



# Murray-Darling Basin Environmental Water Knowledge and Research Project

## Vegetation Theme Research Report

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**Cover Image:** Water entering Clear Lake, Narran Lakes

**Photographer:** Gary Palmer

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# Contents

<b>Executive Summary</b>	<b>1</b>
<b>1 Vegetation Theme: Introduction</b>	<b>3</b>
<b>2 Individual Research Activity Summaries</b>	<b>6</b>
2.1 V1. Conceptualisation – Vegetation outcomes: what are we seeking and why? .....	6
2.2 V2. Data integration and synthesis .....	9
2.3 V3. Field site assessments and germination trials .....	11
2.4 V4. Seedling mesocosm experiments .....	14
<b>3 Theme Synthesis</b>	<b>17</b>
<b>4 Management relevance</b>	<b>22</b>
<b>5 Knowledge Status</b>	<b>24</b>
<b>6 References</b>	<b>27</b>
<b>7 List of appendices</b>	<b>29</b>

## Glossary/Key terms

Term	Definition
<b>Adventitious roots</b>	Roots which grow from an area of the plant other than the root zone (for example off the stem) and which may grow above the soil surface
<b>Anoxic soil conditions</b>	No or very low concentrations of dissolved oxygen
<b>Antecedent conditions</b>	Preceding conditions, e.g. the conditions prior to an environmental watering event. Can refer to the condition of the vegetation or to the flow conditions, e.g. wet or dry prior to an event
<b>Aquatic environments</b>	Relating to water, typically refers to inundated environments
<b>Biomass</b>	The quantity or weight of plant material, typically material that has been dried. Can refer to total biomass of a plant, or parts of a plant (e.g. below-ground roots or above ground stems and leaves)
<b>Community assembly rules</b>	Rules which determine the composition of species within a community
<b>Ecological level of organisation</b>	The way in which components of an ecosystem are organised, e.g. species, populations, communities and mosaics of communities (vegscapes)
<b>Ecosystem</b>	A biological community of interacting organisms (e.g. plants and animals) and their physical environment
<b>Ecosystem functions and processes</b>	The biological, geochemical and physical processes and components that take place or occur within an ecosystem
<b>Expected outcomes</b>	The outcomes predicted to occur in response to an environmental water action
<b>Extant vegetation</b>	Vegetation / species that are present at the time of a survey (as opposed to species present in the seed bank which may or may not be part of the extant vegetation)
<b>Germination</b>	The development of a plant from a seed or spore after a period of dormancy
<b>Heterogeneity</b>	The state of being diverse, e.g. a diverse range of plant communities
<b>Mesocosm</b>	An outdoor experimental system that examines the natural environment under controlled conditions
<b>Physiological response</b>	An automatic reaction that triggers a physical response
<b>Recruitment</b>	When a juvenile organism joins a population, e.g. when a seedling becomes established and has a high likelihood of surviving into adulthood
<b>Resilience</b>	The capacity to recover from disturbance
<b>Seed viability</b>	The ability of a seed to germinate under suitable condition

<b>Term</b>	<b>Definition</b>
<b>Seedling establishment</b>	The process of germination and initial seedling growth, such as root development, to enable a seedling to acquire water and nutrients and increase the likelihood of surviving into adulthood
<b>Soil biota</b>	Organisms which live in the soil
<b>Tap root</b>	The main root of a root system which grows vertically downward
<b>Terrestrial environments</b>	In the context of this report this refers to floodplain environments which are dry. These environments may be inundated by flooding
<b>Traits / attributes</b>	A distinguishing quality or characteristic
<b>Vegscape</b>	A mosaic of vegetation communities

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# Executive Summary

## Key outcomes

- To achieve vegetation outcomes from environmental water, a process of social, ecological and economic consideration is required (1 and 2.1).
- What are we watering for and why? We provide structure and knowledge to help refine objectives, define function and value, and select indicators across a range of spatial and temporal scales to inform environmental watering (2.1).
- Understorey vegetation outcomes are diverse, both spatially and over time. The response of plant communities to watering actions, vary from place to place leading to a diversity of outcomes from the same watering treatments spatially. Across the Basin, the variation in response to the same watering actions, leads to a diversity of vegscapes (2.2 and 2.3).
- Variability in vegetation responses are predicted to arise as a result of differences in location, recent flow conditions (e.g. water depth, time-since-last inundation, proportion time wet), vegetation structure, and medium to long term flow regimes (2.2 and 2.3).
- Watering lignum once in every 1 – 3 years assists in greatest clump size which supports waterbird recruitment (2.3).
- Woody recruitment is variable despite similarities in vegetation type and flooding frequency (2.3).
- Eucalypt tree seedlings have different strategies to respond to watering treatments which reflect the distribution and likely inundation regime experienced by the species (2.4).
- Constant inundation suppresses seedling growth, but may not lead to mortality (2.4).
- Inter-flood dry periods are important for seedling growth, particularly development of roots which are vital for anchorage, stability, access to groundwater and the ability to tolerate dry periods (2.4).
- Coolibah and black box seedlings are sensitive to the timing of floods relative to their age, with both species performing better under a later flood as opposed to an earlier flood (2.4).

Wetland and floodplain plants and communities are critical components of both aquatic and terrestrial ecosystems, supplying energy to support food webs, providing habitat and dispersal corridors for animals and birds, and contributing to other ecosystems processes such as nutrient and carbon cycling, water and sediment oxygenation. They are also beautiful parts of our river landscapes with attributes that underpin ecological, cultural, recreational, aesthetic and economic values. The value of wetland and floodplain vegetation is reflected in the Basin-wide Environmental Watering Strategy which lists maintaining the extent and improving the condition of forests and woodlands, shrublands and non-woody vegetation as expected outcomes. The diversity of plants, vegetation communities and mosaics of communities in Murray-Darling Basin wetlands and floodplains is tremendous. These take a myriad of structural forms, from floating ferns to ancient trees. Environmental water managers may seek to achieve a range of vegetation outcomes that reflect the diversity of functions and values supported by wetland and floodplain vegetation.

For managers to achieve vegetation outcomes from environmental water a process of social, ecological and economic consideration is required. For example, i) stakeholder values need to be identified through consultation, ii) vegetation attributes that support these values need to be identified and used to set clear management objectives, iii) the appropriate management action(s) to achieve objectives need to be identified. Identifying actions will require an understanding of the effects or predicted effects of flow on vegetation responses; and consideration of how non-flow drivers (e.g. climatic conditions, grazing, invasive species) influence predicted vegetation responses to the application of environmental water. Lastly, iv) the effectiveness of the selected suite of management actions needs to be considered in relation to water resource availability scenarios and prioritisation of management actions for other objectives.

As such, there is a need to clearly articulate the values that wetland-floodplain systems support, to improve predictive capacity based on an improved knowledge base and to provide rigorous evidence of the outcomes of environmental flows in achieving management goals and informing adaptive management.

The EWKR vegetation theme sought to:

1. Provide a framework and guiding principles to help define the process of '*what are we watering for and why?*' to help refine objectives, define function and value, and select indicators across a range of spatial and temporal scales, given the myriad of potential vegetation outcomes; and
2. Improve predictive capacity and the underlying knowledge base by determining drivers of responses to watering actions, for:
  - a. Existing understory communities
  - b. Seed bank diversity
  - c. Woody seedling establishment
  - d. Lignum structure

The EWKR vegetation theme shows that there is incredible variation in local plant communities and associated seed banks in space and time. This is even though many wetland and floodplain species have wide distributions, are largely cosmopolitan species and are rarely considered endemic. The vegetation theme looked at what causes this variation and how to predict it, and we are beginning to be able to determine community assembly rules. We're starting to be able to: i) identify what the significant drivers are; ii) determine their relative importance; and iii) understand their interactions.

Location is overwhelmingly the most important predictor of local community composition, followed by recent flow conditions (e.g. preceding three months). After location and recent flow, the story becomes more complicated and interactions between factors play a role. For example, if a wetland has been dry over the medium term (3-10 years), then vegetation structure appears to be a key predictor of wetland community. In contrast, if a wetland has been wet over the medium term then the medium to long term flow regime becomes a key predictor of wetland community. Balancing wet-dry regimes is important for maximising abundance in wetland systems such as herb-fields.

By understanding what the significant drivers are, their relative importance and how they interact, we are improving our capacity to predict expected outcomes to environmental watering events and can use those predictions to help plan or prioritise watering actions.

Seedling establishment is a vulnerable stage for floodplain trees and understanding their specific watering requirements is important for the long-term survival of the species. The three eucalypt species displayed different growth strategies in response to the watering treatments. Understanding the likely mechanisms behind these strategies enables better predictions of outcomes and more targeted watering regimes. Other key outcomes include:

- i) constant inundation suppresses seedling growth in river red gum, black box and coolibah seedlings;
- ii) inter-flood dry periods are important for seedling growth, particularly the development of roots which are vital for anchorage and stability, access to groundwater and the ability to tolerate dry periods;
- iii) coolibah and black box are likely to be more sensitive to the timing of floods relative to their age, with seedlings from both species performing better under a later flood as opposed to an earlier flood.

Maintaining lignum with structural qualities to support processes such as waterbird recruitment is likely to require flow regime characteristics, including flood-return-frequency in the range of 1 flow in every 1 – 3 years. There is a strong association between lignum clump size and flood inundation category, with lignum clump size (volume) greatest in the most frequently inundated categories.

