terrestrial, flood-adapted	
Sedgy Riverine Forest/Tall Marsh Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Mosaic of Floodplain Grassy Wetland/Sedgy Riverine Forest-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Sedgy Riverine Forest/Spike-sedge Wetland Mosaic	Terrestrial, flood-adapted/semi-aquatic	

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Mapped EVC (2005 modelled EVC mapping)	Vegetation group	Comment
Grassy Riverine Forest/Tall Marsh Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Floodplain Grassy Wetland/Floodway Pond Herbland Mosaic	Semi-aquatic	
Mosaic of Floodplain Grassy Wetland/Floodway Pond Herbland-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Floodplain Riparian Woodland/Tall Marsh Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Mosaic of Riverine Grassy Woodland/Floodway Pond Herbland-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	EVC can include river red gum and black box
Grassy Riverine Forest/Drainage-line Aggregate Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Mosaic of Drainage-line Aggregate/Floodway Pond Herbland-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	
Riverine Grassy Woodland/Grassy Riverine Forest-Riverine Swamp Forest Complex	Terrestrial, flood-adapted/semi-aquatic	EVC can include river red gum and black box
Chenopod Mallee	Terrestrial, not flood-adapted	Presumed not flood-adapted
Ridged Plains Mallee	Terrestrial, not flood-adapted	Presumed not flood-adapted
Woorinen Mallee	Terrestrial, not flood-adapted	Presumed not flood-adapted
Creekline Grassy Woodland	Terrestrial, flood-adapted	River red gum is a character species
Grassy Woodland	Terrestrial, not flood-adapted	
Plains Grassy Woodland	Terrestrial, flood-adapted	EVC can include river red gum and black box
Plains Grassy Woodland/Grassy Woodland Complex	Terrestrial, flood-adapted	EVC can include river red gum and black box
Riverine Grassy Woodland/Sedgy Riverine Forest/Wetland Formation Mosaic	Terrestrial, flood-adapted/semi-aquatic	EVC can include river red gum and black box
Tall Marsh/Aquatic Herbland Mosaic	Aquatic	
Water Body - man-made	Water body	
Floodplain Riparian Woodland/Grassy Riverine Forest Mosaic	Terrestrial, flood-adapted	
Valley Grassy Forest	Terrestrial, not flood-adapted	Moister habitat but assumed not flood adapted

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Mapped EVC (2005 modelled EVC mapping)	Vegetation group	Comment
Plains Grassy Woodland/Plains Grassland/Plains Grassy Wetland Mosaic	Terrestrial, flood-adapted/semi-aquatic	EVC can include river red gum and black box
Box Ironbark Forest	Terrestrial, not flood-adapted	
Floodplain Riparian Woodland/Plains Grassy Woodland Mosaic	Terrestrial, flood-adapted	EVC can include river red gum and black box
Floodplain Riparian Woodland/Floodplain Wetland Mosaic	Terrestrial, flood-adapted/semi-aquatic	
Herb-rich Foothill Forest	Terrestrial, not flood-adapted	Moister habitat but assumed not flood adapted
Plains Grassland/Plains Grassy Woodland/Gilgai Wetland Mosaic	Terrestrial, flood-adapted/semi-aquatic	EVC can include river red gum and black box
Riverine Grassy Woodland/Plains Woodland/Gilgai Wetland Complex	Terrestrial, flood-adapted/semi-aquatic	EVC can include river red gum and black box

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Attachment 7: Vegetation quality assessment detail

When considering the total changes that were observed within the Murray River reach, the modelling assessed the proportion of time a unit of vegetation (with a unit being 1.56 ha) was in either good or critical condition with respect to the base case. This included total areas of no change from the base, total areas where proportion of time in good or critical condition improved or declined and the net change (improvement – decline). It also included total areas of no change from the base case proportions of time, total areas where proportion of time in good or critical condition improved or declined and the net change (improvement – decline) in the vegetation condition between alternate scenarios and the base case (Table 7 to Table 10).

Table 7 *Change to the proportion of time pixels of black box woodland (BBW) and river red gum (RRG) spent in good and critical classes in the reach between Hume dam to Yarrawonga weir.*

Vegetation type	Condition	Comparison	No Change (ha)	Increase (ha)	Decrease (ha)	Net Change (ha)
BBW	Good	base_WOD	10.94	59.38	28.13	31.25
		base_Y25D25	89.06	0.00	9.38	-9.38
		base_Y30D30	81.25	6.25	10.94	-4.69
		base_Y40D40	76.56	21.88	0.00	21.88
		base_Y45D40	75.00	23.43	0.00	23.43
	Critical	base_WOD	6.25	0.00	4.69	-4.69
		base_Y25D25	9.38	0.00	1.56	-1.56
		base_Y30D30	9.38	0.00	1.56	-1.56
		base_Y40D40	9.38	0.00	1.56	-1.56
		base_Y45D40	9.38	0.00	1.56	-1.56
RRG	Good	base_WOD	800.00	739.06	434.38	304.69
		base_Y25D25	1939.06	17.19	17.19	0.00
		base_Y30D30	1906.25	34.38	32.81	1.56
		base_Y40D40	1778.13	195.31	0.00	195.31
		base_Y45D40	1795.31	178.13	0.00	178.13
	Critical	base_WOD	96.88	739.06	296.88	442.19
		base_Y25D25	640.63	425.00	0.00	425.00
		base_Y30D30	782.81	282.81	0.00	282.81
		base_Y40D40	468.75	253.13	343.75	-90.63
		base_Y45D40	946.88	85.94	32.81	53.13

Table 8 *Change to the proportion of time pixels of black box woodland (BBW) and river red gum (RRG) spent in good and critical classes in the reach between the Yarrawonga weir and Wakool Junction*

Vegetation type	Condition	Comparison	No Change (ha)	Increase (ha)	Decrease (ha)	Net Change (ha)
BBW	Good	base_WOD	7014.06	2668.75	287.50	2381.25
		base_Y25D25	8854.69	940.63	175.00	765.63
		base_Y30D30	8759.38	1010.94	200.00	810.94
		base_Y40D40	8801.56	985.94	182.81	803.13
		base_Y45D40	8754.69	1085.9375	129.6875	956.25
	Critical	base_WOD	0.00	540.63	643.75	-103.13
		base_Y25D25	6885.94	15.63	253.13	-237.50
		base_Y30D30	7043.75	29.69	81.25	-51.56
		base_Y40D40	7085.94	12.50	56.25	-43.75
		base_Y45D40	7007.81	15.625	131.25	-115.625
RRG	Good	base_WOD	14420.31	26206.25	1410.94	24795.31
		base_Y25D25	25039.06	11792.19	5206.25	6585.94

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Vegetation type	Condition	Comparison	No Change (ha)	Increase (ha)	Decrease (ha)	Net Change (ha)
		base_Y30D30	22420.31	11387.50	8229.69	3157.81
		base_Y40D40	23990.63	14656.25	3390.63	11265.63
		base_Y45D40	22032.81	16065.625	3939.06	12126.5625
	Critical	base_WOD	0.00	2618.75	1620.31	998.44
		base_Y25D25	9648.44	1264.06	206.25	1057.81
		base_Y30D30	10134.38	893.75	90.63	803.13
		base_Y40D40	9589.06	759.38	770.31	-10.94
		base_Y45D40	10151.56	753.125	214.06	539.0625

Table 9 *Change to the proportion of time pixels of black box woodland (BBW) and river red gum (RRG) spent in good and critical classes in the Mid Goulburn reach*

Vegetation type	Condition	Comparison	No Change (ha)	Increase (ha)	Decrease (ha)	Net Change (ha)
RRG	G	base_M10L17	128.13	18.75	14.06	4.69
		base_M10L21	140.63	20.31	0.00	20.31
		base_M12L21	128.13	18.75	14.06	4.69
		base_M14L25	128.13	20.31	12.50	7.81

Table 10 *Change to the proportion of time pixels of black box woodland (BBW) and river red gum (RRG) spent in good and critical classes in the Lower Goulburn reach*

Vegetation type	Condition	Comparison	No Change (ha)	Increase (ha)	Decrease (ha)	Net Change (ha)
BBW	Good	base_M10L17	1637.50	0.00	467.19	-467.19
		base_M10L21	1637.50	0.00	467.19	-467.19
		base_M12L21	1087.50	550.00	467.19	82.81
		base_M14L25	1087.50	550.00	467.19	82.81
	Critical	base_M10L17	1668.75	985.94	0.00	985.94
		base_M10L21	2706.25	0.00	467.19	-467.19
		base_M12L21	568.75	467.19	518.75	-51.56
		base_M14L25	568.75	467.19	518.75	-51.56
RRG	Good	base_M10L17	14159.38	742.19	0.00	742.19
		base_M10L21	14901.56	0.00	0.00	0.00
		base_M12L21	8712.50	6189.06	0.00	6189.06
		base_M14L25	8712.50	6189.06	0.00	6189.06
	Critical	base_M10L17	12404.69	2795.31	10040.63	-7245.31
		base_M10L21	14175.00	1025.00	10040.63	-9015.63
		base_M12L21	3268.75	2053.13	4810.94	-2757.81
		base_M14L25	3268.75	3012.50	6581.25	-3568.75

By comparing the proportion of time spent in each of the condition phases (Figure 11, Figure 12, Figure 13, Figure 14), the shift in area in each phase can be seen. Note that for Figure 11, Figure 12, Figure 13 and Figure 14 the density, or vegetation area, is on the Y-Axis, with the X-Axis being the portion of the time series vegetation spend in those phases (with 0 being 0% and 1 being 1%). The results illustrate the changes that the relaxation of constraints can have. The distributions illustrate the move out from the critical phase and up to the good phase as constraints are relaxed.

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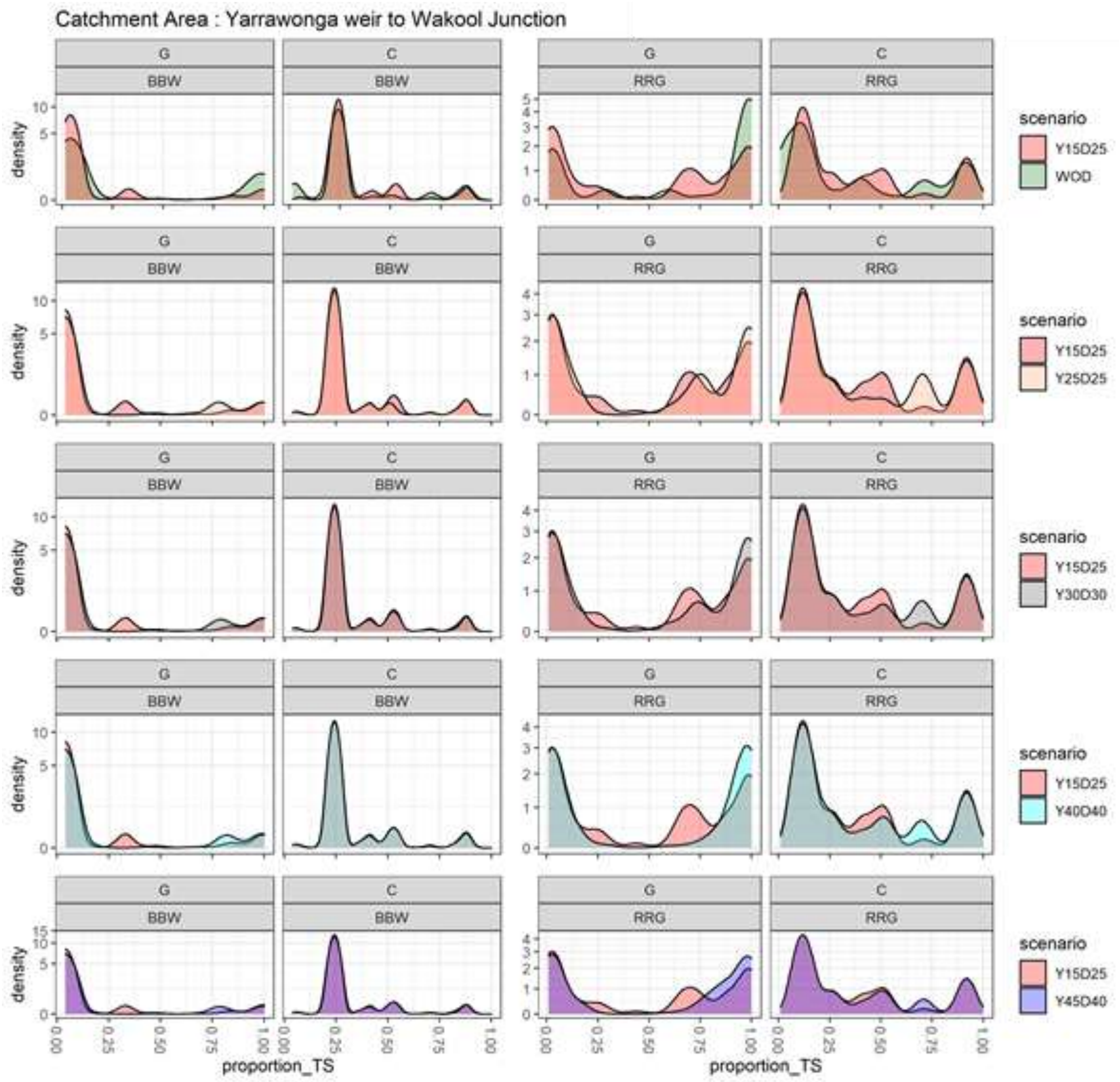

