A State and Transition framework to guide riparian woodland vegetation management and environmental water decisions

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Abstract

River regulation and water extraction are major threats to the health and persistence of water-dependent ecosystems, such as riparian woodlands and forests. In heavily modified agricultural landscapes, riparian vegetation is also impacted by site-level stressors like livestock grazing, tree clearing, and weed invasions. Complex interactions among spatial and temporal drivers in water-dependent ecosystems can result in poorly articulated conservation objectives and inefficient or siloed management decisions. Where restoration funds and environmental water allocations are limited, these inefficiencies are magnified. We propose a management-focused State and Transition Model to describe the expected interactions among management at different spatial scales, develop measurable objectives and implement targeted monitoring. Derived from a multi-community eucalypt woodland model, the riparian State and Transition Model further refines the states to better describe key indicators of riparian condition and provides a catalogue of transitions describing the key site-level interventions, biotic processes and changes to flows that are expected to drive changes from one state to another. This resource can be used to support spatially explicit strategies and prioritisation of environmental flows or other management actions to improve vegetation condition along regulated waterways. Additionally, we demonstrate how the riparian State and Transition Model can be used for structured decision making, targeted monitoring and adaptive management by land and waterway managers.

Introduction

Water extraction supports human communities and global industries, but changes to river flows and catchment-scale degradation are a threat to global riverine ecosystem integrity and biodiversity (Bunn & Arthington 2002; Millennium Ecosystem Assessment 2005; Richardson et al. 2007; Bernhardt & Palmer 2011). Waterway management occurs at local and catchment scales, often at great expense due to the high cost of infrastructure, water, or intensive restoration (Richardson et al. 2007). Effects of management and restoration efforts in water dependant ecosystems are difficult to predict accurately due to the complex interactions among spatial and temporal variables and regimes (Campbell et al., 2023; Overton et al., 2014). For instance, at the catchment scale, river regulation influences the entire flow regime (e.g. frequency, magnitude, timing and duration of flows), causing local and catchment-wide impacts on riverine biota. These flow impacts interact with local site conditions, such as livestock grazing, channel morphology and land clearing, resulting in site-level responses that may be exacerbated by facilitative impacts or offset by opposing impacts. As such, most attempts to understand and manage riparian and floodplain ecosystems focus on hydrology or land management separately (González et al., 2015).

The riparian zone occupies the ecotone between aquatic and terrestrial vegetation from the high-water mark of a watercourse to the terrestrial dominated floodplain zone (Good et al. 2017; Riis et al. 2020). The unique composition of species in riparian ecosystems contributes disproportionately to landscape biodiversity (Sabo et al. 2005; Bennett et al. 2014; Hansen et al. 2019), provides significant human cultural resources (Humphries 2007) and can act as a refuge for fauna during climatic extremes (Nimmo et al. 2016). Furthermore, riparian vegetation influences the structure, function and composition of the in-stream environment, both locally and downstream (Gurnell et al. 2012; Paice et al. 2017). However, their ecotonal nature makes them particularly sensitive to changes in hydrological conditions (Riis & Biggs 2003; Poff & Zimmerman 2010). Degradation and loss of riparian vegetation is especially severe along lowland waterways (Feld et al., 2011; Fraaije et al., 2019; Tonkin et al., 2020) due to the intensification and expansion of river regulation for agriculture and this impacts the overall health of river systems and landscape-level diversity. The effects of climate change on precipitation patterns, temperatures, and water cycles will likely exacerbate these impacts (Palmer et al. 2009; Rivaes et al. 2022).

Various frameworks and tools have been developed to support the management and restoration of water-dependent ecosystems globally. These frameworks typically focus on understanding and modelling hydrological changes to guide flow management (Bunn et al. 2014; Swirepik et al. 2016; Arthington et al. 2023) or site-level management such as livestock removal, weed control, or revegetation (Holmes et al. 2008; Omidvar et al. 2021;

Jones et al. 2022). However, there are limitations to these approaches given the known interactions between flow and site interventions (Richardson et al. 2007). The apparent disconnect between site-scale restoration efforts in riparian zones and the management of flows in waterways may also reflect organisational challenges, such as different funding sources, or different staff or organisational responsibilities for flow and site management. However, identifying and highlighting opportunities and risks for flow and site interactions is crucial, given the importance of riparian vegetation condition to overall waterway health, and the importance of management on riparian vegetation condition (Merritt et al. 2010; Rivaes et al. 2015; Campbell et al. 2023).

State and transition models (STMs) can be used to describe and predict how ecosystems change over time due to natural processes or human activities. STMs delineate and describe common states (groups of structural and/or compositional expressions that a given ecosystem can exist in) and the transitions between them, aiding in ecosystem management and conservation planning. They are commonly used as a framework to describe ecosystem state changes and they offer a distinct approach to ecosystem management by emphasizing the importance of the current condition of a site or system on its response to management interventions and/or resilience to disturbance events (Westoby et al. 1989; Briske et al. 2008; Yates & Hobbs 1997; Standish et al. 2008; Sinclair et al. 2019; Sato & Lindenmayer 2021). Cataloguing and describing common condition states and drivers of transitions can allow for planning and prioritisation at multiple spatial and temporal scales (Bestelmeyer et al. 2009; Sinclair et al 2019). Further, STMs can integrate different types of knowledge, including experimental data, field survey data, expert knowledge, and practitioner experiences into one framework (Knapp et al. 2011; Bestelmeyer et al. 2017). They are effective for highlighting knowledge gaps and uncertainties, turning them into testable hypotheses that can drive an increasing understanding of the system and supporting adaptive management (Rumpff et al. 2011). The use of system states enables clear articulation of changes to multiple univariate measures simultaneously (such as tree density and native groundcover) to reach multiple system endpoints (Rumpff et al. 2011; Jones et al. 2023). Additionally, they allow for more meaningful articulation and assessment of goals that apply to target systems (as opposed to individual variables), which are key elements of effective conservation planning (Margoluis et al. 2009; Biggs et al. 2011).

Understanding and accounting for state-dependent trajectories of ecosystems in response to managed environmental river flows is vital to the restoration and maintenance of highly modified and regulated river basins in agricultural regions. Bond et al. (2018) demonstrated the importance of understanding the current condition of riparian and floodplain ecosystems when making predictions about the impacts of environmental flows on future ecosystem condition. In floodplain areas with extensive remnant vegetation, historical flow regimes are likely to be good predictors of the current condition (Bond et al. 2018). However, for riparian vegetation in highly modified agricultural landscapes, multiple additional stressors acting at the site level are just as likely to have resulted in the current vegetation condition (Campbell et al. 2023). Therefore, the recovery pathways for these systems will require a combination of site-level and river- or reach-level interventions (Campbell et al. 2023), especially in river basins where regulated waterways intersect highly modified agricultural landscapes.