# 1 Vegetation Theme: Introduction

Wetland and floodplain vegetation communities have a high intrinsic value and play a critical role in supporting a wide range of ecosystem functions, services and human values (Capon et al. 2013, Capon and Pettit 2018). Wetland and floodplain plants are critical components of both aquatic and terrestrial ecosystems through the supply of energy to support food webs, provision of habitat and dispersal corridors for fauna (Boulton and Brock 1999, Bornette and Puijalon 2011), and contribution to other ecosystem services such as nutrient and carbon cycling, riverbank stabilisation and water and sediment oxygenation (Boulton and Brock 1999, Aldridge and Ganf 2003, Brookes et al. 2005, Baldwin et al. 2013). Wetland and floodplain vegetation also support aesthetic and other social values, such as the provision of shade in important recreational sites. Many plants also have significant cultural value such as the use of sedge species for basket weaving (Clarke 2012).

Throughout the world, changes to flow regimes resulting from river regulation, water extraction and other human activities (e.g. land clearing) have compromised many of these values (Davidson 2014, Kuiper et al. 2014, Kingsford et al. 2015, Reis et al. 2017), leading to widespread efforts to restore floodplain and wetland vegetation through the delivery of environmental flows (Arthington 2012). Management of environmental water, however, is complex and presents many challenges (Harris and Heathwaite 2012, Bond et al. 2014).

For managers to achieve vegetation outcomes from environmental water requires a process of social, ecological and economic consideration. For example, i) stakeholder values need to be identified through consultation, ii) vegetation condition attributes that support these values need to be identified and used to set clear management objectives, iii) the appropriate management action(s) to achieve objectives need to be identified. Identifying actions will require an understanding of the effects or predicted effects of flow on vegetation responses; and consideration of how non-flow drivers (e.g. climatic conditions, grazing, invasive species) influence predicted vegetation responses to the application of environmental water. Lastly, iv) the effectiveness of the selected suite of management actions needs to be considered in relation to water resource availability scenarios and prioritisation of management actions for other objectives.

As such, there is a need to clearly articulate the values that wetland systems support, to improve predictive capacity and to provide rigorous evidence of the outcomes of environmental flows in achieving management goals and informing adaptive management.

It is within this context that we designed our EWKR research program for the Vegetation Theme, with a focus on informing Basin-scale management. Due to other work that was underway at the time assessing the condition of long-lived woody vegetation (e.g. MDBA Basin-scale Stand Condition Model) we chose to focus our research efforts on non-woody vegetation and recruitment of long-lived woody vegetation.

## *Non-woody vegetation*

Non-woody wetland and floodplain vegetation encompasses a variety of vegetation types, from submerged macrophytes to flow responsive herbs, grasses, sedges and rushes and tall reed beds. The water requirements of these diverse vegetation species and communities differ (Roberts and Marston 2011, Rogers and Ralph 2010), their functional values differ, and their key attributes differ (e.g. species diversity, structural complexity, cover). There was also emerging evidence of spatially distinct vegetation communities despite similar watering histories (LTIM and TLM data). This diversity and complexity present challenges when trying to make predictions or assess outcomes for non-woody vegetation, particularly at a Basin-scale.

To help inform evaluation and predictive processes for non-woody vegetation we wanted to provide some context and structure around the types of vegetation responses that occur across different vegetation traits (e.g. compositional, structural and process), levels of ecological organisation (e.g. species, community, vegscape), and spatial and temporal scales. Using consistent methods, we also wanted to test the spatial diversity of responses (both extant and seed bank) at a Basin-scale, at sites with similar influence of flooding history (flood-return-frequency) and similar broad vegetation structure (non-woody wetlands, inland shrubland, inland woodland). In addition, we wanted to draw on the wealth of existing data to

explore relationships between non-woody vegetation responses and environmental factors such as flow and climate variables.

### *Recruitment of long-lived woody vegetation*

Long-lived woody vegetation such as river red gum (*Eucalyptus camaldulensis* Dehnh.), black box (*Eucalyptus largiflorens* F.Muell.), coolibah (*Eucalyptus coolabah* Blakely & Jacobs) and lignum (*Duma florulenta* Meissner) are key structural components across the Basin and their importance is reflected in objectives in the Basin-wide Environmental Watering Strategy (MDBA 2014). Mature woody plants of these species can withstand varying degrees of stress associated with both floods and drought, through a wide range of physiological and morphological traits (Capon et al. 2016). Seedlings of these woody species, however, are considerably more vulnerable to the stresses associated with floods and droughts than their mature counterparts due to their smaller stature (Cooper et al. 1999; Gindaba et al. 2004). Seedling establishment, rather than seed supply or germination, is widely perceived to be the critical bottleneck determining population structure of floodplain tree species in arid and semi-arid regions (Streng et al. 1989; Hughes 1990; Cooper et al. 1999; Horton and Clark 2001; George et al. 2005; Maxwell et al. 2016).

We wanted to better understand the relationships between seedling establishment of long-lived woody species and hydrological conditions through controlled mesocosm experiments. We also took the opportunity to record the occurrence of woody seedlings in the field to assess relationships with flood-return frequency and vegetation structure.

### *Research program*

The overarching research question for the Vegetation Theme was: What are the drivers of sustainable populations and diverse communities of water-dependent vegetation?

This high-level aim was applied to two priority research topics:

1. **Diversity** of non-woody (understory and wetland) plants.
2. **Recruitment** of long-lived woody vegetation (river red gum (*Eucalyptus camaldulensis* Dehnh.), black box (*Eucalyptus largiflorens* F.Muell.), coolibah (*Eucalyptus coolabah* Blakely & Jacobs) and lignum (*Duma florulenta* Meissner)).

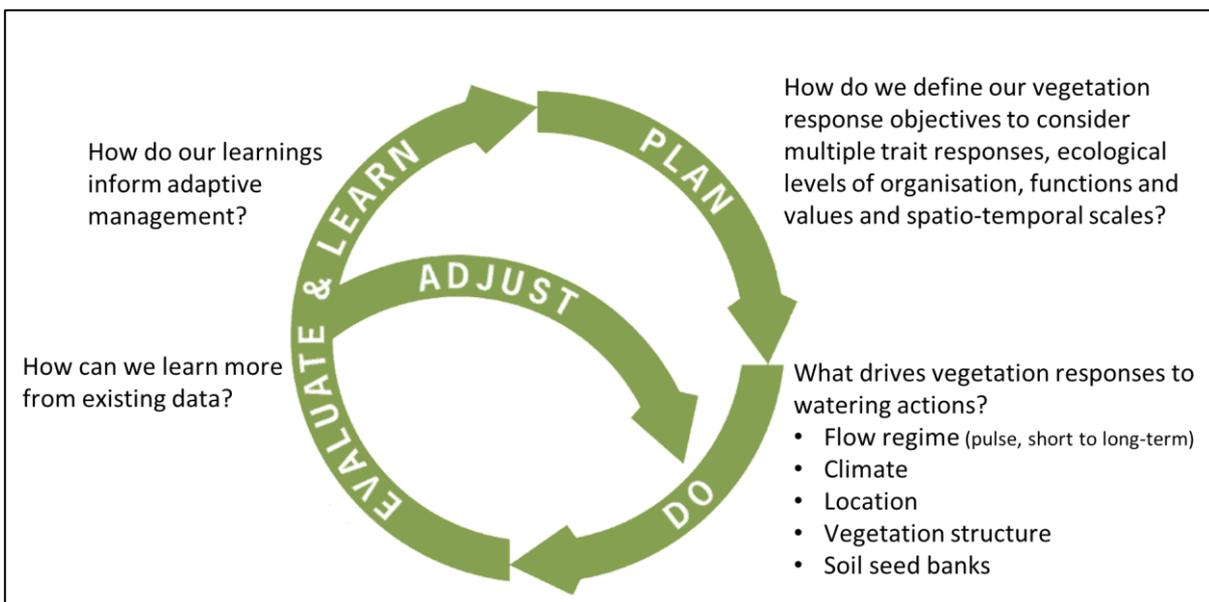
The theme undertook four research components, supported by planning and coordination activities, to address the research topics and aims:

- V1: Conceptualisation
  - How do we define vegetation response objectives to consider multiple trait responses, ecological levels of organisation, functions and values, and spatio-temporal scales?
    - Framework and guiding principles to develop robust and defensible objectives and identify SMART indicators
- V2: Data integration and synthesis
  - What drives vegetation responses to watering actions?
  - How can we learn more from existing data?
    - Utilise existing long-term data sets to assess vegetation responses to flow
- V3: Field site assessments and germination trials
  - What drives vegetation responses to watering actions?
    - Assess the influence of location, flood-return-frequency and vegetation structure on extant understory communities and seed bank diversity
- V4: Seedling mesocosm experiments
  - What drives vegetation responses to watering actions?

- Improve the understanding of seedling establishment responses of three floodplain tree species to hydrological conditions
  - Theme planning, coordination and reporting
    - How do our learnings inform adaptive management?
      - Synthesise outcomes and learnings with respect to adaptive environmental water management

In line with the ‘one-project’ approach of MDB EWKR, the research components aim to complement each other with the theme planning, coordination and reporting bringing together outputs in a holistic way. To assist with theme synthesis and to relate our research outcomes to different aspects of environmental water management, we placed our research priorities and questions within an adaptive management cycle (Figure 1).