Figure 11 *Density distributions of all pixels in the Yarrawonga weir to Wakool Junction reach for good (G) and critical (C) condition of black box woodland (BBW) and river red gum (RRG).*

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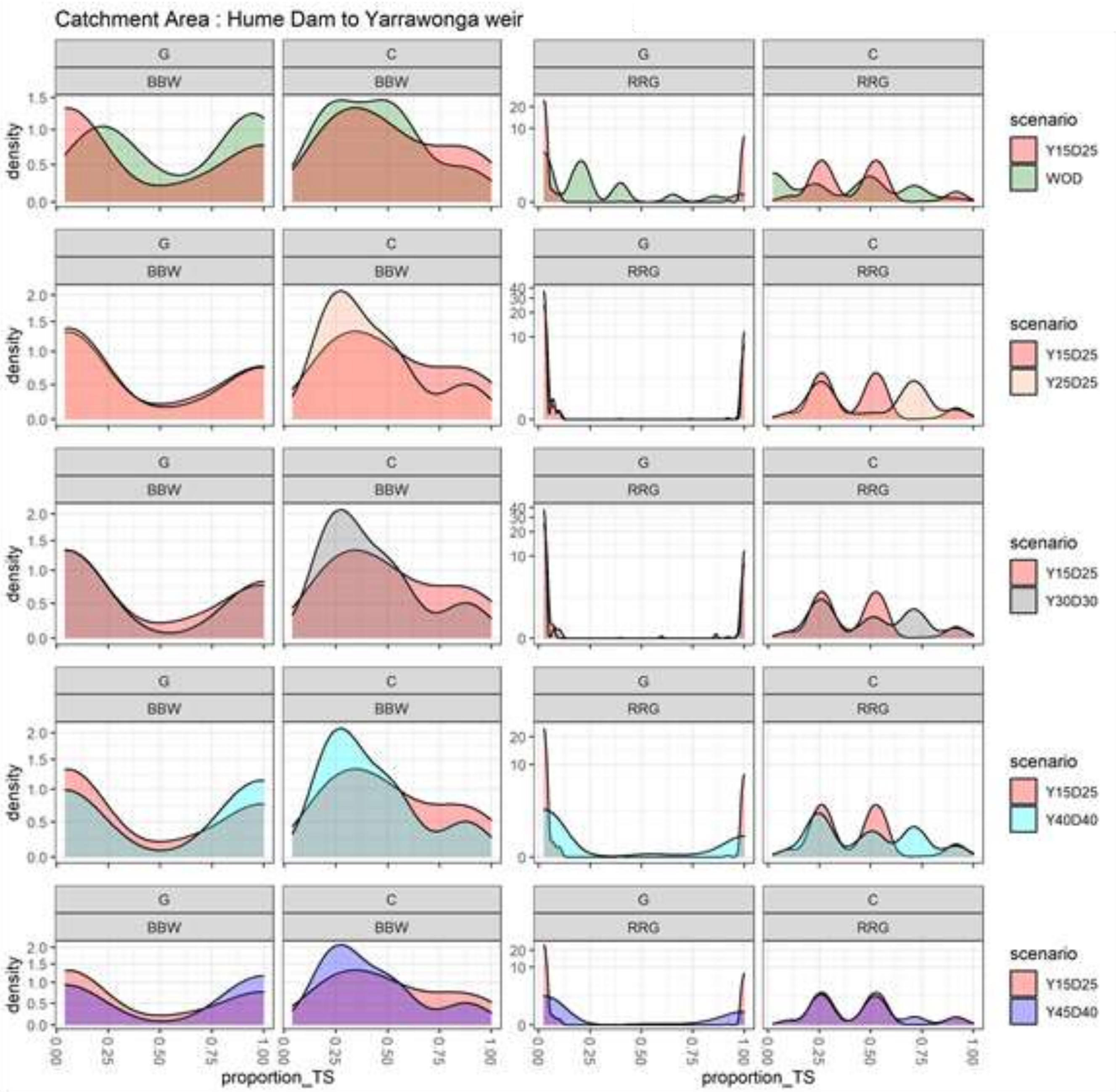

Figure 12 *Density distributions of all pixels in the Hume Dam to Yarrawonga weir reach for good (G) and critical (C) condition of black box woodland (BBW) and river red gum (RRG).*

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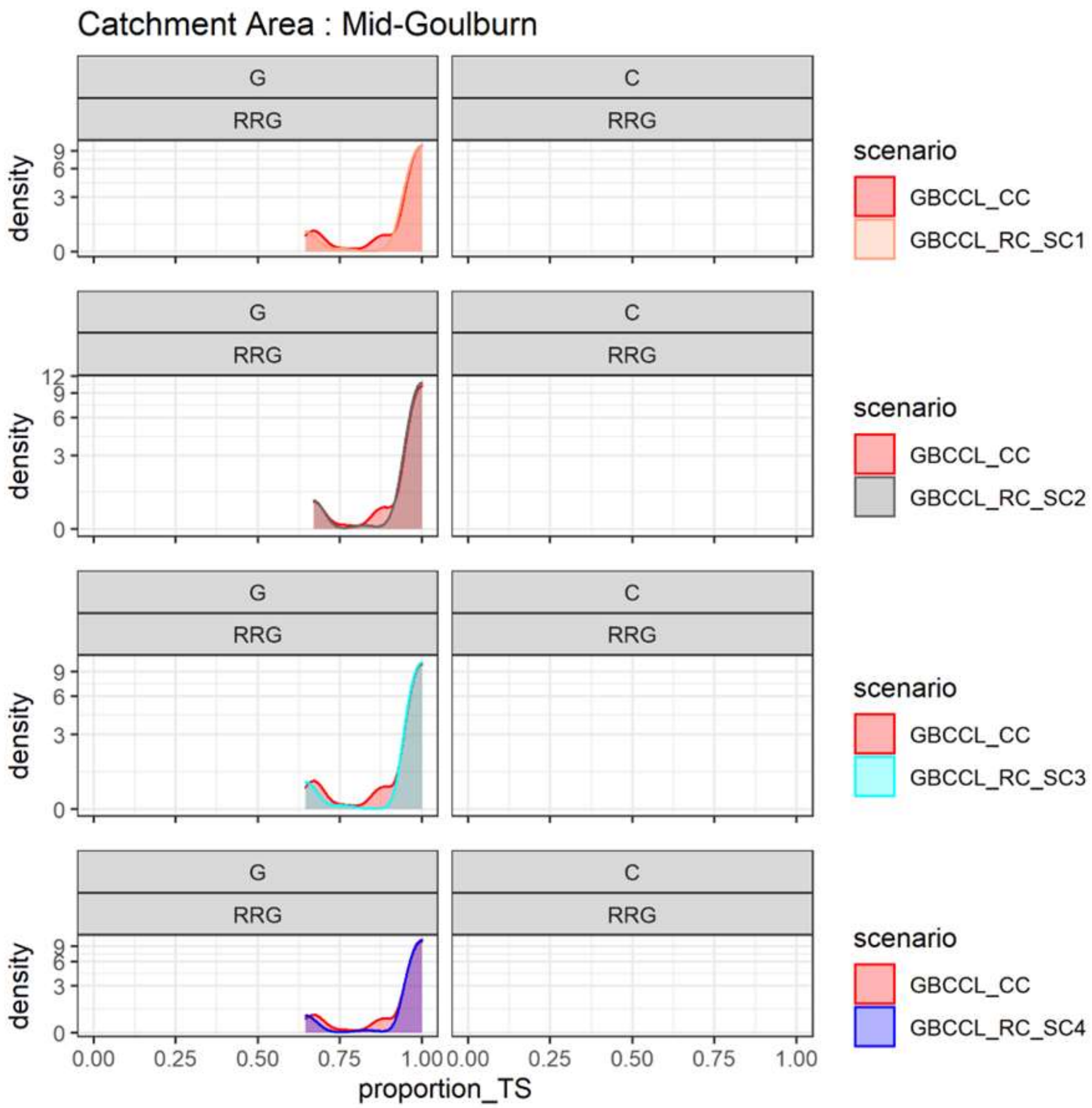

Figure 13 *Density distributions of all pixels in the Mid Goulburn reach for good (G) and critical (C) condition of river red gum (RRG)*

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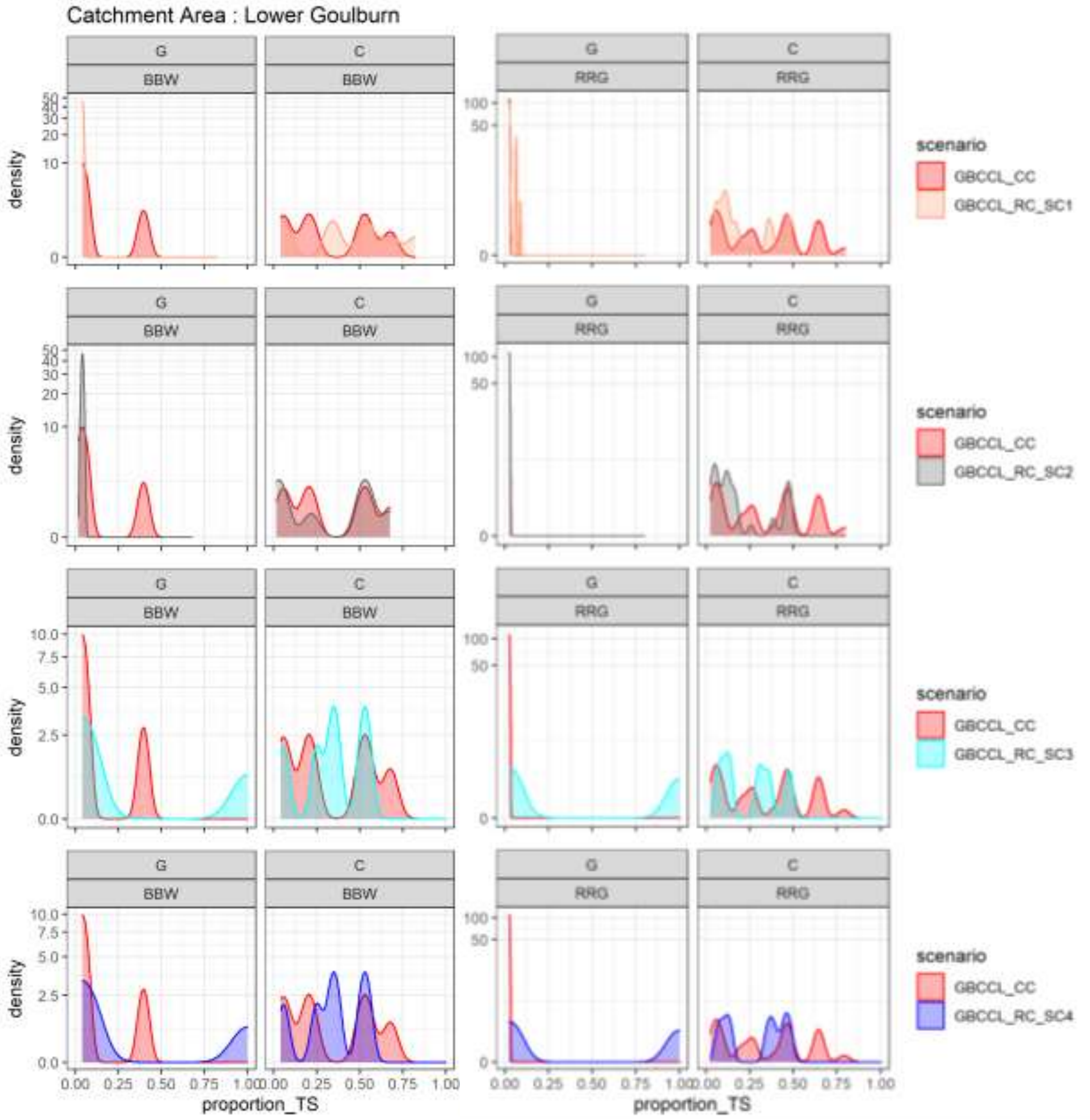

Figure 14 *Density distributions of all pixels in the Lower Goulburn reach for good (G) and critical (C) condition of river red gum (RRG) and black box woodland (BBW)*

