LA TROBE UNIVERSITY

CENTRE FOR FRESHWATER ECOSYSTEMS (CFE)
School of Life Sciences

Reconnecting River Country – Floodplain Vegetation Condition Predictive Modelling

Part 2: Murrumbidgee River floodplain

Prepared for the Department of Planning and Environment NSW

April 2022

Prepared by
Luke McPhan, Samantha Capon and Nick Bond

CFE report #278

ENQUIRIES
Luke McPhan
La Trobe University
Victoria 3086

T 0407 009 320
E L.McPhan@latrobe.edu.au
W: latrobe.edu.au/freshwater-ecosystems

Document history and status

VERSION	DATE ISSUED	REVIEWED BY	APPROVED BY	REVISION TYPE
Draft	18/07/2022	Luke McPhan	Nick Bond	Draft
Draft v2	02/09/2022	Luke McPhan	Nick Bond	Draft
Final Report	21/09/2022	Luke McPhan	Nick Bond	Final

Distribution of copies

VERSION	QUANTITY	ISSUED TO
Draft	2	Department of Planning and Environment
Final Report	1	Department of Planning and Environment

Report citation

McPhan L.M., Capon S., Bond N.R., (2022) “Reconnecting River Country – Floodplain Vegetation Condition Predictive Modelling; Part 2: Murrumbidgee River floodplain”, CFE Publication #278, Prepared for the Department of Planning and Environment NSW

Traditional Owner acknowledgement

The Centre for Freshwater Ecosystems, Albury–Wodonga is located on the land of the Wiradjuri people. We undertake work throughout the Murray–Darling Basin and acknowledge the traditional owners of this land and water. We pay respect to Elders past, present and future

Executive Summary

Improving the condition of floodplain vegetation communities impacted by river regulation and modified flow regimes is one of the key goals of the 'Reconnecting River Country' program. Floodplain vegetation consists of multiple community types (e.g. river red gum forest, emergent wetland communities), which may benefit from a relaxation of constraints on water for the environment deliveries. This report summarises the predicted vegetation outcomes in the Mid-Murrumbidgee River system under a current conditions scenario and three relaxed constraint scenarios to identify impacts to the condition of the vegetation community under alternative constraint relaxation scenarios.

Vegetation responses were modelled using the Floodplain Vegetation Condition Model (FVCM) a newly developed state and transition simulation model (STSM) applied to rasterised layers of vegetation community type and condition. The STSM approach provides dynamic time-series of vegetation condition in response to different inundation sequences (defined in terms of frequency, timing and duration) for individual pixels in the vegetation rasters. Inundation levels were based on the Computer Aided River Management system (CARM) inundation model for the reaches between Burrinjuck Dam and Hay Weir. The implementation of the FVCM is a major improvement to typical vegetation condition assessments and attendant decision making, providing a spatially and temporally explicit framework for quantifying vegetation outcomes in ways that have not previously been possible.

Combining the STSM with hydrologic time-series and associated inundation sequences allowed projection of the initial vegetation state (veg type and veg condition) across 124 year hydrologic time series representing different constraint relaxation scenarios. Vegetation condition was quantified on an interval scale (*critical*, *poor*, *intermediate*, *moderate*, and *good*), with numeric values for condition ranging from 0-1. Outputs from the model consist of annual (n=124) rasters describing vegetation type and condition within each pixel (125 m resolution) across the floodplain area. Individual raster extents were aligned with zones in the inundation models. In total there are over 112,000 individual "pixels" where this 124 year time series was produced and stored from each scenario/model-run (n = 4).

Several key outputs were produced to allow comparisons between scenarios;

1. Maps showing proportion of years that the vegetation was predicted to be in 'good' condition under each scenario.

2. Difference maps showing the change in proportion of years that vegetation condition was predicted to be in ‘good’ condition relative to the baseline scenario.
3. Density plots showing the changes in the proportion of time that pixels were in good condition relative to the baseline scenario.
4. Time series projections of the total annual area of vegetation for floodplain areas of interest.
5. Tables summarising the total floodplain area that showed either a) no change, b) an increase, or c) a decrease in the proportion of time that vegetation was in good condition. The net outcome from these changes was also tabulated.

To provide a succinct summary for comparing outcomes, the main body of this report relies on the summary tables only, with graphical outputs (maps and plots) included as appendices.

Key findings from the modelled outcomes were:

- The model was able to capture the dynamic nature of vegetation condition over time, in particular capturing declines in condition associated with drought sequences.
- Generally, the response of river red gum forests and woodlands to the relaxation of constraints was a net improvement in the area of good/moderate condition. However, this net improvement with constraint relaxation was not uniform across constraint scenarios or locations of interest within the catchment.
- Comparing each scenario to the base case of W22, W40 delivered the best outcomes overall for the area of river red gum in good/moderate condition.
- In all scenarios there were consistent declines in the area of black box woodland in good/moderate condition over time. While it is possible that modelled flow regimes are insufficient to sustain current stands of black box woodlands in the Mid-Murrumbidgee, this result may be sensitive to input datasets to the model or inundation response inaccuracies, and thus requires further testing.
- Differences in condition change were observed between key sites and floodplain elevations. For example, the relaxation of constraints to deliver higher flows for the environment reduced the magnitude of large “natural flood” events present in the base case scenario. Resultant improvements in mean vegetation condition at lower elevations may be offset by declines in mean vegetation condition at higher elevations.

In summary, the FVCM provides a step-change in the ability to assess floodplain vegetation responses to changes in floodplain inundation. Due to large variability in the spatial distributions, including inundation thresholds, of vegetation types across the catchment, constraint scenarios were species-specific at the whole of catchment scale. The net benefit to river red gum was greatest under the ‘W36’ scenario while for black box woodland no option improved the overall area of good/moderate condition over the base case. While the model will benefit from further refinement and validation, the current projections align with expert opinion of expected changes under modified constraints and improves understanding by providing a spatially and temporally explicit framework for quantifying outcomes in ways that have not previously been possible.

Contents

Introduction and context for study

Globally, floodplain vegetation communities have been heavily impacted by altered flow regimes due to river regulation and water extraction for off-stream use. Floodplain vegetation communities respond to specific inundation regimes (extent, duration, timing) to persist (Roberts & Marston, 2011) which, in many regions have been significantly modified, leading to changes, often declines, in vegetation extent and condition. Projected climate change will exacerbate hydrologic change and is predicted to cause further declines in the 'hydrological health' of river ecosystems (Peterson, Saft, Peel, & John, 2021). As a mitigating measure, environmental watering offers a potentially effective way of maintaining and improving the condition of floodplain vegetation communities, although determining the flow-regime required to reverse declines in condition, as well as assess the feasibility of delivering such flows is a major management challenge.

The Reconnecting River Country program aims to improve wetland and floodplain connectivity through investigating relaxing or removing some of the constraints or physical barriers that impact delivering water for the environment. Flood-dependant native vegetation communities, including riparian and floodplain forests and woodlands, shrublands and non-woody wetland vegetation, will likely benefit from an improved flow regime when flow limits on water for the environment are relaxed. Floodplain vegetation of the Murrumbidgee catchment was modelled under base case (current) constraints and under three scenarios of constraint relaxation (Table 1) to identify impacts to the condition of the community. Modelled projections of floodplain vegetation condition in response to inundation between these hydrologic scenarios was generated by staff at La Trobe University and are analysed within.

Table 1. Flow limit scenarios for the Murrumbidgee River, including flow limit options considered in the Reconnecting River Country Program.

Scenario name	Flow limit at Wagga Wagga (410001) ML/day
W22 (base case)	22,000
W32	25,000
W36	30,000
W40	40,000

This report focuses on the results of modelled vegetation states within the floodplain inundation extent of the Murrumbidgee River between Burrinjuck Dam and Hay Weir. The modelling was based on previously developed vegetation condition state-and-transition models. This approach extends previously developed models (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, and 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 themselves 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 customised functions within R for statistical computing (R Development Core Team, 2020) to run matrix projections of Vegetation state. Using this model, a time series of state transitions (vegetation condition change) was generated across a 124-year period of flows.

Methodology

Project areas

This report presents and discusses results for the Mid-Murrumbidgee reach: Burrinjuck Dam to Hay Weir (see Model Results and Discussion sections; and Appendix 1). Results were also generated for lower Murrumbidgee reach (Lowbidgee: Hay Weir to Murray confluence) and are presented in Appendix 2, however they are not presented in the main report, or considered in the executive summary or discussion. This is due to uncertainty regarding the validity of input datasets to the model for evaluating the effect of raised flow limits arising from two issues:

1. DPE has identified that further work is still needed on the Murrumbidgee Source model. Specifically, more work is needed to improve gauge/flow relationships of the lower Murrumbidgee (including Maude and Balranald) to improve the reliability of flow estimates. This means that further caution needs to be taken in estimating the effects of modelled flows in the Lowbidgee. The current version of the Murrumbidgee Source model Flow was identified to reliably estimate flows for the mid Murrumbidgee.
2. Large areas of the Lowbidgee floodplain are regularly inundated by water deliveries made via infrastructure meaning in most years, the area inundated in these sections of the floodplain is not able to be related to river flow levels. Importantly, there are still portions of the floodplain below Hay that are not able to be watered by infrastructure, and here the area inundated is still related to river flow levels, and therefore will possibly be affected by raised flow limits proposed by the Program.

Model inputs

To our knowledge, this is the first implementation of state and transition frameworks to describe changes to the floodplain vegetation of the Murrumbidgee River catchment. As such, in developing the state and transition framework it was determined that a single driver of changes to vegetation condition, inundation spell (duration and frequency), was appropriate for an initial assessment of the approach. The modelling framework considers the joint effects of antecedent vegetation state, and antecedent inundation conditions after each annual time-step. We largely followed the methodology of Bond et al. (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 (CARM; DPI Water (2015)),
- 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'), given different combinations of antecedent hydrological and ecological states, and
- Rule set of the inundation requirements for transitions between vegetation states for each vegetation type (Appendix 3).

These data sources are described in detail below.

Inundation maps

The floodplain inundation map of the Mid-Murrumbidgee River, the Computer Aided River Management model (CARM, DPI Water (2015)) models the floodplain inundation from the outlet of Burrinjuck Dam at the furthest upstream extent to Hay weir at the furthest downstream extent. This was used by the model as a raster dataset containing 'commence-to-fill' thresholds relative to the gauged flow at Wagga Wagga (410001) Burrinjuck Dam to Hay Weir.

Due to hardware constraints for modelling pixels at this resolution, pixels were aggregated into 125 m square pixels (i.e. 1.56 ha/pixel) and the mode 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 (McPhan and Bond, 2022; Milestones 3e and 3f). Additionally, the inundation volumes of the maps which used daily discharge were binned to 1000 ML day^{-1} increments between 16,000 and 150,000 ML day^{-1}. A quality assessment of the CARM model undertaken by DPE based on satellite imagery and expert opinion found that flows above 22,000 ML day^{-1} at Wagga Wagga were suitable for this purpose, but flows under this amount significantly overstated inundation. To address this, flows of 16,000 ML day^{-1} at Wagga Wagga were attributed as in channel and all flow bands between 16,000 ML and 22,000 ML day^{-1} at Wagga Wagga were removed. In the model, this means that the floodplain begins to inundate at 22,000 ML day^{-1} at Wagga Wagga.

Flow constraint timeseries and spells analysis

Multiple hydrological scenarios were assessed to determine the influence of different constraint relaxations on various outcomes across the multiple themes of the 'Reconnecting River Country' project. For the responses of vegetation in the CARM reach of the Mid-Murrumbidgee these scenarios simulated flows gauged at Wagga Wagga (gauge number 410001) that were processed into spells of inundation experienced by vegetation on the floodplain.

To generate the flow options DPE EES staff used 'Source Model' software (version 5.10) to generate four constraint relaxation scenarios (See RRCP Murrumbidgee Environmental Benefits and Risk Analysis Synthesis Report (DPE, 2022)for greater detail on the Source hydrological modelling). These constraint volumes of daily discharge were parameterised by flow constraints at Wagga Wagga (W). For example, the base level of constraints, 22 GL day^{-1} at Wagga Wagga is expressed as 'W22'. The 3 remaining scenarios were named 'W32', 'W36' and 'W40' using this convention to describe relaxation of the flow constraints at Wagga Wagga. For each scenario simulated flows at corresponding gauges for the four inundation maps 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 determine the hydrological year (*hydro.year*) across the entire time series. This resulted in a 123 year time series (and 1 initial state, n = 124) after flows were standardised to the hydrological year (i.e. start/finishing in the average annual driest conditions) between April 1st to March 30th.

Within these annual windows a spells analysis determined the durations of both 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 "Reconnecting River Country" program through both workshops and regular meetings. Spells of appropriate duration were then summarised as a binary time series of a specific spell occurring in a year which was then used to inform transitions of vegetation based on its expected response (transition) to inundation by a flow event (see "rules" in the "State and transition simulation modelling" section). This usually takes the form of a sum of spells across a period of one or more years at each unique inundation threshold of the inundation map.

One aspect of these inundation maps is that they are based on commence to fill volumes and not correlations of observed inundation extents on the floodplain and antecedent flow in the river. This means that water on the floodplain will rise and fall on the floodplain as rapidly as it 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 our spells analysis. This was a similar approach that is implemented in several functions of the *hydrostats* package (N. Bond, 2021) that allows spells occurring within a short enough lag of one another to be counted as the same spell and their inundation durations to be joined together. When describing the averaging of our inundation maps, a previous sensitivity analysis (McPhan and Bond, 2021; Milestones 3e and 3f) allowed us to assess the validity of values that were suggested by expert elicitation via workshops. We found that a 'between spells duration' of 15 days was adequate to better represent the inundation durations occurring on the floodplain showing a greatly reduced decline in the mean condition of most vegetation types.

Vegetation layers

High quality vegetation layers were generated from the NSW PCT classes were consolidated to the vegetation states modelled here. A detailed description of the approach to generate spatial datasets of this vegetation (Figure 1) can be found in Appendix 4, which is applicable to the Murrumbidgee catchment. In aggregating these many classes 28 sub-categories of vegetation type within 12 broad categories were derived for future work using these vegetation layers (Table 2).

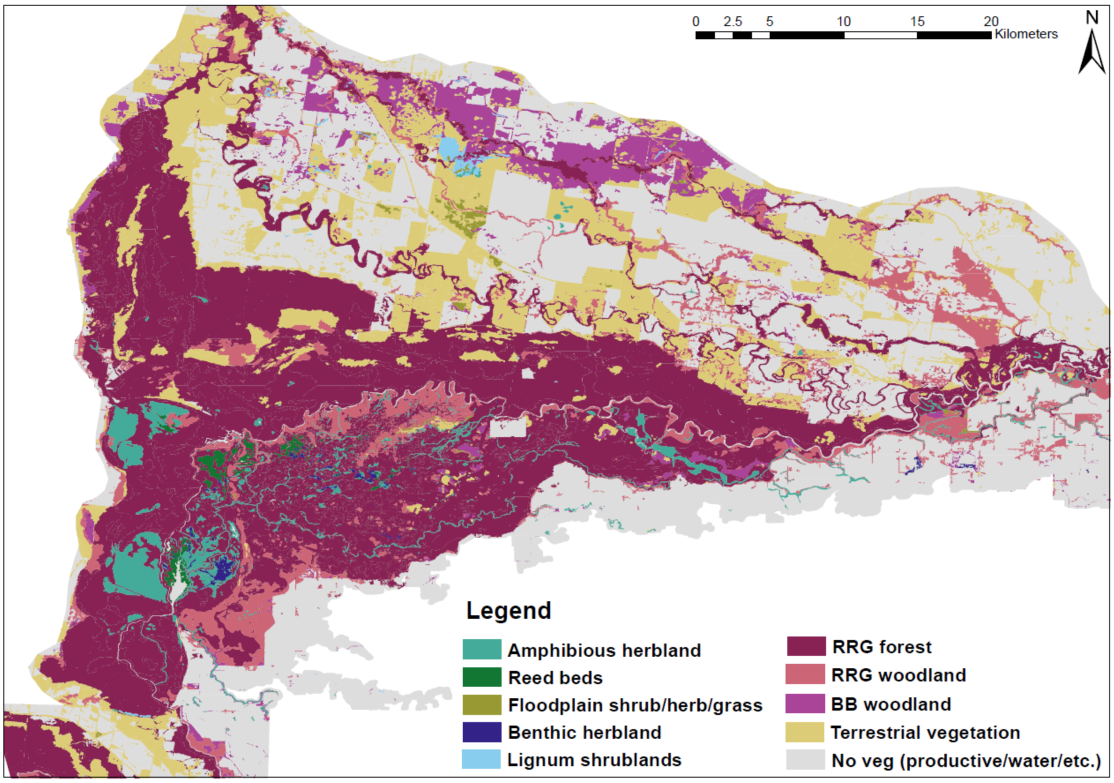

Figure 1. An example of the vegetation data used in the condition modelling of multiple vegetation types. Presented here is the Barmah-Millewa Forest region of the Murray River system.