For further information about the research prioritisation process and background logic and rationale please refer to MDFRC (2016).



**Figure 1** MDB EWKR Vegetation Theme research questions aligned with the adaptive management cycle

## 2 Individual Research Activity Summaries

### 2.1 V1. Conceptualisation – Vegetation outcomes: what are we seeking and why?

#### 2.1.1 Research Question and Summary

The conceptualisation component sought to disentangle the question ‘what are we watering for and why?’ The term ‘water-dependent vegetation’ can mean many different. Over 800 plant species have been recorded in wetland and floodplain habitats across the Murray–Darling Basin (Campbell and Nielsen 2014), representing a range of life forms, from floating ferns to 600-year-old trees. Furthermore, these species combine to form a wide variety of distinctive communities and vegscapes which, in turn, provide a diversity of functions across multiple spatial and temporal scales. Human values associated with ‘water-dependent vegetation’ are also many and varied, depending on social, economic, cultural and political contexts. Given this complexity, we asked the question ‘*How do we define vegetation response objectives to consider multiple trait responses, ecological levels of organisation, functions and values and spatio-temporal scales?*’

In this component we sought to provide a framework and guiding principles to aid the development of objectives, indicators and management of water for vegetation outcomes. The framework is graphically represented in Figure 2. We propose four principles: i) alignment of vegetation management objectives, targets and indicators to broader ecological, socio-cultural and economic values; ii) the use of multiple scales and levels of ecological organisation; iii) temporal dynamics, the influence of nested flow regimes and long-term trajectories of change; and iv) non-flow modifying factors.

The framework and guiding principles encompass the diversity of vegetation responses at key levels of ecological organisation (individual, species, population, communities, landscape/vegcape), across multiple spatial scales and with respect to broad classes of trait response (i.e. compositional, structural, process). Our approach also clearly acknowledges the ecological, socio-cultural and economic functions and values associated with different vegetation responses, which typically drives the desire to protect regions or attributes, either explicitly or implicitly. The guiding principles also aim to incorporate an understanding of dynamics over time, including nested flow regime components and long-term trajectories of change, as well as the influence of non-flow drivers (Figure 2). We also provide a table of potential indicators relevant at these different hierarchical scales (see Appendix V1.1).

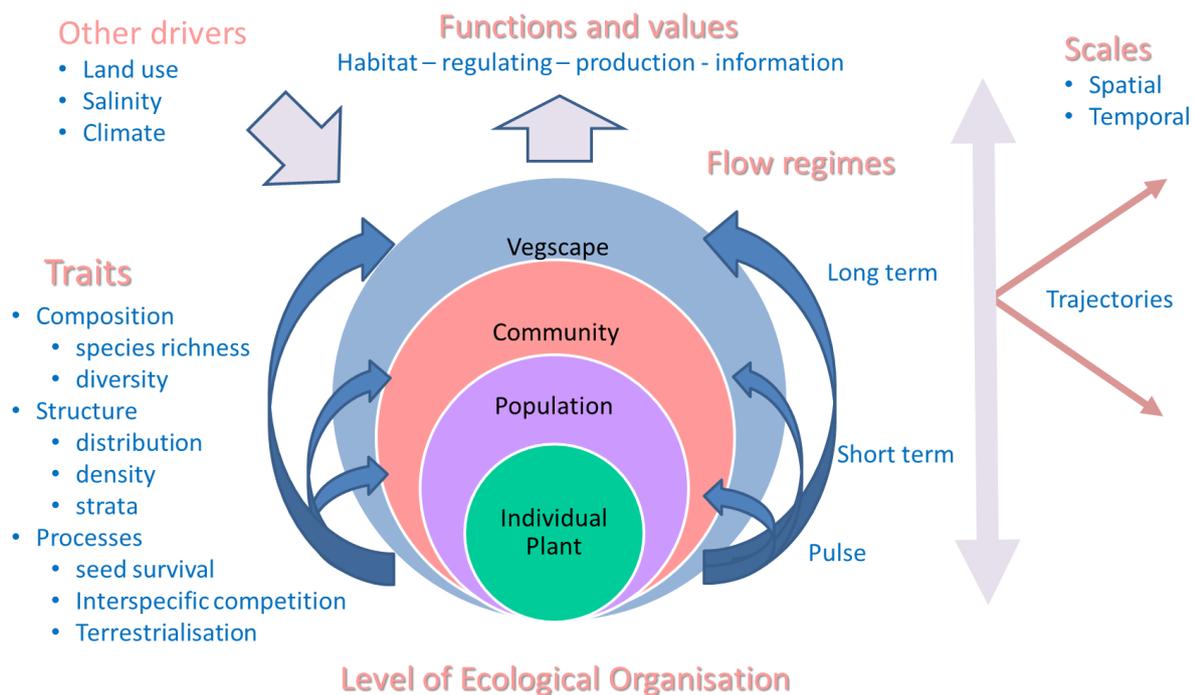
As part of setting management objectives and planning environmental watering actions for vegetation outcomes, values need to be identified (ideally through a process of stakeholder consultation) and expected outcomes needs to be articulated. Information to support these expected outcomes and evaluate success requires a level of detail that; helps identify relevant attributes (traits) and indicators to measure success; defines the spatial scale; identifies the relevant timeframe over which to assess outcomes; and considers influences such as recent to longer-term flow regimes and non-flow modifiers which are likely to affect expected outcomes. Water managers instinctively undertake this process. This framework provides the structure to aid and document this process – to prompt the consideration of factors such as flow regime, grazing and exotic species pressure; to consider the types of attributes which support the expected outcomes and values (e.g. richness and diversity, or height and cover, or flowering and seed viability); and to consider the relevant spatial (e.g. a localised population or a larger mosaic of communities within a wetland complex) and temporal scales (e.g. an immediate physiological response to the application of water, successional communities over a six-month flood recession and drying, or multi-year events to build resilience or support seedlings through to establishment).

For more information regarding the framework components refer to Appendices V1.1 to V1.4.

## 2.1.2 Water Management Application

The concepts within this component feed directly into the planning stages of environmental water decisions (see Figure 1) at a range of management scales. The framework provides the structure to support managers to identify: i) more explicit vegetation management objectives that are linked to values; ii) relevant response attributes / traits to inform the selection of appropriate indicators to monitor; iii) expected time frames for measurable responses of relevant attributes / traits to inform target setting; and iv) appropriate spatial scale for measuring response. Clearly defining the vegetation response objective has implications for the design of flow regimes to meet these objectives, developing monitoring / research programs to detect relevant responses and in evaluating the outcomes of the delivery of environmental water. The identification of five key components within the framework (Figure 2), aids in the discussion and documentation around the planning process for environmental water decisions.

The challenge now is to operationalise the framework and guiding principles and further develop them into useful decision support tools for water decision makers operating at a range of scales (e.g. local, regional, State-based, Basin-scale). There is a range of research and consultation which could help inform this process. In particular, we suggest: i) a workshop to test the utility of the framework with a diversity of water decision makers; ii) a review of existing processes to ‘scale-up’ information from plot to landscape scales from other disciplines; iii) development of a consistent classification systems for non-woody vegetation at a range of levels of ecological organisation; iv) research to better understand relationships between vegetation responses and the functions and values these support; v) better alignment or development of response indicators for different vegetation trait responses at different levels of ecological organisation and different spatial and temporal scales; vi) development of improved predictive capacity around response indicators, flow regimes and non-flow drivers.



**Figure 2** Vegetation response framework, incorporating five key components: 1) different levels of ecological organisation; 2) different trait responses at each of the levels of organisation; 3) ecological, socio-cultural and economic functions and values of different vegetation responses; 4) temporal dynamics including the influence of nested flow regimes on long-term trajectories of change; and 5) modifying effect of non-flow drivers.

### 2.1.3 Research Outcomes

Environmental water managers may seek to achieve a range of vegetation outcomes that reflects the diversity of functions and values supported by wetland and floodplain vegetation. To evaluate the success of environmental water decisions, there needs to be clear articulation of the expected outcomes. This articulation needs to simplify the vast array of potential outcomes in a structured way that captures the value or function of that outcome – ‘what are we watering for and why?’.

In this research component we propose four principles to guide the development of robust objectives and evaluation approaches for the adaptive management of environmental flows with respect to vegetation outcomes: i) alignment of vegetation management objectives, targets and indicators to broader ecological, socio-cultural and economic values; ii) multiple scales and levels of ecological organisation; iii) temporal dynamics, the influence of nested flow regimes and long-term trajectories of change; and iv) non-flow modifying factors. These principals are graphically represented as five key components – our framework (Figure 2): 1) different levels of ecological organisation (individual, species, population, community, landscape/vegscapes); 2) different trait responses at each of the levels of organisation (e.g. compositional, structural, process); 3) ecological, socio-cultural and economic functions and values of different vegetation responses (e.g. habitat, regulating, production or information functions and values); 4) temporal dynamics including the influence of nested flow regimes on long-term trajectories of change (e.g. the recent flow regime pulse, short-term and longer-term regimes); and 5) modifying effect of non-flow drivers (e.g. land use, salinity, climate, invasive species).