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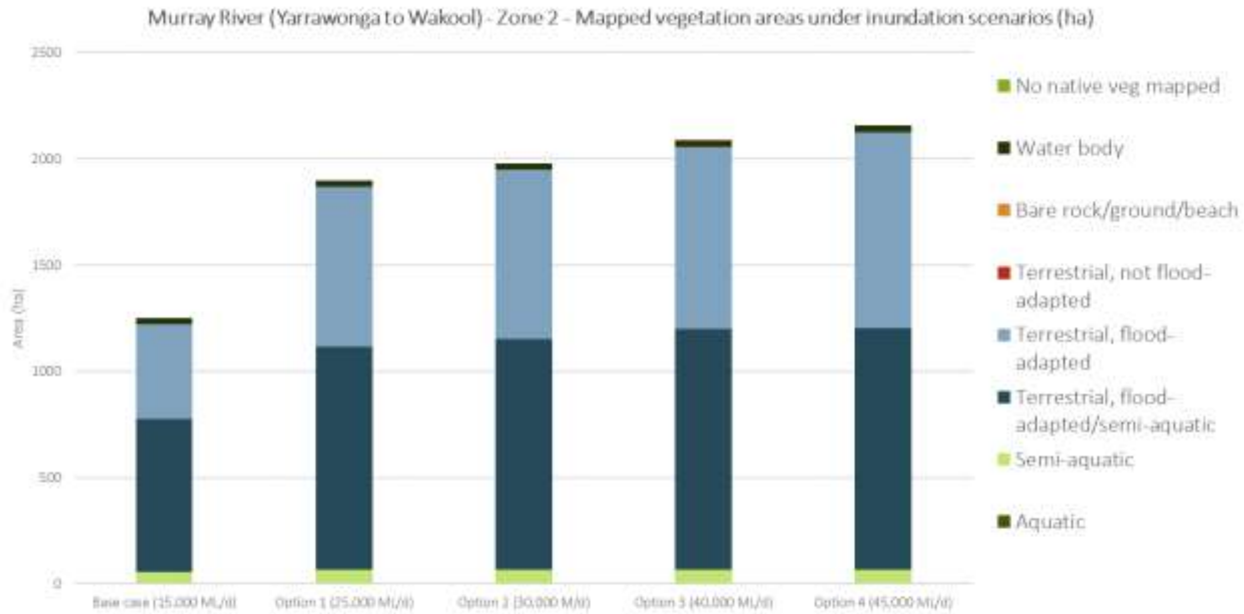
Attachment 8: Murray River vegetation quantity results



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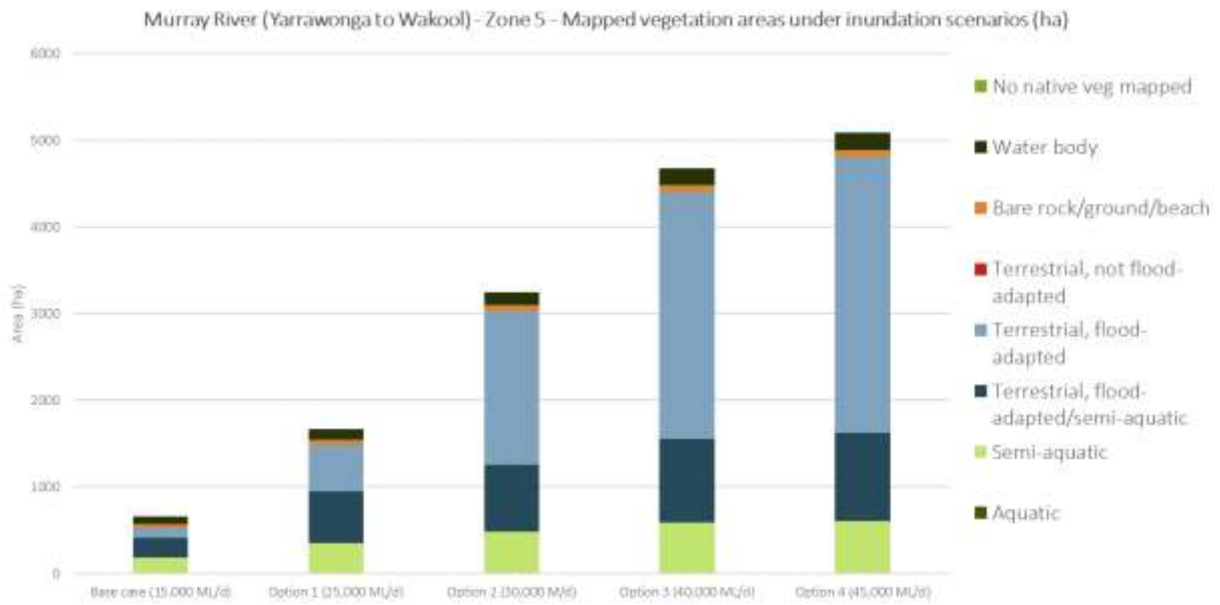

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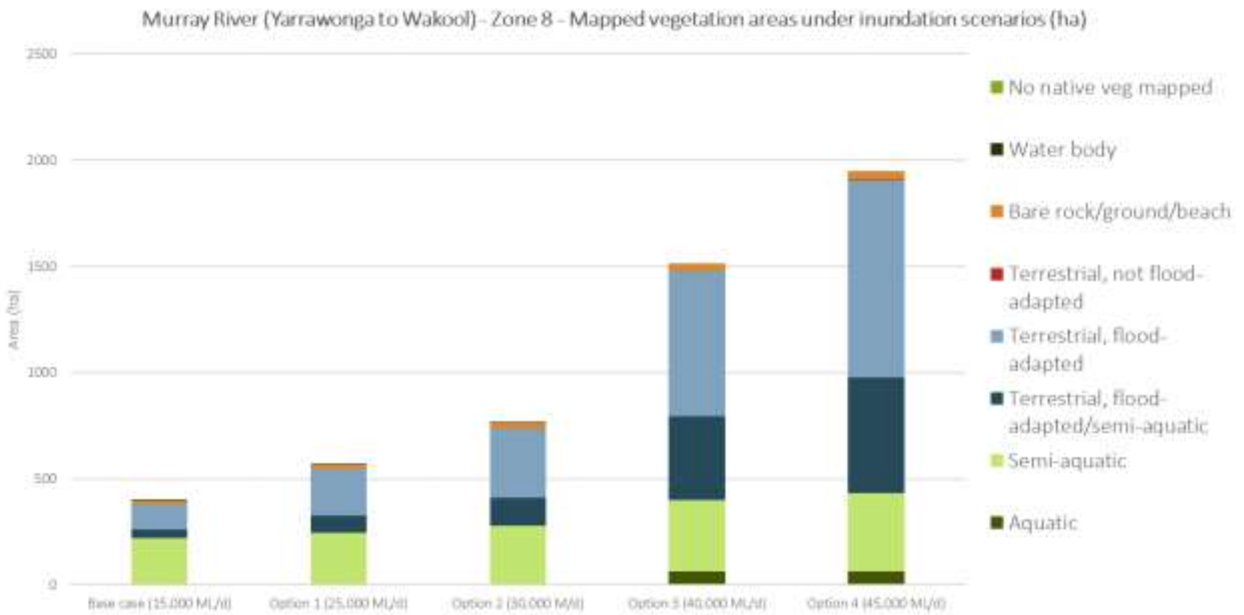

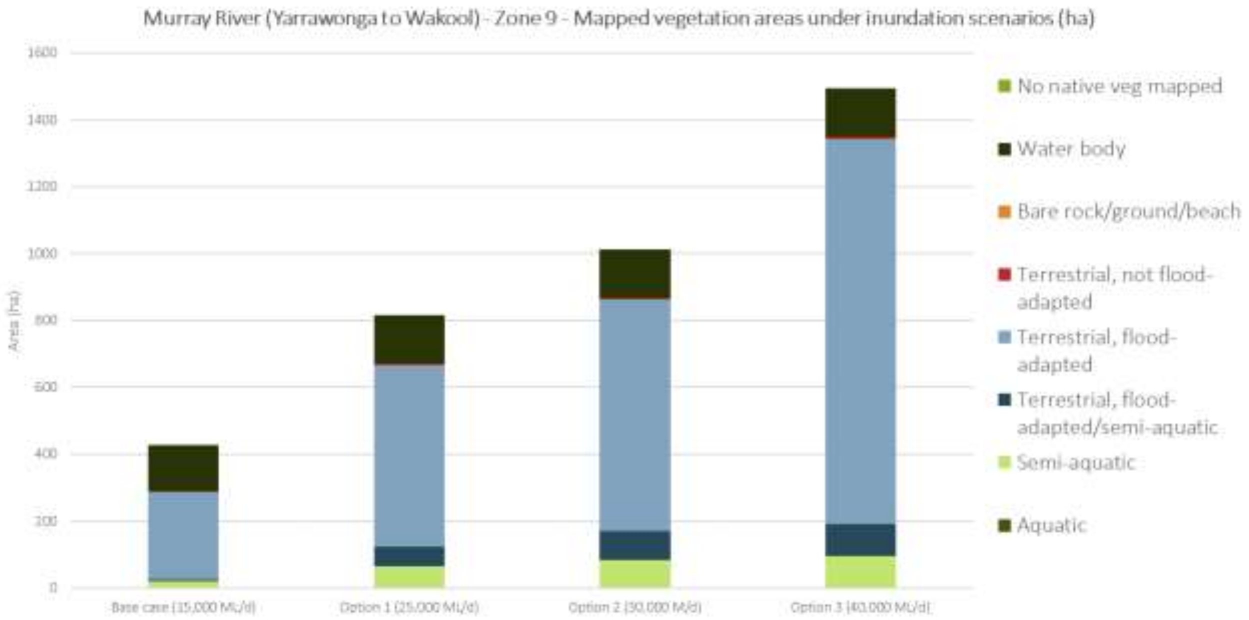

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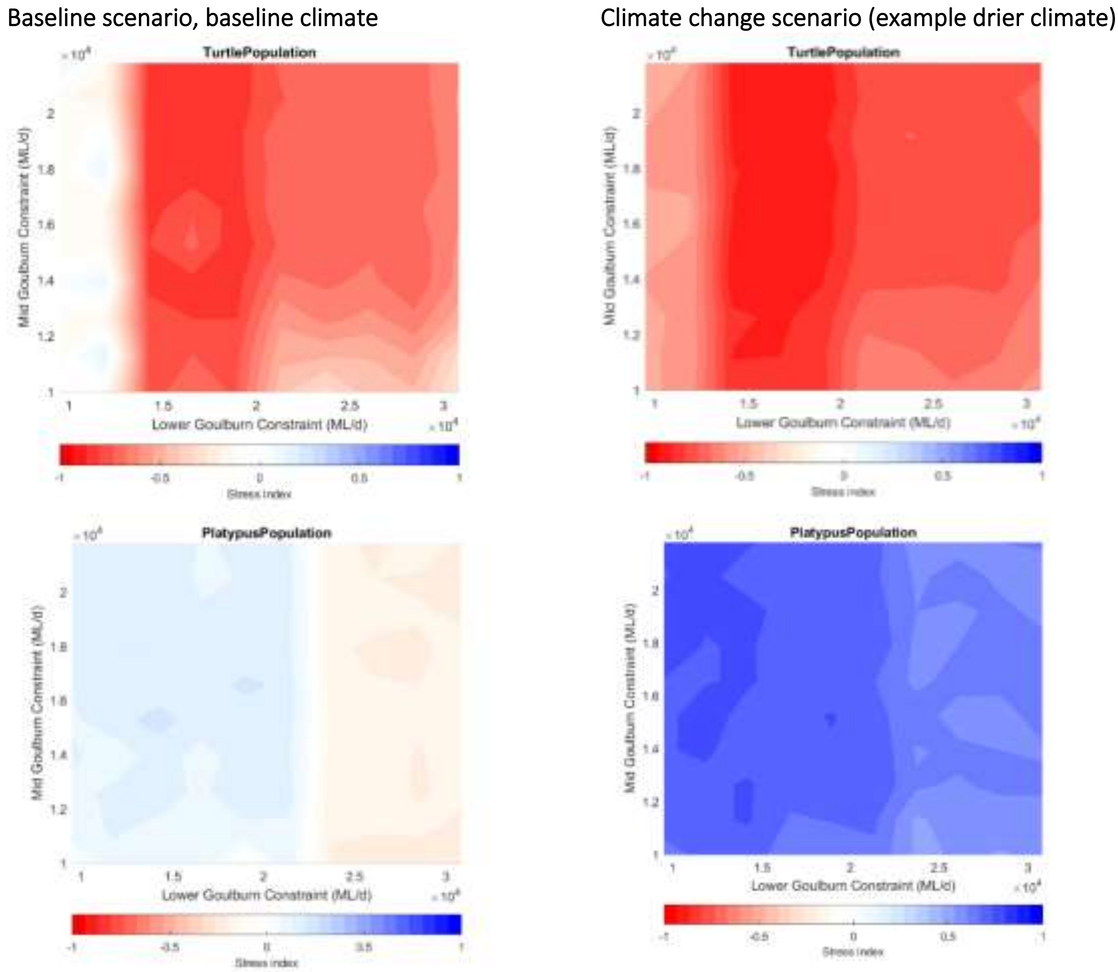
Attachment 9: Modelled benefits on hydrological metrics and ecological models in the Goulburn River system

Figure 15 provides the comparison of modelling results under current climatic conditions and climate change scenarios (John et al. 2022).

