The Living Murray Hattah Lakes Intervention Monitoring

Understorey Vegetation Program Annual Report

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Acknowledgment

We acknowledge and respect Victorian Traditional Owners as the original custodians of Victoria's land and waters, their unique ability to care for Country and deep spiritual connection to it. We honour Elders past and present whose knowledge and wisdom has ensured the continuation of culture and traditional practices.

We are committed to genuinely partner, and meaningfully engage, with Victoria's Traditional Owners and Aboriginal communities to support the protection of Country, the maintenance of spiritual and cultural practices and their broader aspirations in the 21st century and beyond.

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Front cover photo
Floodplain north-east of Lake Kramen, Lake Marramook and *Calostemma luteum* beside Lake Arawak (Dylan Osler (photo one (2020)), Sally Kenny (photos two (2014) and three (2020)).

Contents

Summary

Project Context
The Hattah Lakes floodplain has been severely degraded by Murray River regulation, drought and water extraction for agriculture, industry and urban use. The Living Murray (TLM) initiative is a river restoration program designed to improve the health of the Murray River and its floodplain through targeted environmental watering events. The Hattah Lakes Icon Site is one of six locations in the TLM program selected for its significant ecological, cultural, recreational, heritage and economic values. The overarching ecological objective is to 'restore a mosaic of healthy wetland and floodplain communities to maintain the ecological character of the Ramsar site'. In particular, increasing the abundance of water-dependent communities. Predicting and demonstrating the effectiveness of environmental watering to maintain ecosystem health is important, particularly in drying climates where there is often insufficient rainfall and flooding to maintain semi-arid floodplain ecosystems. Demonstrating conservation outcomes will aid in maintaining public support and help improve the success of management interventions.

Aim
This report provides an update on the seven-year TLM Intervention Monitoring Hattah Lakes understorey vegetation program. The program seeks to determine the response of understorey vegetation to environmental watering events, with a specific focus on the River Red Gum, Black Box and lake bed herbland vegetation associated with the network of semi-permanent and temporary wetlands at Hattah Lakes Icon site. The current analysis involved an innovative rigorous statistical model evaluation between multiple scales of the plant community and environmental water management, compared to no water management.

Key findings
This monitoring program has demonstrated that the three large environmental watering events over a seven-year period have maintained and improved the water dependent semi-arid floodplain plant communities of the Hattah Lakes Icon Site. This meets one of the ecological objectives of environmental water management. Key findings include:

- Development of an innovative multi-plant taxa statistical model to evaluate multiple scales of plant community responses to environmental water delivery, incorporating unmanaged responses.
- Most native water-dependant plant community metrics (e.g. water plant functional groups and key taxa) displayed a positive response to environmental watering. Whereas, terrestrial dryland taxa and functional groups displayed more negative responses.
- Vegetation responses differed at multiple scales from individual plants to functional groups and system wide changes.
- Each flood event and the frequency of events affected water plant functional groups differently.
- Native water-dependent plant responses to flooding were time bound with short (e.g. < 6 months) and longer-term responses (e.g. > 12 months) evident.
- This long-term dataset has enabled determination of the intricate workings of the wet-drying-dry floodplain cycle to refine management approaches.
- Overall most plant species and functional groups experienced declines in occurrence and richness from 2014 to 2020; this decline was greater under the no environmental watering scenario; highlighting the importance of long-term monitoring data and the essential role of environmental watering in maintaining the semi-floodplain system of the Hattah Lakes Icon site.

Management implications and recommendations
These findings demonstrate the importance of environmental watering to maintain and improve the native water-dependent plant community of Hattah Lakes. It also provides a modelling tool for future refinement of environmental water delivery to improve biodiversity outcomes and program efficiency and effectiveness.

From the current findings, it is recommended that:

- Ongoing environmental water delivery is required to maintain the wet-drying-dry cycle of this semi-arid floodplain into the future.
- A larger response from the floodplain system can be achieved with lower-volume water delivery by leveraging rainfall and natural flooding during and prior to the delivery.
- Delivery of environmental water during times of below average annual rainfall, is most beneficial for water-dependent vegetation.
- The next stage of the monitoring program should involve using the model to predict future vegetation responses to environmental watering scenarios followed by on ground monitoring to evaluate the accuracy of the model predictions.
- The predictive model is used to determine vegetation responses to a range of management scenarios including water deliveries (timing, duration, magnitude), climatic influences (natural flooding, rainfall, drought), management objectives (e.g. competing objectives: understorey vegetation, fish etc) across a range of riparian systems (e.g. other icon sites and assets).

Since the inception of the understorey vegetation monitoring program it has generated an evidence-base that has addressed key ecological knowledge gaps and evaluated the effectiveness of environmental watering at the Hattah Lakes Icon Site. These outcomes inform the management of the Hattah Lakes floodplain system and may also be extrapolated to similar systems within the Murray-Darling Basin.

Introduction

1.1 Semi-arid floodplain vegetation dynamics

In most floodplain ecosystems, vegetation community dynamics are predominantly driven by the hydrological regime (Junk *et al.* 1989; Ralph and Rogers 2011). Semi-arid floodplains have an irregular flooding regime alternating between prolonged periods of drought and floods (Walker *et al.* 1995; Colloff and Baldwin 2010; Baldwin *et al.* 2013; Bino *et al.* 2015). Hence, plants and associated communities are adapted to variability in moisture availability (Thapa *et al.* 2015). The mosaic of plant communities in these semi-arid floodplain systems often exist within one of three main 'phases' related to water availability (e.g. rainfall and/or flooding; Figure 1):

1. 'wet' when the wetland is inundated, and aquatic species are often present;
2. 'drying' when the lake is drying. This vegetation state is dominated by water respondent and mudflat species (e.g. terrestrial damp species); and
3. 'dry' when the lake is dry (often for long periods). This vegetation state is often dominated by dry terrestrial floodplain species such as grasses and saltbushes (i.e. terrestrial dry species).