This research has identified key principles and components to guide the development of robust objectives and evaluation approaches for the adaptive management of environmental flows with respect to vegetation outcomes. Other outputs (e.g. Appendices V1.1 to V1.4) provide more detail around each of the principles and components. Further research could provide case-study examples and define relationships between specific vegetation outcomes and their associated function, value, spatial and temporal scales of relevance and key flow and non-flow drivers.

This research component is conceptual and provides guidance to inform existing processes, such as discussions and documentation around planning for environmental water decisions.

- *What are we watering for and why?* We provide structure to help refine objectives, define function and value, and select indicators across a range of spatial and temporal scales.

Four individual research outputs were produced as part of this component and are provided in Appendices V1.1 to V1.4:

- Paper: Campbell et al. (submitted), Blue, green and in-between; setting objectives for and evaluating wetland vegetation responses to environmental flows. (Appendix V1.1)
- Conceptualisation Research Activity Report (Appendix V1.2)
- Presentation: Campbell et al. 2016. Vegetation outcomes: what are we seeking and why? Australian Society of Limnology Conference, Ballarat, 27<sup>th</sup> September 2016 (Appendix V1.3)
- Article: Grow with the flow, RipRap V40, 2017, pp 16-18, Australian River Restoration Centre, Canberra (Appendix V1.4)

## 2.2 V2. Data integration and synthesis

### 2.2.1 Research Question and Summary

The Data integration and synthesis component (DISC) addressed two of the broad EWKR research questions:

- What drives vegetation responses to watering actions?
  - With a focus on non-woody vegetation, flow regimes and climate
- How can we learn more from existing data?

The aim of this component was to utilise existing long-term data sets to assess vegetation responses to flow. Long-term monitoring of wetland and floodplain complexes provides an opportunity to look at how vegetation responses relate to hydrological regimes across longer time frames and to interrogate the influences of precursor condition and historical legacies on these responses. This work relates to predicting expected outcomes to environmental watering events and using those predictions to help plan or prioritise watering actions. This component comprised several related phases: i) workshop and initial consideration of potential datasets and approaches; ii) collation and exploration of accessible data and iii) development of vegetation response models.

This component summary focuses on the outcomes of the vegetation response model. For details of the other component phases refer to Appendices V2.1 to V2.2. A key outcome of the initial exploration of data (Appendix V2.2) from multiple wetland complexes was the influence of location – a finding supported by research in component V3 Field site assessments and germination trials.

To develop vegetation response models, we explored the influence of hydrological and climatic conditions on the contrasting wet and dry floristic components of temporary semi-arid wetlands using understory plant species data collected from Hattah Lakes as part of The Living Murray program. We used the plant functional groups of Brock and Casanova (1997), to categorize species as wetland species and dryland species. A temporal hierarchy of antecedent conditions was considered from relatively recent (3 months), short term (4 months to 12 months) and medium term (1 year to 3 years) to longer term (30-year flood frequency). We investigated the relative importance of hydrological and climate variables on four wetland vegetation response metrics: i) native wetland plant species richness; ii) native wetland plant species abundance; iii) native dryland plant species richness; and iv) native dryland plant species abundance.

The wetland response model found several hydrological indicators influenced the richness and abundance of inundation tolerant species. These were found to be: i) water depth, which had a negative effect on richness and abundance for both three month and three-year timeframes; ii) time-since-last inundation, which demonstrated a non-linear relationship with abundance; and iii) proportion time wet, with abundance maximised when plots were dry ~50% of the year. Recent to medium-term flow regimes were the most important in terms of explaining wetland vegetation responses.

The main drivers affecting dryland plant richness and abundance were: i) recent inundation (mean depth and proportion time wet in the last three months) and ii) time-since last inundation, which again demonstrated a non-linear relationship. The recent regime was the most important in terms of explaining dryland vegetation responses.

For detailed methods and results, refer to Appendices V2.1 and V2.2.

This component also highlighted several the challenges associated with long-term data sets and the collation of datasets with different survey methods (see also Appendix V2.2).

### 2.2.2 Water Management Application

Response model outcomes provide additional evidence for the key drivers and timeframes for non-woody vegetation responses. This in turn helps to explain current vegetation conditions or helps to predict responses to regimes. Recent (last three months) and short to medium-term (last three years) regimes have

the strongest influence on non-woody wetland vegetation richness and abundance while longer term regimes are likely to have more of an interactive effect. Time-since-last inundation has a non-linear (hump-shaped) relationship with abundance, indicating that abundance is maximised at an intermediate point; wetland plant abundance increases as water recedes (as time-since-last inundation increases); and as soil moisture decreases however, there comes a point when maximum abundance is reached, and abundance then decreases with increasing time-since-last inundation. For data modelled from Hattah Lakes, abundance was maximised when plots were dry approximately 50% of the time. In a nutshell, the results support the need to maintain wet-dry regimes in semi-arid wetland systems.

While the model has been developed using understory data from wetland habitats at Hattah Lakes, there is good potential to test the transferability of the relationships identified here with other datasets. These may include data from other habitats at Hattah Lakes (e.g. floodplain understory data), from other locations using the same sampling methods (e.g. Lindsay-Mulcra-Wallpolla Islands and Chowilla Floodplain), or other location based or combined data sets (e.g. TLM icon sites, LTIM, EWKR field data). There is also the potential to test other defined vegetation responses, e.g. response metrics based on classifications such as life-form, life-history or functional group.

This component also provided many learnings related to the analysis of existing data. In particular, we determined that to obtain more knowledge from existing vegetation datasets, there is an urgent need for: i) available and easily accessible complementary data, such as hydrology and mapping of inundation patterns, ii) good data management processes to enable access to data in comparable formats, and iii) analytical expertise and accepted methods for the analysis of data from different sources (with different survey methods and sampling effort). It is also worth noting that future projects seeking to analyse existing data would benefit from factoring in the potentially considerable amount of time required to source and clean data, transform and collate data (from potentially quite different original formats), consistently align metrics (e.g. plant species names, units, trait classifications) and quality check data.

### 2.2.3 Research Outcomes

This component has improved predictive capacity and the underlying knowledge base by helping to determine drivers of responses to watering actions for understory communities.

- Understory vegetation outcomes are diverse, both spatially and over time. A diversity of responses (heterogeneity) is a Basin-scale outcome. Outcomes should be planned to encompass this diversity and assessed over time.
- Variability in vegetation responses are predicted to arise as a result of differences in location, recent flow conditions (e.g. water depth, time-since-last inundation, proportion time wet), vegetation structure, and medium to long term flow regimes.

A series of research outputs were produced at different stages of this component. A list of these outputs is provided below and, where practical, copies are provided in Appendices V2.1 to V2.2. Please also see Appendix V5.1, Theme data inventory.

- Workshop and meta-data collation: Internal workshop notes (including copies of presentations) and database of potentially available vegetation datasets
- Hattah Lakes Inundation Model validation: Worked with Andrew Keogh (MDBA) to incorporate on-ground observations of inundation into the hydrodynamic model for Hattah Lakes
- Dataset 1: Combined TLM understory data (See Appendix V5.1, Theme data inventory)
- Dataset 2: Hattah Lakes understory wetland data (See Appendix V5.1, Theme data inventory)
- Paper: James et al. (draft). *Disentangling flow-vegetation relationships and antecedent legacies to inform environmental flows* (Appendix V2.1)
- Model: Vegetation response model which can be applied to different datasets
- Data integration and synthesis research activity report (Appendix V2.2)

## 2.3 V3. Field site assessments and germination trials

### 2.3.1 Research Question and Summary

Understanding factors that structure plant assemblages is not only a key goal of ecology but is critical to informing sound conservation planning and management. Wetland and floodplain vegetation assemblages are strongly influenced by water regimes. In response to reduced water availability, environmental water is used to complement components of the natural water regime. A better understanding of how components of the water regime influence and interact with other factors to structure plant assemblages will help inform water management.

The field site vegetation assessments and germination trials conducted in EWKR addressed the broad research question '*What drives vegetation responses to watering actions?*' This study assessed the influence of regional location, flood-return-frequency and woody vegetation structure on extant and soil seed bank vegetation assemblages, lignum structure and woody seedling recruitment. There was emerging evidence to suggest location is a key driver of vegetation assemblages (LTIM and TLM data). The influence of location has important implications for the transferability of predications and prioritisation processes at the Basin-scale. Wetland vegetation is typically sensitive to hydrologic changes, and studies within wetlands have frequently found spatial patterns of seed bank species richness and density related to flood history (e.g. Holzel and Otte 2001, Capon and Brock 2006). Structural vegetation classes for this study were defined along an assumed canopy-cover gradient from none to low fringing cover in non-woody wetlands, to woody lignum cover in inland shrublands, to highest canopy cover in inland woodlands. The presence of overstory or perennial shrubs can influence extant vegetation, seed banks and woody recruitment through a variety of physical and chemical pathways that can be both positive and negative. These pathways include: competition for resources (water and nutrients), light availability / shading, climate regulation (canopy cover reduces air temperature and both canopy and litter reduces soil temperature), protection from grazing (e.g. lignum (James et al., 2015)) and eucalypt leaf litter potentially providing both physical and chemical barriers to germination (May and Ash, 1990; Moradshahi et al., 2003; Sasikumar et al., 2002). Due to the influence of the existing canopy, recruitment may not always occur in woodland environments and may occur in neighbouring open patches.