Figure 15 *Individual ecological model outputs showing modelled ecological benefits (blue area) or disbenefits (red area) relative to the baseline scenario and baseline climate. The left panel shows the impact of relaxing constraints with baseline climate and the right panel shows the impact of relaxing constraints under example drier climate.*



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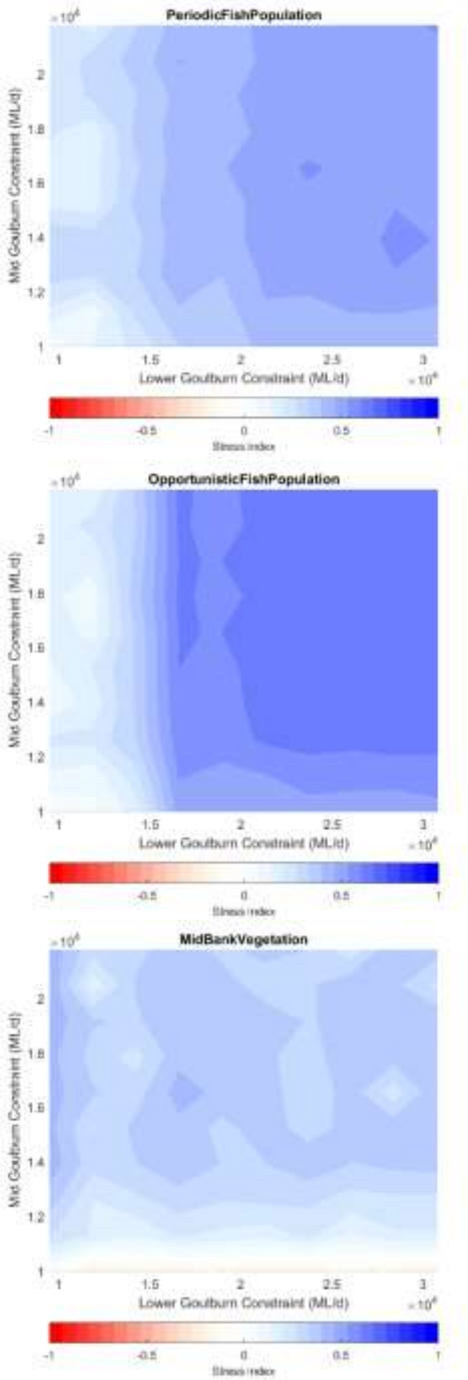
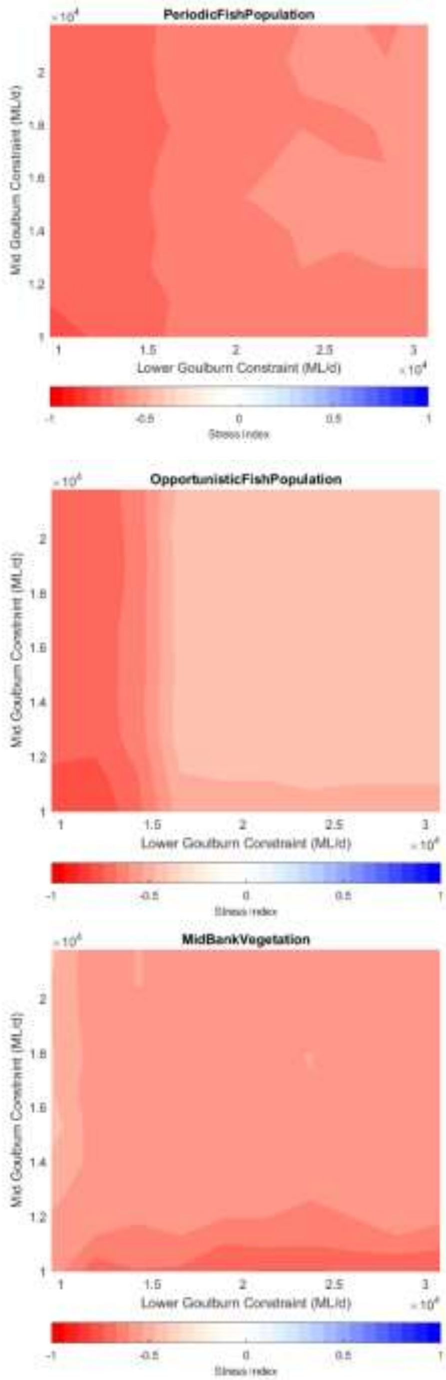
Baseline scenario, baseline climate



Climate change scenario (example drier climate)



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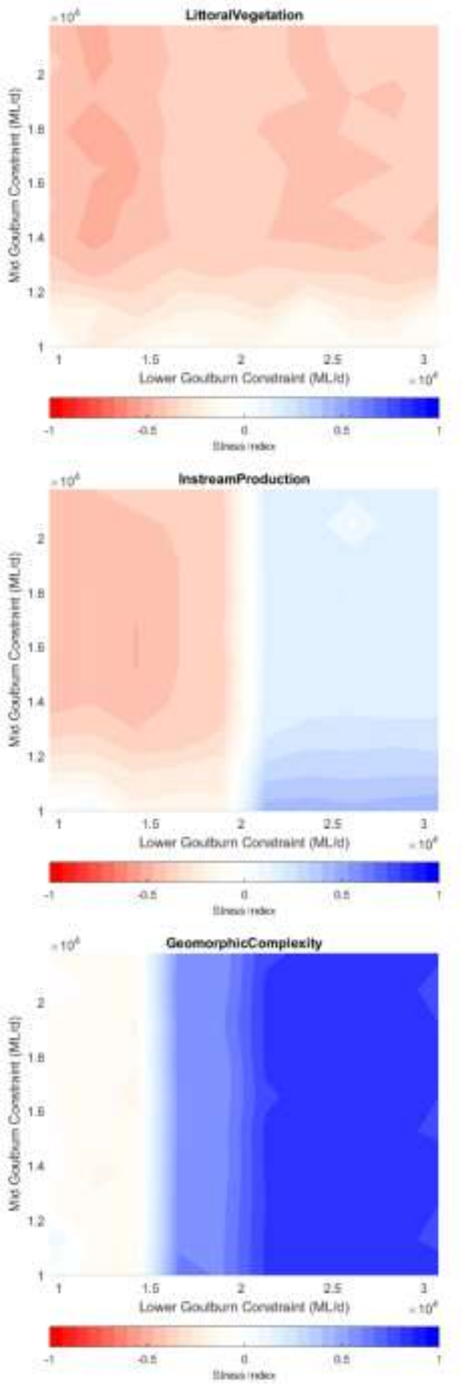
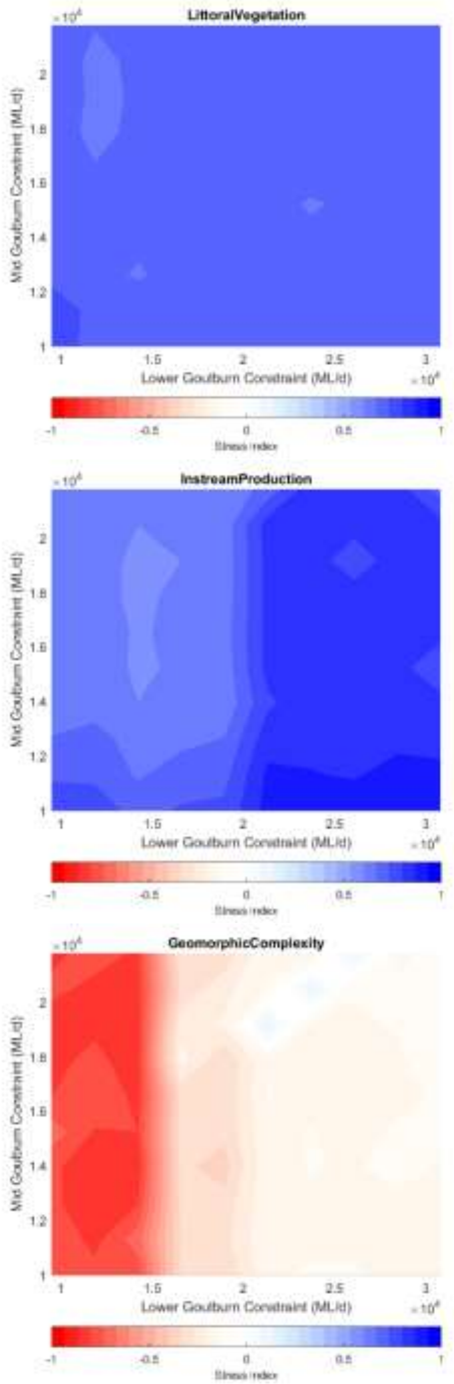
Baseline scenario, baseline climate



Climate change scenario (example drier climate)



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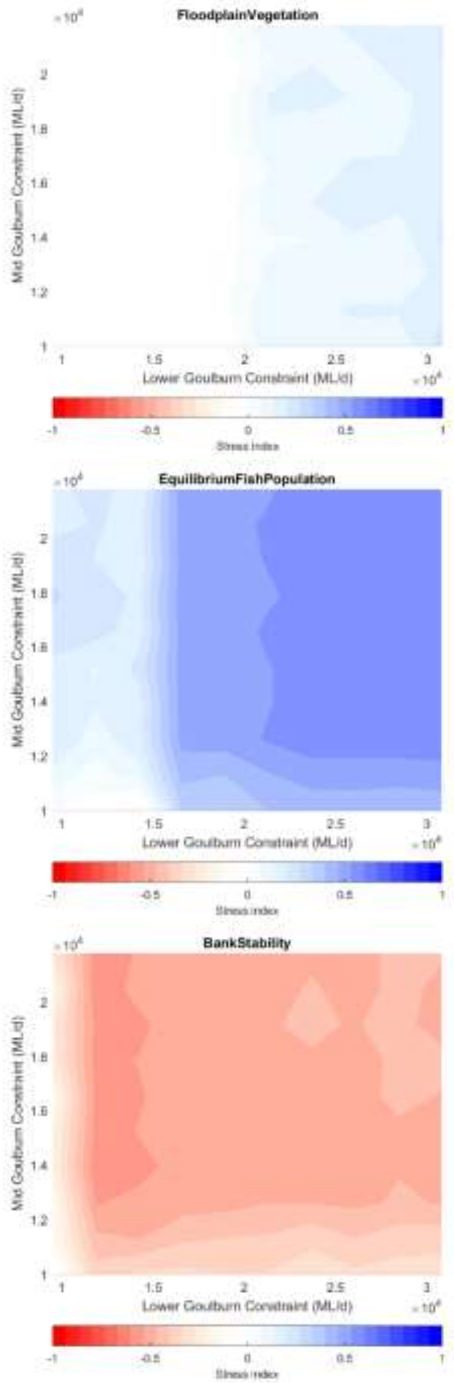
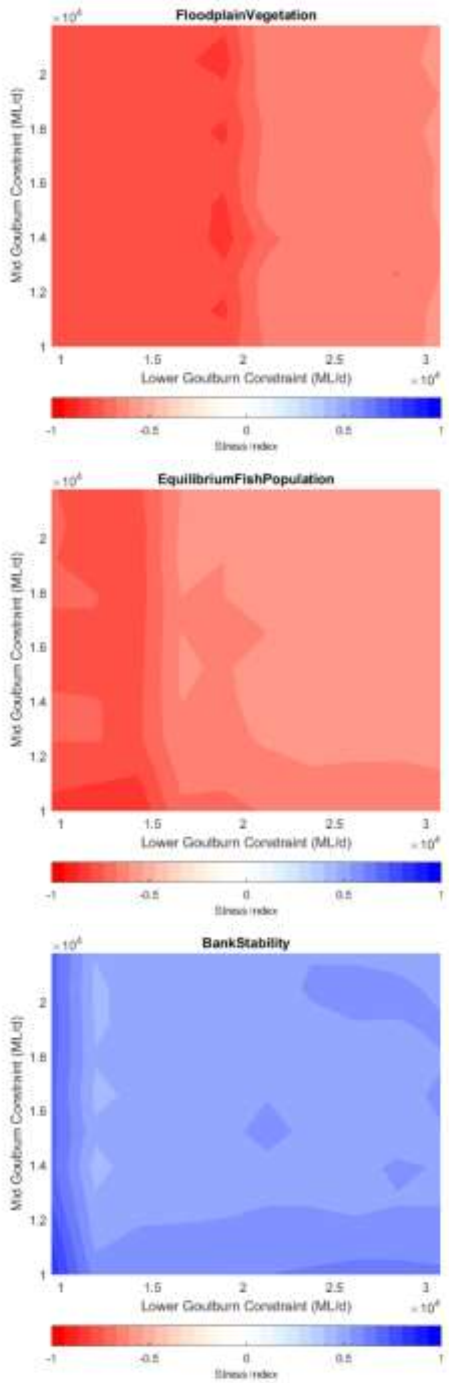
Baseline scenario, baseline climate



Climate change scenario (example drier climate)