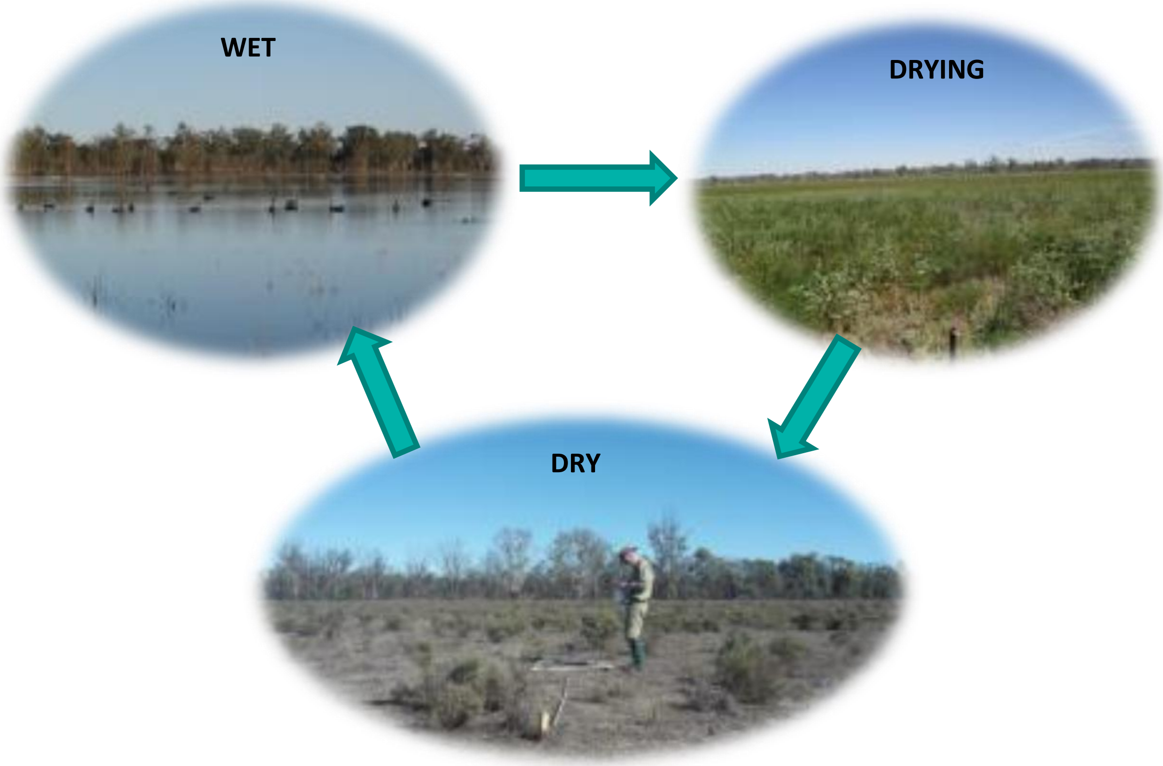

Figure 1. A simplified diagram of the wet-drying-dry cycle of floodplain vegetation.

In semi-arid floodplain systems, the dry phase may occur over long-time frames (e.g. decades) while the wet phases may last for several years. Following inundation, it is expected that terrestrial dry plant species will die due to their susceptibility to flooding (Casanova and Brock 2000; Capon 2003; Nishihiro *et al.* 2004; Raulings *et al.* 2010). As water begins to recede (i.e. drying state), the littoral zone is inhabited by species that can tolerate damp soil (e.g. mudflat or terrestrial damp species). Over time these species may die and be replaced by terrestrial dry species that are more capable of surviving the drying conditions. However, the suite of species able to return following inundation is dependent upon propagule availability (Brock and Rogers 1998; Capon 2003). In addition, in semi-arid environments climatic events that do not lead to flooding, such as localised high rainfall, may also influence plant community dynamics (Walker *et al.* 1995; Capon 2005). This wet-drying-dry cycle varies over time, and it may take months or years to complete the full cycle depending on external ecological drivers such as climate and flooding frequency.

In drying climates where there is insufficient rainfall to maintain semi-arid floodplain vegetation (Colloff and Baldwin 2010; McGinness *et al.* 2013) the flooding regime is becoming increasing important. However, river regulation and extraction of water for agriculture, industry and urban use (Poff *et al.* 1997; Naiman *et al.* 2015) has altered the connectivity, hydrology and the ecology of riverine and floodplain ecosystems (Nilsson *et al.* 2005; Kingsford *et al.* 2006). In response, altered or degraded floodplain ecosystems are being restored by artificially reinstating aspects of the natural flood regime - often called environmental watering or flows (Tharme 2003; Arthington 2012).

1.2 The Living Murray program

The Living Murray (TLM) initiative is a river restoration program designed to improve the environmental health of the Murray River and its floodplain (MDBA 2013). The program is coordinated by the Murray-Darling Basin Authority (MDBA) in partnership with national and state governments. The program has the long-term goal of achieving a healthy working Murray River system for the benefit of the environment and all Australians (MDBA 2011).