A total of 180 sites were surveyed: four geographical regions (Mid-Murray, Lower-Murray, Macquarie Marshes and Narran Lakes) of the Murray-Darling Basin (MDB), three flood intervals (near annual, 1.5-3 years, 3-5 years and 5-10 years) and three vegetation structural types (non-woody, inland shrublands and inland woodlands). Sites were surveyed on two occasions, in autumn 2017 and 2018. The hydrological phase of each wetland at the time of survey (e.g. inundated, flow recession, dry) varied between the wetlands.

To explore the potential diversity within each site we germinated soil collected from field sites under both damp and submerged treatments for six months. We then assessed how extant understory communities and seed bank diversity differ between location, flood-return-frequency and vegetation structure.

To address our overarching research priorities for both non-woody wetland vegetation, as well as woody seedling recruitment, we looked at the responses of these aspects separately. Due to the structural importance of lignum to processes such as waterbird breeding, we also looked specifically at the structural response of lignum.

Woody seedlings were found to be sparse, patchily distributed across sites and variable in abundance among sites and between surveys. In 2017 and 2018, seedlings (<1.3m) were recorded at 24 – 29% of sites, ranging from a single individual to hundreds of seedlings. The patchy occurrence and variability in density can make it difficult to link a response in seedling density to changes in the environment, which are also variable in space and time. Consequently, there is no clear relationship with flood history, indicating we have a limited understanding of the full suite of conditions required to support seedling recruitment. This finding is supported by other research on floodplain eucalypt seedlings (Nerissa Haby, pers comm, unpublished data), and is likely to reflect, among other things, a limited understanding of the interactive

effect of other environmental conditions (e.g. grazing pressure, competition, shading etc.) and the need for surveys targeting seedling recruitment.

There is no resident soil seed bank for floodplain eucalypts and, while unknown, it is considered unlikely that river cooba forms persistent seed banks (Roberts and Marston 2011). This was supported by the very minimal number of seedlings recorded in seed bank germination trials (in total one river cooba seedling and four river red gum seedlings were recorded across all 180 sites).

There were notable differences between the structure of lignum across the Lower Murray, Macquarie Marshes and Narran Lakes (N.B. lignum isn't a significant component of the vegetation in the Mid-Murray). The majority of lignum recorded at the Lower Murray is relatively small and sparse (in terms of volume as determined from measurements of height and width). Conversely, there are very large clumps of lignum at both the Macquarie Marshes and Narran Lakes, with more than 50 individual clumps  $\geq 3\text{m}$  high, with the largest individual clump at Narran Lakes recorded as 4m high and 20m wide! There is a strong association between lignum clump size and flood inundation category, with lignum clump size (volume) greatest in the most frequently inundated categories (near annual to 1 in every 1.5-3 years).

In terms of the non-woody vegetation response, there was an overwhelming influence of location on both the extant vegetation and seed bank communities, with each of the four locations having quite distinct assemblages. Within each location, there were also different influences on the understory vegetation response. For example, there was a strong relationship with flood frequency and the composition of soil seed bank communities at the Macquarie Marshes, a moderate relationship at the Mid Murray and only weak relationships at Narran Lakes and the Lower Murray. In relation to vegetation structure and soil seed bank communities, there were strong relationships at Narran Lakes and the Mid Murray but only weak relationships at the Macquarie Marshes and Lower Murray.

For detailed methods and results please refer to Appendices V3.1 to V3.4.

### **2.3.2 Water Management Application**

Outcomes from this component inform how environmental watering events might be undertaken, including considerations such as what are the key components of the flow regime or how should non-flow drivers be considered to achieve target responses. These outcomes can be used to better predict responses to environmental watering events and use those predictions to help plan or prioritise watering actions.

Given the variability in woody seedling responses, specific, targeted surveys, including in neighbouring open patches, need to be undertaken where seedling recruitment is a key response outcome. No clear relationship with flood history suggests that other drivers are influential. Consideration should then be given to what might be limiting the success of recruitment, such as soil moisture and grazing pressure, as well as the extent of flowering and seed viability, and germination cues.

Maintaining lignum with structural qualities to support processes such as waterbird breeding and fledging is likely to require flow regime characteristics, including flood-return-frequency in the range of 1 flow in every 1 – 3 years. Further analysis of lignum structural responses with inundation mapping and additional hydrology metrics, such as depth and duration, will aid refinement of the characteristics required. Further consideration of where these flow characteristics do not support desirable structural qualities (such as certain sites within the Lower Murray) will help to identify potential non-flow drivers limiting responses.

The overwhelming influence of location highlights the diversity of understorey communities in space and time at a landscape scale. This has implications for water management decisions in terms of prioritising areas for inundation to maximise the potential diversity at a Basin-scale. There will inevitably still be trade-off questions that arise in long-term planning such as should we maximise the extent of inundation to potentially maximise diversity spatially or should we build up resilience and temporal diversity at a more limited suite of locations? Basin-scale management should aim to be equitable and representative of many vegetation types in a range of areas over time (cumulative spatial representativeness across multiple years), while retaining the flexibility to build resilience and temporal diversity at identified locations (targeted, multi-year watering's). The key is to balance outcomes over time.

### 2.3.3 Research Outcomes

This component has improved predictive capacity and the underlying knowledge base by helping to determine drivers of responses to watering actions, for: i) understory communities; ii) seed bank diversity; iii) woody seedling establishment; and iv) lignum structure. This component assessed the influence of regional location, flood-return-frequency and woody vegetation structure on extant and soil seed bank vegetation assemblages, lignum structure and woody seedling recruitment.

- Understory vegetation outcomes are diverse, both spatially and over time. A diversity of responses (heterogeneity) is a Basin-scale outcome. Outcomes should be planned and assessed over time.
- Variability in vegetation responses are predicted to arise as a result of differences in location, recent flow conditions, vegetation structure, and medium to long term flow regimes.
- Watering lignum annually to 1 in every 1.5 – 3 years assists in greatest clump size which supports waterbird recruitment.
- Woody recruitment is variable despite similarities in vegetation type and flooding frequency.

Several research outputs were produced as part of this component. A list of these outputs is provided below and, where practical, copies are provided in Appendices V3.1 to V3.5. Please also see Appendix V5.1, Theme data inventory.

- Methods and site selection: Field Assessment Experimental Design report (Appendix V3.1)
- Dataset 1: Extant field site assessment (See Appendix V5.1, Theme data inventory)
- Dataset 2: Seed bank germination trials (See Appendix V5.1, Theme data inventory)
- Presentation: Campbell et al 2018. *From the four corners of the Basin: assessing vegetation responses to flow regimes*. Ecological Society of Australia conference, Brisbane, 25-29 November 2018. (Appendix V3.2)
- Paper: Campbell et al (draft). *Vulnerability of resilient systems to the Anthropocene* (target journal Global Change Biology) (Appendix V3.3)
- Field site assessment and germination trials Research Activity Report (Appendix V3.4)

## 2.4 V4. Seedling mesocosm experiments

### 2.4.1 Research Question and Summary

Seedling establishment is a vulnerable stage for floodplain trees and is a well-known bottle-neck to the spatial and temporal dynamics of woody floodplain species. Watering requirements for seedling establishment are different to adult trees, largely due to their initial reliance on soil water availability from the unsaturated zone of the soil profile (until roots establish and access groundwater). One of the key vulnerabilities facing floodplain tree seedlings is the influence of flooding. Flooding is important for the establishment of seedlings because it creates moist soil conditions suitable for germination, alleviates moisture stress, extirpates potential competitors and promotes seedling growth. Flooding, however, may also cause stress. Flooding can restrict access to atmospheric carbon dioxide (CO<sub>2</sub>) and oxygen causing anoxic soil conditions and depleted soil biota. While some species are adapted to survive periods of flooding by elongating leaves and/or stems to maintain an emergent canopy above the waterline, and/or increasing biomass allocation to adventitious roots, other species are less adapted or incapable of adjusting growth, which will likely result in seedling mortality.

This component addressed the question '*What drives vegetation responses to watering actions?*', with a focus on the response of woody floodplain seedlings. Specifically, this research sought to improve the understanding of flow requirements for seedling establishment, including an understanding of whether responses varied with seedling age. Three floodplain tree species were examined including river red gum (*Eucalyptus camaldulensis*), black box (*Eucalyptus largiflorens*) and coolibah (*Eucalyptus coolabah*). Five watering treatments were applied reflecting different intra-annual flow regimes: i) constant dry, ii) constant wet, iii) an early wet, iv) a late wet and v) multiple wet events.

We measured individual trait responses such as seedling height, root length and biomass. Some traits, such as height, demonstrated a strong species effect, with river red gum seedlings consistently growing taller than black box and coolibah respectively under all watering treatments. Other traits, such as root length, demonstrated a strong treatment effect, with root length being severely constrained in the constant wet treatment for all species. Other traits, such as leaf count, demonstrated an interaction, or species-specific effect. For example, black box responded to a few the watering treatments by developing large numbers of small leaves.

Collectively, responses of plants traits of each species indicate some broad differences in overall species' establishment strategies. Different strategies were observed for the three species, and these reflect the distribution and likely inundation regime experienced by the three species.