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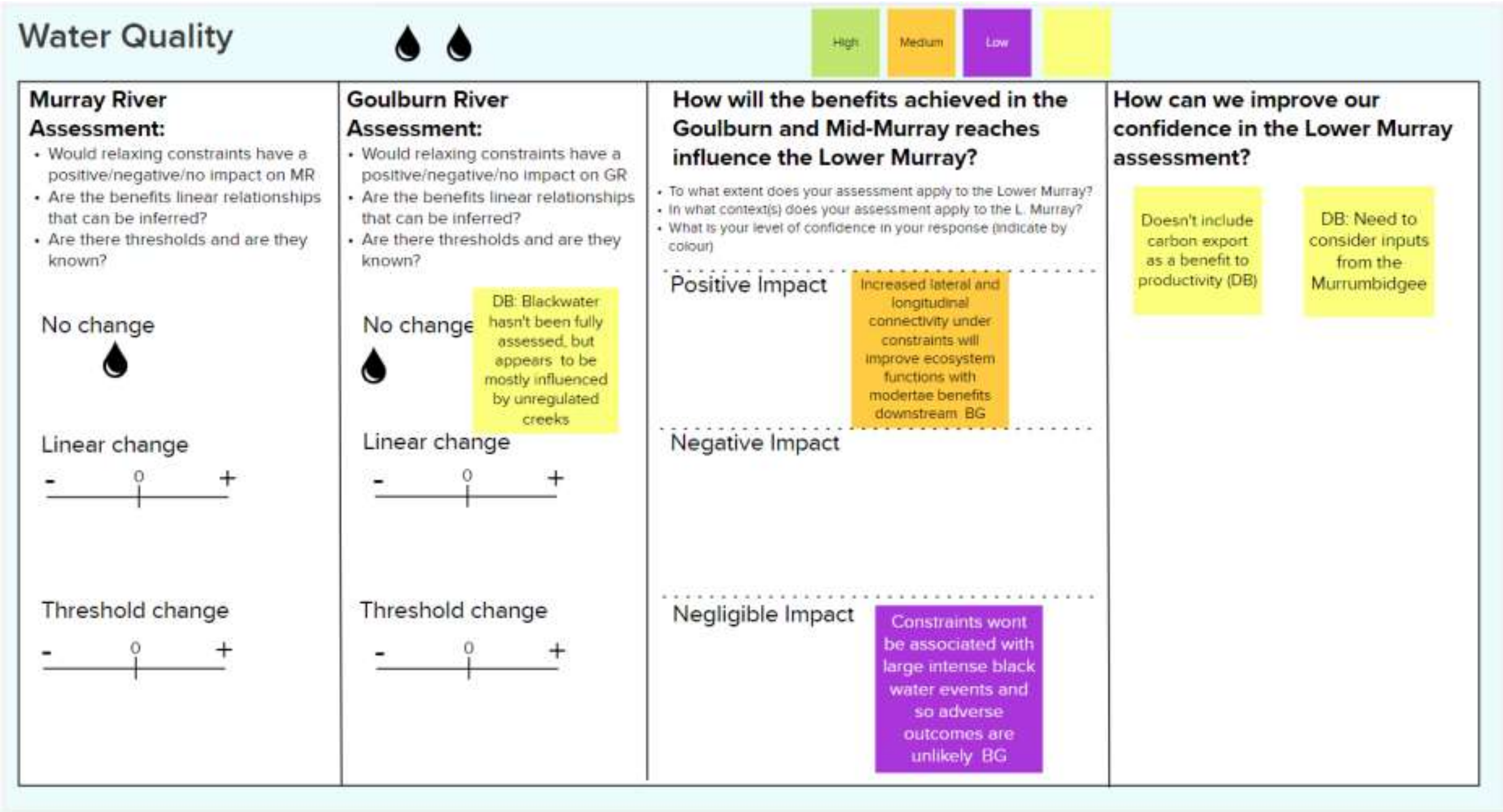
Attachment 10: System benefits workshop Mural board



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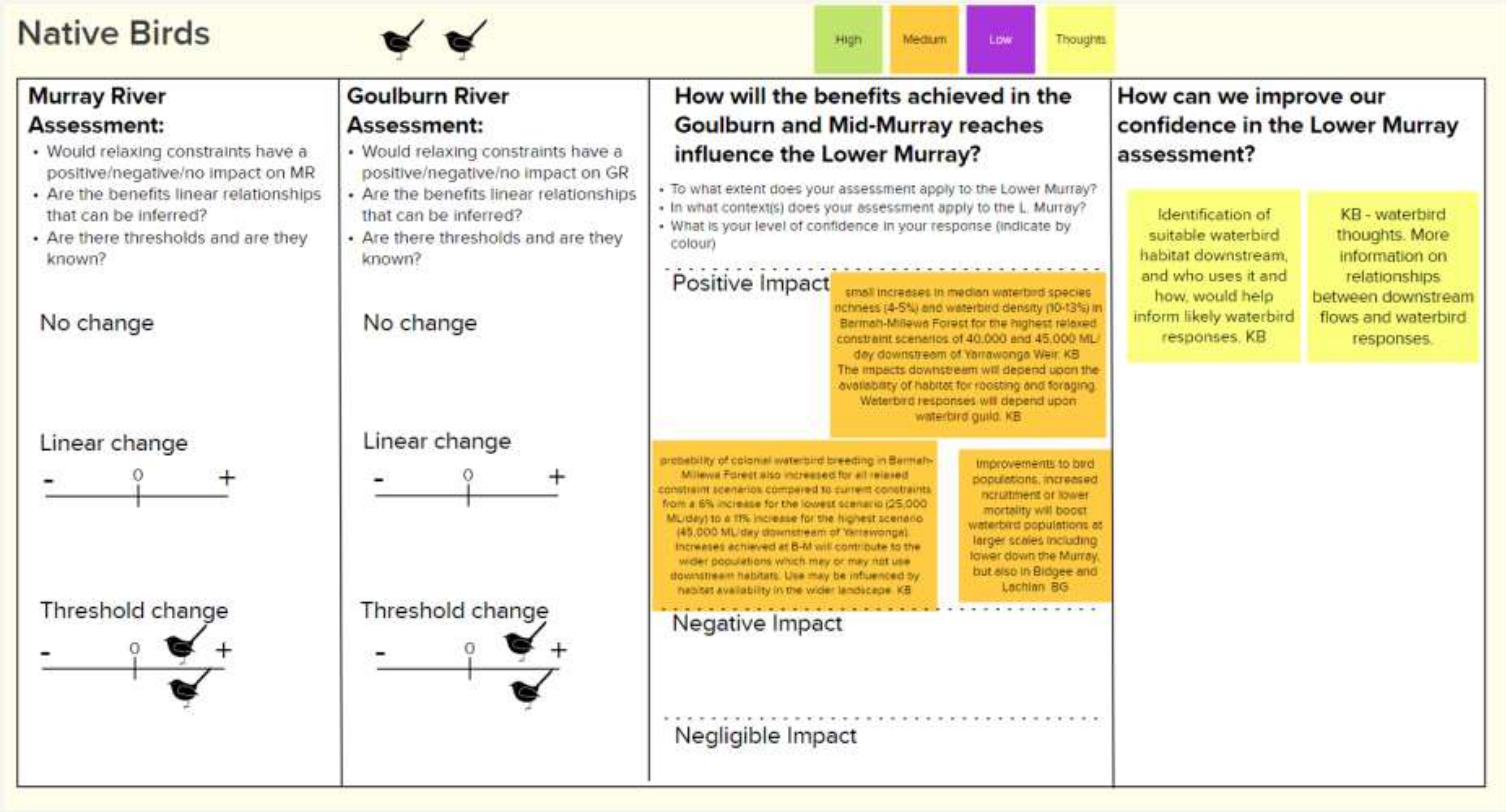

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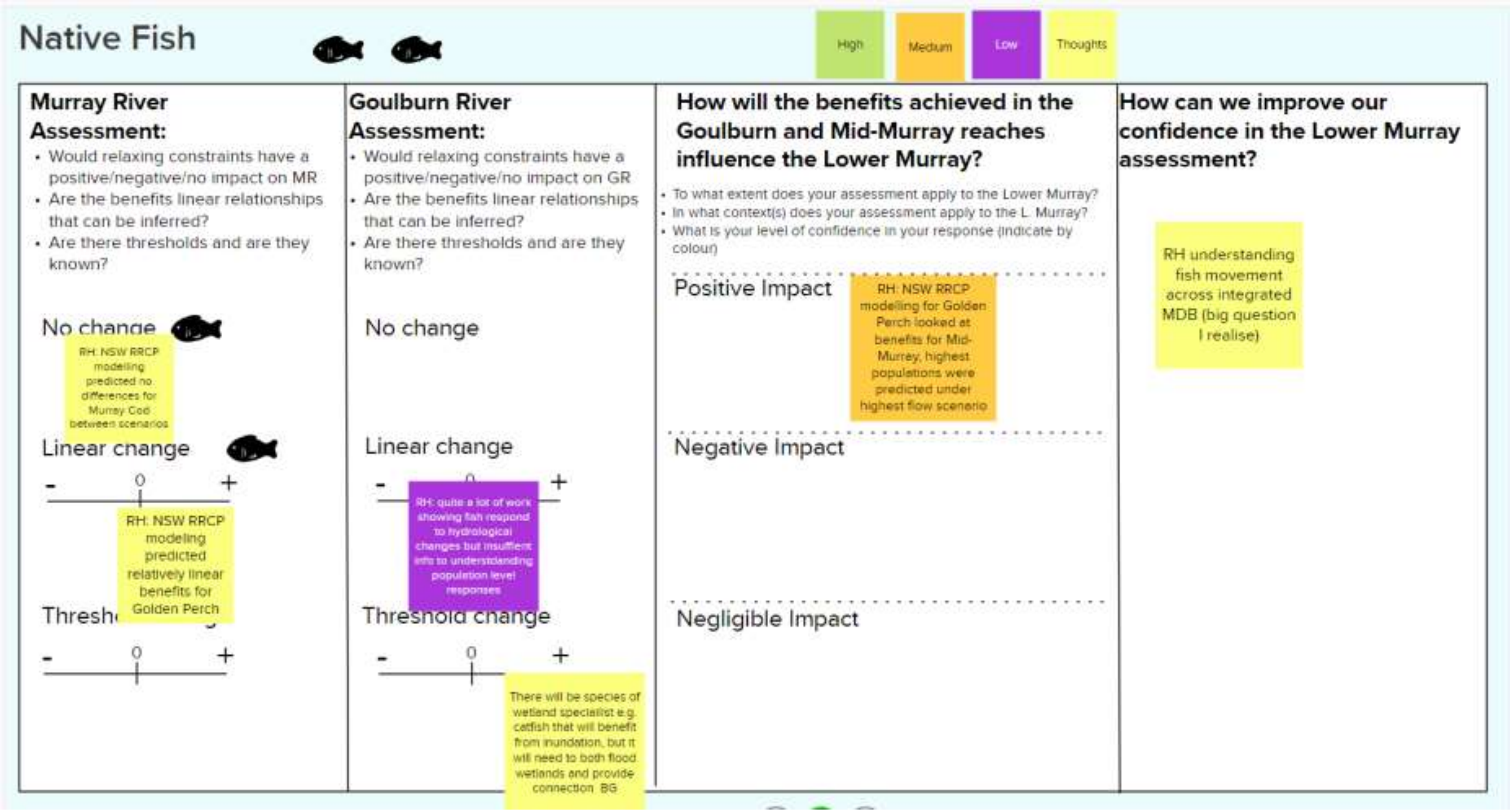

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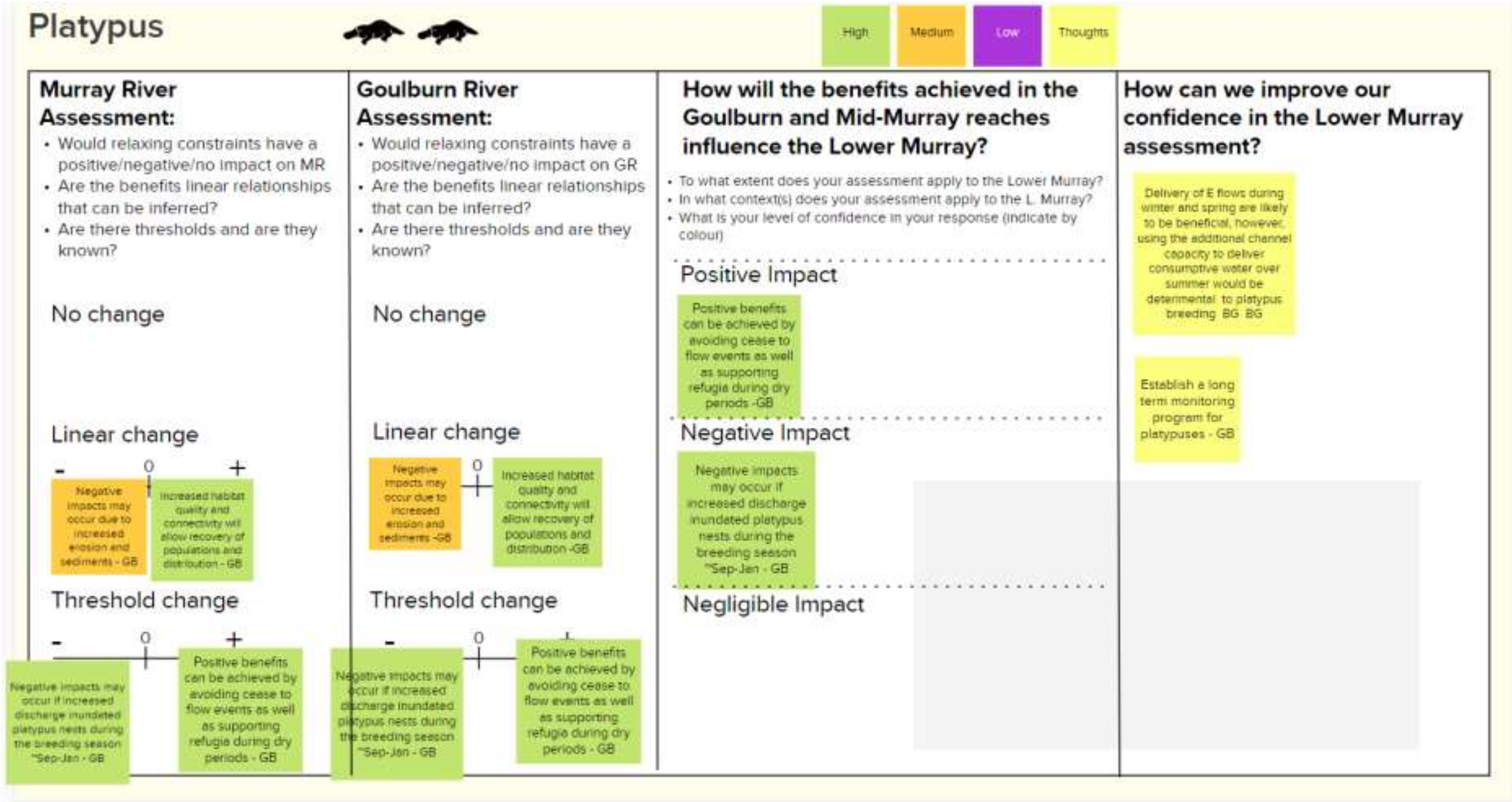