Hattah Lakes is one of six 'Icon Sites' located along the Murray River and was selected to be part of TLM program for its significant ecological, cultural, recreational, heritage and economic values (MDBA 2009). The Hattah Lakes Icon Site is a semi-arid ecosystem comprising a 13,000-ha complex of lake systems and floodplains, in north-west Victoria (MDBA 2012). The Icon Site forms part of the Hattah-Kulkyne National Park and the Murray-Kulkyne Park (48,000 ha; MDBC 2006; MDBA 2012) and contains important habitat for threatened terrestrial and aquatic plants and animals. Twelve of the lakes are listed under the Ramsar convention on wetlands of international significance, underpinning the role the Icon Site plays in the conservation of native water birds (DSE 2003; MDBA 2012).

The lack of connectivity between the Hattah Lakes and the Murray River, together with river regulation and water extraction, has had a negative impact on vegetation condition in Hattah Lakes (MDBA 2012). As a result, the overall environmental health of the system and habitat value for fauna has declined (Cunningham *et al.* 2009). Environmental watering has been implemented since 2005 to mitigate the effects of the reduced frequency of natural flooding (MDBA 2009, MDBA 2012).

1.3 Demonstrating environmental watering outcomes

Predicting and demonstrating the effectiveness of environmental watering to maintain ecosystem health is becoming increasingly important, particularly in drying climates where there is insufficient rainfall to maintain semi-arid floodplain ecosystems (Colloff and Baldwin 2010; McGinness *et al.* 2013). Monitoring is a key component of this process because it provides feedback on system responses to management objectives and allows managers to learn about the effectiveness of different management actions, thereby, refining management strategies for increased effectiveness and efficiency.

However, monitoring the effectiveness of environmental watering for maintaining or improving the quality of semi-arid floodplain vegetation is difficult. This challenge to determine the outcome of management actions is due to the high costs of monitoring, the inherent variability in natural ecosystems, the lack of long-term data collected prior to management, and the lack of appropriate unmanaged "control" sites for comparison. These limitations can impact our ability to experimentally investigate key questions that will improve natural resource management.

In addition, most available information on vegetation responses to flows is based in riverine systems (including River Red Gum) and wetland ecosystems in temperate environments (e.g. Colloff and Baldwin 2010; Capon and Reid 2016). Little information is available on the response of semi-arid floodplain understorey vegetation, specifically Black Box plant communities, to hydrological and climatic drivers. As semi-arid floodplains have sporadic hydrology, external drivers such as climatic events may have stronger influences on plant community dynamics compared to riverine systems. System differences combined with the variety of vegetation response indicators frequently used (e.g. species richness and abundance, functional group classifications) as well as spatial and temporal scales complicate informing environmental watering outcomes.

The TLM program implements two types of monitoring programs (MDBA 2012): (1) Condition Monitoring assesses the condition of each Icon Site in relation to its ecological objectives using standard techniques; and (2) Intervention Monitoring (Icon Site specific) investigates the links between environmental watering events, works and measures, and ecological outcomes, often targeting key ecological knowledge gaps.

1.4 Understorey vegetation monitoring program

In 2014, the TLM Intervention Monitoring program established an understorey vegetation monitoring program for the network of semi-permanent and temporary wetlands within the Hattah Lakes Icon Site. The program seeks to determine the response of understorey vegetation to environmental watering events, with a specific focus on the River Red Gum and Black Box plant communities and lake bed vegetation. It also aims to develop an understanding of vegetation composition dynamics (i.e. species richness and abundance) along the floodplain mosaic, a gradient from lake bed to lake edge and the higher floodplain.

The monitoring program aims to address two key ecological knowledge gaps: (1) What is the effect of multiple environmental watering events on the floristic composition and distribution of key plant communities within the vegetation mosaic? and (2) How effective is environmental watering at 'restoring a mosaic of healthy wetland and floodplain communities to maintain the ecological character of the Ramsar site?'

The monitoring design incorporates two timescales:

- <u>Immediate</u> impacts of the environmental watering events; and
- <u>Medium-term</u> impacts of environmental watering events by monitoring change over time.

To date, the outcomes of this program have allowed managers to optimise the application of environmental watering events at Hattah Lakes, and may also be applicable to environmental management for a number of floodplain wetlands within the Murray-Darling Basin.

This annual report provides an update on the understorey vegetation monitoring program over the last seven years (2014-2020). Past program analyses provided general validation of the use of environmental watering for achieving understorey vegetation objectives at Hattah lakes (Moxham *et al.* 2018; Moxham *et al.* 2019a). As part of a separate project, a new dynamic joint species distribution model was developed to more accurately evaluate vegetation response to environmental watering (Gwinn *et al.* in preparation). This new model was highly successful in predicting vegetation responses to the current management of environmental watering <u>and</u> the counterfactual case of no environmental water management. Determining this counterfactual case of no environmental water management effects on vegetation responses has not been undertaken until now and provides a rigorous scientific base to compare the effectiveness of environmental water deliveries.

For this year's analysis, we apply this cutting-edge model to seven years of data to provide a rigorous evaluation of the statistical associations between the understorey vegetation composition, environmental water management and the counterfactual case of no environmental flow management. This also includes the interaction between annual measures of rainfall and flooding.

2 Monitoring program overview 2014-2020

2.1 Program design

The monitoring design uses a scalable approach to monitoring. The primary scale was the entire lake systems including the floodplain at the Hattah Lakes Icon Site. Therefore, each lake within the system was treated as a replicate within the overall lake system. The design was used to investigate the effects of environmental watering on key vegetation communities (e.g. understorey components of Intermittent Swampy Woodland, Riverine Chenopod Woodland, Lakebed Herbland Ecological Vegetation Classes (EVCs)). The design focussed on the lake system and the three dominant EVCs.