River red gum displayed an opportunistic strategy, capturing resources quickly. River red gum seedlings put on height quickly and produced a single dominant stem with few, larger leaves. River red gum seedlings have a greater likelihood of being flooded again soon; putting on height quickly is likely to be advantageous in terms of outcompeting other species, such as grasses, and surviving subsequent flooding.

Black box displayed a drought stress strategy. These seedlings produced a multi-stemmed branching structure with lots of small leaves (with a total leaf area like river red gum). Black box seedlings are most likely to experience drying stress. The multi-stemmed branching structure and small leaves may be adaptations that have been selected for by drought (e.g. maximise water use efficiency) and or grazing pressure.

Coolibah displayed a conservative strategy, with seedlings putting comparatively more effort into root length as opposed to height. This is likely to reflect the unpredictability of the floodplain environments that coolibah typically occurs in and their reliance on groundwater as adult trees, a finding of the Queensland floodplain vegetation component of EWKR (DSITI and DNRM 2017).

While the three species displayed different growth strategies, there were also several common responses:

- Constant inundation suppresses seedling growth in all three species.
- Inter-flood dry periods are important for seedling growth, particularly the development of roots.

- Coolibah and black box are likely to be more sensitive to the timing of floods relative to their age, with both species performing better under a later flood as opposed to an earlier flood.

## 2.4.2 Water Management Application

The outcomes from this component directly relate to the management of water for seedling establishment of woody floodplain trees.

Understanding seedling establishment responses of different woody species, including their growth strategies, enables watering events to be targeted to traits associated with seedling establishment for species, such as root length or height.

While constant flooding suppresses growth, seedlings were observed to be very flood tolerant. Inundation will not always lead to mortality, particularly if the inundation depth is insufficient to overtop seedlings. If seedling encroachment is an issue and the control of seedlings (mortality) locations is a desirable management outcome, the implication is that flooding needs to occur very early in their life to improve the likelihood of mortality, especially if these seedlings have established in habitats where drying stress is likely to be lesser, e.g. lake beds, creeks etc.

Inter-flood dry periods were determined to be important for growth, particularly the development of roots, in all three species. Root length and biomass were significantly suppressed under constant flooding. While it is unclear what the long-term impacts may be on the development of tap roots, we hypothesise that prolonged waterlogged conditions during early seedling establishment may lead to suppression of long tap roots and greater development of surface roots. Well-developed tap roots are vital for access to groundwater as well as anchorage and stability as an adult tree. Consequently, seedlings establishing under prolonged waterlogged conditions may be less tolerant of subsequent drying.

Both black box and coolibah seedlings performed better under a later flood as opposed to an earlier flood. The implications for management are that if you're designing watering events for coolibah or black box establishment, then allow a dry period (of ~ 6 months) post germination before providing top up flows. This comes with the caveat that individual site conditions, such as soil type, soil moisture, temperature and rainfall will influence the need for flow up inundation.

## 2.4.3 Research Outcomes

This component has improved predictive capacity and the underlying knowledge base by helping to determine drivers of responses to watering actions, for woody seedling establishment.

- Eucalypt tree seedlings have different strategies to respond to watering treatments which reflect the distribution and likely inundation regime experienced by the species (2.4).
- Constant inundation suppresses seedling growth, but may not lead to mortality (2.4).
- Inter-flood dry periods are important for seedling growth, particularly development of roots which are vital for anchorage, stability, access to groundwater and the ability to tolerate dry periods (2.4).
- Coolibah and black box seedlings are sensitive to the timing of floods relative to their age, with both species performing better under a later flood as opposed to an earlier flood (2.4).

Several research outputs were produced as part of this component. A list of these outputs is provided below and, where practical, copies are provided in Appendices V4.1 to V4.6. Please also see Appendix V5.1, Theme data inventory.

- Literature review: Durant et al 2016. Recruitment of long-lived floodplain vegetation: literature report (Appendix V4.1).
- Methods document: Durant et al 2016. Recruitment of long-lived floodplain vegetation: mesocosm study experimental design (Appendix V4.2).

- Dataset: Seedling mesocosm experiments (See Appendix V5.1, Theme data inventory)
- StorySpace video, <http://ewkr.com.au/valiant-vegetation/>
- Presentation: Durant et al 2018. *Early, late or constant – what are long-lived woody floodplain seedlings looking for?* 58th Australian Freshwater Sciences Society Congress, Adelaide, 23-28 September 2018 (Appendix V4.3).
- Article: *Giving woody seedlings a fighting start*, RipRap V40, 2017, pp 19-20, Australian River Restoration Centre, Canberra (Appendix V4.4).
- Paper: Campbell et al (draft), *Contrasting establishment strategies amongst three dominant tree species of Australian floodplains* (Appendix V4.5).
- Seedling Mesocosm Research Activity Report (Appendix V4.6)

### 3 Theme Synthesis

What are the implications and ‘big picture’ outcomes that can be drawn together from all the research undertaken in the EWKR vegetation theme?

Returning to the adaptive management cycle and the EWKR research questions (Figure 1) we can consider how our findings can be used to inform adaptive water management and further research (Figure 3).



**Figure 3** MDB EWKR Vegetation Theme outcomes aligned with the adaptive management cycle

**Plan:** The framework (Figure 2, Appendices V1.2 to 1.4) and guiding principles (section 2.1, Appendix V1.1) help to address the question ‘*What are we watering for and why?*’ The concepts feed directly into the planning stages of environmental water decisions at a range of management scales. As part of setting management objectives and planning environmental watering actions for vegetation outcomes, values need to be identified (e.g. more large trees will provide habitat for animals) and expected outcomes needs to be articulated (e.g. a 20% increase in seedling recruitment).

Information to support the development of objectives and expected outcomes and to evaluate success requires a level of detail that; acknowledges the value of the outcome (from ecological function to cultural value); helps identify relevant attributes (traits) and indicators to measure success; defines the spatial scale; identifies the relevant temporal timeframe over which to assess outcomes; and considers influences such as recent to longer-term flow regimes and non-flow modifiers which are likely to affect expected outcomes. Water managers instinctively undertake this process. This framework provides the structure to aid and document this process – to prompt the consideration of factors such as grazing and exotic species pressure; to consider the types of attributes which support the expected outcomes and values (e.g. richness and diversity, or height and cover, or flowering and seed viability); and to consider the relevant spatial (e.g. a localised population or a larger mosaic of communities within a wetland complex) and temporal scales (e.g. an immediate physiological response to the application of water, successional communities over a six-month flood recession and drying, or multi-year events to build resilience or support seedlings through to establishment). Table 1 provides potential examples of vegetation management objectives and their associated function/value; ecological level of organisation (ELO) and relevant spatial scale; traits and indicators; potentially appropriate flow regimes; other potential drivers; and trajectories of change.

Other research in the EWKR vegetation theme (sections 2.2 to 2.4) sought to improve predictive capacity and the underlying knowledge base by determining drivers of responses to watering actions, for i) understory communities; ii) seed bank diversity, iii) woody seedling establishment and iv) lignum structure. By understanding what the significant drivers are, their relative importance and how they interact, we are

improving our capacity to predict expected outcomes to environmental watering events and can use those predictions to help plan or prioritise watering actions.

**Table 1 Potential application of the framework and guiding principles**

Objective	Function / Value	Ecological Level of Organisation (inc. spatial relevance)	Traits and indicators (inc. temporal relevance from watering event)	Flow regimes (inc. temporal relevance)	Other drivers and antecedent conditions	Trajectories
Maintain health of a culturally significant tree	Cultural significance	Individual plant Relevant spatial scale: local	Process – physiological responses to flow Structure – canopy Relevant indicators: new tip growth (weeks to months), water status (instant/ continuous), canopy extent and density (across years)	Flow pulse to short-term Relevant temporal scale: months to years, periodically reviewed based on tree health	e.g. fire, insect damage, surrounding land-use, long-term flow regime	Maintenance flows to maintain current health (assume current health is good or above) More frequent recovery flows (where seek to improve / restore condition)
Provision of lignum habitat to support waterbird recruitment	Provision of required structural attributes Support successful recruitment of waterbirds	Population Relevant spatial scale: landscape	Structure – clump size Process – viability, physiological responses to flow Relevant indicators: Height and width (across years), visual colour and viability (weeks to months, across years), leaf production (weeks to months), water status (instant/continuous) Would also want to monitor indicators of waterbird outcomes	Flow pulse (immediate response) to short-term (maintain vegetation attributes between recruitment events) Relevant temporal scale: months to years, periodically reviewed based on vegetation condition and recruitment success	e.g. grazing, salinity, access to groundwater and groundwater quality  Other drivers will also affect recruitment success, such as predation, food resources, disease, surrounding land-use	Based on current condition of lignum habitat Maintenance flows – maintain current condition Recovery flows – seek to improve / restore condition

N.B. Other drivers and antecedent conditions are likely to be site specific. Relevant spatial and temporal scales are not prescriptive and will relate to the scale of the watering action and the contiguousness of the vegetation. Indicators are examples only – the selection of indicators will need to include budgetary considerations.

**Do:** Multiple research components within the EWKR vegetation theme addressed the question ‘*What drives vegetation responses to watering actions?*’. We can consider our results in terms of the priority research topics: i) understory diversity, iii) recruitment of long-lived woody vegetation and ii) survival and condition of long-lived woody vegetation.