Of the 12 broad vegetation categories, we have parameterised rules for six to reflect our focus on floodplain vegetation: river red gum woodland, river red gum forest, black box woodland, lignum shrublands, perennial wetland grass, sedge and rush lands, and wetland herblands. Modelling vegetation in this report, we have focussed strongly on three of the broad categories (river red gum woodland [RRGW], river red gum forest [RRGF], black box woodland [BBW]).

*Table 2. Vegetation groupings resulting from grouping of EVC and PCT codes to broad categorical and sub-categorical vegetation groups. Broad categories denoted with an * are those assessed in this report, and those with + have rules under review for future reports.*

Broad category	Subcategory
River red gum woodland*	RRG woodland lignum understorey
River red gum woodland*	RRG woodland grassy understorey
Black box woodland*	BB woodland chenopod understorey
black box woodland*	BB woodland grassy understorey
Black box woodland*	BB woodland lignum understorey
Terrestrial grasslands	Terrestrial grasslands
Wetland herblands+	Amphibious herbland - grassland/forbland
River red gum forest*	RRG forest sedge understorey
River red gum forest*	RRG forest herb-grass understorey
Terrestrial woodlands	Terrestrial woodlands
Terrestrial woodlands	Floodplain transition woodlands
River red gum forest*	RRG forest lignum understorey
Lignum shrublands+	Lignum shrublands
Perennial wetland grass, sedge and rush lands+	Common Reed
Wetland herblands+	Floodplain terrestrial herbland/grassland
Perennial wetland grass, sedge and rush lands+	Tall GSR
Terrestrial shrublands	Chenopod shrublands
Terrestrial shrublands	Terrestrial shrublands
River red gum woodland*	RRG woodland mixed understorey
Wetland herblands+	Amphibious herbland - low-mid sedgeland
Wetland herblands+	Benthic perennial herbland 2
Wetland herblands+	Floodplain shrublands
Terrestrial shrublands	Saltbush forbland
Saline wetlands	Saline wetlands
Wetland herblands+	Benthic perennial herbland 1
River red gum woodlands*	RRG woodland sedge understorey
Terrestrial grasslands	Chenopod grasslands
Wetland herblands+	Terrestrial shrublands

State and transition simulation modelling

In recent years there has been a strong push for the development and adoption of modelling approaches to assist with environmental flows planning that are better able to replicate the response of ecosystems to specific flow sequences (e.g. Horne et al., 2019; Shenton, Bond, Yen, & Mac Nally, 2012; Tonkin et al., 2019). This motivated our use of a state and transition framework for projecting likely responses of vegetation in flood dependant ecosystems. In their most basic form state-and-transition models (STMs) assume transition probabilities adhere to a constant first-order Markov process. This means looking only one time step back to determine if a transition occurs. 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).

While we haven't implemented probabilistic aspects to state transitions in our framework being fully deterministic, with respect to the relationship between a transition parameter (spell rule) and the state change, we have generated very high-order lags e.g. 30 years of 365 day dry spells for the decline from black box woodland in a "good" state to a "dead" state. This allows a significant amount of model "memory" for individual units of simulation and in simulating many millions of pixels across floodplains 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 time series of rule transitions is used to construct annual transition matrices for each inundation threshold specific to that inundation map. Initialising the vegetation layer as "good" for their relevant type and storing this value as a binary vector of all possible states, the projections are a simple process of multiplying the initial state vector by these transition matrices.

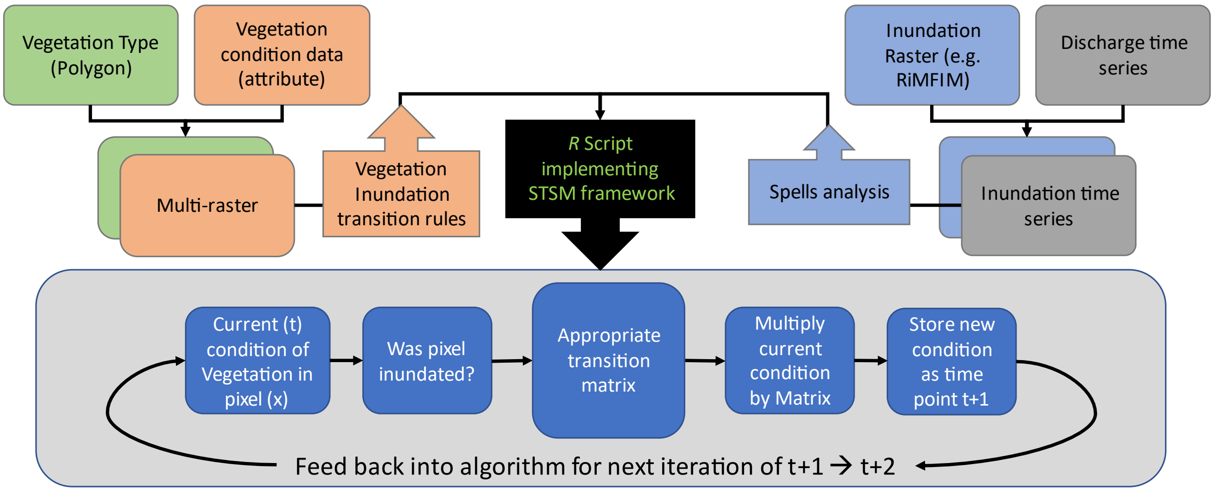

Figure 2. Visual representation of workflow for the data sources and computing that needs to be completed for the vegetation condition projection. The top left pannels of the diagram show vegetation data preprocessing (Polygons and condition attributes to raster layers). The top right plannels show where the hydrological spells analysis/preprocessing occurs prior to being piped into a script that performs the state transitions for vegetation condition projection.

Rules

To determine the rules of state transitions three aspects of the current time point were necessary: 1) the current state of the vegetation, 2) the antecedent inundation time series of spells, 3) the duration, across which a rule would function (Figure 3). The first two are explained in previous sections but the third aspect is one that required fair consideration of the species tolerance to both drought and prolonged inundation. Initial parameterisation of some of our rules (Appendix 3) was based largely on the following research:

- N. R. Bond et al. (2018). "Assessment of environmental flow scenarios using state-and-transition models." Freshwater Biology 63(8): 804-816.
- Casanova (2015). "Review of Water Requirements for Key Floodplain Vegetation for the Northern Basin." Literature Review and expert knowledge assessment. Report to the Murray–Darling Basin Authority, Charophyte Services, Lake Bolac.
- Telfer, Charles, and Jensen (2015). "Black box health and management options." Prepared for the Commonwealth Environmental Water Office. Adelaide: Australian Water Environments.
- Roberts and Marston (2011). Water regime for wetland and floodplain plants: a source book for the Murray-Darling Basin, National Water Commission Canberra.
- Overton et al. (2014). "Development of the Murray-Darling Basin Plan SDL adjustment ecological elements method." Report prepared by CSIRO for the Murray-Darling Basin Authority, Canberra: 45-54.

- Capon, James, Williams, and Quinn (2009). "Responses to flooding and drying in seedlings of a common Australian desert floodplain shrub: *Muehlenbeckia florulenta* Meisn. (tangled lignum)." Environmental and Experimental Botany 66(2): 178-185.
- Jensen, Walker, and Paton (2008). "The role of seedbanks in restoration of floodplain woodlands." River Research and Applications 24(5): 632-649.

In addition, workshops were arranged with external vegetation experts consulted to give feedback on the pathways that had been identified from work above and assess the hydrological conditions that caused rules to project vegetation states into the future. Feedback from these experts included advising that we should focus on:

- Trial mean, mode, max and min inundation values when averaging inundation maps
- Assess multiple durations for inundation spells.
- Test the sensitivity of the period in between spells.

Further to the rules specification process above, the Murrumbidgee woody vegetation inundation rules were altered to better reflect flow regimes and inundation durations operating differently to the Murray. Preliminary Murrumbidgee vegetation models (Appendix 2) using flow responses determined for the Murray were not representative of inundation in the Murrumbidgee system. This is most likely due to inundation durations being directly linked to river flows in the current model. Compared to the Murray, the Murrumbidgee generally has shorter flow events, but connected Mid-Murrumbidgee wetlands can fill from a shorter flow. Expert advice from floodplain ecologists familiar with the Murrumbidgee catchment also identified that these connected floodplain wetlands "tend to be non-shedding floodplain" (i.e., stay inundated for longer) with respect to the short inundation spells. To adequately model this hydrological difference with the input datasets available the inundation rules for woody vegetation types were adjusted. A range of shortened spell durations were modelled for the Base Case scenario and the vegetation inundation responses were discussed with Murrumbidgee vegetation experts and adjusted for the system (Appendix 5). As shrub- and herb-lands were not reported on in this phase of the modelling, transition rules were not changed.

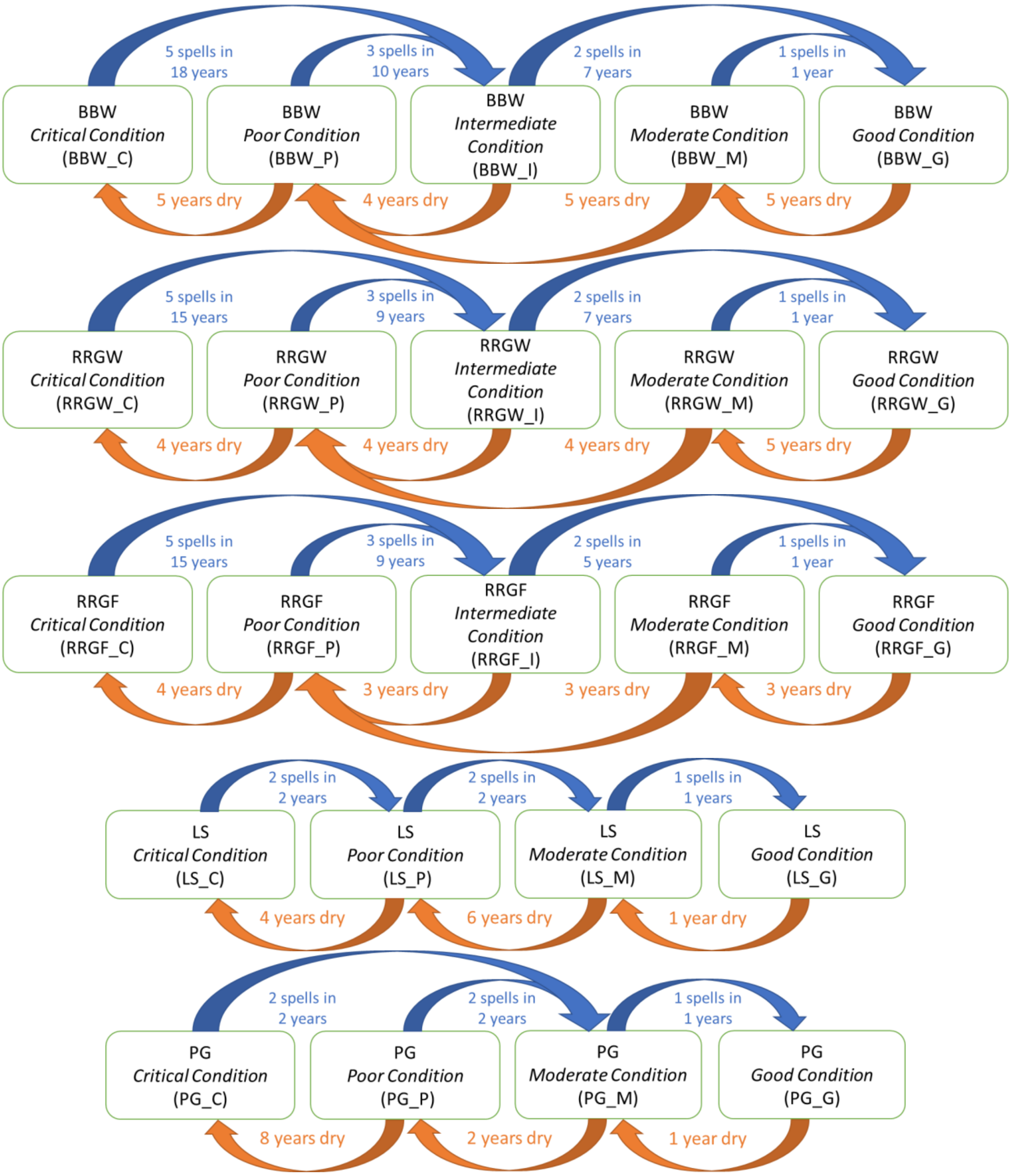

Figure 3. Visual representation of a subset of transition rules for inundation frequency of broad vegetation categories. Blue arrows show the pathway of state transitions in response to flood spells in this case 10 days. Orange arrows show the state transitions in response to drying periods of 300 days.

Model Results

The results from a dynamic model such as this are challenging to summarise in a single metric because the condition of the vegetation is changing in multiple dimensions – in two dimensions across the floodplain and along a third dimension of time. To enable comparison of the multiple constraint options we derived a simple response metric at the pixel level, which was the proportion of years (n=124) during which the vegetation state for that pixel were in a "good" condition. This provided a simple summary metric that could be mapped for each scenario, and which also allowed for differences between scenarios to be visualised and summarised in both a graphical and tabular format (Figures 4 to 6). We also combined river red gum woodland and river red gum forest areas into a single 'river red gum' vegetation class due to a significantly smaller extent of river red gum woodland. We have presented time series of annual trajectory of vegetation across each of the flow scenarios and provided two conceptual figures to improve interpretation of the spatial and summary figures and tables. The conceptual figures show how results were assessed spatially (Figure 5) and summarised into a tabular or graphical format for interpretation and comparison (Figure 6).

In addition to the tabular results in the main body of the report, we also derived a range of other summary outputs, including time-series of vegetation condition and more detailed comparisons of the changes in condition under individual scenarios (see Appendix 1). Multiple states of vegetation condition are modelled as a part of the model analysis, though assessing the changes to states in good and moderate condition will elucidate the influence of these flow scenarios on high condition vegetation. Below are the key findings and reference to relevant tables and figures for greater spatial context in specific locations.

- In the targeted reaches of the Mid-Murrumbidgee catchment a total of 175,600 ha of floodplain vegetation was modelled which included 53,349 ha of river red gum forest and woodland, 4,952 ha of black box woodland and 597 ha of Lignum shrubland (Table 3).
- A large reduction in the area of both river red gum and black box woodland in good or moderate condition over time is observed from the initial state under all flow limit option scenarios which can be seen as a 'model burn in' as we assume all vegetation is in a good state in the first time-step and antecedent rules which hindcast inundation influences are yet to influence transitions correctly. While the declining trend of river red gum areas in good/moderate condition appears to stabilise after ~1912 the area of black box woodland in good/moderate condition continues to decline.