In April 2014, 20 monitoring sites were established across ten lakes at the Hattah Lakes Icon Site (Figure 2, Appendix 1). Lakes were selected to represent a range of post-regulation watering regimes. These comprised seven persistent temporary lakes (the dominant lake type in the system), two semi-permanent lakes, and one episodic lake (Lake Kramen; the only within the system of this kind).

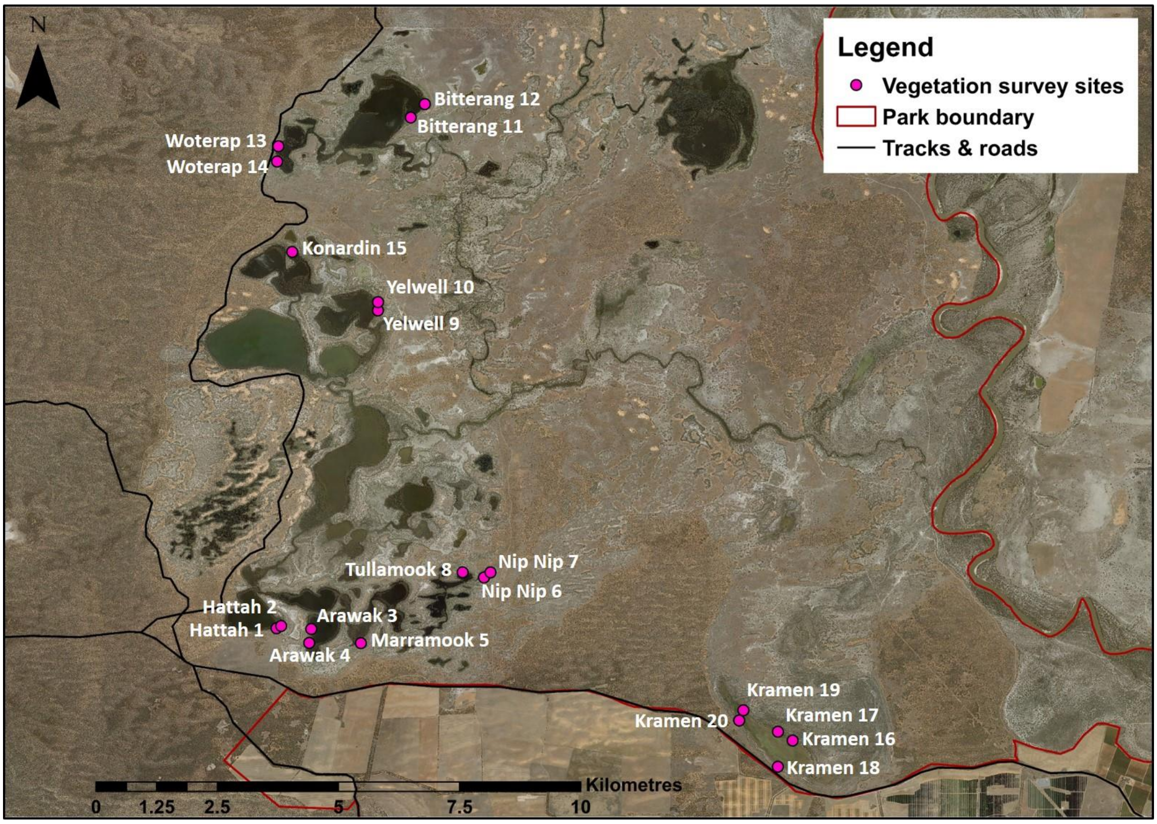

Figure 2. Site distribution across the Hattah Lakes Icon Site. Note points represent the 2014 lake edge.

The monitoring program and rationale, site locations and sampling measures are presented in Moxham *et al*. (2014). The location of each monitoring site along each lake was randomly selected. The monitoring protocol (Moxham *et al.* 2014) established a systematic sampling regime along a moisture, elevation and vegetation gradient. Biological and environmental attributes were measured along a transect running perpendicular to the lake from the 2014 lake edge or bed (lake dependent) onto the surrounding floodplain.

Sampling measures

Key ecological attributes (Table 1) were assessed along each transect to examine changes in floristic composition, distribution of target vegetation communities and environmental characteristics in relation to environmental watering events. Environmental characteristics which also affect community composition include bare ground, litter and biological soil crust.

Table 1. Summary of the ecological attributes assessed within the understorey vegetation monitoring program.

Ecological attribute	Assessment type	Rationale
1. Floristics	1.1 Broad-scale assessments (225 m^2 quadrats)	Species richness at broader scales
	1.2 Floristic assessments (1 m^2 quadrats)	Presence and abundance of understorey species at finer scales
2. Woody plant recruitment	2.1 Quadrat searches (1 m^2 quadrats)	Woody species recruitment
3. Canopy cover	3.1 Canopy photos	Canopy abundance and health
4. Visual vegetation characterisation	4.1 Site photos	Visual representation of sites
	4.2 Vegetation community changes	Visual site characterisation and EVC changes
	4.3 Browsing by animals and damage by pigs	Degree of browsing and disturbance can influence interpretation of results
5. Hydrology	5.1 Water level	Inundation measure

Data management

All data were entered into a custom-built Microsoft Access database developed for the program. The floristic data were entered into the Victorian Biodiversity Atlas (VBA; DELWP 2015). The VBA, Royal Botanic Gardens Board Victoria (2015), and Walsh and Entwisle (1994, 1996, 1999) were used to confirm plant nomenclature and origin (i.e. native or exotic).