*Understorey:* Our data, and data from other projects such as LTIM and TLM, indicate there is incredible variation in local plant communities and seed banks in space and time. This is even though many wetland and floodplain species have wide distributions, are largely cosmopolitan species and are rarely considered endemic. As ecologists and water managers we’re trying to determine what causes this variation and to predict it. From our research in EWKR we are starting to be able to determine community assembly rules. We’re starting to be able to: i) identify what the significant filters are; ii) determine their relative importance; and iii) understand their interactions.

Location is overwhelmingly the most important predictor of local community composition, followed by recent flow conditions (e.g. preceding three months) in terms of determining community responses. After location and recent flow, the story becomes more complicated and interactions between factors play a role. For example, if a wetland has been dry over the medium term, around 3-10 years, then vegetation structure appears to be a key predictor of wetland community. In contrast, if a wetland has been wet over the medium term, around 3-10 years, then the medium to long term flow regime becomes a key predictor of wetland community.

By understanding what the significant filters are, their relative importance and how they interact, we are improving our capacity to predict expected outcomes to environmental watering events and can use those predictions to help plan or prioritise watering actions.

*Recruitment of long-lived woody vegetation:* Seedling establishment is a vulnerable stage for floodplain trees and understanding their specific watering requirements is important for the long-term survival of the species. Seedlings are often sparse and patchily distributed in the landscape, making it difficult to draw clear relationships between distribution and flow regime. So, in addition to collecting records of occurrence in the field, we also ran a mesocosm experiment looking at the effects of different watering treatments. The three eucalypt species displayed different growth strategies in response to the watering treatments. Understanding the likely mechanisms behind these strategies enables better predictions of outcomes and more targeted watering regimes. Other key outcomes include: i) constant inundation suppresses seedling growth in all three species; ii) inter-flood dry periods are important for seedling growth, particularly the development of roots which are vital for anchorage and stability, access to groundwater and the ability to tolerate dry periods; iii) coolibah and black box are likely to be more sensitive to the timing of floods relative to their age, with seedlings from both species performing better under a later flood as opposed to an earlier flood.

*Survival and condition of long-lived woody vegetation:* While this research topic wasn’t a main priority for the EWKR vegetation theme, data was collected around the structural condition of lignum. Maintaining lignum with structural qualities to support processes such as waterbird breeding and fledging is likely to require flow regime characteristics, including flood-return-frequency in the range of 1 flow in every 1 – 3 years. There is a strong association between lignum clump size and flood inundation category, with lignum clump size (volume) greatest in the most frequently inundated categories. Further analysis of lignum structural responses with inundation mapping and additional hydrology metrics, such as depth and duration, will aid refinement of the characteristics required.

**Evaluate:** In line with adaptive management principles we wanted to consider how lessons from EWKR could be incorporated into future research or monitoring, particularly in terms of comparing patterns at larger spatial and temporal scales. In particular, we determined that to obtain more knowledge from existing vegetation datasets, there is an urgent need for: i) available and easily accessible complementary data, such as hydrology and mapping of inundation patterns, ii) good data management processes to enable access to data in comparable formats, and iii) analytical expertise and accepted methods for the analysis of data from different sources (with different survey methods and sampling effort).

In a nutshell:

- To achieve vegetation outcomes from environmental water requires a process of social, ecological and economic consideration (1 and 2.1).
- *What are we watering for and why?* The framework will assist managers to refine objectives, define function and value, and select indicators across a range of spatial and temporal scales (2.1).
- We are starting to determine community assembly rules: i) identify what the significant filters are; ii) determine their relative importance; and iii) understand their interactions. By improving the underlying knowledge base we are improving our predictive capacity (2.2, 2.3, 2.4).
- Understorey vegetation outcomes are diverse, both spatially and over time. The response of plant communities to watering actions, vary from place to place leading to a diversity of outcomes from the same watering treatments spatially. Across the Basin, the variation in response to the same watering actions, leads to a diversity of vegscapes (2.2 and 2.3).
- Variability in vegetation responses are predicted to arise as a result of differences in location, recent (e.g. preceding three months) flow conditions (e.g. water depth, time-since-last inundation, proportion time wet), vegetation structure, and medium to long term flow regimes (2.2 and 2.3).
- Watering lignum once every 1 – 3 years assists in greatest clump size which supports waterbird recruitment (2.3).
- Woody recruitment is variable despite similarities in vegetation type and flooding frequency (2.3).
- Eucalypt tree seedlings have different strategies to respond to watering treatments which reflect the distribution and likely inundation regime experienced by the species (2.4).
- Constant inundation suppresses seedling growth, but may not lead to mortality (2.4).
- Inter-flood dry periods are important for seedling growth, particularly development of roots which are vital for anchorage, stability, access to groundwater and the ability to tolerate dry periods (2.4).
- Coolibah and black box seedlings are sensitive to the timing of floods relative to their age, with both species performing better under a later flood as opposed to an earlier flood (2.4).

## 4 Management relevance

Wetland and floodplain vegetation outcomes are influenced by flow as well as factors such as climatic conditions, grazing pressure and invasive species. The priority for and effectiveness of environmental flows will depend on Resource Availability Scenarios (Table 2). Impacts on vegetation condition and resilience are cumulative and the severity of risks under each of the Resource Availability Scenarios will depend on the sequence of scenarios in preceding years.

**Table 2 Potential vegetation outcomes, risks, key considerations and knowledge requirements under four different resource availability scenarios**

	Resource Availability Scenarios			
	Very dry	Dry	Moderate	Wet to Very Wet
<b>BWES Management objective</b>	Avoid irretrievable loss of or damage to, environmental assets	Ensure environmental assets maintain their basic functions and resilience	Maintain ecological health and resilience	Improve health and resilience of water dependent ecosystems
<b>Scale</b>	Site, reach	Site, reach, segment	Site, reach, segment, catchment	Site, reach, segment, catchment, basin
<b>Potential vegetation outcomes</b>	Limited wetland or river reach scale outcomes. Maintenance of a limited extent or number of local communities. Small-scale promotion of seed bank germination.  No or limited river floodplain connectivity, potential drying of all floodplain wetlands.	Maintenance of a limited extent or number of local communities. Small-scale promotion of seed bank germination.	Potential opportunities for dispersal and connections between habitats (e.g. river to wetlands, wetlands to floodplain). Opportunities to promote woody recruitment, if the resource availability scenario is likely to be maintained for multiple years.	Potential opportunities for ‘recovery’ flows (sequential flows across multiple years) to improve condition. Potential to inundate high elevation floodplain habitats. Opportunities for dispersal. Opportunities to promote connected ‘vegscapes’ (large, connected habitats)
<b>Risks</b>	Encroachment of invasive species (native and non-native)  Impacts of grazing pressure  Failure to complete life cycles and set seed (short-lived species)  Loss of condition (long-lived woody vegetation)  Loss of inundation-dependent macrophytes  Plant and seed bank death across successive very dry scenarios.	Encroachment of invasive species (native and non-native)  Impacts of grazing pressure  Failure to complete life cycles and set seed (short-lived species)  Loss of condition (long-lived woody vegetation)  Loss of inundation-dependent macrophytes	Dispersal of invasive species via hydrochory  Woody recruitment is promoted but can’t be sustained  For vegetation communities above the flood level the same risks as for the very dry and dry scenarios still apply.	Dispersal of invasive species via hydrochory  Prolonged duration and depth may lead to loss of condition or death (long-lived woody vegetation) Sediment deposition may bury macrophytes and seed banks  Increased grazing pressure as populations boom in response to available resources  For vegetation communities above the flood level the same risks as for the very dry and dry scenarios still apply.

Resource Availability Scenarios				
	Very dry	Dry	Moderate	Wet to Very Wet
<b>Key considerations</b>	Prioritise watering of critical habitat and refuges (^see note for definition) with reference to 'natural/optimal' flood frequency	Prioritise watering of critical habitat and refuges (^see note for definition) with reference to 'natural/optimal' flood frequency	Connections between habitat types (e.g. river to wetlands, wetlands to floodplain)	Ability to support lateral connectivity to high floodplain regions
	Evidence of altered processes (e.g. degree of deviation from altered flow regimes, woody encroachment)	Evidence of altered processes (e.g. degree of deviation from altered flow regimes, woody encroachment)	Timing of flows to link with or trigger key phenological events (e.g. flowering, seed set, seed fall)	Ability to create connected 'vegscapes'
	Inundation duration to enable completion of life-cycles (e.g. short-lived species and high temperature/evaporation)	Inundation duration to enable completion of life-cycles (e.g. short-lived species and high temperature/evaporation)	Timing of follow up flows to support woody recruitment	Flow-promoted movement of invasive species
	Condition of vegetation prior to inundation and feasibility of multi-year watering (e.g. commitment to deliver multiple events to very highly stressed woody vegetation, where only one event may cause additional shock/stress)	Condition of vegetation prior to inundation and feasibility of multi-year watering (e.g. commitment to deliver multiple events to very highly stressed woody vegetation, where only one event may cause additional shock/stress)		Upper tolerance limits of flow duration (long-lived woody vegetation)
	Extent of non-flow pressure (e.g. grazing, invasive species)	Extent of non-flow pressure (e.g. grazing, invasive species)		Impacts of extended duration (e.g. suppressed seedling root development)
<b>Knowledge requirements</b>	Location of critical habitats (^see note for definition) at landscape scales	Location of critical habitats (^see note for definition) at landscape scales	Relationship between phenology and flows for key species	Characteristics and attributes of key 'vegscapes'
	Characteristics and attributes of different critical habitat types	Characteristics and attributes of different critical habitat types	Hydraulic requirements for dispersal	Dispersal mechanisms of key invasive species
	Minimum durations for different habitat types	Minimum durations for different habitat types		Extent and impact of sediment deposition on extant macrophytes and seed bank communities
	Critical thresholds (minimum and maximum) for long-lived woody vegetation (including minimum thresholds where watering may have perverse or ineffective outcomes)	Critical thresholds (minimum and maximum) for long-lived woody vegetation (including minimum thresholds where watering may have perverse or ineffective outcomes)		Upper tolerance limits of flow duration (long-lived woody vegetation; known for some species)
	Interactive impact of non-flow pressures (e.g. grazing, invasive species)	Interactive impact of non-flow pressures (e.g. grazing, invasive species)		