*Table 3. Area of selected vegetation species as the model is initially parameterised. These values are broken down by each inundation map (raster) and the total area of the raster is shown. * indicates that the Darlington Point to Carrathool raster was not included in the totals, being it is a subset of CARM. For each vegetation type we represent their dominance as a percentage of total raster area.*

Source	Raster	Raster area (ha)	Red gum Area (%)	Black box Area (%)	Lignum Area (%)
CARM	Burrinjuck Dam to Hay weir (*full model*)	175606.25	30.38	2.82	0.34
	*Darlington point to Carrathool (*subset*)	39050.00	49.33	6.54	1.33

- Two discrete events of river red gum decline occur after 1912 that proceed the WWII and Millennium droughts respectively. While relative recovery after the WWII Drought decline is seen, recovery from the Millennium Drought decline has not occurred by July 2019 (end of modelled time-series).
- Outcomes of constraint scenarios for the whole Mid-Murrumbidgee catchment found for all vegetation types, the area unchanged by raised flow limits (i.e. 'No change', Table 4) was larger than the area where improvement or decline to the time in good/moderate condition occurred relative to base case (W22).

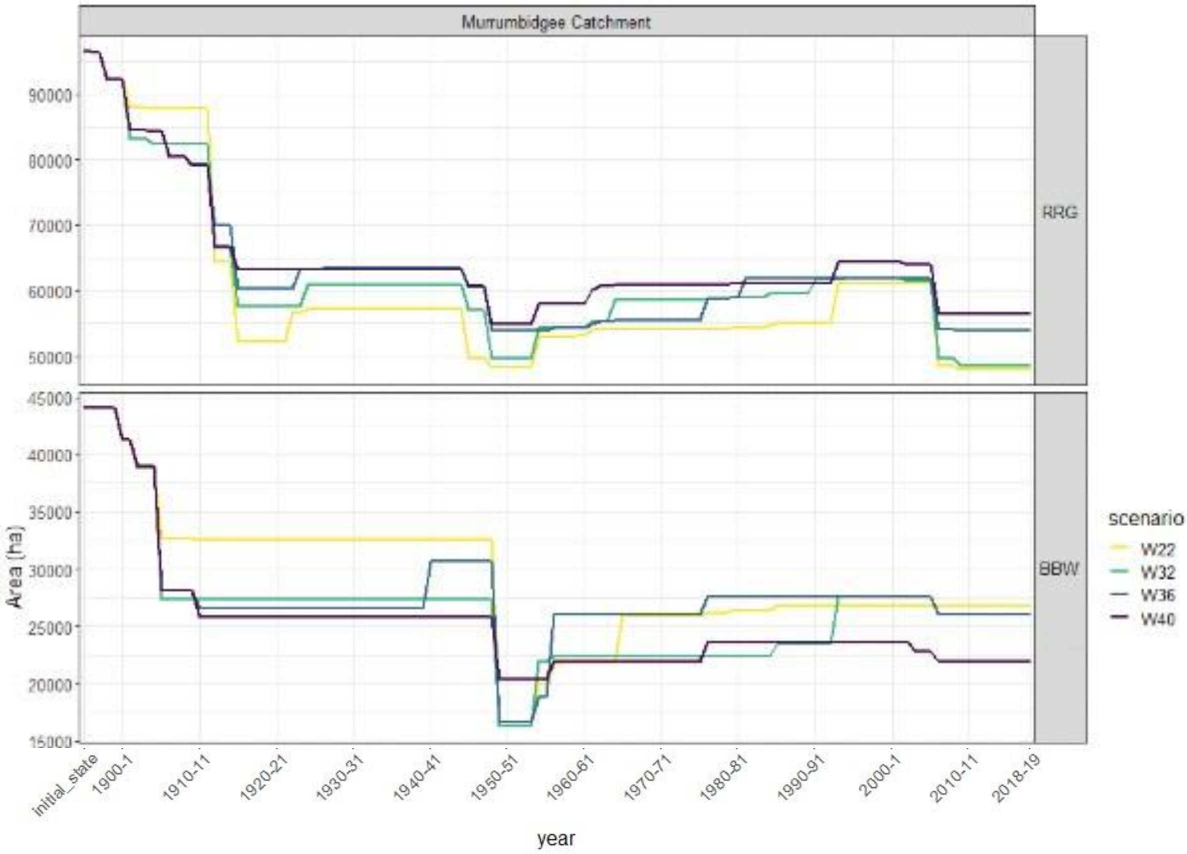

Figure 4. Mid-Murrumbidgee (CARM) time series of the area of good/moderate condition vegetation for each vegetation type (RRG = river red gum, BBW = black box woodland) under alternate constraint relaxation scenarios (Yellow = base case W22, Teal = W32, Blue = W36, Purple = W40).

- As the modelled flow limit increased (32 to 40 GL day^{-1}) the areas experiencing change (improvement or decline) generally increased for all vegetation types (Table 4). When compared to the base case (W22) the largest improvements were found in the 'W40' scenario for river red gum forest/woodland. No scenario yielded any improvement for black box woodland areas (Table 4). For both vegetation communities the largest areas experiencing decline were seen in the W36 scenario.
- In all raised flow limit scenarios, there was a net gain in area where the amount of time river red gum spent in good/moderate condition was increased (Table 4. Net $change_{RRG}$ [Table 4; 7,692 to 9,648 ha]). The largest area of net improvement [9,648 ha] resulted from the W40 scenario. For black box woodland, more areas experienced decline when evaluating the time spent in good/moderate condition under all raised flow limit scenarios (Table 4. Net $change_{BBW}$ [-686 to -1,536 ha]).

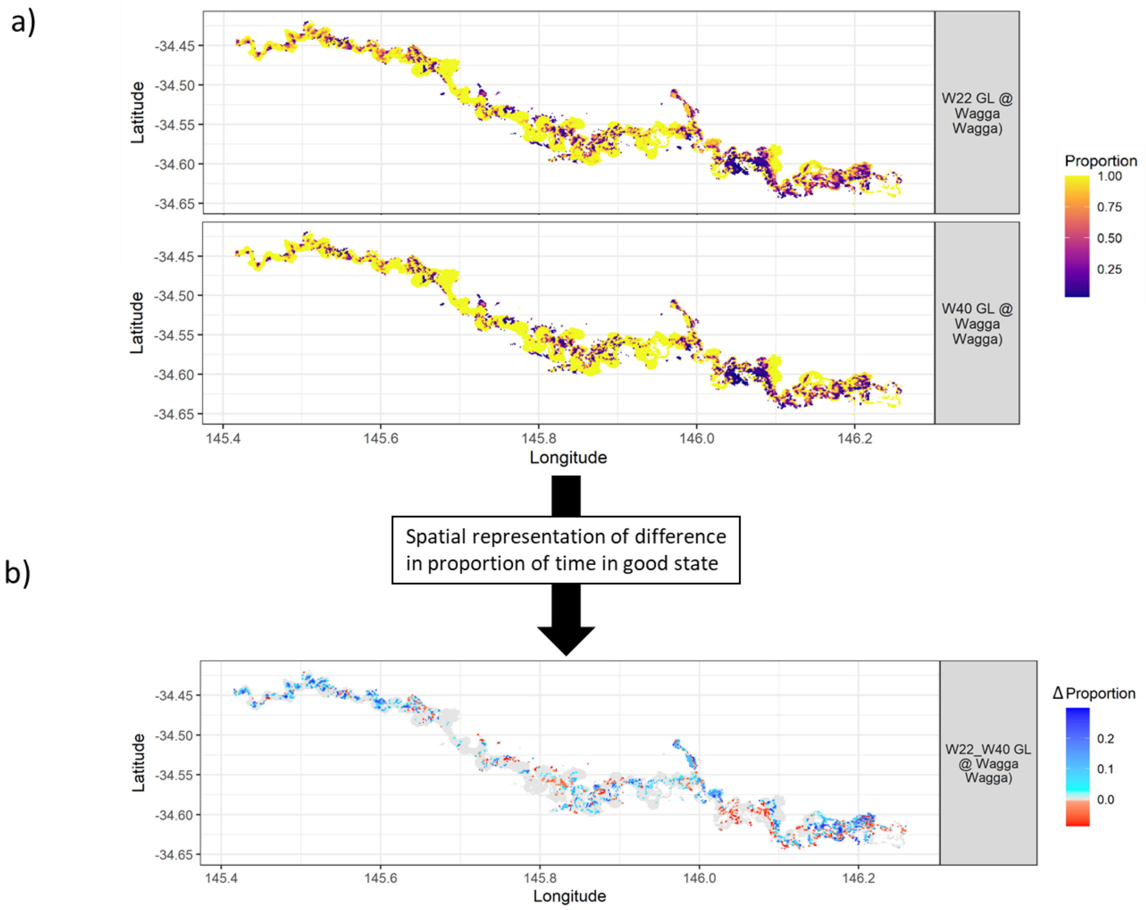

Figure 5. Mid-Murrumbidgee (CARM) time series of the area of good/moderate condition vegetation for each vegetation type (RRG = river red gum, BBW = black box woodland, LS = Lignum Shrubland) under alternate constraint relaxation scenarios (Yellow = base case W22, Teal = W32, Blue = W36, Purple = W40).

- The Darlington point to Carrathool (DP_CAR) area of interest, a reach of the Murrumbidgee containing multiple ecologically significant wetlands, had a larger area of river red gum in good or moderate condition on average relative to the greater Mid-Murrumbidgee region in all modelled scenarios (Table 5; +9 to +10 %). Improvements to the mean area in good/moderate condition for river red gum in the Darlington Point to Carrathool from raised flow limits were similar to improvements across the full Mid-Murrumbidgee catchment (~+ 3% of total area on average).

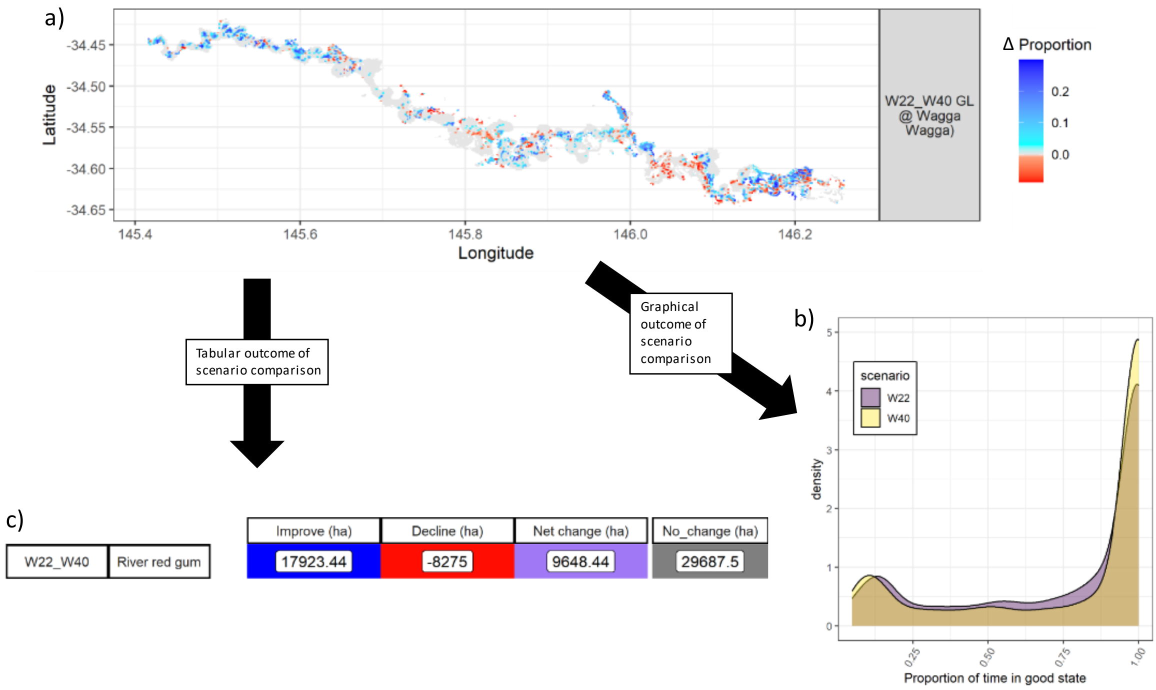

Figure 6. Derivation of summary metrics from the constraint comparisons of proportion of time in good state between a) the base scenario (W22) and constraint option (W36) b) a distribution of the difference in proportion of time, positive values are areas of net increase in condition and negative are areas of net decline, that are then c) represented in a tabular format of all modelled pixels.

- For black box woodlands the simulation shows a reduction of average time in good/moderate states overall (decline of up to -4.5 % of the total model duration; Table 5), however an increase is seen for river red gum (increase of up to +3.3 % of the total model duration)

Table 4. Total area (ha) changes for the Mid-Murrumbidgee catchment (improve, decline, Net change, and No change) to time spent in good/moderate condition comparing constraint for good/moderate states of river red gum (RRG_G) and black box woodland (BBW_G). Cell shading is grouped by vegetation type with Darker shades of grey indicate larger areas where there was no difference in the time in good/moderate state between Scenarios, the darkest red within vegetation types indicating the largest declines, darkest blue shading showing the largest improvements.

		Improve (ha)	Decline (ha)	Net change (ha)	No_change (ha)
W22_W32	River red gum	11537.5	-3845.31	7692.19	40503.12
W22_W36	River red gum	17845.31	-8353.12	9492.19	29687.5
W22_W40	River red gum	17923.44	-8275	9648.44	29687.5
		Improve (ha)	Decline (ha)	Net change (ha)	No_change (ha)
W22_W32	Black box woodland	0	-685.94	-685.94	5121.88
W22_W36	Black box woodland	0	-1356.25	-1356.25	4451.56
W22_W40	Black box woodland	0	-1356.25	-1356.25	4451.56

Table 5. Mean percentage (with Standard deviation) of time river red gum (RRG) black box woodland (BBW) and were in a good/moderate state over modelled time periods. Coloured shading has been included to allow comparison of the constraint options within selected areas of interest both including both the CARM model and Darlington Point to Carrathool (subset of CARM). The darkest red shading shows the shortest mean time in good or moderate condition, and darkest blue shading shows the longest mean time in a good/moderate state

		CARM	DP_CAR
W22	River red gum	64.73 (34.97)	75.17 (32.77)
W32	River red gum	65.40 (35.67)	75.94 (33.09)
W36	River red gum	67.79 (36.54)	77.66 (33.38)
W40	River red gum	68.07 (36.67)	77.85 (33.42)
		CARM	DP_CAR
W22	Black box woodland	62.18 (35.04)	58.26 (36.25)
W32	Black box woodland	59.83 (37.08)	56.34 (37.77)
W36	Black box woodland	57.66 (38.45)	53.92 (39.04)
W40	Black box woodland	57.66 (38.45)	53.92 (39.04)

Discussion

The condition of floodplain vegetation communities along the Murrumbidgee River has declined considerably as a result of river regulation and altered flow regimes. The Reconnecting River Country Program is assessing options for raised flow limits for water for the environment to improve the condition of floodplain vegetation communities. This report summarises the projected vegetation outcomes in the Murrumbidgee valley between Burrinjuck Dam and Hay weir under four modelled scenarios of constraint relaxation to identify impacts to the condition of the community under alternative constraint relaxation scenarios.

Vegetation responses were modelled using the Floodplain Vegetation Condition Model (FVCM) a newly developed state and transition simulation model (STSM) applied to rasterised layers of vegetation community type and condition. The STSM approach provides dynamic time-series of vegetation condition in response to different inundation sequences (defined in terms of frequency, timing and duration). Vegetation condition was quantified on an interval scale (*critical*, *poor*, *intermediate*, *moderate*, and *good*), with numeric values for condition ranging from 0-1. Adoption of this type of modelling to assess environmental flow options is a step-change from previous work and it is the first time it has been used in the Murrumbidgee system.

The model provides an estimate of expected vegetation condition at each time-step, which can be mapped across the floodplain and summarised by aggregating results in space and/or time. The overall finding from the modelling is that relaxation of operational constraints on river flows has the potential to improve outcomes for floodplain vegetation, although there were some notable differences between the four scenarios in long-term outcomes. The findings can be summarised as follows:

- The model was able to capture the dynamic nature of river red gum condition over time, in particular capturing declines in condition associated with drought sequences. The timing and magnitude of predicted changes align with expert opinion of the impacts of alternate flow regimes under raised flow limits.
- The response of river red gum forests and woodlands to raised flow limits was a net improvement in good/moderate condition area, with higher flow limits yielding higher net improvements. This suggests an increased frequency of wetland connection and small overbank flows as limits are raised which yields a net-benefit for river red gum vegetation.
- Higher flow limits caused river red gum condition to decline in some modelled areas and highlights that the net improvement with constraint relaxation is not uniform across the

catchment. This is likely due, in part, to changes at the upper and lower end of the inundation regime including:

  - reductions in the peak magnitude of large unregulated flows as observed in the modelled flow time-series reducing the inundation frequency of vegetation at higher floodplain elevations;
  - Increased inundation in lower floodplain areas (e.g. connected wetlands) where river red gums are essentially getting 'water-logged' (see inundated states in Appendix 3). This potentially indicates that RRC flows could combat river red gum encroachment in Mid-Murrumbidgee wetlands that have been drying out.