Monitoring schedule

Baseline data were collected at all sites in April 2014 prior to environmental watering. Monitoring occurred annually in March to April spanning seven monitoring periods and four environmental watering events, since the program's inception (Figure 3). The proportion of each transect monitored differed each year depending on the extent of inundation; however, the newly developed modelling framework uses recently published methods that account for this sampling variation (Conn *et al.* 2017).

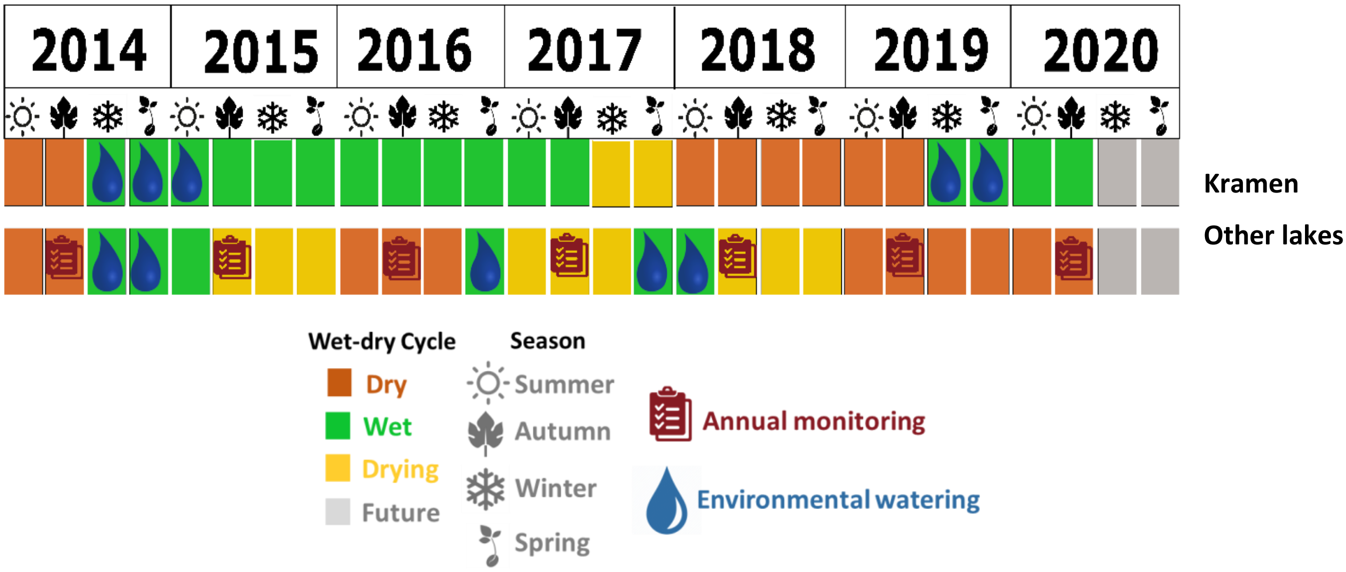

Figure 3. The wet-drying-dry semi-arid floodplain cycle at Hattah Lakes including environmental flows and annual autumn (March/April) vegetation monitoring. Note the episodic Lake Kramen has received a different environmental flow regime than the other nine lakes.

2.2 Hattah Lakes hydrological regime

Environmental watering

The Hattah Lakes Icon Site consists of waterways, floodplains and more than 20 lakes ranging in size from 10 to 200 ha (MDBA 2012). The targets for environmental watering are selected based on lake characteristics and associated biological and environmental attributes. To aid management of environmental watering, the target lakes have been classified into three water regime scenarios (MDBA 2012):

(1) Persistent temporary (often flooded): inundation once in every three years to 43.5 m above sea level (ASL) – targeting lakes, waterways and fringing vegetation.

(2) Semi-permanent (intermittently flooded): inundation once in every six to eight years to 45 m ASL targeting the higher floodplain.

(3) Episodic (rarely flooded): inundation to 45 m ASL once every eight years targeting Lake Kramen and the higher floodplain.

Environmental watering has been implemented since 2005 and until 2014, followed scenario one. Since 2014, three environmental watering events have occurred targeting the higher floodplain:

- In spring 2014, a one-in-eight-year flood event (watering scenarios two and three) occurred following the release of environmental water inundated the floodplain to 44.65 m ASL. This was the first time that the higher floodplain vegetation (43-45 m) had received water since the 1990s (SKM 2004; MDBA 2012). All lakes received water. Lake Kramen received water in September 2014.
- In spring 2016, natural flooding, was topped up with environmental watering inundating the floodplain to 44.7 m ASL. All lakes, other than Kramen were inundated.
- In spring/summer 2017-2018, environmental watering inundated the floodplain to 44.85 m ASL. All lakes, other than Kramen were inundated.
- In spring 2019, environmental watering inundated the floodplain to 45.2 m ASL at Lake Kramen. All other lakes did not receive water and were allowed to dry out.

Rainfall patterns in the region

Climate, particularly rainfall, is a key external driver of plant community dynamics and management outcomes (Moxham *et al.* 2017a). For example, below average rainfall will result in lower plant growth and abundance, while high rainfall has the inverse effect (Thompson and Eldridge 2005). Thus, it is important that monitoring programs consider annual rainfall, particularly in drought-prone landscapes, such as the Mallee (Figure 4). In semi-arid floodplains, climatic events that do not lead to flooding, such as localised high rainfall, may also influence plant community dynamics of the wet-dry floodplain cycle (Walker *et al.* 1995; Capon 2005). Over recent decades rainfall has become more variable, with extended dry periods (Min *et al.* 2011; Smith 2011). Rainfall in the Mallee region fluctuates both within and between years depending on changes in the Southern Oscillation Index (SOI; from periods of El Niño to La Niña). Drought is common in the region with the most recent drought ('The Millennium Drought') between 1999 and 2009, followed by a period of above-average rainfall ('The Big Wet') in 2010-2011. Monitoring sites were established in 2014 which was an above-average rainfall year, as was 2016/2017 (Figure 4).