Globally, significant resources have been invested into improving ecological health in highly modified and economically significant river basins, by allocating environmental water and reducing river regulation influences (Overton et al. 2014; Marshall & Alexandra 2016; Hart 2020), but inconsistent attempts at implementing effective and targeted monitoring to demonstrate the impacts of these allocations are notable (Swirepik et al. 2016). Additionally, while broad objectives for vegetation management and monitoring exist, quantified targets that align with feasible and desirable ecosystem condition states are uncommon (but see Richards et al., 2020). Further, while there are excellent resources and research into the management and effects of inundation and environmental water in the more expansive areas of floodplain and wetland vegetation (Bino et al., 2015; I. Overton et al., 2018), the specific combination of site scale management and river flows that best support the recovery of the narrow and dynamic riparian zone have not been well articulated to date. We propose a framework that ensures transparency around: the decision-making process undertaken by water managers; the expected outcomes from environmental flows; how flows might interact with site-level management; and the best variables to measure progress towards or away from those outcomes. Such a framework can support the implementation of structured, consistent and explicit adaptive management.

In this paper, we describe a State and Transition Model that synthesizes current knowledge about common riparian woodland condition states and the factors driving inland riparian woodland condition in southeastern Australia. Our model is based on the expert-elicited multi-community STM for eucalypt woodlands of southern Australia (Good et al. 2024) which synthesized the knowledge and expertise of Australian woodland ecologists to provide a framework for conservation planning and decision making. Using the ‘Floodplain and Riparian’ sub-group from the General Woodland Model, we refined this template model with a focus on lowland riparian woodlands, aiming to summarise the states, transitions, thresholds, and management actions that are relevant to waterway managers in southeastern Australia. Our model provides a framework to guide management at multiple spatial and temporal scales via the classification of site-level riparian condition and reasonable desired target states achievable within relevant management timeframes. We illustrate how the model can be used to guide both water allocation and vegetation management decisions and discuss how this approach is more likely to achieve and detect a transition towards the target state.

Methods

Study region

We refined the multi-community State and Transition Model for eucalypt woodlands of southern Australia (Good et al. 2024; hereafter 'General Woodland Model') to demonstrate how it can be applied to decision making for lowland regulated rivers of temperate southeastern Australia. This includes most lowland areas within the Australian States of South Australia, Victoria and New South Wales, which includes waterways throughout the Murray Darling Basin that are dominated by woodland vegetation communities. While this vast area occupies many different ecosystem types, the lowland riparian woodland communities are similar, mostly dominated by a canopy of Eucalyptus camaldulensis (river red gum), variable shrub layer, and herbaceous understorey. This similarity enables a 'Riparian Woodland Model' to be relevant to a very large spatial area, although the specific model details will require understanding the local reference vegetation types. The Riparian Woodland Model does not apply to upland areas that generally have different flow conditions, regulation actions, disturbances, and vegetation communities, but it will be an approximate analogue for lowland regulated waterways with woodland vegetation communities globally.

Refining the General Woodland Model for lowland riparian management

We adapted and refined the General Woodland Model to increase its applicability to temperate lowland riparian vegetation in southeastern Australia. We first considered and revised the existing set of eight general condition states and all existing plausible direct transitions between each unique pair of states, then revised the drivers of these transitions using simple causal chains (e.g. Figure 2). We aimed to increase the specificity for riparian ecosystems, especially in relation to the interaction between changes to flow management and changes to site management, while trying to maintain simplicity and generality across waterways.

We extracted all data associated with the Floodplain and Riparian sub-group of the General Woodland Model (available publicly here). Given we altered the number of condition states, we revised the plausible transitions that were presented in the General Woodland Model to better reflect lowland regulated waterways within southeastern Australia. We applied the logic described in Good et al. (2024), when determining plausible direct transitions, specifically 'direct transitions are those that would plausibly occur over 20 or 100-year timeframes without passing through any of the other states, assuming that resources and effort are not limited.' Plausibility of the riparian transitions was estimated by the authors. We also removed drivers that were not directly relevant to riparian condition.

For each of the plausible riparian woodland transitions, we selected the relevant site management drivers, flow management drivers, and biotic processes required for the transition to occur, as well as the likelihood that (if all these factors are present) the transition would happen within 20 and 100-year timescales. Likelihoods were qualitative categories (Almost no chance; Very unlikely; Unlikely; Neither likely nor unlikely; Likely; Very likely) and were estimated by the authors based on the assumption that the specified management was implemented. These pathways (including all drivers, processes, and measurable attributes that might indicate the transition has occurred and their associated likelihoods) were given a unique identifier and are herein referred to as 'causal chains' (Niemeijer & De Groot 2008).

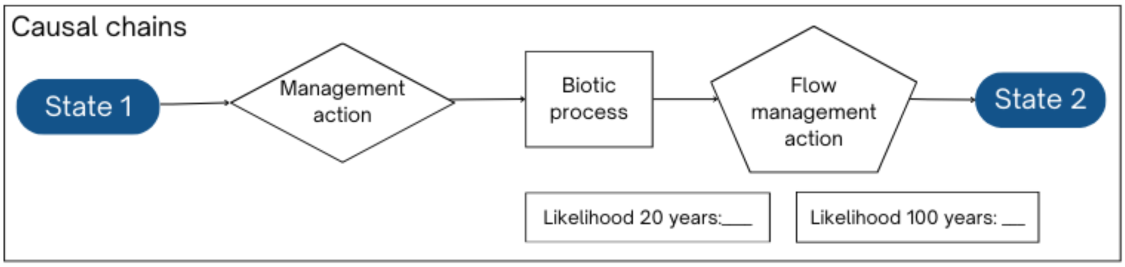

Figure 1. An example of a causal chain indicating the drivers required to cause a state transition to occur. The chain may be simple or complex with one or many actions or processes that drive the transition.

We didn't include drivers that are external to the system such as climatic events, intense bushfires, disease or outbreaks of insects. However, these factors do influence the condition of riparian vegetation and so we've included them as 'hazards' which will need to be considered as modifiers of the likelihood of transitions being successful.