- Continual decline in the area of black box woodlands in good/moderate condition over time was observed in all modelled scenarios. While this is consistent with the generally poor condition of black box woodlands within the southern basin, it may be an artefact of the FVCM currently only modelling the response of vegetation to inundation and thus requires further testing. Possible drivers of this result include:
  - All modelled flow regimes (volume, and spell frequency, timing, and duration) may be inadequate to sustain existing extents of black box woodland in the Mid-Murrumbidgee. Conversely, the state transition rules for black box woodland may be too conservative to be responsive to modelled inundation events and requires empirical derivation.
  - The condition of black box woodlands within the Mid-Murrumbidgee is not reliably modelled by floodplain inundation alone. It is likely that black box condition relies on water from other sources (groundwater or rainfall) and is not sustained by floodplain inundation alone.
  - The inability of the CARM inundation model to accurately reflect floodplain inundation persistence after the flow peak indicates the influence of flow events may be underestimated with respect to the required spell duration, This was adjusted specifically for the Murrumbidgee in this study (see methods; Appendix 4) but could be improved in the future.
  - Given the general trend for black box woodlands to exist at higher elevations/inundation levels in the southern basin, the alteration of flows to allow higher volume operational constraints may be reducing the magnitude of "large scale" flood events that exist in base case scenario, and thus causing declines in vegetation condition at these elevations. This potential effect of raised flow limits needs to be investigated in more detail.

- Confidence in the specific magnitude of vegetation condition decline and/or recovery experienced within a zone requires calibration and validation of the vegetation state transition rules. Further, an inundation model that sufficiently accounts for floodplain inundation persistence will be key for realistic modelling of inundation dynamics critical to underpinning the state transition rules.

In summary, the FVCM provides a step-change in the ability to assess floodplain vegetation responses to changes in floodplain inundation. Due to large variability in the spatial distributions of vegetation types, including across inundation thresholds in the catchment, there are likely effects across the constraint scenarios that were species specific at the catchment scale. Given the new nature of this type of modelling in environmental assessments the model will benefit from further refinement. Model performance is strongly linked to the quality of input data sources. Input dataset refinement including, improved hydrologic models, improved hydraulic models instead of a corrected CARM model, more accurate vegetation mapping and empirical vegetation flow response rules, would generate significant model improvement. Further, validation and calibration of the model using ground or remote sensing data would enhance model confidence and interpretation. Finally, the current model only uses river flow as an input, meaning floodplain vegetation is modelled only in response to inundation flows and does not count the contribution of rainfall or groundwater. Despite this, the current FVCM projections align with expert opinion of the impacts of alternate flow constraints. The significant improvement this model provides is providing a spatially and temporally explicit framework for quantifying outcomes in ways that have not previously been possible. The FCVM has been found to be a powerful decision-making tool for evaluating the potential effects of altered flow regimes on flood-dependent vegetation.

Acknowledgments

Thanks to the following people that participated in and formed the workshop group of experts that that helped determine the transition rules for the State and Transition framework for floodplain vegetation: Cherie Campbell, Tanya Mason, Thomas Job, Keith Ward, Rachael Thomas, Susan Gehrig, Mark Henderson, Samantha Dawson, Paul Doyle, Ian Burns and Iwona Conlan. Additionally, thanks to Skye Wassens and James Maguire for their contributions to the refinement of the FVCM Vegetation rules from the Murray for application to the Mid-Murrumbidgee.

Appendix 1. Vegetation condition results

River red gum outputs

Accumulation plots

Comparisons within constraints

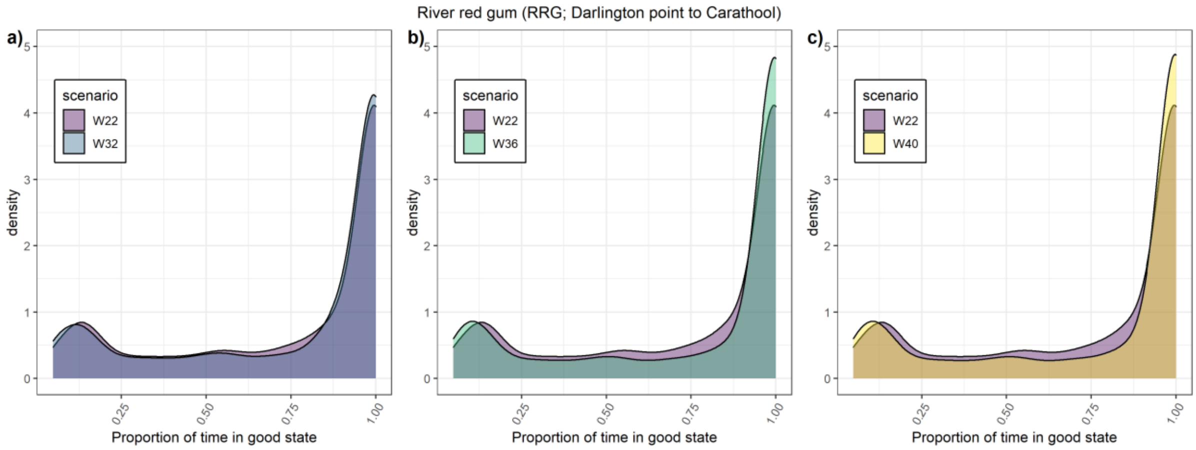

Figure 7. Darlington Point to Carrathool all pixels, Difference in proportion of time river red gum was in a good/moderate state between constraint options (W22, W32, W36, W40).

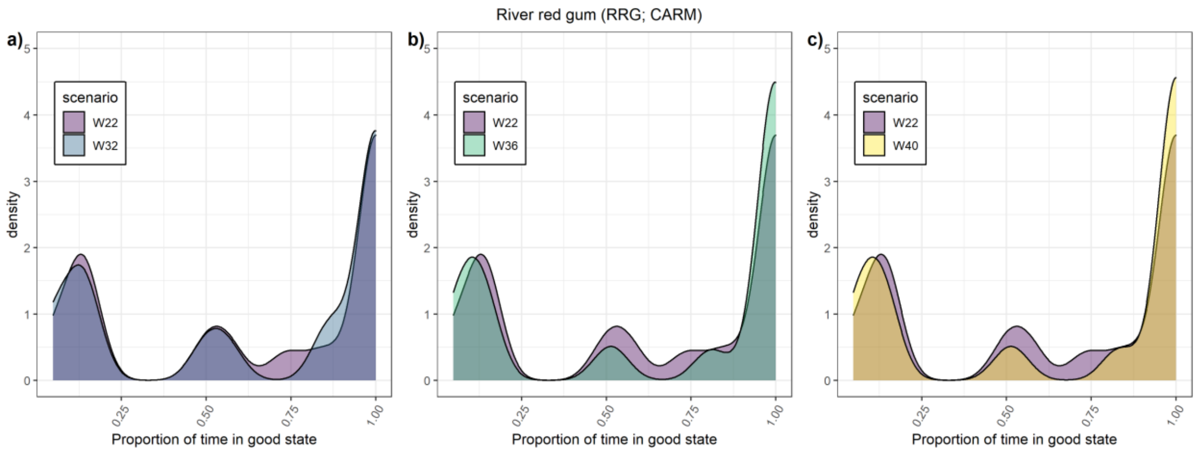

Figure 8. CARM all pixels, Difference in proportion of time river red gum was in a good/moderate state between constraint options (W22, W32, W36, W40). Top panels show the cumulative distribution of proportion of time in a good/moderate state for RRG pixels and the bottom pannels show the proportional difference in the time in good/moderate state between W22 and each other Constraint scenario

Spatial plots of proportion good/moderate condition

Proportion good/moderate by constraint option

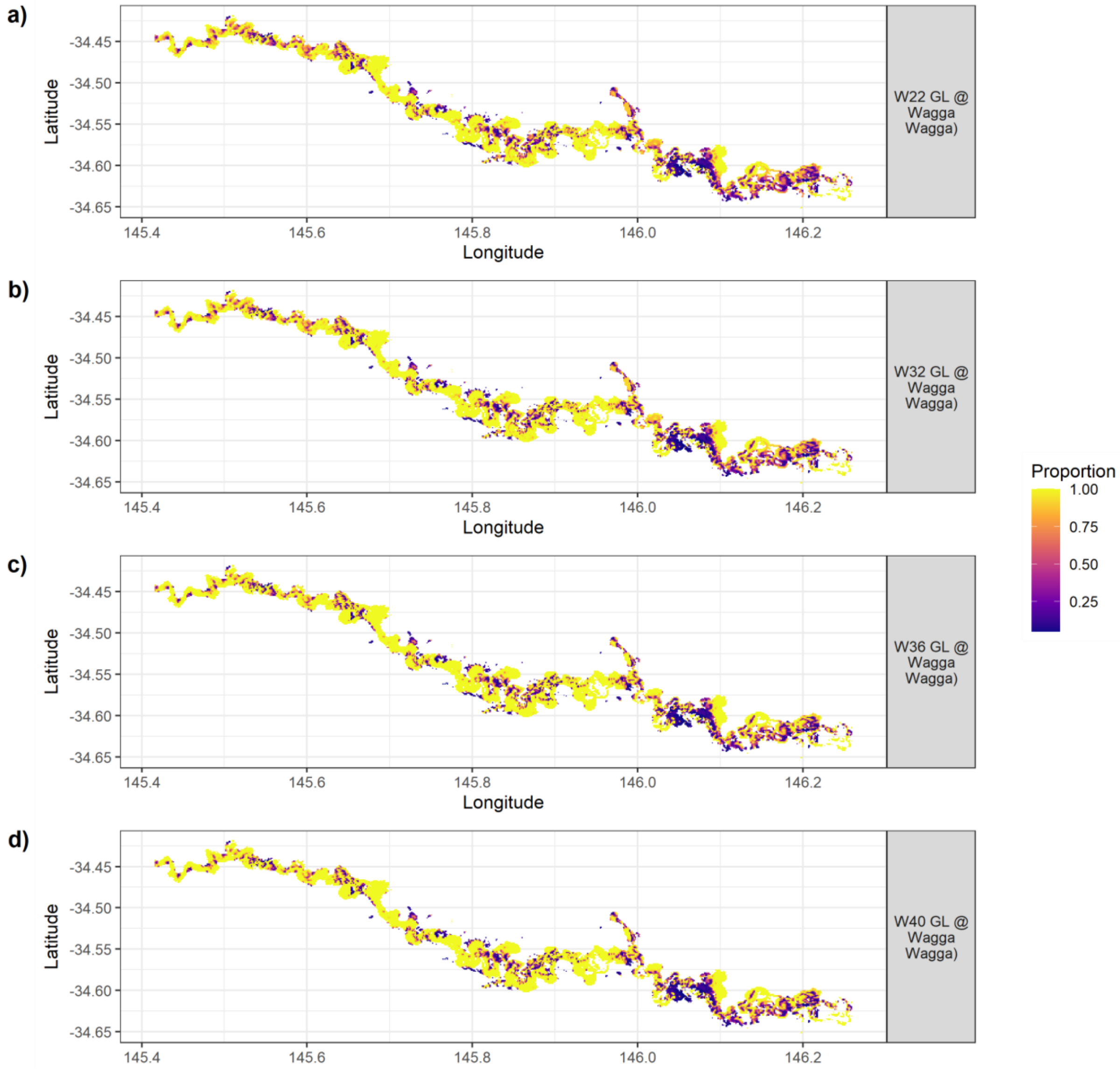

Figure 9. Darlington point to Carrathool, showing the proportion of time river red gum is in a good/moderate condition in each constraint option (W22, W32, W36, W40). Colour scale shows yellows as highest proportion of the 124 years in good/moderate condition

Change in proportion good/moderate between constraint options

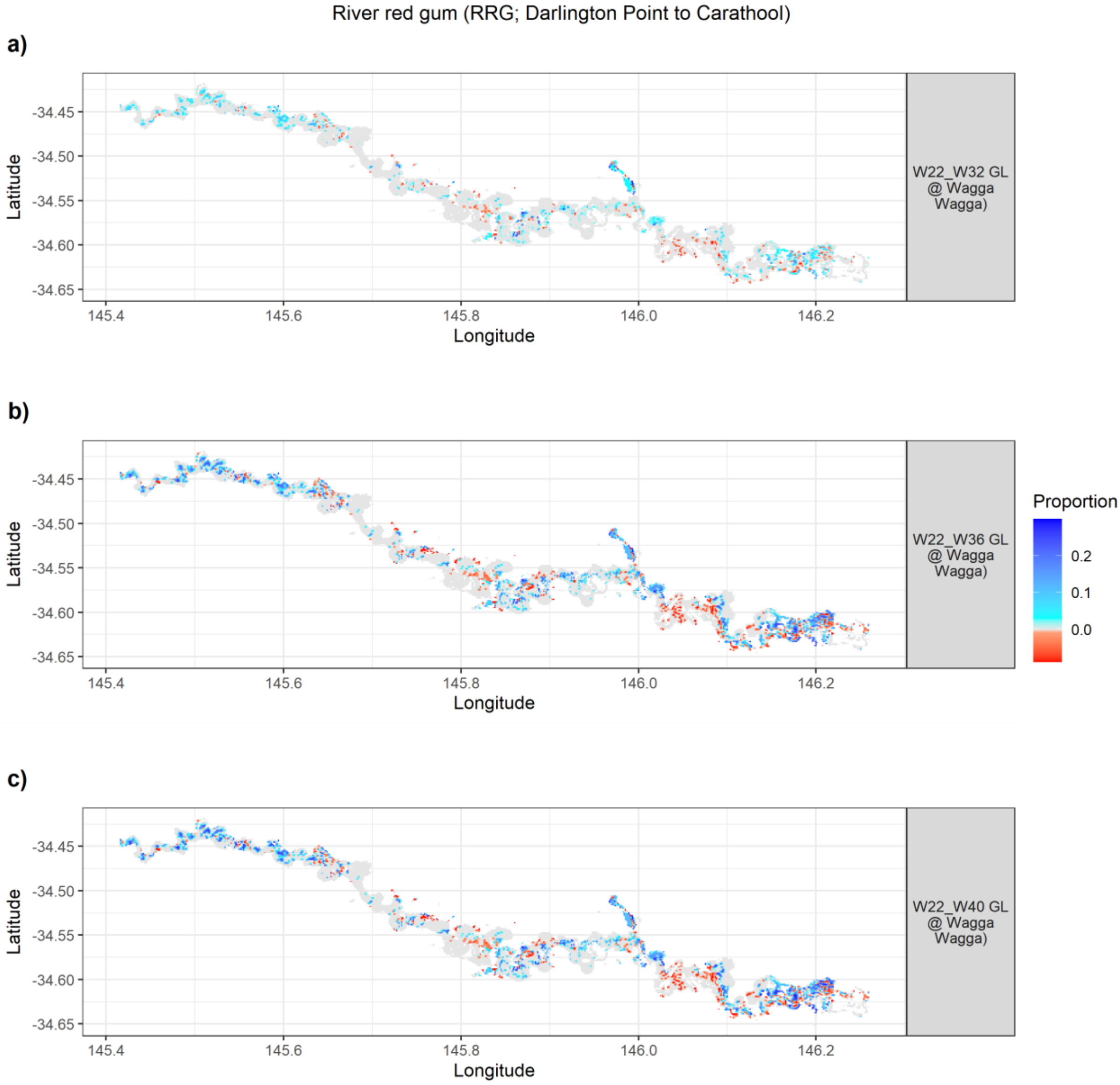

Figure 10. Darlington Point to Carrathool showing the difference in proportion of time river red gum is in a good/moderate condition between the base case (W22) and each constraint option (W32, W36, W40). Colour shows areas where constraint relaxation, from baseline increased (darker blues correlate with greater increase) or decreased (reds correlate with greater decrease) the proportion of time a pixel was in a good/moderate condition. Areas with No difference between the base case and scenario are grey.