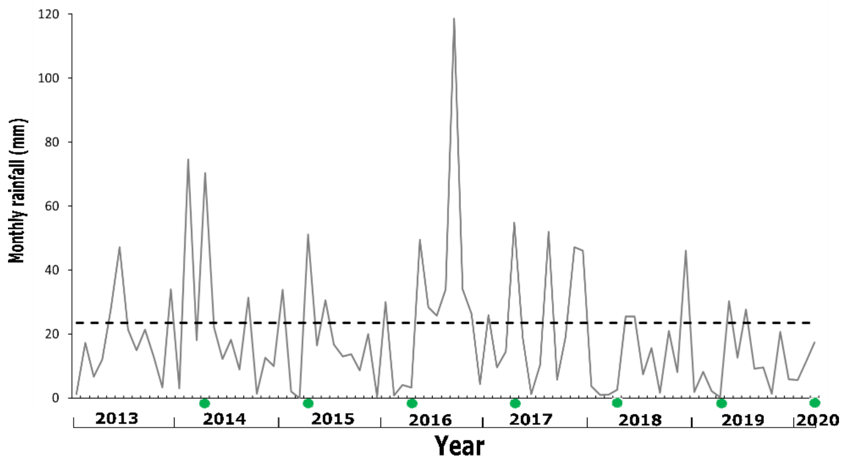

Figure 4. Average monthly rainfall (mm) from 2013 to 2020 and average annual rainfall (mm; dotted line) showing the annual monitoring period in April (green dot).

2.3 Program highlights 2014-2020

Over the lifespan of the monitoring program the data collected has improved our knowledge base of the Hattah Lakes icon site vegetation and provided evidence on the effectiveness of environmental watering on improving the abundance of water-dependant vegetation. As data accumulated over the life of this program, the analyses have increased in sophistication, to best use the available information and refine our ability to answer pertinent management questions. Key outcomes in each financial year are briefly outlined below.

2014-2015 (Moxham and Kenny 2015)

What is the community composition of the vegetation mosaic at the Hattah Lakes Icon site?

Three plant communities were defined which occur as a mosaic across the floodplain (along an elevation/moisture gradient), often with a clearly delineated overstorey and a more variable understorey, where species may occur in more than one plant community. The three communities align with the Ecological Vegetation Classes: Lake Bed Herbland (lake), Intermittent Swampy Woodland (lower floodplain along lake edges) and Riverine Chenopod Woodland (higher floodplain; Figure 5).

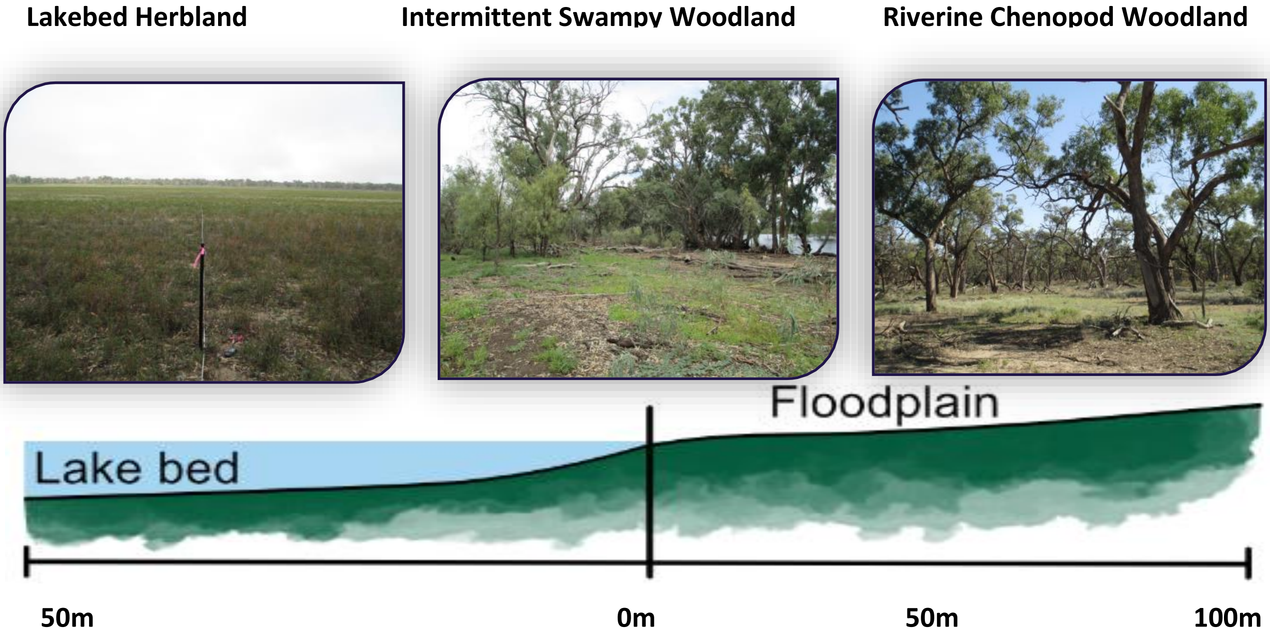

Figure 5. The three vegetation communities along the floodplain gradient showing the site monitoring transect lengths (not to scale): Lake Bed Herbland (lake bed), Intermittent Swampy Woodland (lower floodplain) and Riverine Chenopod Woodland (higher floodplain).