Incorporating flow management into the model

We describe flows only in their relative change from the flow regime that supported the starting state. The reason we chose not to describe flows in absolute terms is because the impact on the riparian vegetation is closely associated with site-scale variables that cannot be accommodated in this model. For example, the riparian zone is a function of bank steepness, channel depth, water movement (which can be influenced by in-stream structures) and therefore absolute values for flows would be impossible to estimate at the site or reach level across such a large region. Therefore, we describe the change in overall flow regime (increase, decrease or status quo) that would be required for the transition to occur. While these categories are a simplification of the detailed flow regime requirements of riparian communities, there is extensive literature and management plans for environmental watering that would guide decisions within system constraints for increased or decreased flow regimes. For example, an increased flow regime is an increase in flow volume above the current conditions, which can be achieved through the increase in volume and duration of baseflows, and/or the increase in volume, duration or frequency of high flows, but the specific actions will differ between waterways and years.

To investigate potential dependencies among drivers that occur at different spatial scales, we compared the frequency of transitions that require combinations of site or flow management interventions. Each transition was summarised by the presence or absence of drivers relating to changed flows, changed site management and/or other biotic processes. We removed those containing any mention of ‘status quo’ and cross-checked to ensure all drivers included in this part of the analysis represented significant interventions. To visualise the intersections among different types of drivers, we used UpSetR (Conway et al 2017) which is a package that visualises intersecting sets (observations) and their properties (variables). In this study, each transition represents a set, and each driver group is either present or absent in the causal chain for that transition. To visualise the intersections of driver groups, the number of transitions involving each combination of driver groups were tallied and presented in an UpSetR plot.

Applying the state and transition model to real-world riparian management

We demonstrate how the Riparian Woodland Model could be incorporated into different levels of management, monitoring and decision making in riparian and river systems. Application of a STM requires some structured breakdown of transitions into their constituent parts and the strategic application of those parts to the most relevant use-case. We take the Riparian Woodland Model presented in this paper and provide some practical examples of how to convert the information provided in the model to real-world management pathways. In doing so, we show how the causal chains describing a given transition (from a starting state to an end or target state) can be used for setting targets, developing management plans, communicating with different stakeholders, measuring progress and impact on target variables and progress reporting.

Results

Riparian woodland states

We reviewed the eight General Woodland Model vegetation states described in Good et al. (2024) as a starting point and systematically refined them to better reflect common categories of riparian woodland vegetation condition in temperate southeastern Australia. The resultant set of states shares most of the original eight-state structure (Table 1), but includes nested sub-states for the Highly Modified Woodlands to account for the strong influence of functional-group dominance (riparian vs terrestrial) in the groundstorey (Table 1). This distinction between riparian and terrestrial plant dominance was essential because of the close links between these groups and flow regimes, as well as being a common indicator of ecological objectives for riparian woodlands (Tonkin et al. 2020). We also added an ‘Intermediate Restoration’ state which is not a stable state but represents a longer transition that will likely span years to decades, depending on the growth and development of a mature eucalypt woodland structure.

Table 1. Comparison of the condition states described in the General Woodland Model and the refined condition states used in the Riparian Woodland Model described in this paper.

General woodland states	Riparian woodland states	Description of riparian model state	Rationale for change
Exemplar	Exemplar	All vegetation strata are intact; native riparian species richness is high in all strata and includes disturbance sensitive species; low weed cover; soil is stable and has a natural nutrient balance.	No change
Modified woodland	Modified Woodland	Overstorey is mostly intact; mid/understorey are depleted in both richness and cover; understorey flora is primarily native and riparian; soil nutrient levels and stability close to reference.	No change
Highly modified woodland	Highly Modified Woodland A	Overstorey and midstorey reduced; understorey is depleted in richness and is dominated by terrestrial species; possible altered soil processes and degraded structure (bank erosion).	A switch from riparian to terrestrial understorey requires flow management that wasn't captured in original model
	Highly Modified Woodland B	Overstorey and midstorey reduced; understorey is dominated by exotic riparian species; possible altered soil processes and degraded structure (bank erosion).	A switch from native riparian species to exotic riparian species signals a significant functional and compositional change that requires different site and flow interventions
Diverse derived grassland	Diverse Derived Understorey	Overstorey and midstorey mostly absent; understorey mostly intact and dominated by native riparian species; soil nutrient levels and stability close to reference.	A name change, as riparian zones where trees have been removed aren't typical 'grasslands'
Depleted derived grassland	Depleted Derived Understorey	Overstorey and midstorey mostly absent; understorey is depleted and dominated by exotic riparian species; soil may have degraded structure (bank erosion).	
Thicket	Tree Thicket	Mature trees mostly absent; overly dense native overstorey; understorey cover suppressed, and may be dominated by native or exotic species; soil stability may be compromised	A name change to specify difference between shrub and tree thickets (which are more common in riparian zones)
Overstorey and midstorey thicket	Shrub Thicket	Mature trees mostly absent; overly dense native shrubs; understorey cover suppressed, and may be dominated by native or exotic species; soil stability may be compromised	
Transformed	Transformed	Mature native trees and shrubs mostly absent or dominated by exotic species (e.g. Willow or Blackberry); understorey dominated by exotic or native terrestrial species; bare or low groundcover; erosion may be severe; may have high cover of exotic trees and/or shrubs	No change
N/A	Intermediate Restoration	Tree and shrub species composition similar to Exemplar but not in size or basal area. Understorey and soil may range from slightly depleted to degraded, and may need further management.	An added transition state to capture the need for long time-scales to allow mature woodland development, and the possibility for requiring different management interventions based on the likely trajectory.

Transitions among riparian states

There were 39 plausible direct transitions among the ten riparian woodland condition states (Appendix S1: Table S1). The management interventions and biotic processes expected to drive each transition included 21 site-scale drivers, of which 16 were common to both the General Woodland Model and the Riparian Woodland Model (Table 2). Riparian-specific biotic processes were added to account for the recruitment of riparian weeds, including exotic trees and shrubs, the removal of exotic trees and shrubs, control of pest animals and thinning of shrubs (Table 2). We removed drivers that aren't common in riparian zones such as cropping and soil nutrification. An additional five flow-management drivers were included to specify the direction of the change in flows replacing the less specific mention of flood and flow regimes from the General Woodland Model.

Site management drivers include common restoration activities such as revegetation, livestock access controls and exotic plant removal, as well as activities that are associated with degradation of riparian zones such as inappropriate livestock grazing and removal of native vegetation. Some management interventions could be used for restoration purposes or could be associated with site degradation depending on the transition being described (for example thinning of midstorey might be required for restoration of shrub thickets but could be associated with degrading transitions if applied to Exemplar riparian woodlands). For this reason, we didn't group management interventions as negative or positive in terms of their potential effect on riparian condition.

Table 2. Drivers used to describe transitions in the Riparian Woodland Model compared with those used in the Floodplain and Riparian causal chains in the General Woodland Model. Hazards were added but not included in the individual transitions because they are likely to have unpredictable but generally negative impacts on the condition of Riparian vegetation. Any transitions involving an increase in condition, therefore, would be less likely to occur if any of these hazards are present.