Black box outputs

Accumulation plots

Comparisons within constraints

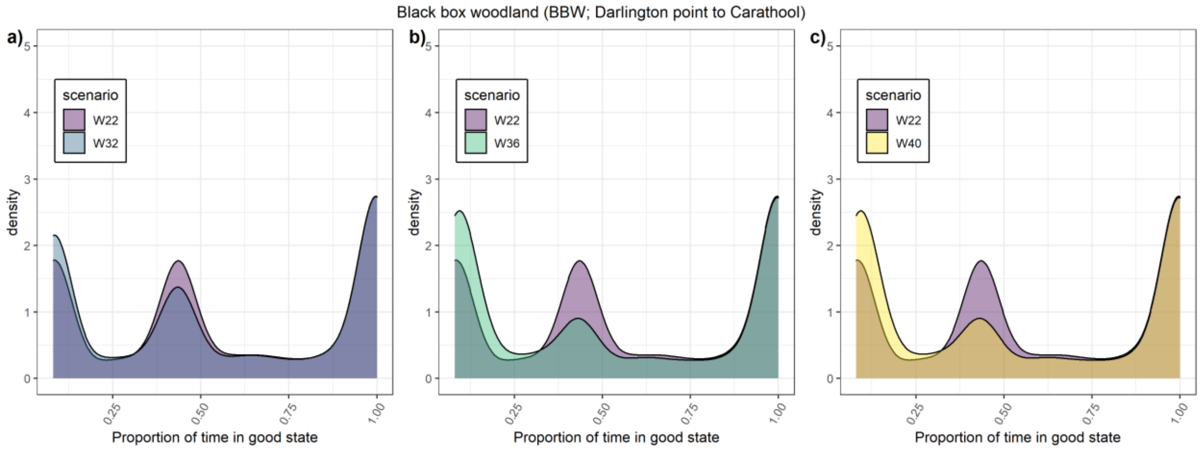

Figure 11. Darlington Point to Carrathool all pixels, Difference in proportion of time black box woodland was in a good/moderate state between constraint options (W22, W32, W36, W40). Top panels show the cumulative distribution of proportion of time in a good/moderate state for RRG pixels and the bottom pannels show the proportional difference in the time in good/moderate state between W22 and each other Constraint scenario

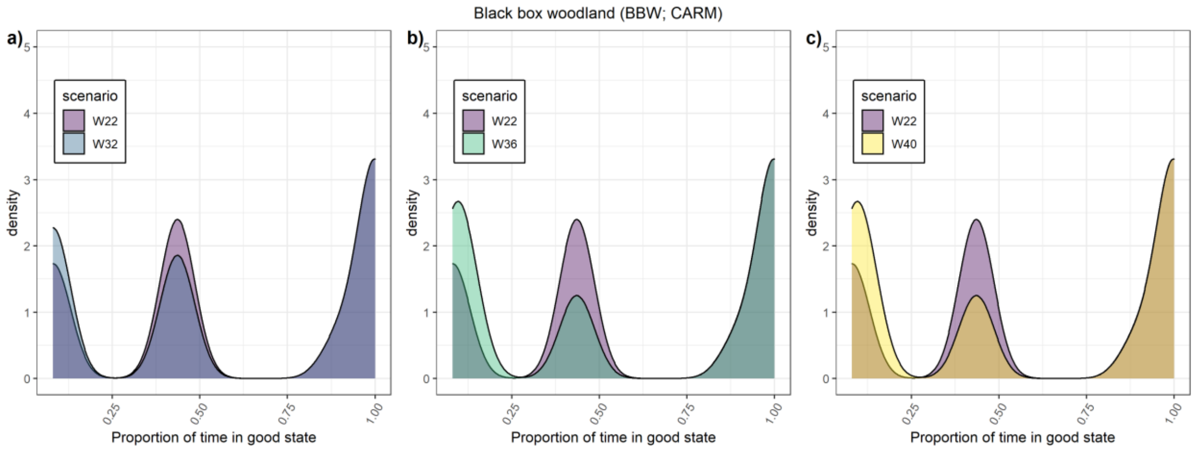

Figure 12. Maude to Balranald, Difference in proportion of time black box woodland was in a good/moderate state between constraint options (W22, W32, W36, W40). Top panels show the cumulative distribution of proportion of time in a good/moderate state for RRG pixels and the bottom pannels show the proportional difference in the time in good/moderate state between W22 and each other Constraint scenario

Spatial plots of proportion good/moderate condition

Proportion good/moderate by constraint option

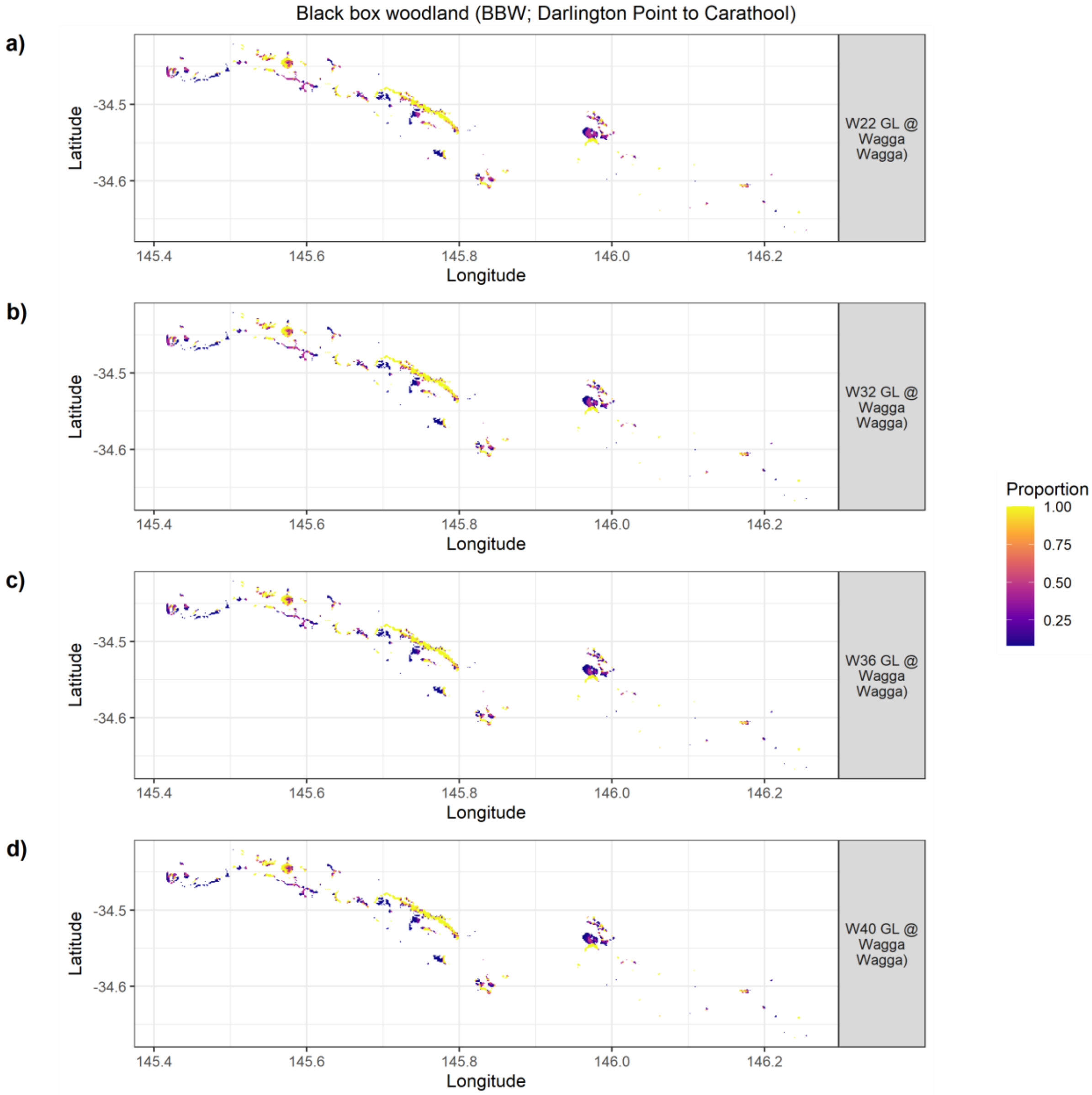

Figure 13. Darlington point to Carrathool, showing the proportion of time black box woodland is in a good/moderate condition in each constraint option (W22, W32, W36, W40). Colour scale shows yellows as highest proportion of the 124 years in good/moderate condition.

Change in proportion good/moderate between constraint options

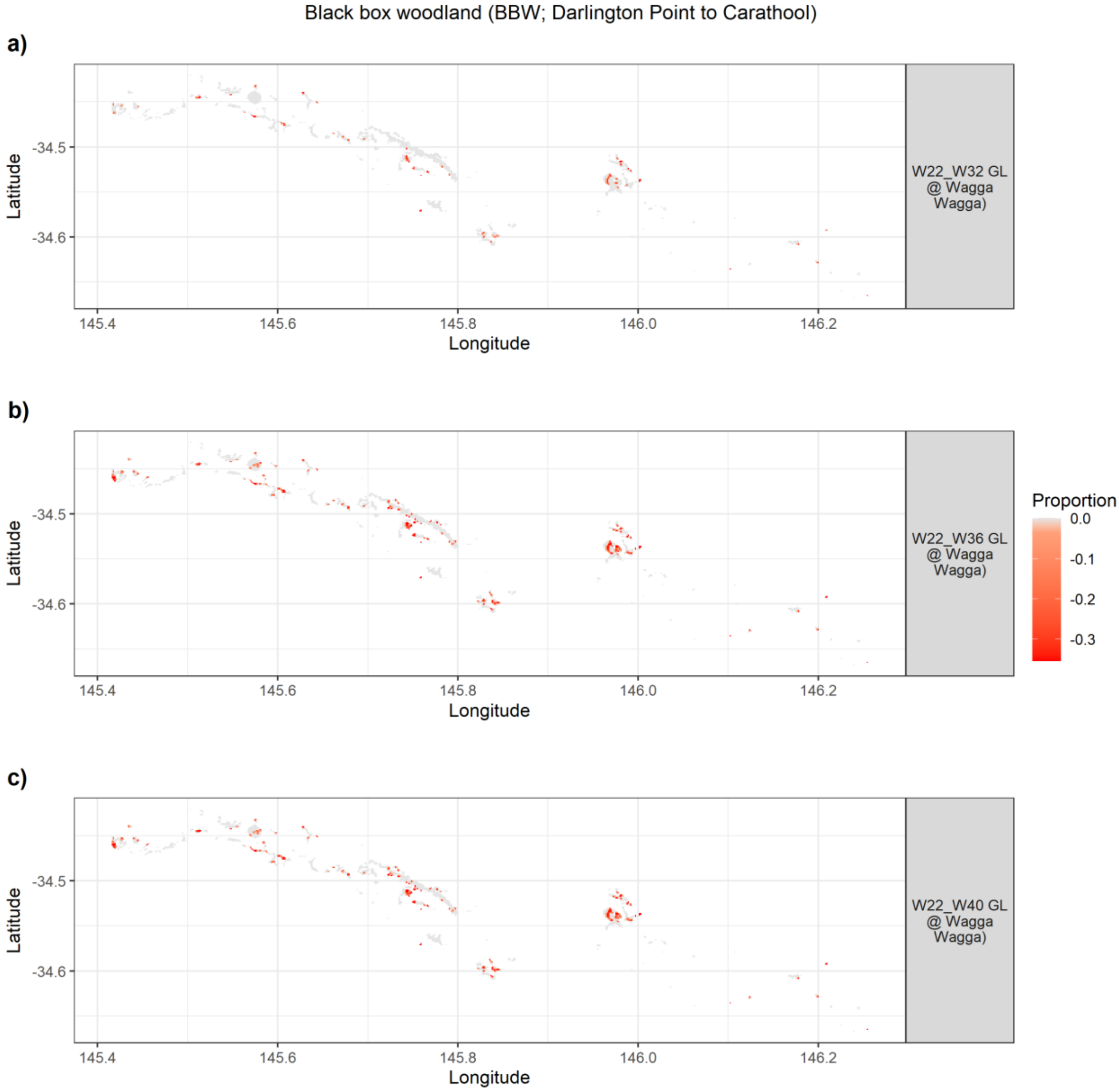

Figure 14. Darlington Point to Carrathool, showing the difference in proportion of time black box Woodland is in a good/moderate condition between the base case (W22) and each constraint option (W32, W36, W40). Colour shows areas where constraint relaxation, from baseline increased (darker blues correlate with greater increase) or decreased (reds correlate with greater decrease) the proportion of time a pixel was in a good/moderate condition. Areas with No difference between the base case and scenario are grey.

Appendix 2. Preliminary vegetation condition results for Lowbidgee reaches (Murrumbidgee downstream of Hay)

These model results for the low Murrumbidgee floodplain have used a preliminary set of vegetation transition rules (30 day inundation and 30 day spell gap; details Appendix 5) that were modified for the main report. In light of inundation mapping inaccuracies and further research being required these results require further investigation.

River red gum outputs

Tabulated summary statistics

Table 6. Mean percentage (with Standard deviation) of time river red gum (RRG) were in a good/moderate state over modelled time periods. Coloured shading has been included to allow comparison of the constraint options within selected areas of interest (Maude to Balranald (lbz_2_ctf_clip)). The darkest red shading shows the shortest accumulated time, and darkest blue shading shows the longest accumulated time in a good/moderate state.

	Scenario	Maude to Balranald	
RRG	22W	75.46	(33.66)
	32W	77.06	(32.97)
	36W	75.59	(34.22)
	40W	75.65	(35.41)

Table 7. Total area (ha) changes of time in good/moderate condition for river red gum (RRG) forest and woodland in each area of interest in the Murrumbidgee catchment (No change, improve, decline, and net change). We compare constraint options (W32, W36, W40) in reference to the Base case (W22). Cell shading is grouped by area of interest with darker shades of grey indicate larger areas where there was no difference in the time in good/moderate state between scenarios, the darkest red within area of interest indicates the larger declines, darker blue shading showing the largest improvements.