What is the effect of a single environmental watering event on vegetation composition?

- Plant community responses were variable and differed with the scale of analysis (i.e. lifeforms, species etc.). The watering event explained 64% of the plant community variation observed, with 32 species closely associated with inundated areas.
- Broad-scale vegetation changes included an overall increase in tree canopy cover and a decline in bare ground.
- At a finer scale, vegetation and species responded differently in each plant community; for example, a decline in exotic species cover occurred in Intermittent Swampy Woodland, but not in Riverine Chenopod Woodland.

Are threatened flora species present at the monitoring sites?

Over two monitoring periods, 26 rare or threatened plant species were recorded, including six threatened plant species never before recorded at Hattah Lakes, and over 80 new species records for the region.

2015-2016 (Moxham and Gwinn 2016; Moxham et al. 2016)

Development and implementation of vegetation response models

A multi-plant taxa Bayesian hierarchical model of occurrence was developed and was the first step in providing explicit information that addressed the key knowledge gaps in relation to vegetation responses to environmental watering (Moxham and Gwinn 2016). The model provided a new tool to predict and evaluate the effectiveness of management interventions to inform environmental watering planning. The unique advantage of the multi-taxa model was that inference could be drawn at the plant community level while maintaining species (taxa) identity for further inquiry when the management context necessitated. This enabled the development of site-specific management tools for use by on-ground managers.

Key findings:

- At the lake system scale, individual *taxa* models provided more useful response indicators than *plant functional group* metrics.
- Of the 100 plant taxa evaluated, 46 taxa displayed significant responses to the watering event.
- Plant taxa fell into two main groups: species favouring either the lake edge or the floodplain (Figure 6).
- Overall, plant taxa favouring the lake edge had positive responses to the watering event, whereas plant taxa favouring the floodplain had a more even mix of both positive and negative responses (Figure 6).

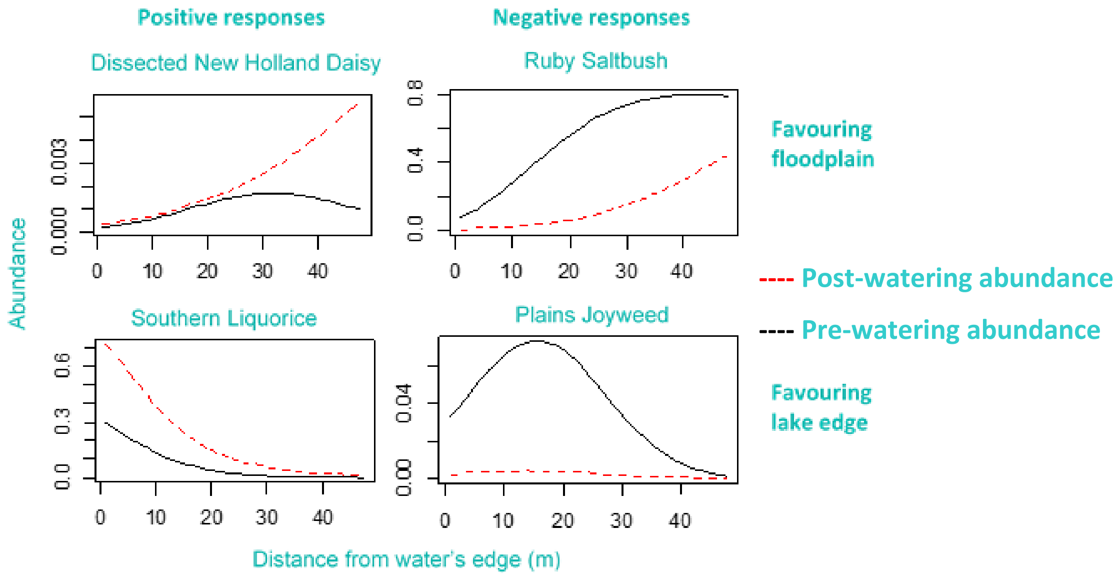

Figure 6. Change in abundance of four plant taxa before (solid line) and after (red dotted line) the environmental water event along a moisture gradient from the 2014 lake edge (i.e. '0' on the x-axis).

The model could be further utilised and explored through:

- Incorporation of long-term data, as results to date are based on a single watering event. Long-term data are required to fully evaluate the effects of environmental watering on vegetation quality.
- The multi-taxa models developed here can be used to predict and demonstrate the effects of future environmental watering events and scenarios on plant assemblages.
- External climatic drivers (e.g. rainfall, natural flooding) could also be incorporated into the model.
- The new modelling tool provides a suitable approach to analysing other long-term data types (e.g. Icon Site Condition monitoring) to gain an understanding of the temporal effects of environmental watering on vegetation responses.
- The modelling tool could be further developed into an online management tool outlining generalised vegetation responses and environmental watering scenarios.

What is the effect of one environmental watering event on vegetation composition two years later?
The key effects of one environmental watering event on plant taxa and plant functional groups were:

- At the lake system scale, individual *taxa* models proved more useful response indicators than *plant functional group* metrics.
- Of the 91 plant taxa evaluated, 60 taxa displayed significant responses to the watering event.
- Plant taxa fell into two main groups: species favouring either the lake edge or the floodplain.
- Overall plant taxa favouring the lake edge had positive responses to the watering event, whereas plant taxa favouring the floodplain had a more even mix of both positive and negative responses.
- Shrub (terrestrial dry taxa) occurrence decreased over the three-year monitoring.
- Native, perennial and forb (e.g. terrestrial damp taxa) richness increased one-year post-watering, but then decreased by 2016, which is likely due to below average rainfall conditions.
- Eucalypt seedling occurrence increased post-watering.