Drivers of transitions		
General and Riparian Models	**Riparian Model only**	**General Model only**
Site management drivers	*Site management drivers*	*Site management drivers*
Inappropriate grazing pressure	Thin shrubs	Cease land use
Thin mature trees	Exotic tree and shrub removal	Status quo
Degrade soil structure	Manage pest animals	Cropping
Remove all vegetation		Soil nutrient increase
Remove understorey		
Remove overstorey	*Flow drivers*	*Flow drivers*
Remove midstorey	Reduce flows	Flow or flood regime altered
Thin saplings	Increase flows	Reinstate appropriate flow or flood regime
	Status quo*	
Manage total grazing pressure	Status quo or reduce flows*	*Biotic processes*
Control erosion	Status quo or increase flows*	Self-thinning
Weed control		Weed recruitment
Plant understorey	*Biotic processes*	
Plant midstorey	Riparian weed recruitment	
Plant overstorey	Exotic tree and shrub recruitment	
Biotic processes		
Native recruitment dense woody	*Hazards*	
Mature tree death	High intensity fire	
	Ongoing drought	
	Extreme heat wave	
	Defoliating insect outbreak	
	Pathogen outbreak	

*denotes drivers that were not included in the driver interaction analysis

Flow management interventions were categorized by the direction of change from current flows (increase, decrease, status quo), rather than individual flow components, to avoid overcomplicating the model. Similarly, the direction of change in flows could be associated with restoration or degradation pathways depending on the starting and ending states.

Causal chains describing the 39 transitions among states were described by identifying which drivers (site or flow) and biotic processes are required to shift from one state to another. To simplify the visualization of the model we grouped states with similar structure: mature woodlands, no overstorey, and dense woody (Figure 3) and if there was overlap in the drivers associated with transitions among these grouped states, we represented these as one arrow in the box and arrow plot. For example, the two causal chains describing the transitions from Diverse Derived Understorey and Depleted Derived Understorey to the Intermediate Restoration state are summarised by the same arrow pathway (Figure 3) and the same corresponding drivers (Appendix S1: Table S1).

In general, reductions in flow regimes resulted in shifts to more degraded states (those with a terrestrial understorey), and subsequently, increased regimes were required for state improvements (Figure 3). However, increased flows were associated with some 'negative' transitions when they were coupled with negative drivers (e.g. from the Highly Modified Woodland A to Depleted Derived Understorey), which highlights the importance of considering the influence of current flows, other drivers, current site condition and the desired transition when making decisions about changes to flows. At the site scale, inappropriate grazing pressure and vegetation removal were the most common drivers for transitions towards the more degraded riparian states, while weed control, revegetation and livestock removal were common drivers of transitions to less degraded states.

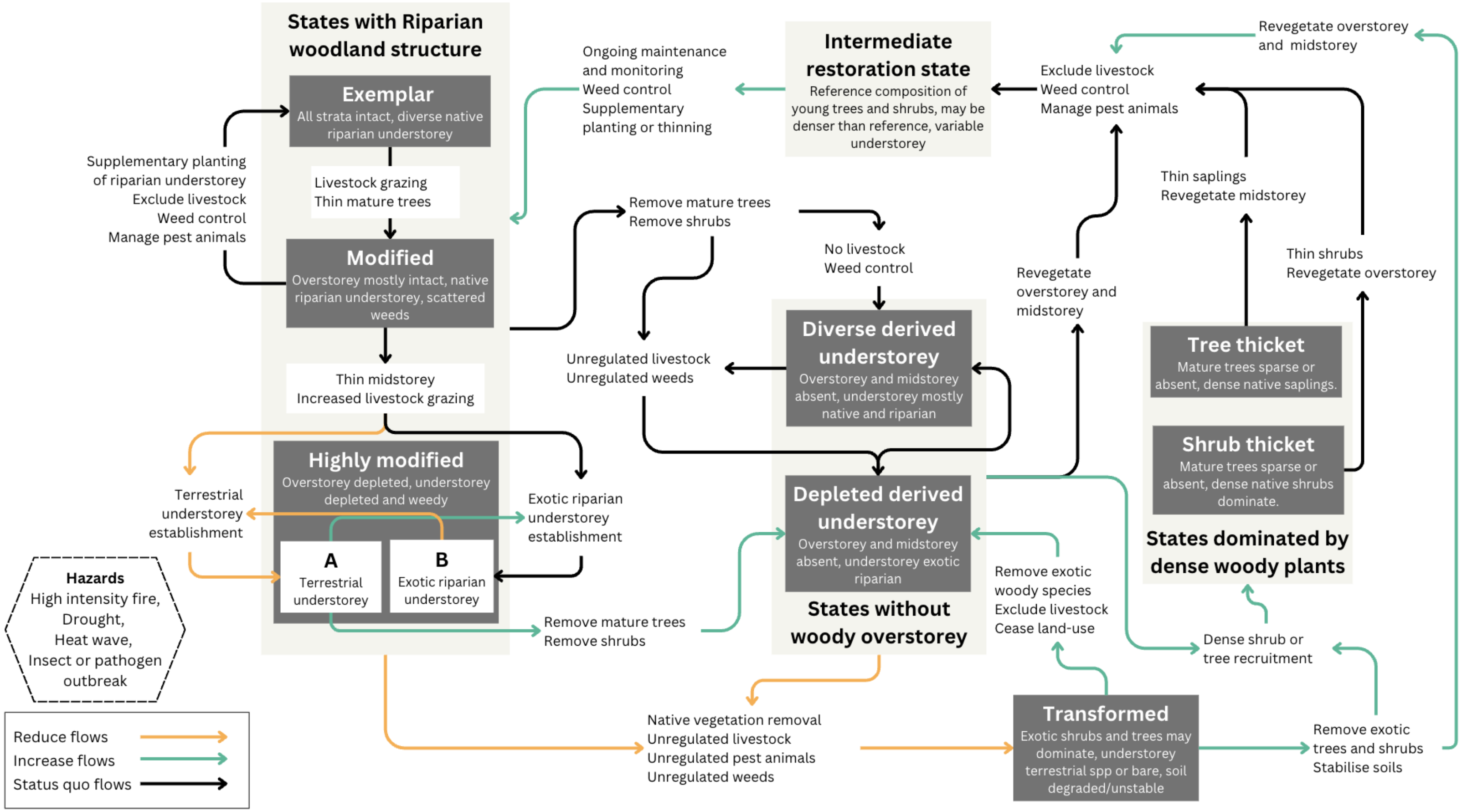

Figure 2. Diagram showing riparian states and transitions among states for the Riparian Woodland Model. Where arrows originate or end at one of the shaded boxes (containing several states), the transition represents the combination of the states within the shaded box (thus one arrow may represent several distinct transitions). For example, the transition from the Diverse Derived Understorey and the Depleted Derived Understorey states to the Intermediate Restoration state involve the same drivers (perhaps with slightly different levels of effort required to 'control weeds'). Arrows are coloured where a decrease or increase in flows is required for the transition to occur. For example, from Highly Modified Woodland A (which has a terrestrial understorey), an increase in flows, along with removal of woody species is required to get to the Depleted Derived Understorey state. The full suite of transitions, drivers, indicators and likelihoods for each unique transition can be found in Appendix Table A1.