Vegetation	Areas of interest	Scenario	No change	Improve	Decline	Net change
RRG	*Lower Bidgee Zone 1 (lbz1_ctf)*	W32 to W22	1692.19	1053.13	-107.81	945.31
		W36 to W22	1740.63	965.63	-146.88	818.75
		W40 to W22	1568.75	1129.69	-154.69	975.00
	Maude to Balranald (lbz2_ctf)	W32 to W22	25101.56	5098.44	-6225.00	-1126.56
		W36 to W22	25101.56	5207.81	-6115.63	-907.81
		W40 to W22	25101.56	4601.56	-6721.88	-2120.31
	Balranald to Murray confluence (lbz3_ctf)	W32 to W22	3298.44	284.38	-345.31	-60.94
		W36 to W22	2917.19	512.50	-498.44	14.06
		W40 to W22	2725.00	514.06	-689.06	-175.00

Accumulation plots

Comparisons within constraints

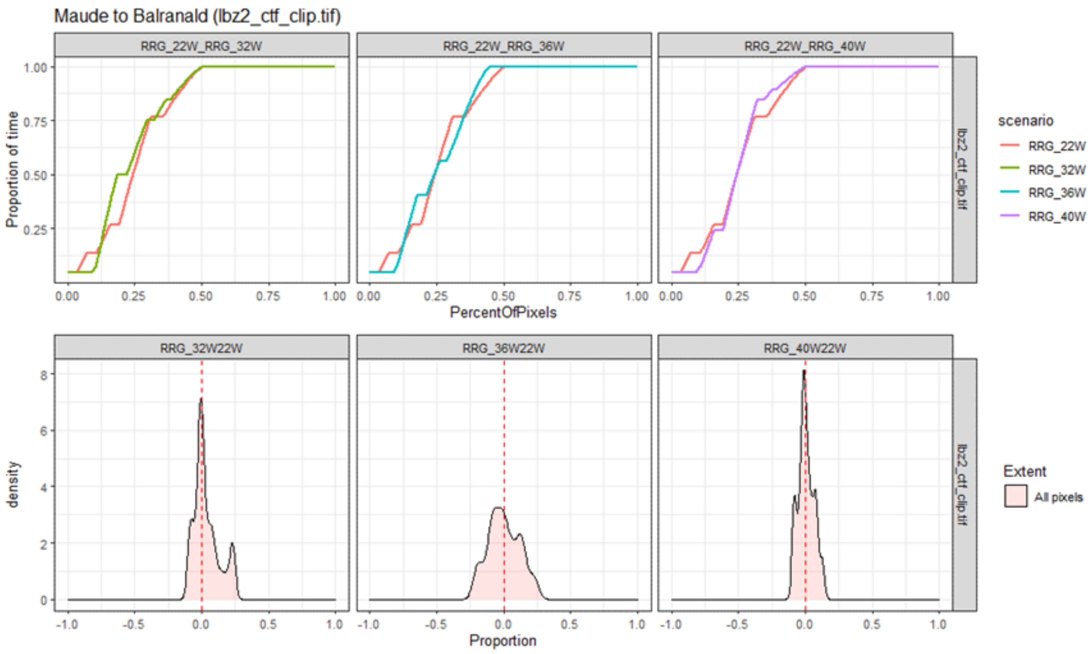

Figure 15: Maude to Balranald all pixels, Difference in proportion of time river red gum was in a good/moderate state between constraint options (W22, W32, W36, W40). Top panels show the cumulative distribution of proportion of time in a good/moderate state for RRG pixels and the bottom pannels show the proportional difference in the time in good/moderate state between W22 and each other Constraint scenario.

Spatial plots of proportion good/moderate condition

Proportion good/moderate by constraint option

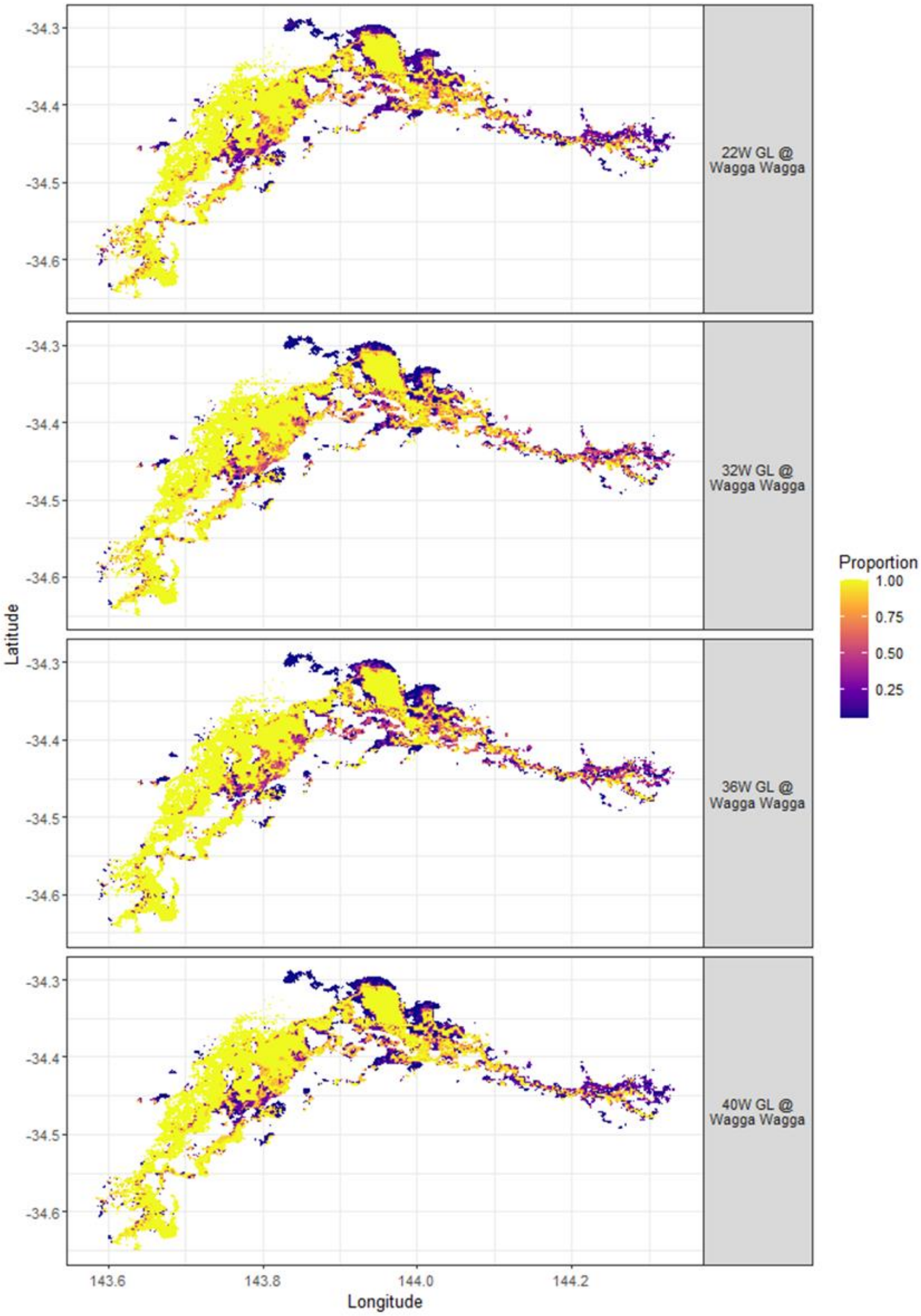

Figure 16. Maude to Balranald, showing the proportion of time river red gum is in a good/moderate condition in each constraint option (W22, W32, W36, W40). Colour scale shows yellows as highest proportion of the 124 years in good/moderate condition.

Change in proportion good/moderate between constraint options

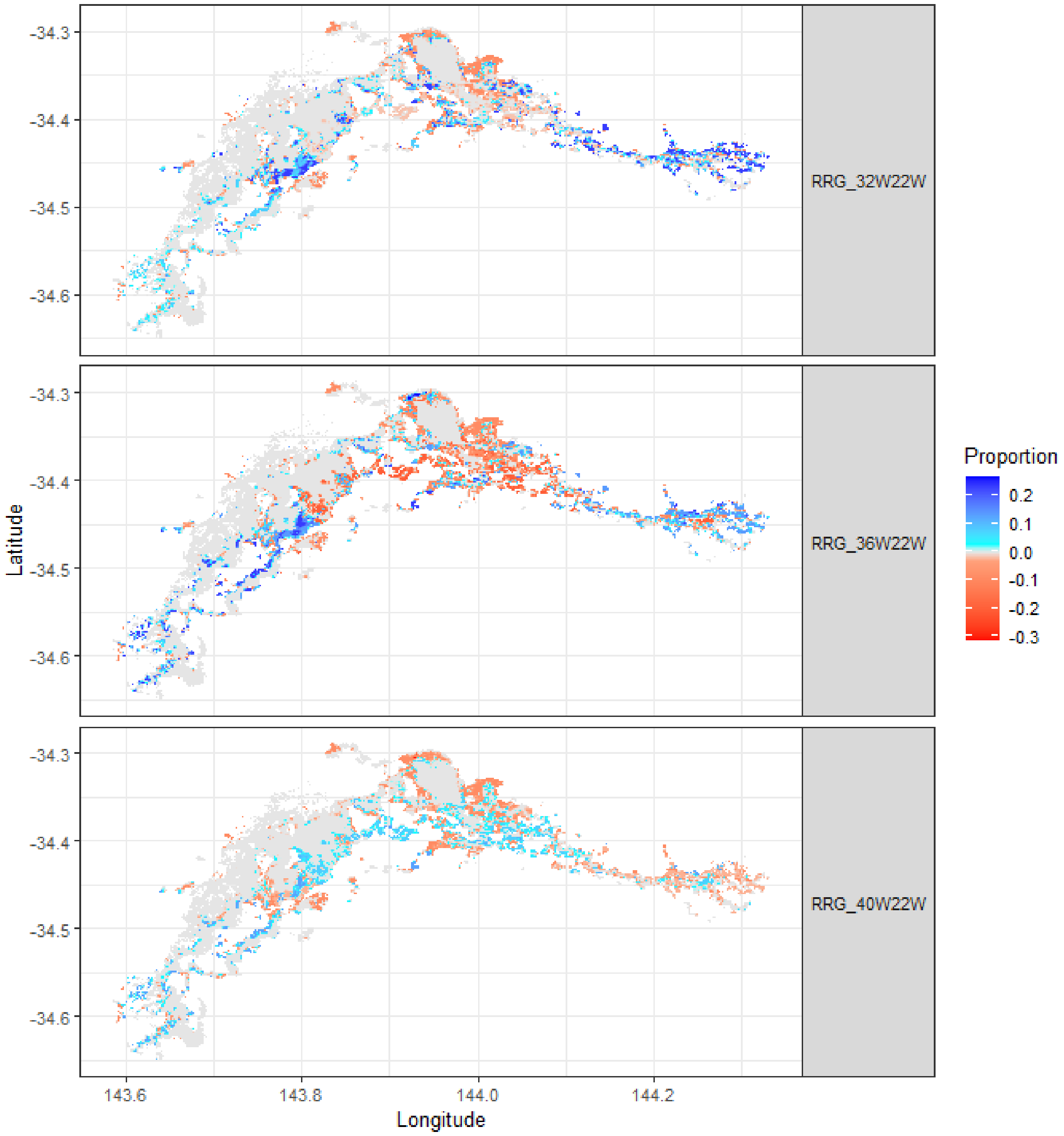

Figure 17.Maude to Balranald showing the difference in proportion of time river red gum is in a good/moderate condition between the base case (W22) and each constraint option (W32, W36, W40). Colour shows areas where constraint relaxation, from baseline increased (darker blues correlate with greater increase) or decreased (reds correlate with greater decrease) the proportion of time a pixel was in a good/moderate condition. Areas with no difference between the base case and scenario are grey.

Black box outputs

Tabulated summary statistics

Table 8. Mean percentage (with Standard deviation) of time river red gum (RRG) were in a good/moderate state over modelled time periods. Coloured shading has been included to allow comparison of the constraint options within selected areas of interest (Maude to Balranald (lbz_2_ctf_clip)). The darkest red shading shows the shortest accumulated time, and darkest blue shading shows the longest accumulated time in a good/moderate state.

	Scenario	Maude to Balranald	
BBW	22W	79.90	(33.39)
	32W	70.45	(37.68)
	36W	76.45	(33.72)
	40W	67.25	(41.5)

Table 9. Total area (ha) changes of time in good/moderate condition for black box woodland (BBW) in each area of interest in the Murrumbidgee catchment (No change, improve, decline, and net change). We compare constraint options (W32, W36, W40) in reference to the base case (W22). Cell shading is grouped by area of interest with darker shades of grey indicate larger areas where there was no difference in the time in good/moderate state between scenarios, the darkest red within area of interest indicates the larger declines, darker blue shading showing the largest improvements.

Vegetation	Areas of interest	Scenario	No change	Improve	Decline	Net change
BBW	*Lower Bidgee Zone 1 (lbz1_ctf)*	32W to 22W	2693.75	146.88	-1071.88	-925.00
		36W to 22W	2198.44	492.19	-1221.88	-729.69
		40W to 22W	1587.50	535.94	-1789.06	-1253.13
	Maude to Balranald (lbz2_ctf)	32W to 22W	18457.81	1470.31	-4064.06	-2593.75
		36W to 22W	19928.13	0.00	-4064.06	-4064.06
		40W to 22W	18457.81	1470.31	-4064.06	-2593.75
	Balranald to Murray confluence (lbz3_ctf)	32W to 22W	9190.63	1481.25	-484.38	996.88
		36W to 22W	6209.38	2468.75	-2478.13	-9.38
		40W to 22W	5237.50	3235.94	-2682.81	553.13

Accumulation plots

Comparisons within constraints

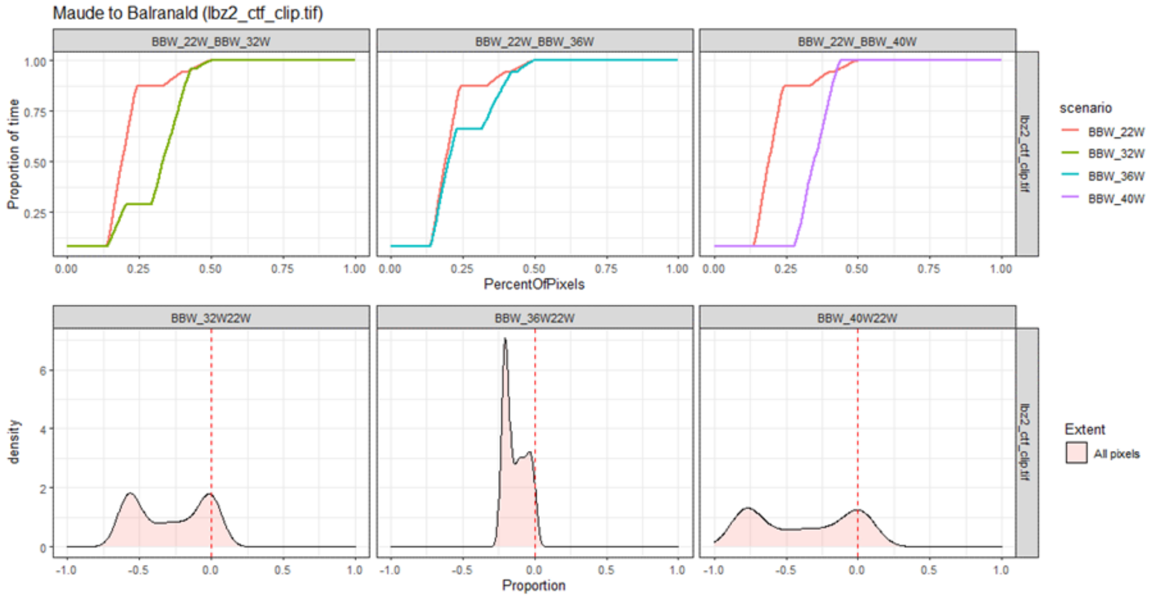

Figure 18. Maude to Balranald, difference in proportion of time black box woodland was in a good/moderate state between constraint options (W22, W32, W36, W40). Top panels show the cumulative distribution of proportion of time in a good/moderate state for RRG pixels and the bottom pannels show the proportional difference in the time in good/moderate state between W22 and each other Constraint scenario