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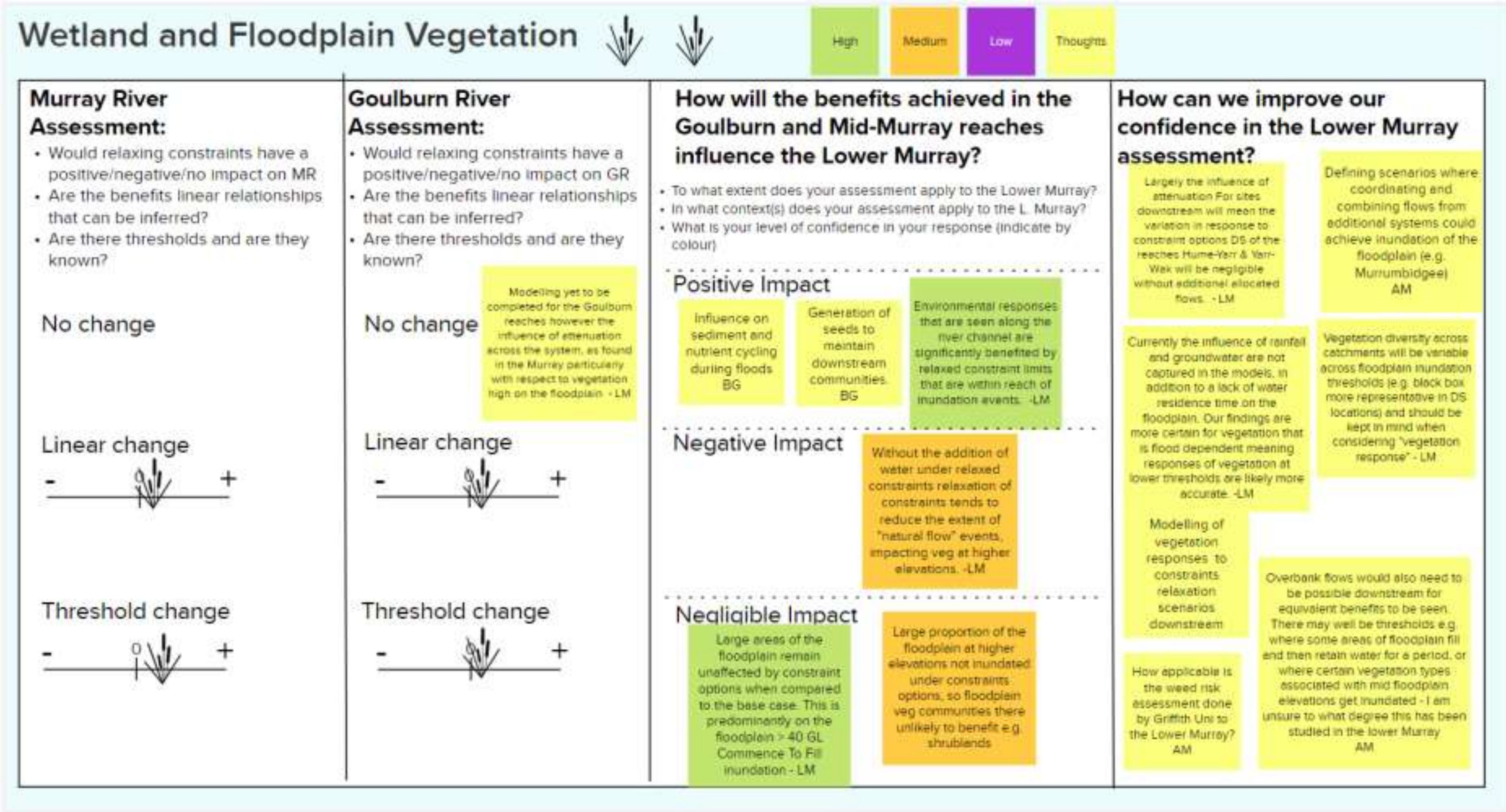

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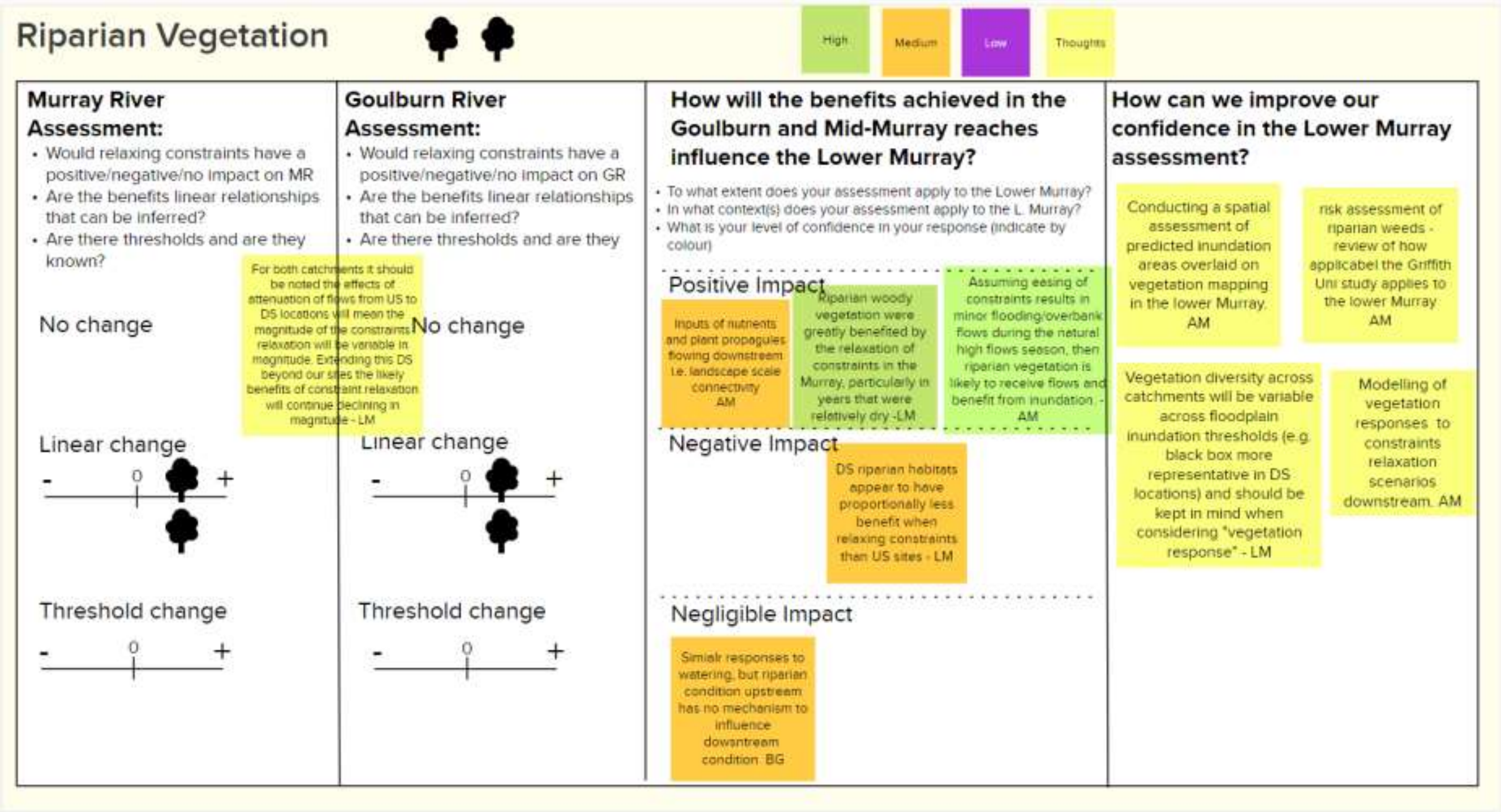

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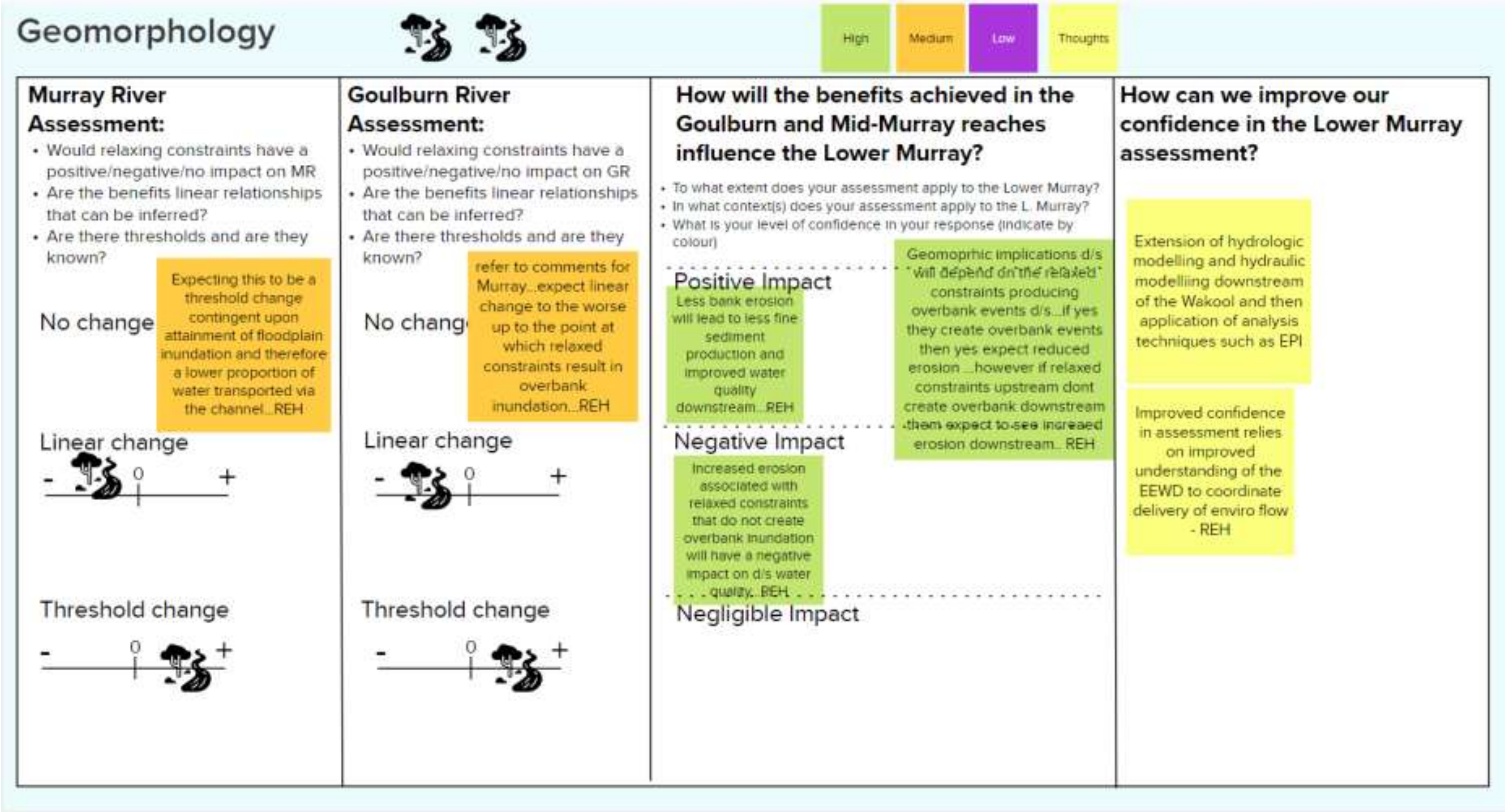

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Attachment 11: Assessment theme detail

Vegetation

The water regime is a major determinant of vegetation community structure and distribution (Brock and Casanova 1997; Casanova and Brock 2000). Maintaining a 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 suit some species better than others. One of the best understood examples is River Red Gum (*Eucalyptus camaldulensis*) (Rogers and Ralph 2010) whose growth, condition and survival is influenced by flood frequency. There is considerable variation in the frequency that River Red Gums require, depending on rainfall, groundwater and other factors, but for a given site, the frequency of inundation required is greater than for other communities such as Black Box (*Eucalyptus largiflorens*) (Rogers and Ralph 2010; Roberts and Marston 2011).