Interactions between flow and site management

We grouped the drivers that influence transitions into three broad groups: 1) changes to site management; 2) changes to flows; and 3) biotic processes; Table 2). We found that most transitions required some kind of management at the site level (37 of the 39 transitions) and 12 of the transitions required only site interventions (Figure 4). Changes to flows without any site management (including the biotic processes) only accounted for two transitions, although flow management had some role in over 20 of the 39 transitions (most of which were positive). Both site management and changes to flows (+/- biotic processes) were required for 18 of the 39 transitions.

The most frequent monitoring indicators that may be used to assess transitions between condition states were midstorey density and mature tree density, however measuring the cover of native and exotic riparian groundcover and terrestrial groundcover were also associated with more than half of the transitions (Appendix S1: Table S1). For all transitions to or from states with mature woodland structure, or from thickets to other states, monitoring of mature tree density is an essential variable. Monitoring of understorey was more important for transitions between states within the structural groups e.g., the Derived Understorey states; Appendix S1: Table S1). The density of tree saplings and shrubs was an important distinguishing variable for many transitions but usually alongside the mature tree or understorey variables, except for thicket transitions. The Intermediate Restoration state contains a wide range of understorey vegetation conditions but a specific (and unstable) density of immature and mature trees and shrubs. This means that transition thresholds to or from the Intermediate Restoration state cannot be determined, but rather, vegetation conditions of this state will represent an intermediate level somewhere between the starting state prior and one or more possible end states. While this defies the typical definition of states, it is a useful component of the model due to the prolonged period that vegetation communities can occupy this transition, and the common occurrence of this 'state' in degraded landscapes.

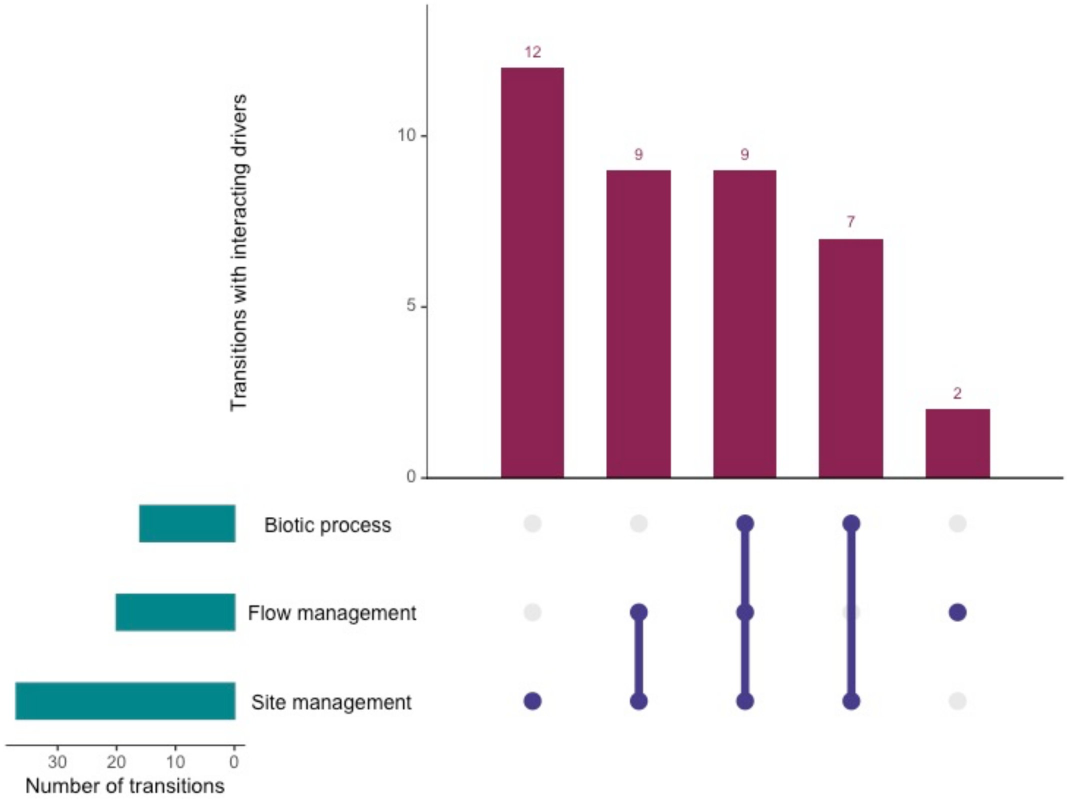

Figure 3. An UpSetR plot showing the number of transitions that required different combinations of site management, flow management and various biotic processes. Blue filled circles represent driver groups that are associated with transitions, vertical bars represent the number of transitions in which the driver group (or combination of driver groups if there are multiple filled circles connected by a vertical line) are involved. The horizontal bars represent the total number of transitions that involve the corresponding driver group (irrespective of intersecting driver groups). Drivers, indicators and likelihoods of each unique transition can be found in Appendix Table A1.

Applying the Riparian Woodland Model to management scenarios

The Riparian Woodland Model described above can be used by managers to inform and structure decision making related to vegetation management in regulated rivers. This STM feeds into all levels of the existing management hierarchy common to most regulated waterways in southeastern Australia, and will be relevant to many systems internationally (Figure 5). Inputs into each component of the hierarchy are iterative and are updated as new information is obtained or constraints are altered, e.g. funding or infrastructure. Objectives can be altered to align with the STM either explicitly or indirectly. For example, objectives for a waterway or region can be made to maintain or improve the state of existing vegetation communities. Following this, management targets can then specify a desirable proportion of the waterway (or representative sites) within a particular state, or alternatively, to increase the levels of vegetation attributes (e.g. tree density, plant cover or richness) to be above thresholds that correspond to desirable states. The management strategy is then designed to alter relevant vegetation attributes in specific locations to meet these objectives and targets. Importantly, this process provides quantitative targets and thresholds that enable targeted monitoring data and analysis to evaluate progress towards targets over time – a process that is poorly achieved in many management programs.