Spatial plots of proportion good/moderate condition

Proportion good/moderate by constraint option

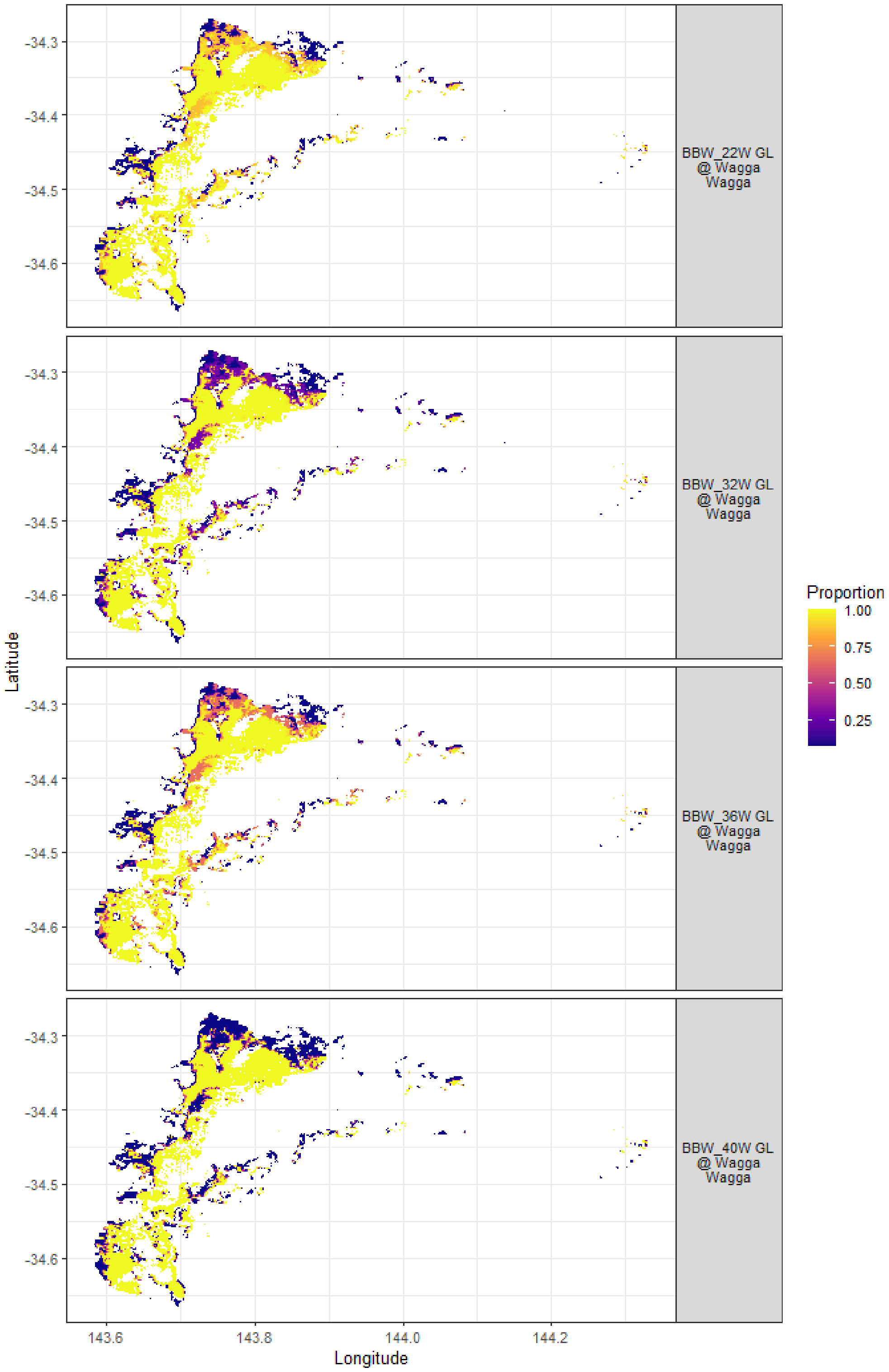

Figure 19. Maude to Balranald, showing the proportion of time black box woodland is in a good/moderate condition in each constraint option (W22, W32, W36, W40). The colour scale shows yellows as highest proportion of the 124 years in good/moderate condition. Note that we suspect large areas of vegetation on the North Redbank floodplain are mapped incorrectly in the NSW PCT dataset. Specifically, areas where the canopy species is dominated by river red gum are mapped as black box woodland. This would need to be validated and resolved in future vegetation assessments of the North Redbank floodplain.

Change in proportion good/moderate between constraint options

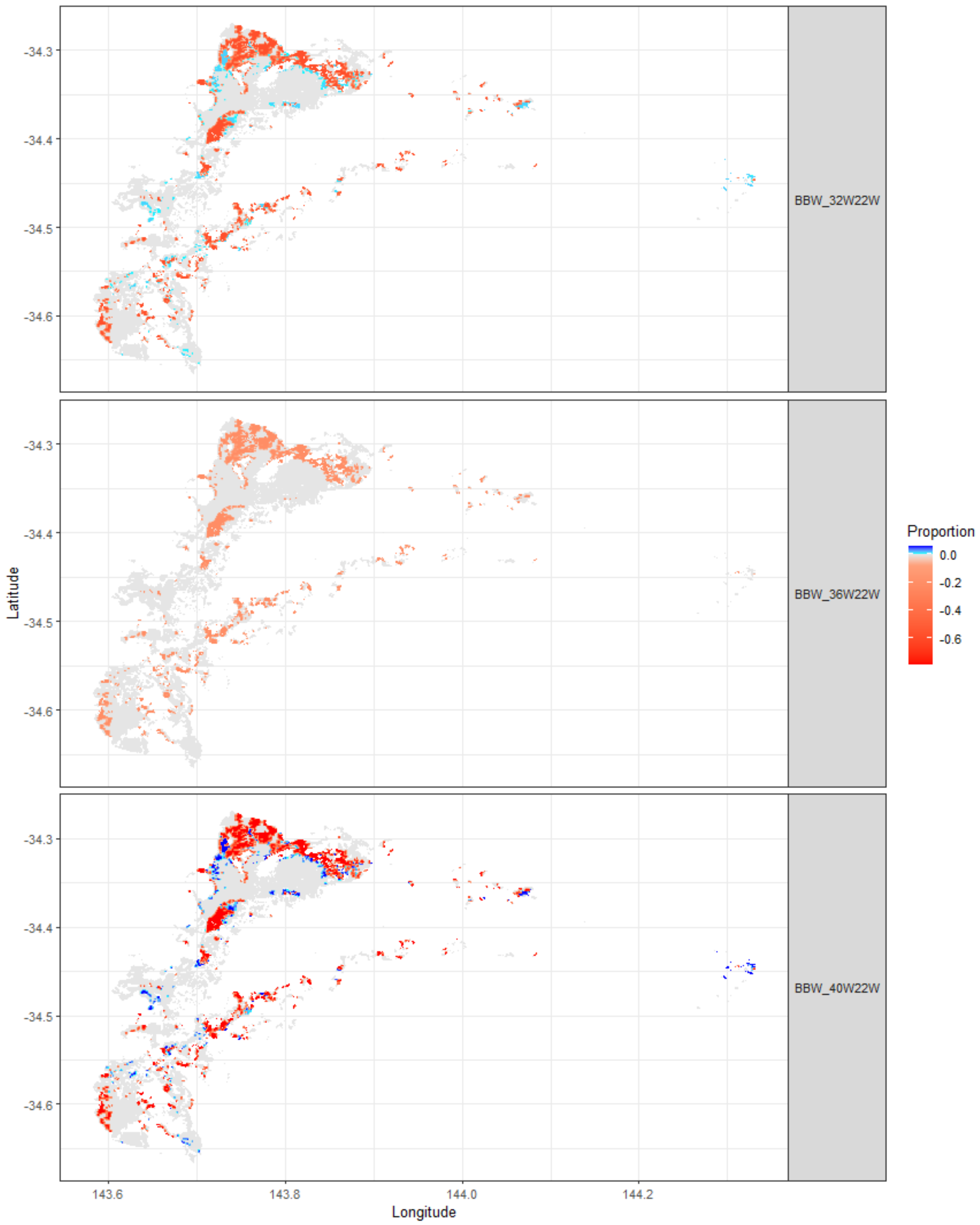

Figure 20.Maude to Balranald, showing the difference in proportion of time black box woodland is in a good/moderate condition between the base case (W22) and each constraint option (W32, W36, W40). Colour shows areas where constraint relaxation, from baseline increased (darker blues correlate with greater increase) or decreased (reds correlate with greater decrease) the proportion of time a pixel was in a good/moderate condition. Areas with no difference between the base case and scenario are grey. Note that we suspect large areas of vegetation on the North Redbank floodplain are mapped incorrectly in the NSW PCT dataset. Specifically, areas where the canopy species is dominated by river red gum are mapped as black box woodland. This would need to be validated and resolved in future vegetation assessments of the North Redbank floodplain.

Appendix 3. State Transition Rules

In this appendix the hydrological rules for each of the vegetation classes have been represented in separate tables. Below is a list of terms and a brief description of each that will assist in the interpretation of the response of vegetation to inundation spells.

Rule variables

initial_state_t0
This is the current state of the unit being simulated after the previous time step/matrix multiplication. It is stored in the model as a binary vector of all states and is the input vector to the next matrix multiplication for projecting the state.

future_state_t1
This is the resulting state from the matrix multiplication of the of the *initial_state_t0* unit and is the next state in the simulated state transition time series. Under iteration, once the future state is determined after 1 or many years, the recorded state becomes the *initial_state_t0* for the subsequent matrix multiplication.

rule_number
This is a value identifying each unique rule.

spell_duration
This is the number of uninterrupted days that will be required to have a 'spell' of a specific type recorded. In the case where a spell is interrupted, e.g. in a 365 day dry spell there is a period of 16 days of inundation (one more than out spell gap of 15) then the 365 day transition does not occur and the unit stays in the initial_state_t0.

spell_type
This determines whether the rule is to do with an inundation ('inun') or drying ('dry') spell.

spell_count
This is the number of spells that must occur within the antecedent 'annual window'

annual_window
This is a value determining the maximum number of years within which the spell count must occur. For example if the rule states spell_count = 5 and annual window = 5 if any one year of the previous 5 years does not include a spell the spell count would be 4 and the transition does not occur.

Black box woodland transition rules

Table 10.Transitions rules for states of black box woodland

initial_state_t0	future_state_t1	rule_number	spell_duration	spell_type	spell_count	annual_window
BBW_G	BBW_M	1	365	dry	5	5
BBW_G	BBW_Inun	2	300	inun	5	7
BBW_M	BBW_G	3	10	inun	1	1
BBW_M	BBW_P_GM	4	365	dry	10	10
BBW_P_GM	BBW_P	5	10	inun	1	1
BBW_P_GM	BBW_C_GMP	6	365	dry	15	15
BBW_P_I	BBW_C_IP	7	365	dry	9	9
BBW_P_I	BBW_P	8	10	inun	1	1
BBW_P	BBW_I	9	10	inun	3	10
BBW_P	BBW_C_P	10	365	dry	5	5
BBW_I	BBW_G	11	10	inun	2	7
BBW_I	BBW_P_I	12	365	dry	4	4
BBW_C_GMP	BBW_Dry	13	365	dry	45	45
BBW_C_GMP	BBW_C	14	10	inun	1	1
BBW_C_IP	BBW_Dry	15	365	dry	39	39
BBW_C_IP	BBW_C	16	10	inun	1	1
BBW_C_P	RRG_Dry	17	365	dry	35	35
BBW_C_P	BBW_C	18	10	inun	1	1
BBW_C	BBW_I	19	10	inun	5	18
BBW_C	BBW_Dry	20	365	dry	30	30
BBW_Inun	BBW_Recruit	21	245	dry	2	5
BBW_Dry	BBW_Recruit	22	10	inun	2	5
BBW_Dry	BBW_Dead	23	365	dry	5	5
BBW_Recruit	BBW_I	24	10	inun	2	2
BBW_Recruit	BBW_Dry	25	365	dry	3	3
BBW_Recruit	BBW_Dead	26	90	inun	1	1
BBW_Dead	TV	27	10	inun	3	10

River red gum woodland transition rules

Table 11. Transition rules for states of river red gum woodland

initial_state_t0	future_state_t1	rule_number	spell_duration	spell_type	spell_count	annual_window
RRGW_G	RRGW_M	28	365	dry	3	3
RRGW_G	RRG_Inun	29	300	inun	5	7
RRGW_M	RRGW_G	30	30	inun	1	1
RRGW_M	RRGW_P_GM	31	365	dry	9	9
RRGW_P_GM	RRGW_C_GMP	32	365	dry	13	13
RRGW_P_GM	RRGW_P	33	30	inun	1	1
RRGW_P_I	RRGW_C_IP	34	365	dry	8	8
RRGW_P_I	RRGW_P	35	30	inun	1	1
RRGW_P	RRGW_I	36	30	inun	3	9
RRGW_P	RRGW_C_P	37	365	dry	4	4
RRGW_I	RRGW_G	38	30	inun	2	7
RRGW_I	RRGW_P_I	39	365	dry	4	4
RRGW_C_GMP	RRG_Dry	40	365	dry	28	28
RRGW_C_GMP	RRGW_C	41	30	inun	1	1
RRGW_C_IP	RRG_Dry	42	365	dry	23	23
RRGW_C_IP	RRGW_C	43	30	inun	1	1
RRGW_C_P	RRG_Dry	44	365	dry	19	19
RRGW_C_P	RRGW_C	45	30	inun	1	1
RRGW_C	RRGW_I	46	30	inun	5	15
RRGW_C	RRG_Dry	47	365	dry	15	15

River red gum forest transition rules

Table 12. Transition rules for states of river red gum forest

initial_state_t0	future_state_t1	rule_number	spell_duration	spell_type	spell_count	annual_window
RRGF_G	RRGF_M	48	365	dry	3	3
RRGF_G	RRG_Inun	49	300	inun	5	7
RRGF_M	RRGF_G	50	30	inun	1	1
RRGF_M	RRGF_P_GM	51	365	dry	6	6
RRGF_P_GM	RRGF_C_GMP	52	365	dry	10	10
RRGF_P_GM	RRGF_P	53	30	inun	1	1
RRGF_P_I	RRGF_C_IP	54	365	dry	7	7
RRGF_P_I	RRGF_P	55	30	inun	1	1
RRGF_P	RRGF_I	56	30	inun	3	9
RRGF_P	RRGF_C_P	57	365	dry	4	4
RRGF_I	RRGF_G	58	30	inun	2	5
RRGF_I	RRGF_P_I	59	365	dry	3	3
RRGF_C_GMP	RRG_Dry	60	365	dry	25	25
RRGF_C_GMP	RRGF_C	61	30	inun	1	1
RRGF_C_IP	RRG_Dry	62	365	dry	22	22
RRGF_C_IP	RRGF_C	63	30	inun	1	1
RRGF_C_P	RRG_Dry	64	365	dry	19	19
RRGF_C_P	RRGF_C	65	30	inun	1	1
RRGF_C	RRGF_I	66	30	inun	5	15
RRGF_C	RRG_Dry	67	365	dry	15	15
RRG_Inun	RRG_Recruit	68	245	dry	2	5
RRG_Dry	RRG_Recruit	69	30	inun	2	5
RRG_Dry	RRG_Dead	70	365	dry	5	5
RRG_Recruit	RRGF_I	71	30	inun	2	2
RRG_Recruit	RRG_Dry	72	365	dry	3	3
RRG_Recruit	RRG_Dead	73	90	inun	1	1
RRG_Dead	TV	74	30	inun	3	10

Appendix 4. Methods for classification of PCT and EVC into vegetation categories for state and transition modelling

Process led by Samantha Dawson (DPIE EES Water for the Environment)

Contributors: Rachael Thomas (DPIE Science), Tanya Mason (DPIE Science), Tim Barlow (Vic DSE; ran by Keith Ward, other Vic folk), Mark Henderson (DPIE), Susan Gehrig (employer), Cherie Campbell (employer)

Note for Murrumbidgee: this is the description of a combined NSW/Victorian dataset that included both the Murray and Murrumbidgee River valleys, therefore some references to EVC (Victorian) datasets remain.

The purpose of reclassifying existing vegetation mapping was two-fold: first, to implement the categories that are defined in the state and transition models; second, to match the vegetation layers on the NSW and Victorian sides of the Murray River to enable a single model to be run. State and transition (S&T) models developed by consultants at La Trobe University and Griffith University were based on published literature and expert opinion and delineated a set of rules for riverine and floodplain vegetation types outlining expected vegetation condition and transition between vegetation communities based on flooding regimes. The vegetation categories they identified consisted of two tiers: a broader category between which transitions occur and PCT/EVC based categories which, in the case of non-woody vegetation, defined phases of vegetation across a wetting/drying spectrum (Table 13). Files on the various stages with comments attached can be found in the Teams drive.

To extract the PCT/EVC polygons of interest, we used a polygon that defined the floodplain for the Murray River (below Hume Dam), Murrumbidgee River (including Tumut River and Yanco/Billabong Creek system) and the lower Darling and Darling Anabranch. The polygon defines the area of interest and is based on the RIMFIM boundary (1956 flood extent). PCT and EVC spatial polygon layers were then clipped to this boundary for all NSW and Victorian bioregions that covered the extent. From the attribute tables of the clipped polygon layer we were able to extract a list of the PCT and EVC classes that were present in our area of interest. This list formed a table by which we could then attribute S&T categories to various vegetation classes. Note: we used spatial information to extract a table and the table was used in the categorisation – this was not a spatially informed categorisation process.