Inundation duration is also a key flow variable that defines habitat for different types of vegetation communities. Species tolerance for inundation varies widely and so some species are eliminated through prolonged inundation, providing opportunities for other species. In some instances, the duration of inundation is important for the effects it has on soil moisture which is critical for short-lived wetland species that occur on damp mud following the recession of floodwater. Spiny Mud Grass (*Pseudoraphis spinescens*), which grows after flooding from rootstock, requires a duration of inundation of seven months on average. Lignum (*Muehlenbeckia florulenta*) thrives after three to seven months inundation, however it will not tolerate continuous flooding. In contrast, the shoots of Spiny Sedge (*Cyperus gymnocaulos*) will only tolerate inundation of two to four weeks (Roberts and Marston 2011)

As for duration of inundation, different vegetation communities require and occupy different depth zones. Submerged macrophytes, such as Ribbonweed (*Vallisnaria australis*) ideally grow in water ranging from 50cm to 1m depending on water temperature and turbidity (Roberts and Marston 2011). A broad range of species occupy the wet-dry ecotone around the waterline, while other species are typically found above the waterline or germinating on exposed mud and will not tolerate continuous inundation (Brock and Casanova 1997).

Patterns of dispersal have a profound influence on the diversity of plant communities (Jansson et al. 2005; Brederveld et al. 2011), community dynamics (Hopfensperger and Baldwin 2009), distribution (Santamaría 2002) and the outcomes of restoration initiatives (Hopfensperger and Baldwin 2009; Brederveld et al. 2011).

Plants disperse in a variety of ways as either seeds or fragments that are capable of developing into an independent plant. Plants may disperse by wind, water or animals by either sticking to their bodies or by surviving passage through their gut (Figuerola and Green 2002). Different species have different dispersal strategies with some being heavily reliant on flow while others are more reliant on wind (e.g., cumbungi). Flow has the potential to influence dispersal either directly or indirectly through its influence on animals.

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 believed to be 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).

Timing of flows is also an important influence (Greet et al. 2011) as different species reproduce at different times of the year and so the timing of the connection will influence dispersal of individual species (Moggridge and Gurnell 2010). For example, the period of peak seed-fall for river River Red gum is September to November, while many annual species reproduce later in the year, for example cumbungi seeds disperse in summer and autumn (Roberts and Marston 2011). Once seeds settle out, they will reside in the sediments until conditions for germination occur or in some instances they are once again entrained by flow (Roberts and Marston 2011).

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The other way that flow can be important is in providing the cues and habitat to support germination and establishment of seeds and fragments once they have been deposited (Stella et al. 2006).

Production

Photosynthesis (primary production) is the process used by plants and algae to transform energy from sunlight into chemical energy of organic material. During photosynthesis, water and carbon dioxide are taken up by the organism and oxygen is released. Plants, algae and phytoplankton are subsequently consumed by bacteria, fungi, and animals, which use the chemical energy and nutrients to grow and reproduce (secondary production). Together, these producer and consumer organisms form a vast food web that represent ecosystem nutrient and energy cycles.

Floodplains and wetlands are highly productive catchment components (Beesley et al. 2012) and their inundation can increase energy budgets of downstream rivers (Cook et al. 2015). Inundation of floodplains mobilises terrestrial nutrients (dissolved and particulate) into the water column, drives the movement and deposition of nutrient-rich sediments and encourages distribution and germination of seeds, both within the wetland/floodplain and downstream (Junk et al. 1989, Thoms et al. 2000, Higginson et al. 2022). Beyond nutrient cycling and food abundance, floodplain wetlands form structurally diverse and complex habitats that support aquatic, riparian and floodplain biodiversity (Beesley et al. 2012).

Flood-initiated nutrient pulses lead to measurable increases in secondary productivity. Positive relationships have been observed between the duration of cumulative wetland filling and the abundance (recruitment) of native carp gudgeon (*Hypseleotris spp*.) in six wetlands of the mid-Murray River (Beesley et al. 2012). The duration of wetland filling was also associated with increased body condition of carp gudgeon, although only small flooding events occurred during the study. A monitored 2019 environmental watering event (coordinated releases from Hume Dam and Lake Eildon, reaching 15,000 ML/day at Yarrawonga) caused partial (25%) inundation of the Barmah-Millewa Forest that was associated with a short-lived pulse of higher densities of microcrustaceans (Chydoridae, Macrothricidae and Copepod nauplii) at sites in the Edward River, and in the River Murray at Barmah and Echuca (Furst et al. 2020). Such taxa are key food sources for large-bodied native fish. Elevation of zooplankton densities in the lower-Murray also coincided with the peak of the spring flow pulse (Furst et al. 2020). DOC, Total Phosphorus, Total Nitrogen and chlorophyll-a concentrations were measured in the Murray River during the same flow event (Rees et al. 2020). Increases in nutrients were directly attributed to the flow event, the magnitude of which decreased with distance from the Barmah-Millewa Forest. For example, carbon concentrations were unaltered 100km downstream. Only small increases in nutrients were detected in the mid-Murray, which the authors suggested was due to the consumption of nutrients for primary and secondary production (Rees et al. 2020b).

Consistent across the three productivity/inundation studies above is that a large flood is required to mobilise nutrients as a post-flooding pulse, and to increase wetland productivity. Small flooding events appear to be capable of flushing nutrients beyond the floodplain.

Water quality

Hypoxic Blackwater

When water floods a previously dry area (e.g., a river bench, dry channel or floodplain) carbon is rapidly leached from accumulated plant litter (Baldwin 2021). Carbon is a basal energy source for aquatic food webs, and hence is important for riverine productivity. The carbon enters the food web through microbial metabolism. In the process of consuming the carbon, the bacteria also consume oxygen from the water (Howitt et al. 2007). If the rate of oxygen depletion is greater than the rate that oxygen can be supplied from the atmosphere (re-aeration), then the oxygen concentration in the water column will begin to fall. Under the right conditions, this can lead to hypoxia, which is typically defined in waterways of the Murray-Darling Basin as an oxygen concentration of less than 2 mg/L - which is putatively the level below which large-bodied native fish begin to die (e.g., Gehrke, 1988).

Several factors determine the oxygen concentration in the waters downstream of a floodplain (Figure 16). These include the area inundated and the type and amount of litter present, which combined determine how much carbon is available for microbial consumption. The more carbon, the higher the likelihood of hypoxia. Temperature influences both the rate of microbial metabolism and oxygen carrying capacity of water

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(Whitworth et al. 2014). Figure 16 shows a schematic representation of the factors that influence dissolved organic carbon concentration ([DOC]) and dissolved oxygen concentration ([DO]) following the inundation of a forested floodplain. Boxes with red fill are temperature dependent; boxes with blue fill are flow/volume dependent; and boxes with green fill are vegetation type dependent; (modified from Whitworth and Baldwin, 2016).

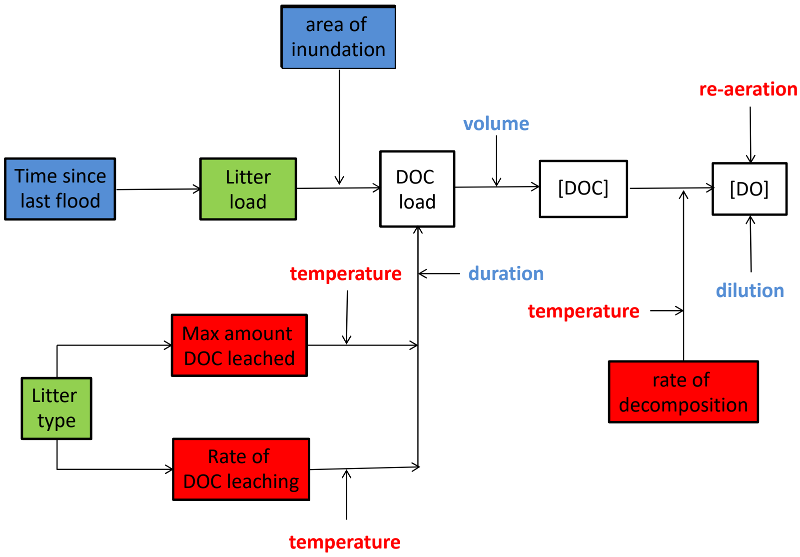

Figure 16 *Factors influencing dissolved organic carbon concentration ([DOC]) and dissolved oxygen concentration ([DO]) (modified from Whitworth and Baldwin, 2016).*

Here, BRAT modelling was performed to assess the risk of hypoxia in Murray and Goulburn Rivers following relaxation of constraints.

Eutrophication

There are several definitions of eutrophication, but a common feature is an increase in the biomass of photosynthetic organisms (in particular phytoplankton) in response to an increase in nutrient concentrations or loads (usually phosphorus and/or nitrogen). If the system is currently depauperate in primary production as a consequence of human interventions, then the increase in productivity can be seen as a benefit. However, from a water quality perspective, it is when excessive growth that occurs, that issues arise. Excessive algal growth can lead to substantial shifts in DO concentrations throughout any 24-hour period. During the day excessive production of oxygen during photosynthesis can lead to supersaturation of oxygen in the water column. Supersaturation of oxygen can promote gas bubble disease in fish - potentially resulting in fish mortality (Pleizer et al. 2020). At night the phytoplankton use oxygen for respiration. If the rate of respiration is high, it can lead to the point where oxygen concentrations fall below levels which are lethal to aquatic organisms such as fish.

There are several links between flow magnitude and eutrophication. Nutrients are released from floodplain soils and plant litter following inundation. Both phosphorus (Baldwin, 1999) and nitrogen (Harris et al. 2016) are leached from plant litter in an analogous way to carbon. This additional nutrient load can be exported directly back to the river or alternatively, can promote the growth of phytoplankton on the floodplain, which returns to the river channel. For example, Rees et al. (2020) recorded a net yield of total nitrogen and chlorophyll a (a surrogate for phytoplankton) peaking at about 5 and 0.1 tonnes/day respectively following an environmental flow into Barmah Millewa Forest.

Alternatively, the increased flows can disrupt algal bloom formation (e.g., Maier et al. 2001). This is important specifically for blue-green algal bloom formation.

Blue-green algal blooms

In essence blue-green algal (cyanobacteria) blooms are just a subset of the overall issue of eutrophication. Excessive growth (blooms) of blue-green algae can have the same impact on DO as excessive growth of other

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photosynthetic organisms, but in addition have other attributes that make excessive growth of these organisms undesirable in aquatic systems. Cyanobacteria can have impact human health through exposure to the variety of cyanotoxins (Funari and Testai, 2008; Merel et al. 2013). These toxins can cause liver, dermatological, digestive, and neurological diseases when ingested by humans and other mammals (Carmichael 2001). Recently, the amino acid BMAA, which is associated with increased incidence of neurodegenerative disease, has been identified in eight genera of cyanobacteria found in eastern Australian freshwater systems (Violi et al. 2019).

From an ecological perspective, excessive growth of blue-green algae (rather than other types of phytoplankton) can disrupt riverine food webs. In particular, fish require specific omega fatty acids for growth which they get from their food, with algae being the ultimate source of the fatty acids. Cyanobacteria lack a number of the essential fatty acids necessary for the growth of higher organisms (Müller-Navarra et al. 2000) and zooplankton feeding on cyanobacteria therefore become depleted in poly-unsaturated fatty acids and sterols (Demott and Müller-Navarra, 1997). If these zooplankton are a major component of the diet of higher consumers such as fish (e.g., King, 2005), then the consumers in turn will be depleted in those fatty acids.

For a bloom to form, blue-green algae generally require warm, still nutrient rich water. Many blue-green algal species can regulate their position in the water column. In still water, heavier phytoplankton (e.g., diatoms) will sink. Depending on depth and turbidity, they can sink to depths where there is insufficient light for photosynthesis. At higher flows, the ability to float is negated, minimising the likelihood of a bloom forming (see Davis and Koop, 2006 for a review). If blooms do form, increased flows can be used to disrupt the bloom (e.g., Maier et al. 2001).

Salinity

Salinity is a major problem in the Murray-Darling Basin. Land-use changes (particularly the removal of large native trees and their replacement with annual crops and grasses as well as the introduction of irrigated agriculture in the arid and semi-arid parts of the basin) have resulted in the raising of saline water tables, which, in places, are high enough to impact on the root zones of plants and/or be intercepted by wetlands and creeks.

Increased flows have the potential to increase the export of salt from floodplains (Jolly et al. 2012), through leaching of surface deposits of salt, mobilisation of salt that has accumulated in low lying areas of the floodplain (e.g., wetlands and creek channels) and, through exchange with salt in shallow aquifers.

Turbidity

Turbidity is a surrogate measure of how much material is suspended in the water column. The main impacts of high turbidity levels include:

- Lower light penetration through the water column, decreasing overall riverine productivity
- A shift towards blue-green algae as the dominant source of primary production
- Smothering of benthic organisms, include submerged macrophytes
- A decrease in benthic habit diversity through the infilling of cracks and crevices.

High levels of turbidity in the southern Murray-Darling Basin are related to European settlement (Rutherford, et al. 2020). These activities include land clearing, sediment mobilisation through mining activities (especially in the mid to late 1800's - Davies et al. 2018) and delivery of irrigation water. Furthermore, the introduction of carp into Australian waterways has also led to localised increases in turbidity. One mode of feeding of carp is mumbling, where the carp forage in the sediments looking for food.