Here we demonstrate how to extract relevant information provided in the Riparian Woodland Model and apply this to different levels of management decision making, restoration implementation, monitoring, adaptive management and progress reporting (Figure 4). A key step in applying the STM to management and monitoring is to develop plans that incorporate components of the STM, including likelihoods of transitions with specific time-frames, as well as the most likely indicators for transitions in order to objectively evaluate impacts of interventions. Once the monitoring plan is developed, a process for feeding new monitoring data into the management framework needs to be determined, via an adaptive management framework. This can follow simple or complex processes, such as to continue a management action until a threshold is crossed (i.e. transition to a new state), or to refine and adapt management actions from a suite of approaches to reach desired targets.

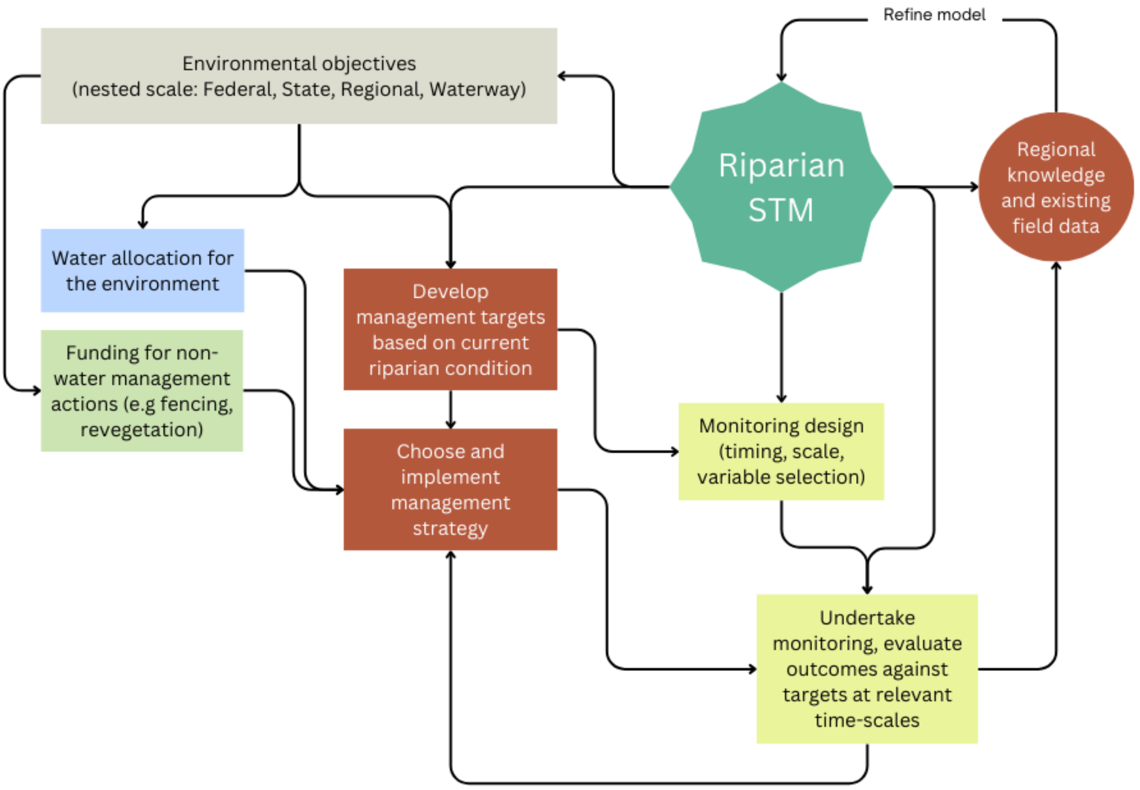

Figure 4. An illustrated suggestion for incorporating the Riparian Woodland Model 'Riparian STM' into multiple levels of waterway and vegetation management. For example, the Riparian Woodland Model can be used to help to identify objectives (i.e. preferred states), develop management targets and assist in monitoring design via selection of variables. Finally, the STM provides a means of synthesising and storing systems understanding that is easy to communicate and is amenable to updating over time.

The broad steps to integrate the Riparian Woodland Model into management at the State or regional scale are:

1. Review objectives for the region and integrate the STM into these at the highest level. For example, objectives ‘to maintain vegetation condition’ (a common but imprecise objective) can be modified to speak to the STM and improve clarity, such as ‘maintain condition of healthy states and improve degraded states’ – as defined by the model application.
2. Assess current riparian vegetation condition (or tree cover from aerial imagery if condition information is not available) and categorise deviation of flows relative to reference for all waterways – then use this to estimate proportions of each waterway in each state;
3. Develop targets (at the regional scale) for changes in the proportion of condition states, e.g. all waterways to have >20% of the linear extent of riparian communities in XX state and <5% in XX state in 10 years;
4. Develop high-level management plans for each transition relating to the targets (including any requirements for changes in flows) and include high-level monitoring plans using suggested indicators of transitions;
5. Evaluate success based on targets and monitoring indicators and incorporate lessons back into the STM.

The broad steps to integrate the Riparian Woodland Model into management at the waterway or reach scale are:

1. If regional objectives do not refer to STM, review waterway or reach scale objectives and modify to incorporate locally appropriate objectives that refer to the STM.
2. Assess current riparian vegetation condition (or tree cover if condition information is not available) and categorise deviation of flows relative to reference for the waterway – then use this to estimate proportions of the waterway in each state;
3. Develop targets (at the waterway scale) for changes in the proportion of condition states, e.g. >40% of the linear extent of XX waterway riparian communities in either XX or XX state in 10 years;
4. Develop detailed management plans for each transition relating to the targets (including any requirements for changes in flows) and include detailed monitoring plans using suggested indicators of transitions;
5. Evaluate success based on targets and monitoring indicators and incorporate lessons back into the STM.

Using STMs to structure decision making

The Riparian Woodland Model can be used to support structured decision making to help achieve the best outcomes for riparian vegetation within a complex decision context. In this section we describe examples of how decisions at the site and flow management scale could be informed by the Riparian Woodland Model. In Figure 5A we show how a target transition from Highly Modified Woodland A to Modified Woodland would involve reduced grazing pressure at the site level (if currently grazed) and increased flows to aid the recruitment and establishment of native riparian species. However, if exotic riparian species arrive and establish in place of native species, this represents a transition to

Highly Modified Woodland B and would need to be managed accordingly. The monitoring of understorey composition and cover to ensure that 1) flows are adequate for riparian establishment and survival and 2) native species are dominant, is therefore key to measuring success for this transition. In this example, we used the condition state descriptions, management drivers (grazing and flows) and indicator variables to develop a decision tree based around the starting condition state (Highly Modified Woodland A).