Table 13 Vegetation categories used in the state and transition models.

Revised Broad Wetland Vegetation Types	**Other/understorey vegetation groups to consider (see literature for common transitions) - PCT/EVC BASED CLASSES**
Wetland herblands (WH)	
Benthic perennial herbland with low - moderate biomass, moderate - high diversity (WH_BPH1) *Benthic perennial herbland with high biomass, low – moderate diversity (WH_BPH2)*	Benthic herbland
Amphibious herbland with low - moderate biomass, high diversity (WH_AH_LS)	Low-mid sedgeland
(WH_AH_GF)	Grassland/forbland wetland
Floodplain terrestrial herbland with low - moderate biomass, low - moderate diversity (WH_TH)	Floodplain grasslands
Floodplain chenopod shrubland – high biomass, low diversity (WH_CS)	Floodplain shrublands
Perennial wetland grasslands, sedgelands and rushlands (PG)	
N.B. This class distinguished by persistent dominant canopy.	Pseudoraphis spinescens grasslands (in Barmah-Millewa)
	Giant rush (Juncus ingens)
	Common reed (Phragmites)
	Tall GSR
River red gum forests (RRGF)	
	RRG forest sedge understorey
	RRG forest herb-grass understorey
River red gum woodlands (RRGW)	
	RRG woodland grassy understorey
	RRG woodland lignum understorey
	RRG woodland sedge understorey
Lignum shrublands (LS)	
black box woodlands (BBW)	
	black box woodland chenopod understorey
	black box woodland grassy understorey
	black box woodland lignum understorey

In the NSW/Murrumbidgee dataset there were in total 147 PCT classes that were identified as occurring in the area of interest. SD used the table of classes and to allocate each PCT class to S&T

categories They include extra details not in the EVC classes attribute tables such as dominant species in each storey

Appendix 5. Spells sensitivity analysis and vegetation state and transition rule adjustment

The inundation analysis for the Reconnecting River Country program developed by La Trobe University as a part of the Native Vegetation Condition analysis has been developed using a spells analysis that relies on commence to fill inundation maps of the Mid-Murrumbidgee River floodplain (CARM layer) and hydrology output from the Source River modelling software (See RRCP Murrumbidgee Environmental Benefits and Risk Analysis Synthesis Report (DPE, 2022) for greater detail on the Source hydrological modelling). In the RRCP Murray Vegetation Condition Model project, a spell duration which woody vegetation responded to was set at a duration of, at least, 30 days (spell_duration). However, the preliminary Murrumbidgee results using this spell duration for woody vegetation (Figure 15A) were identified as unrepresentative during expert review. This is most likely due to the use of river flow spell duration to represent inundation duration as the Murrumbidgee typically has shorter flow events and wetlands that are non-shedding when compared to the Murray. To better represent residence times on the floodplain, a range of values for two parameters (spell duration and spell gap) were tested and the results were assessed by experts. Nine options were compared under the base case hydrological scenario; a combination of spell durations of 10, 20 and 30 days and spell gaps of 15, 20 and 30 days (Figure 16 & 17). These were examined by DPE, and the 10 day spell duration and 15 day gap was selected for further investigation. Experts in Murrumbidgee flow and vegetation identified river red gum condition results from this option as aligning with their observations and expectations of river red gum condition over the timeline presented in the base case (Figure 15B). The 10 day spell duration and 15 day spell gap was then used for the woody vegetation rules in all constraint relaxation scenarios.

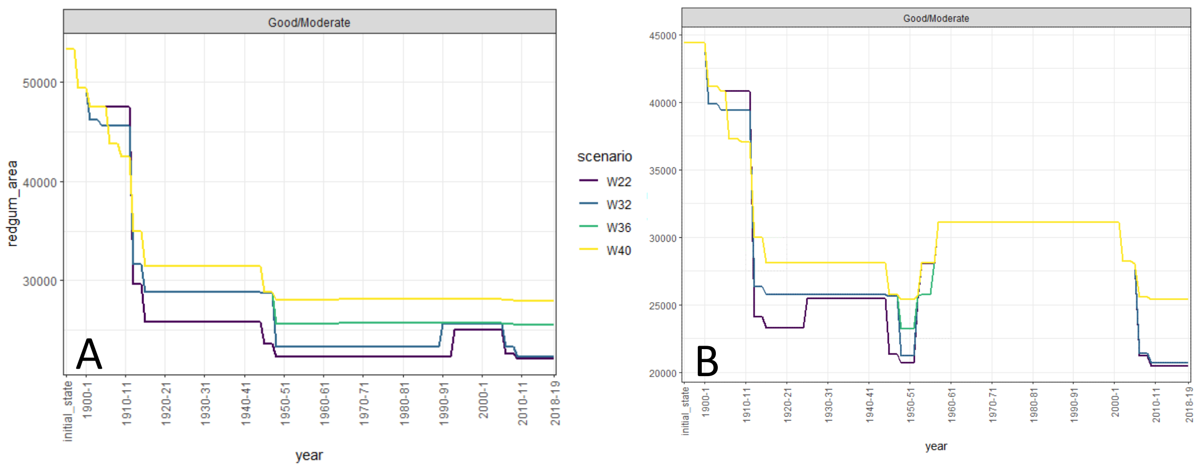

Figure 21. Time series results of river red gum area in good or moderate condition in the base case (W22) scenario with A: Murray-based 30 day spell duration and 15 day spell gap, and B: adjusted spell rules for the Murrumbidgee with a 10 day spell duration and 15 day spell gap. Vegetation projected for Darlington Point to Carrathool.

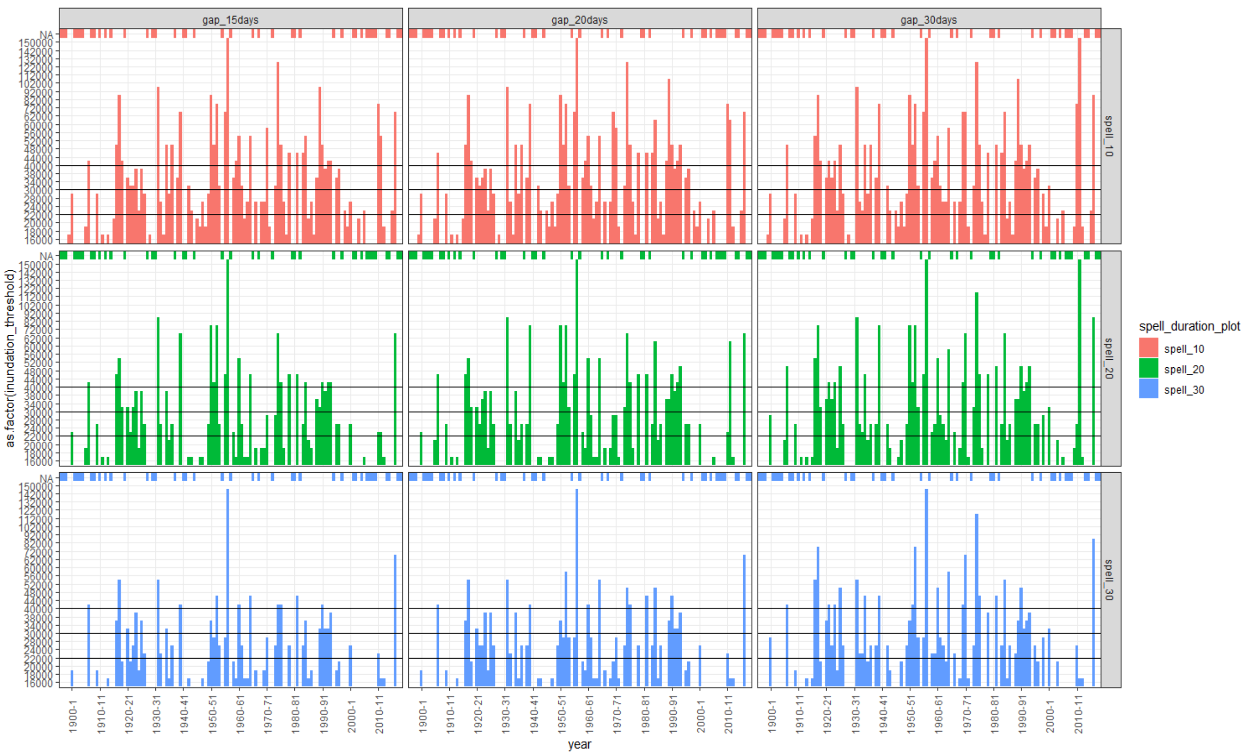

Figure 22. Time series of inundation event occurrence by spell_duration and spell_gap. "NA" on they y-axis represents a dry year with no recorded inundation event of the specific gap and duration. Plot pannels from left to right represent changing spell gaps of 15, 20 and 30 days and panels from top to bottom represent spell durations of 10, 20 and 30 days.

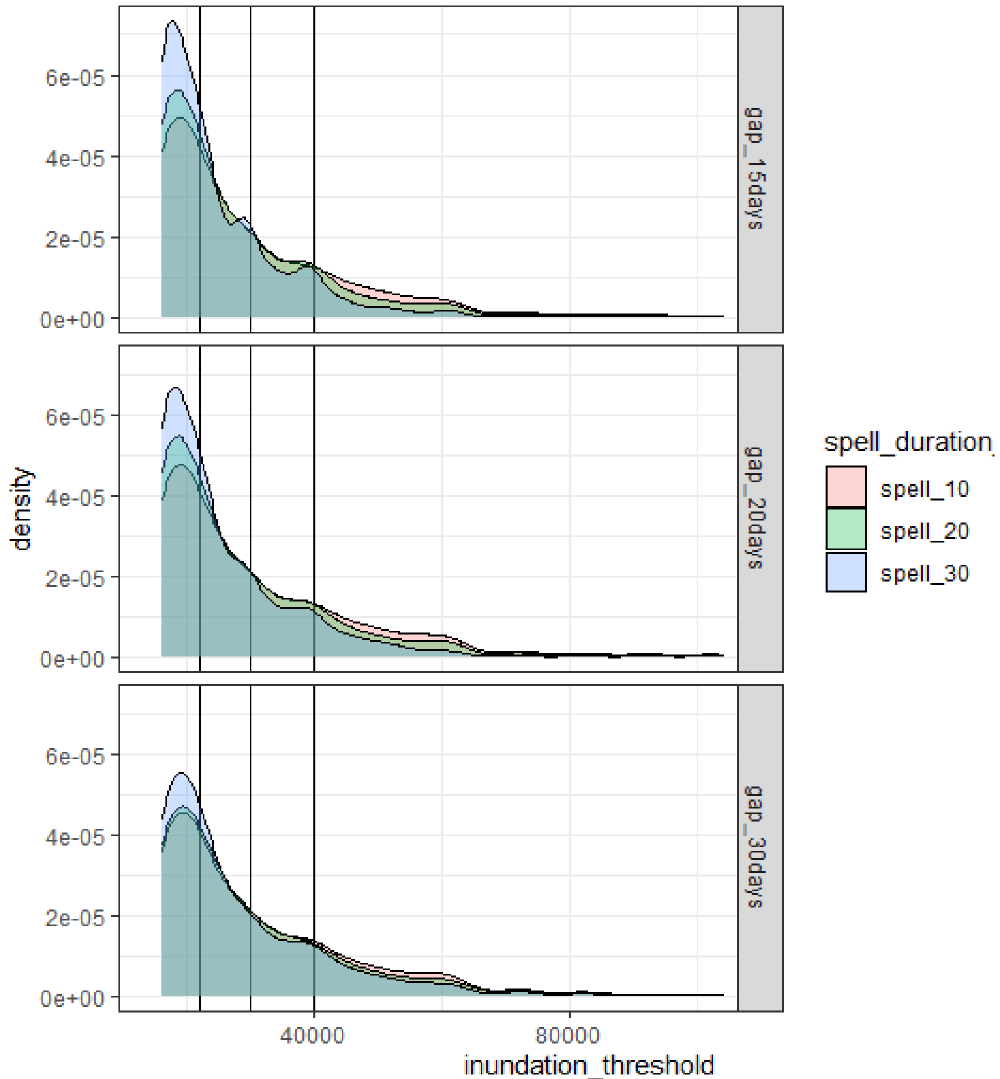

Figure 23. Distribution of spell durations events by different spell gap lengths.

References

Baker, W. L. (1989). A review of models of landscape change. *Landscape Ecology, 2*(2), 111-133.

Bond, N. (2021). Package 'hydrostats'. *The Comprehensive R Archive Network (CRAN)* Retrieved from https://github.com/nickbond/hydrostats

Bond, N. R., Grigg, N., Roberts, J., McGinness, H., Nielsen, D., O'Brien, M., . . . Stratford, D. (2018). Assessment of environmental flow scenarios using state-and-transition models. *Freshwater Biology, 63*(8), 804-816. doi:https://doi.org/10.1111/fwb.13060

Capon, S. J., James, C. S., Williams, L., & Quinn, G. P. (2009). Responses to flooding and drying in seedlings of a common Australian desert floodplain shrub: Muehlenbeckia florulenta Meisn. (tangled lignum). *Environmental and Experimental Botany, 66*(2), 178-185. doi:https://doi.org/10.1016/j.envexpbot.2009.02.012

Casanova, M. T. (2015). Review of Water Requirements for Key Floodplain Vegetation for the Northern Basin. *Literature Review and expert knowledge assessment. Report to the Murray–Darling Basin Authority, Charophyte Services, Lake Bolac.*

Daniel, C. J., Frid, L., Sleeter, B. M., & Fortin, M.-J. (2016). State-and-transition simulation models: a framework for forecasting landscape change. *Methods in Ecology and Evolution, 7*(11), 1413-1423. doi:10.1111/2041-210X.12597

DPE. (2022). *Reconnecting River Country Program: Murray Environmental Benefits and Risk Analysis Synthesis Report*. Report prepared by the Department of Planning and Environment

Horne, A. C., Nathan, R., Poff, N. L., Bond, N. R., Webb, J. A., Wang, J., & John, A. (2019). Modeling Flow-Ecology Responses in the Anthropocene: Challenges for Sustainable Riverine Management. *BioScience, 69*(10), 789-799. doi:10.1093/biosci/biz087

Jensen, A. E., Walker, K. F., & Paton, D. C. (2008). The role of seedbanks in restoration of floodplain woodlands. *River Research and Applications, 24*(5), 632-649.

Overton, I., Pollino, C., Roberts, J., Reid, J., Bond, N., McGinness, H., . . . Barma, D. (2014). Development of the Murray-Darling Basin Plan SDL adjustment ecological elements method. *Report prepared by CSIRO for the Murray-Darling Basin Authority, Canberra*, 45-54.

Peterson, T. J., Saft, M., Peel, M., & John, A. (2021). Watersheds may not recover from drought. *Science, 372*(6543), 745-749.

R Development Core Team. (2020). R: A Language and Environment for Statistical Computing (Version 4.0.3). Vienna, Austria: R Foundation for Statistical Computing. Retrieved from https://www.R-project.org/

Roberts, J., & Marston, F. (2011). *Water regime for wetland and floodplain plants: a source book for the Murray-Darling Basin*: National Water Commission Canberra.

Shenton, W., Bond, N. R., Yen, J. D. L., & Mac Nally, R. (2012). Putting the "ecology" into environmental flows: Ecological dynamics and demographic modelling. *Environmental Management, 50*(1), 1-10. doi:10.1007/s00267-012-9864-z

Telfer, A., Charles, A., & Jensen, A. (2015). Black box health and management options. *Prepared for the Commonwealth Environmental Water Office. Adelaide: Australian Water Environments*.

Tonkin, J. D., Poff, N. L., Bond, N. R., Horne, A., Merritt, D. M., Reynolds, L. V., . . . Lytle, D. A. (2019). Prepare river ecosystems for an uncertain future. *Nature, 570*(7761), 301-303. doi:10.1038/d41586-019-01877-1