^ Critical habitat and refuges for vegetation may include sites that support critical functions, sites of high cultural significance, sites (extant and seed banks) which support rare or threatened plants / communities / vegscapes or are representative of a unique vegetation type. Refining and clearly defining what is meant by critical habitat and refuges and a process for prioritising vegetation outcomes (in conjunction with other outcomes) for environmental watering is a knowledge gap.

## 5 Knowledge Status

Through our research we have identified several recommendations and considerations for future work. These are discussed under six different topics below.

### 1. Objectives and targets for non-woody vegetation:

While the conceptualisation component developed a framework and guiding principles to aid the development of objectives, indicators and management of water for vegetation outcomes, there are still challenges associated with operationalising the framework. Potential research includes:

- Workshop the utility of the framework with water managers
- Develop consistent classification systems for non-woody vegetation at a range of levels of ecological organisation
- Better alignment or development of response indicators for different vegetation trait responses at different levels of ecological organisation and different spatial and temporal scales
- Better understand relationships between function and value for different vegetation responses
- Develop decision support tools or evaluation processes to aid in the evaluation of successful outcomes for understory vegetation, particularly at the Basin-scale

### 2. Improve predictive capacity:

Dr Cassie James, along with the EWKR vegetation theme, has developed a vegetation response model to assess the main drivers affecting plant species richness and abundance. To date, this model has been developed for one habitat type (wetlands) at one location (Hattah Lakes). Initial work in this component, particularly through the workshop held in November 2015, identified many potential data sets and identified a strong willingness from data custodians to see this data further utilised. Further research could test the models transferability to other locations and to other response metrics, and hence determine the transferability of predicted outcomes and key drivers between different locations and situations:

- Where data is available define, develop and test different vegetation response metrics to incorporate structural and process responses or responses at difference levels of ecological organisation (e.g. seedling recruitment, strata, communities)
- Explore the development of environmental metrics (currently hydrological and climate) relevant to different spatial scales
- Explore the inclusion of additional environmental metrics (e.g. soil type, soil moisture, canopy cover/condition)
- Test the response model in different habitat types and different locations:
  - For example, floodplain understory data for Hattah Lakes
  - Data from other TLM icon sites, LTIM, and EWKR

The suitability of datasets may depend on the availability of good hydrological data at relatively fine scales.

Other considerations and lessons were highlighted throughout the DISC project. In relation to some of the lessons learnt from analysing existing data, there is a need for: i) available and easily accessible complementary data, such as hydrology and mapping of inundation patterns, ii) good data management processes to enable access to data in relatively consistent formats, and iii) analytical expertise and accepted methods for the analysis of data from different sources (with different survey methods and sampling effort). It is also worth factoring in the potentially considerable amount of time required to source data, transform and collate data (from potentially quite different original formats), consistently align metrics (e.g. plant species names, units, trait classifications) and quality check data.

### 3. Further determine community assembly rules

Data from the field and germination component highlighted the overwhelming influence of location on community composition. There are, however, other drivers within locations and within vegetation / flood inundation categories. Quite a lot of complementary data was collected in the field that has not been analysed in full (e.g. the potential influence of tree density and condition, site disturbance etc.) as well as data that would enable structural responses to be assessed (e.g. individual plant height data). Further analysis of the existing data would enable additional drivers of vegetation responses to be determined.

- Additional data analysis:
  - Determine relationships between response metrics and explanatory variables
  - Analyse according to different response metrics
    - Define, develop and analyse different vegetation response metrics to incorporate structural and process responses or responses at different levels of ecological organisation (e.g. seedling recruitment, strata, communities)

In the future, re-assessment of field sites, including soil seed banks, could be undertaken to collect additional vegetation response data to different environmental conditions, for example surveys in a different season or specifically following inundation.

4. Continue to understand trait and strategy responses of different species under different flow scenarios and the interactive effect of non-flow drivers:

The seedling mesocosm component investigated the trait and strategy responses of river red gum, black box and coolibah to different watering treatments. Valuable extensions to this work would include assessing the influence of non-flow drivers such as salinity (soil and groundwater), soil type, soil compaction and grazing.

Assessing the effect of seedling provenance would also be a valuable extension. In the current project, the same source of seed (commercially accessed) was used for each species. Repeating the experiment, with seed collected from different locations within the Murray-Darling Basin, would test the effect of seed provenance on seedling establishment and provide details of the variability of responses within species from different locations.

Understanding the trait and strategy responses for a range of wetland and floodplain plant species would assist the targeted delivery of water for the promotion or suppression of specific species. Experiments could be undertaken on a range of key species, including exotic species where an understanding of their trait and strategy responses may influence environmental water management decisions. Trait and strategy responses may include requirements for dispersal, relationships between phenology and flow, impacts of sediment deposition and critical thresholds to flow metrics such as duration.

5. Limits to resilience and key vulnerabilities (e.g. climate change)

Wetland and floodplain systems are known to be resilient, with wetland and floodplain plants demonstrating characteristics that enable them to persist in these 'boom and bust' environments. Throughout this project, however, there have been discussions regarding the limits to resilience and the ability of plant species to adapt to changes such as increased extreme events (e.g. temperature and rainfall). Research investigating limits to resilience and key vulnerabilities for plant species would improve our understanding of the likely risks and effects associated with aspects such as climate change. Understanding the effects and risks would inform the use of environmental water in potentially mitigating the impacts.

6. Basin-wide inundation mapping and hydrodynamic modelling

To accurately predict vegetation responses to flow regimes, adequate flow metrics at appropriate scales need to be available, such as modelled estimates of inundation depth and duration at plot scales for specific time periods (e.g. at time of sampling, 3 months prior, 1 year prior etc.). Continued and increased investment in Basin-wide inundation mapping and hydrodynamic / hydrology modelling would be very valuable.

7. Identification of critical habitat types

Inevitably, and particularly under very dry and dry water resource availability scenarios (refer Table 1), there needs to be a prioritisation process to select outcomes and sites for the delivery of environmental water. Protecting or prioritising critical habitat is often listed as a desirable outcome under very and dry water resource availability scenarios. However, under what criteria do we define 'critical habitats' and where do they exist? Critical habitat and refuges for vegetation may include sites that support critical functions, sites of high cultural significance, sites (extant and seed banks) which support rare or threatened plants / communities / vegscapes or are representative of a unique vegetation type. Refining and clearing defining what is meant by critical habitat and refuges and a process for prioritising vegetation outcomes (in conjunction with other outcomes) for environmental watering is a knowledge gap.

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## 7 List of appendices

- Appendix V1.1. Blue, green and in-between; setting objectives for and evaluating wetland vegetation responses to environmental flows
- Appendix V1.2 Conceptualisation Research Activity Report
- Appendix V1.3 Vegetation outcomes: what are we seeking and why?
- Appendix V1.4 Grow with the flow
- Appendix V2.1. Disentangling flow-vegetation relationships and legacy effects to inform environmental flows
- Appendix V2.2. Data Integration and Synthesis Research Activity Report
- Appendix V3.1. Field Assessment Experimental Design report
- Appendix V3.2. From the four corners of the Basin: assessing vegetation responses to flow regimes
- Appendix V3.3. Vulnerability of resilient systems to the Anthropocene
- Appendix V3.4. Field Site Assessment and Germination Trials Research Activity Report
- Appendix V4.1. Recruitment of long-lived floodplain vegetation: literature report
- Appendix V4.2. Recruitment of long-lived floodplain vegetation: mesocosm study experimental design
- Appendix V4.3. Early, late or constant – what are long-lived woody floodplain seedlings looking for?
- Appendix V4.4. Giving woody seedlings a fighting start
- Appendix V4.5. Contrasting establishment strategies amongst three dominant tree species of Australian desert floodplains
- Appendix V4.6. Seedling Mesocosm Research Activity Report
- Appendix V5.1. Vegetation Theme Data and Model Inventory
- Appendix V5.2. Vegetation Theme Outputs
- Appendix V5.3. Vegetation Theme Engagement and Communications activities
- Appendix V5.4. Vegetation Theme Final Presentation. Vegetation theme: predicting outcomes in response to flow and other drivers