Another approach is to create a decision framework around catchment scale targets (Figure 5B). Here we started with an example of a river or reach with reduced flows. In this situation, areas with a mature overstorey are most likely to have a terrestrial dominated understorey (due to the lack of flow dynamics) and are therefore would most likely be in the Highly Modified Woodland A state. Areas without a mature overstorey structure are most likely to be either Transformed or Thicket states which require some site-level management. All states require increased flows, however, increasing the flows without first implementing site-level management is unlikely to result in improved condition, unless there is already a mature overstorey layer. Therefore, the order in which site and flow management are applied is dependent on the proportion of the river or reach in different condition states.

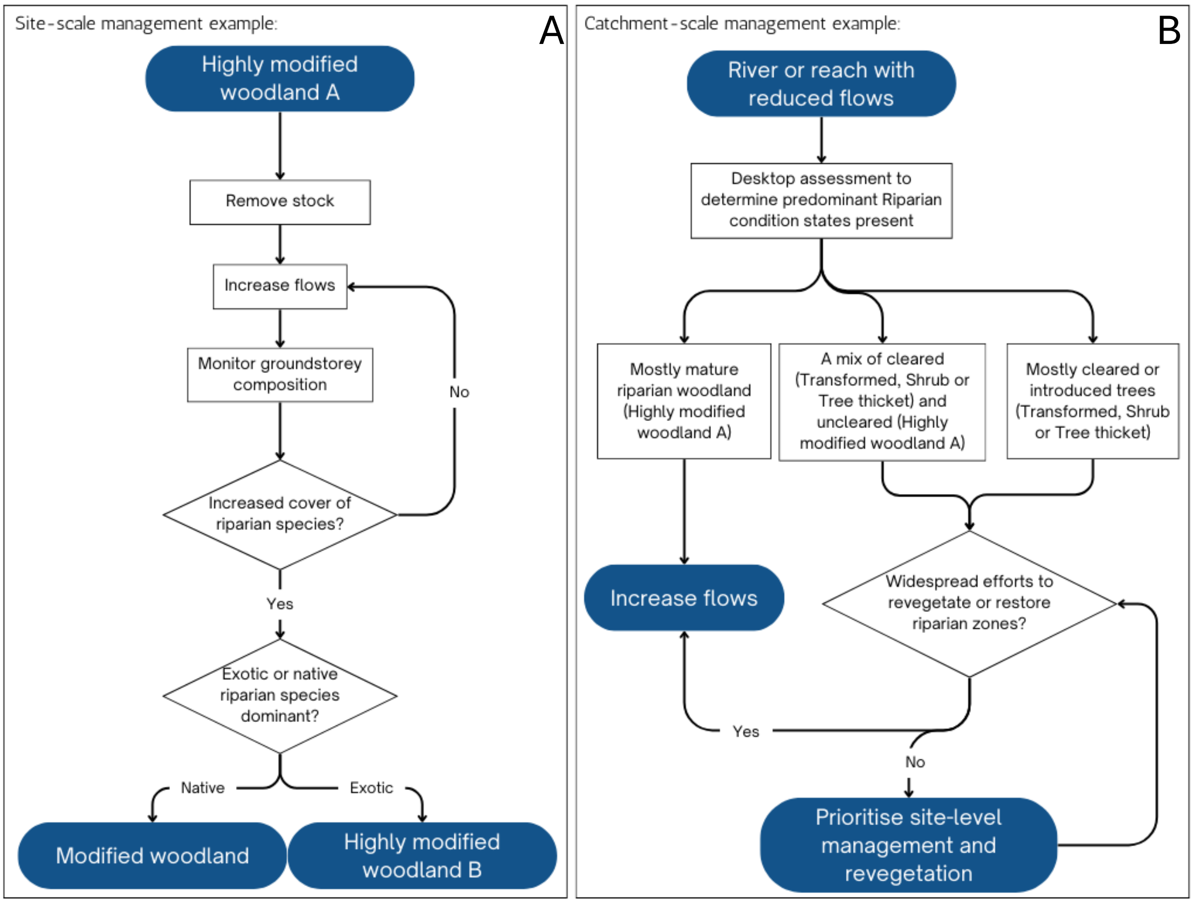

Figure 5. Two decision trees using information from the causal chains developed in the Riparian Woolands Model to guide management at the site-scale (A) and an alternative approach at the river-, reach- or catchment-scale (B).

Discussion

In this study we refined the temperate Australian General Woodland Model (Good et al. 2024) for a specific ecosystem – riparian woodlands in southeastern Australia. The process of refining and articulating changes to the General Woodland Model captured the importance of plant functional groups in riparian systems and the complexity of multi-scale management that may be required to achieve particular transitions. While site interventions were required for most transitions among riparian woodland condition states, changes to flow alone were only associated with two transitions, highlighting that a focus on flow management in isolation of other management actions will most likely not result in achieving ecological objectives particularly in highly modified landscapes. Indeed, our refined model demonstrates that riparian ecosystems cannot be restored at the catchment scale without some site-scale interventions in addition to increased flows. We suggest that the outcomes and impacts of environmental flows could be greatly improved with a coordinated decision-making approach to allocating resources to site-scale interventions and environmental flows.

In general, the set of condition states described in the General Woodland Model (Good et al. 2024) were largely applicable to riparian woodlands, and the changes we made were based on the different management required when groundstorey composition shifts from riparian to terrestrial species, and from native riparian to exotic riparian species. While this reinforces the usefulness of the General Woodland Model as a base STM for temperate Australian woodlands, it highlights the importance of refining the general model to suit the spatial and temporal scope of a particular use. We expect that the General and Riparian Woodland Models would be well suited as baseline models of temperate woodlands, forests, and grasslands globally.

An important addition to our STM is the inclusion of an ‘Intermediate Restoration’ state because it provides a way to track the slow transition from treeless to mature woodland states. Given the amount of time needed for the development of a mature woodland structure from previously cleared states, it is important to identify the variables that might indicate a site is on a recovery pathway within management time-scales. This state can act as a placeholder to encourage monitoring in older revegetation sites that appear to be developing characteristics of the Exemplar state. These attributes could act as indicators of progress towards a longer-term goal (for example when moving from treeless states to states with a woodland structure it's unlikely that you will be able to measure 'success' until many decades after the management is implemented). Indeed, the inclusion of this state reflects the dearth of published studies demonstrating successful restoration from degraded or cleared states to the Exemplar state (in terms of structure, composition and function; Atkinson et al. 2022). Studies of riparian restoration trajectories demonstrate the importance of choosing appropriate indicators and planning for long-term monitoring (Tonkin et al. 2020). Some of these gaps in our understanding of riparian restoration trajectories could be filled by revisiting older restoration sites and comparing their structure and composition to reference conditions.