Environmental water in the southern Basin is usually delivered from headwater or mid-level water-storage reservoirs. Because the water retention times in these reservoirs are relatively long, sediments are deposited in the reservoir rather than exported downstream. For example, the turbidity immediately below Lake Hume (Site 409016 - Murray River at Heywoods Bridge) rarely exceeds 10 Nephelometric Turbidity Units (NTU). Even following substantial inflows of sediment into Lake Hume following the Black Summer bushfires (Baldwin, 2022) hasn't exceeded 20 NTU, except on one occasion in mid-May 2020 when it peaked at 36 NTU. There is a possibility that the environmental water will increase bank erosion downstream, but not to the same extent as the delivery of irrigation water (McInerney et al. 2022).

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Weir Pool stratification/destratification

Under no- or very low-flow conditions, waterbodies can stratify. The surface water heats up at a faster rate than deeper water leading to a state where these is less dense (warmer) water sitting above more-dense (cooler) water. If this condition persists for any extended period of time (days or weeks) the DO concentration begins to decline because the oxygen is consumed through respiration (mostly microbial respiration in the underlying sediment). Because of lack of mixing between the two layers, DO is not replenished from the atmosphere and eventually reaches a point where there the bottom layer become anoxic. Once oxygen is consumed in the bottom layer, nutrients begin to be released from the sediments to the overlying water column.

The strength of the stratification will depend to a large extent on the thermal energy supplied to the surface water from the atmosphere. However, under the right condition the stratification can break-down (e.g., Bormans and Webster, 1997). This can occur if there is a sudden drop in air temperature, cooling the surface water, because of strong winds and/or flow increases. When this happens the two bodies of water mix quite quickly causing the DO concentration throughout the water column to fall. How low it falls depends on both the relative volumes of the surface and deeper pools of water and, the DO concentration in both layers. Recently, destratification events have been linked to fish kills in the both the Murrumbidgee River (Baldwin 2019) and the Darling Rivers (Baldwin 2020). Persistent higher flows should limit the formation of stratification, but if the flow is increased following a period of stratification, it can lead to a destratification event.

Acid sulfate soils

Acid sulfate soils is the generic name given to soils or sediments that contain either sulfide minerals or sulfide minerals that have subsequently oxidised (EP&HC and NRMMC, 2011). Until recently, it was believed that acid sulfate soils did not occur in inland environments, but such soils have now been identified throughout inland Australia (EP&HC and NRMMC 2011), including the Murray Darling Basin (MDBMC, 2011). Acid sulfate soils are formed under waterlogged (anaerobic) conditions, when a group of bacteria converts sulfate associated with inland salt deposits to sulfide. The sulfide can then react with metals, particularly iron, to form sulfide minerals and when these mineral sulfides are exposed to oxygen, they oxidise and produce acid (pH levels of less than 2 have been recorded in wetlands associated with the lower River Murray (McCarthy et al. 2006; MDBMC. 2011)). The ultimate source of the sulfate is usually from salt, so that salinisation of a waterbody and the formation of acid sulfate soils are usually linked.

The principal risk of higher flows inundating acid sulfate is the mobilisation of acid from the acid sulfate soils to the overlying water. However, it can also lead to deoxygenation and the mobilisation of heavy metals as well (EP&HC and NRMMC, 2011).

Thermal pollution

Unless a dam has a multi-level offtake, water releases from water storages tend to be from offtakes at the bottom of the dam. Large dams tend to thermally stratify for extended periods over the summer months. Therefore, the water released from the bottom of the dam in summer can be substantially colder than it would have been if the dam didn't exist. The plume of cold water can persist for hundreds of kilometers downstream of the dam.

Macroinvertebrates

Invertebrates are one of the most diverse components of aquatic ecosystem biodiversity. Macroinvertebrate diversity is strongly influenced by the hydrological regime of the ecosystem and the key drivers of aquatic ecosystem biodiversity with depth, duration of inundation, onset of inundation and history of inundation all influencing biota. Riverine floodplain systems support an array of different ecosystem types, including temporary and permanent wetlands, channels, backwaters, shallow lakes, and the main river channel. All of these habitats contribute to the high biological diversity seen in these systems as a whole.

Within the main river channel, macroinvertebrate responses are highly variable because flow can act as a disturbance or an opportunity in terms of habitat and food resources. High flows disturb macroinvertebrate communities leading to reductions in species richness and abundance for periods ranging from days to months, depending on the system's vulnerability and the severity of the disturbance (Lake, 2000). Despite adverse short-term effects, these disturbances are actually important in sustaining a mosaic of patches and macroinvertebrate diversity. The other effects of high flow events are that they influence habitat availability and food resources. While the underlying mechanisms hasn't been identified, it has been found that floods leave a lasting legacy on

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macroinvertebrate communities in the Murray River (Li et al. 2021, Paul et al. 2018). It is clear that floods lead to significant productivity increases that influence food availability for macroinvertebrates (Cook et al. 2015).

On floodplains and wetlands, high flows are major drivers of macroinvertebrate productivity. 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.

Native fish population assessments have focussed on the outcomes for Golden Perch and Murray Cod across the two rivers. Both species are considered highly important, being totemic species to First Nations peoples and for social outcomes of the regions, and Murray Cod has a national conservation listing (Todd et al. 2022).

Freshwater fish species adopt one of three life-history strategies (Equilibrium, Periodic and Opportunistic) based on based on size, time to maturation, fecundity, yolk size, juvenile survivorship, larval swimming ability and responsiveness of breeding strategies to flow (Table 11).

Table 11 *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. 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.

Table 12 outlines the range of flow characteristics and the related flow requirements for native fish populations. Consequently, these flow requirements were built into modelling of fish responses in the Goulburn River (Horne et al. (2020)).

Table 12 *Summary of flow needs for fish in the Lower Goulburn River. Models considered fish from different life-history groups: equilibrium species (Murray Cod and Trout Cod), periodic species (Golden and Silver Perch), opportunistic species (e.g., Australian smelt) in the Lower Goulburn River. Modified from Horne et al. (2020).*

Flow component	Flow needs for fish
High/overbank flows	Benefit from flows >10,500 ML/day. Best timing August to October
Baseflow winter	Higher winter baseline to provide depth > 40cm (equilibrium and periodic species) or >20cm (opportunistic species)
Baseflow spring/summer	Higher summer baseflow to provide depth >40cm, and temperature <18^{o}C degrees
Rate of rise and fall	Higher during nesting of equilibrium species, especially November-December
Spring fresh	>5600 ML/day for any benefit for periodic species, ideally in November
Fresh (anytime)	Higher for movement

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.

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Platypus

Platypuses (*Ornithorhynchus anatinus*) are evolutionarily distinct monotremes and widely distributed along the east coast of Australia from Tasmania to Cooktown (Grant 1992; Grant and Temple-Smith 1998). The species was recently listed as Near Threatened by the International Union for the Conservation of Nature (IUCN) (Woinarski et al. 2014; Woinarski and Burbidge 2016), and Vulnerable in Victoria, due to mounting evidence of overall population declines and localised extinctions. Substantial declines in platypus distributions have recently occurred, with 41.4% of sub-catchments within the platypus expected range having had no recorded platypus observations in the past 10 years (Hawke et al. 2019). Platypus populations are at risk as they are subject to many potentially synergistic threats to their survival. However, quantifying the impacts of various threats is rarely achieved due to challenges in effectively surveying wild populations.

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). Burrows have multiple openings close to or below the waterline and may be inundated as water levels rise. Short burrows (<5m) are used for resting. Long burrows extend >5m into banks and are used for nests/breeding. Platypus feed almost exclusively on benthic macroinvertebrates (McLachlan-Troup et al. 2010) and are predominantly nocturnal in their foraging activities, although some animals display diurnal activity particularly in winter and breeding season (Gust & Handasyde 1995, Grant and Temple-Smith 1998).

Long distance and large-scale movement have been recorded through radio-tracking and mark-recapture studies, with males having larger 'linear home-ranges' than females (up to 15.1km, Gardner and Serena, 1995), and some juvenile males dispersing over 44km (Serena and Williams, 2012).

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).

Platypuses are clearly tolerant of a wide range of flow regimes as demonstrated by the variety of aquatic habitats they inhabit throughout eastern Australia (Grant 1992; Grant and Temple-Smith 1998). However, as an aquatic dependent species, platypuses are potentially vulnerable to changes in flow regimes either directly through loss of aquatic habitat as well as disruption of foraging movements and dispersal, or indirectly through a reduction in abundance of macroinvertebrate prey. Despite a qualitative understanding of the how different flow components may impact platypuses (Jacobs et al. 2016), few studies have directly linked the health of platypus populations with specific components of the flow regime.

A recent analysis of flow regimes across a range of waterways in greater Melbourne identified long-term cease to flow patterns and flow variability as key metrics attributed to declining platypus populations (Griffith*s et al.* 2019). Waterways that support "healthy" platypus populations, as defined by relatively high captures per unit effort and other metrics (Griffiths and Weeks 2018), are characterised by low to no cease to flow events, and low to moderate variability. Cease to flow events or periods of very low flows can reduce overall habitat availability (total wetted area, Poff et al. 1997), reduce macroinvertebrate abundance (Chessman 2009; Marchant and Grant 2015) and may disrupt longitudinal and lateral connectivity and therefore limit platypus movements and dispersal (Griffiths and Weeks 2015).

Due to the high imperviousness of the surrounding catchments and resultant stormwater run-off, urban streams, particularly smaller streams, typically suffer from high flow variability with increased magnitude and frequency or high flows and reduced and extended baseflows (Walsh et al. 2005, 2012). Generally, this leads to depauperate macroinvertebrate assemblages (Walsh et al. 2001), increased erosion and sedimentation, and facilitates input of litter and pollutants from the surrounding catchment. Platypus distribution throughout Melbourne has previously been demonstrated to be limited by catchment imperviousness (Martin et al. 2013; Serena and Pettigrove 2005) indicating that platypuses are sensitive to direct and indirect impacts of altered flow regimes of urban streams. In addition to the impacts on food availability, platypuses may avoid high flow events that can potentially increase swimming energetics (Gust and Handasyde 1995; Griffiths et al. 2014), although no estimates of threshold flow rates exist. This behaviour can include seeking refuge in backwaters or

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connected wetlands if available. While this may be tolerable in the short term, repeated or extended high flow events may have more significant impacts on platypuses.

In south-eastern Australia, successful reproduction in platypus has been positively correlated with rainfall (and presumably reliable flows) in the months preceding breeding (March-July; Serena and Grant 2017; Serena et al. 2014), while late spring/early summer floods may compromise juvenile recruitment (Bino et al. 2015; Serena et al. 2014). However, there has been little quantitative analyses of the relationship between platypus population dynamics and flow metrics, and it is therefore difficult to quantify benefits of flow management actions.

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. Females nest in the banks of their residence in early summer laying a clutch of between 2 and 10 eggs with the capacity to lay one to three clutches each year. Eggs hatch after three to five months. In contrast eastern Macquarie River turtles (*Emydura macquarii macquarii*) is most often found in rivers and their backwaters. Their habitat preference appears to be deep (>3m), clear and permanent waterbodies. Little is known of the nesting ecology of Macquarie River turtles, however, it has been found they nest between 15 and 30 meters from the water's edge during November.

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. Like eastern long-neck turtles, broad-shelled tortoises will move over land to find other water sources. They also have the capacity to aestivate in the mud until water levels increase. Broad-shelled turtles usually nest in autumn, early winter or occasionally spring. Nests are often located on sandy ridges and can be located up to 1 km but more commonly within 100 m of the water's edge. The eggs incubate on average for between 324 and 360 days. This means that nests would be vulnerable to inundation which may be why nests are selected on either ridges or distant from the water's edge.

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). Major changes to the flow regimes of the Goulburn and Murray Rivers and change in land use practices since European arrival have altered this balance in the following ways:

- Flow regime: Seasonal reversal of flows and the decrease in flow variability due to regulation have the effect of accelerating rates of bank erosion by:
  - Increasing the total time that flow forces are expended against the channel banks.
  - Maintaining water levels at a constant, or near-constant elevation for long periods of time, which can lead to notching and then collapse of the channel bank.
  - Inundation of bank vegetation, leading to die-off and a decrease in the erosion resistance that vegetation provides.
- Land use changes: The clearing of riparian vegetation following European arrival has led to a decrease in erosion resistance of the channel banks. The decrease in bank resistance, due to the absence of stabilising roots or the protection that foliage and branches provide to soils, has the effect of increasing rates of bank erosion compared to pre-European condition.
- Weir pool construction: The construction of weir pools and dams, which maintain a near-constant water surface elevation upstream, has led to an increase in bank erosion. Bank erosion upstream of weir pools or dams is driven by notching of the channel bank, which is exacerbated by wind driven waves (or boat wake).

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Constraints relaxation has the potential to increase or decrease the rate and distribution of channel erosion along both the Murray and Goulburn Rivers. Exactly where, and by what mechanism any erosion occurs in the Goulburn or Murray Rivers will depend on site specific factors such as bank condition, the location of weirs, stock access, the condition of riparian vegetation and the history or erosion at a site.

For the purpose of this investigation the erosion potential has been assessed using the concept of total effective geomorphic work. Total effective geomorphic work can be thought of as the energy the river applies to the bed and banks (which drives erosion). Effective work is undertaken when the erosion forces of the flow are larger than the inherent resistance forces of the channel. Flow is considered ineffective below this threshold as sediment is not mobilised, erosion does not occur, and the channel remains unchanged.