Another key difference in the Riparian Woodland Model compared to the General Woodland Model is the importance of the understorey functional groups (riparian versus terrestrial), rather than exotic versus native. This approach aligns more closely with the framework by Richardson et al. (2007) that describes management actions under three scenarios dictated by the prevalence of invasive plants. While these three scenarios are useful, they fall short of describing the important states that occur and are desired within a riparian woodland context.

Transitions to other states require changes to the strength of drivers, their presence, or their reversal; this reflects a resilience-based idea that is important to capture in the development of STMs (Briske et al 2008). Management interventions associated with transitions from treeless states to treed states generally involve planting trees and shrubs, managing or removing stock and controlling weeds. In most cases, riparian revegetation or natural recruitment requires additional water resources in the first year to enable establishment, either via elevated flows (e.g. Deng et al. 2024) or through on-ground watering of tubestock, which highlights a potential benefit of incorporating site and flow decisions to improve outcomes for plantings and increase efficiency in restoration effort and investment. While some transitions were possible with either site or flow management only, many desirable transitions from degraded states required both flow and site management to occur. Managers of waterways with stable and unchangeable flow regimes may rightfully consider site management actions only, but in regulated systems where flow manipulation is possible, such as the provision of environmental flows, managers will benefit from considering the interactions between site and flow management.

For the Riparian Woodland Model, the monitoring variables expected to be the most beneficial were selected based on differences in vegetation attributes between states. While this process is a very quick and efficient way of identifying vegetation variables that will indicate a transition between states, these variables may not be most effective if the threshold is uncertain due to high variability in variables. A more robust alternative is to use data collected from each state of the target system and quantify threshold values to identify variables that provide discrete or more confident thresholds (Jones et al. 2023). The three vegetation variables that are expected to discriminate most state transitions in our model align well with the findings of Jones et al. (2023) who identified the cover of exotic understorey plants and the density of immature trees as the two most frequently important variables to distinguish transitions in non-riparian woodlands. A similar formal analysis of the relative importance of variables and determination of the quantitative transition thresholds between states could be conducted for states in our Riparian Woodland Model when sufficient data are collected from a representative sample of vegetation communities within each state.

Monitoring should be undertaken to identify and manage unintended transitions (towards the two Highly Modified Woodland states, instead of the Modified Woodland or Exemplar states). This framework demonstrates the role of frequent and targeted monitoring in situations where flows have been altered and the understorey composition is in flux to ensure that highly competitive riparian exotic species do not establish and become dominant (Tonkin et al. 2020). If appropriate flow management has not been undertaken, the primary risk will be a transition towards woodlands with a terrestrial understorey, therefore the relative abundance of terrestrial vegetation is a good indicator which could be used to assess the appropriateness of flows to support riparian vegetation.

This STM framework provides a very high-level recommendation for flow management, i.e. transitions via increased or decreased flow regimes. This is a necessary simplification of the detailed flow management decisions that are required (and are used) to achieve multiple objectives. This context specificity means that it is unrealistic and inappropriate to incorporate detailed flow recommendations into the broad Riparian Woodland Model but we believe that this first step is an important contribution to the management framework. The high-level guidance provided via the STM will indicate what states comprise the vegetation communities of a waterway, what states are desired, what attributes need to be changed using the suite of flow and non-flow factors, and what attributes to monitor to detect transitions. If a change in flow regime is required, managers will need to determine the most effective way to deliver the flow regime within the constraints of their system, such as water availability, physical infrastructure, legal or policy constraints, consumptive water uses, competing objectives, and social constraints.

The influence of different flow components on vegetation is expected to vary, for example, baseflows will help to sustain aquatic vegetation communities (Tonkin et al. 2020) and may provide groundwater resources to deeper rooted plants (Deng et al. 2024). Elevated flow periods in spring and summer will provide water resources and propagules higher up the bank and stimulate germination and enhance recruitment or riparian species (Tonkin et al. 2020, Pereira et al. 2021, Deng et al. 2024). Additionally, each of these flow components that increase soil moisture resources, disperse propagules, and subject plants to periods of inundation will shift the competitive dominance of plants from terrestrial groups to riparian groups (Miller et al. 2013, Main et al. 2022). Regardless of the specific change in the regime, water availability within the soil will increase, propagules will be dispersed to different areas, and competitive interactions between terrestrial and riparian plants will shift in ways that promote condition of riparian vegetation communities, provided that survival thresholds are not exceeded (Vivian et al. 2020, Gower et al. 2024).

We created example decision trees to demonstrate how information can be extracted from the Riparian Woodland Model to operationalize and standardize decisions in a simple and transparent way. These decision trees can be modified to meet the specific conditions of a system for the most common or important state transitions. Even if the process is not fully embedded within a larger management framework of the system, these decision trees can be used to guide management at the local level to improve efficiency and outcomes.

Future work building on this study is hoped to include the development of an interactive and updateable online-interface-tool for managers, researchers and governments (and other river management stakeholders). Such a tool would provide spatially explicit layers to aid in the assessment of current riparian condition states, options for site-scale information to be added (for example where there is on-ground data available), management options based on current and target condition states and a reporting tool for uploading on-ground interventions (such as tree planting). This would allow for multi-scale management decisions to be made, for example where there's a decision about where to allocate flows, having access to the locations and timing of any on-ground projects could help to achieve better outcomes for both environmental flows and on-ground management. Importantly, for the Australian context, this process would include work with Traditional Owners within a region to ensure that Cultural values and Indigenous-led management are incorporated into management decisions (Goolmeer et al 2021).

Conclusions

We adapted a General Woodland Model to riparian woodlands. Using this refined Riparian Woodland Model we were able to assess which drivers were needed to facilitate transitions between states. This analysis revealed that alterations in flows alone will, in most cases, not cause transitions (to better or worser states) without biotic or site level drivers also occurring. Likewise, beneficial transitions are not likely to occur from many degraded states without increasing flows. This study highlights the utility of the General Woodland Model which was straightforward to adapt to a specific vegetation type. Furthermore, we show how the STM can be embedded in a broader framework to guide decision making and management planning at a site-scale and catchment scale.

This framework is scalable and can be linked to broad national objectives while also having the potential to guide on-ground works and management planning. Each condition state is a relative departure from the reference for a given location or vegetation type, thus there is room to specify fine-scale detail such as species or community requirements within the framework, while maintaining a clear link to the broader context.

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Conflict of Interest statement

The authors have no conflicts of interest to declare

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