The key effect of environmental watering on plant community structure was:

- Vegetation abundance and structural complexity decreased over the three years of monitoring.

The key effect of environmental watering on tree canopy cover was:

- The canopy cover of River Red Gum and Black Box remained largely unchanged over the monitoring period. However, the modelling does indicate an increasing trend in canopy cover over time.

2016-2017 (Moxham et al. 2017b)

What is the effect of two environmental watering events on vegetation composition?
Key findings:

- The two environmental watering events resulted in an increase in abundance of native vegetation and water dependant plant functional groups. Conversely, plants favouring terrestrial dry habitats decreased in abundance post-watering.
- The canopy cover of both River Red Gum and Eumong Wattle increased post-watering. However, no change was detected in Black Box suggesting that the recovery of trees higher on the floodplain may occur over longer time periods or require more environmental watering events to demonstrate improvements in canopy cover.
- Since monitoring began in 2014, 30 threatened species have been recorded, some of which have responded positively to environmental watering.

Scientific publication: Kenny SA, Moxham C, Sutter G (2017) The response of rare floodplain plants to an environmental watering event at Hattah Lakes, Victoria. *The Victorian Naturalist* 134(1), 19-27.

2017-2018 (Moxham et al. 2018)

What is the effect of three environmental watering events (over five years) on vegetation composition?
Key findings:

- Short-term changes (e.g. 12 months) in understorey plant abundance were related to water availability.
- The 2014/15 and 2016/17 flood events coincided with average and high rainfall and there was an increase in plant abundance. The spring-summer 2017/18 flood event occurred at a time of low rainfall and there was decreased plant abundance at the time of sampling.
- Multiple flood events affected functional groups differently. In general, watering events increased the abundance of water respondent groups and decreased the terrestrial dry group:
  - Two flood events decreased Terrestrial Dry species abundance (but not three events).
  - One and two flood events increased Terrestrial Damp species abundance (but not three).
  - Emergent and low-growing amphibious fluctuation-tolerator species abundance increased with the increasing number of flood events.
- Tree canopy cover increased, after three flood events, on the lakebed (River Red Gum) and at the lake edge (River Red Gum, Black Box, Eumong), but not on the floodplain (Black Box). This suggests that recovery of higher floodplain trees may occur over longer time periods or require more flood events to exhibit improved canopy cover.

Scientific publication: Moxham C, Kenny SA, Beesley LS, Gwinn DC (2019b) Large-scale environmental flow results in mixed outcomes with short-term benefits for a semi-arid floodplain tree community. *Freshwater Biology* 64, 24-36.

2018-2019 (Moxham et al. 2019a)

What is the influence of both rainfall and flooding regimes on vegetation composition?

Past analyses provided general validation of the use of environmental watering for achieving understorey vegetation objectives at Hattah Lakes. The current analysis involved a more rigorous statistical evaluation between the understorey vegetation composition and annual measures of rainfall and flooding.

The key findings highlighted the importance of water availability in the form of both rainfall and flooding as key drivers of Hattah Lakes plant community composition. They included:

- A strong positive response for most plant community metrics to both rainfall and flooding.
- The general positive temporal pattern in the plant community metrics, particularly natives, to flooding indicates that the system benefited from the environmental water deliveries in 2014, 2016 and 2017/18.
- Generally, tree canopy cover increased over time, suggesting a benefit of the high frequency of environmental watering events over the last six years.
- The plant community positive responses to rainfall and flooding, increased from the lakebed to the floodplain. This enabled refinements in system-wide response predictions to flood regimes.
- The responsiveness of the plant community, and the ability to detect responses with statistical modelling, suggests that further development of a more refined model as a predictive tool to evaluate both observed and hypothetical management scenarios will be useful.

2.4 Dynamic joint species distribution model

As part of a separate project funded by the Department of Land, Water and Planning, and the Victorian Environmental Water Holder, we developed a more sophisticated modelling approach designed to better predict the outcomes of hypothetical flow scenarios beyond what occurred in the system (a dynamic joint species distribution model, Gwinn *et al.* in preparation). This new model was highly successful in predicting the vegetation responses to the current management of environmental watering. Thus, we applied it to predict the counterfactual case of no environmental flow management in the Hattah Lakes system for comparison to the managed state between 2014 and 2019. Determining this counterfactual case of no environmental water management effects on vegetation responses has not been undertaken previously and provided an innovative and rigorous scientific framework to determine the effectiveness of environmental water deliveries.

The model performed very well with low prediction error, particularly given that the data set only contained six years of data. Key outcomes include:

- A model predicting understorey plant species and community level responses to the current environmental watering regime.
- A model predicting plant community composition under the hypothetical condition of no environmental water deliveries (i.e. unmanaged flow regime).
- A base model that can be further developed and adapted for a range of managed environmental watering scenario responses for plant species, vegetation types and riparian systems (e.g. floodplains, wetlands, rivers).

Scientific publication: Gwinn DC, Moxham C, Kenny SA, Reich P, Sharpe A, Robertson DA, Keogh A, Middleton JA. and Greenfield A. (in preparation) Advancing environmental water management for riparian vegetation by predicting the counterfactual case. Draft Manuscript.

3 Modelling system wide outcomes

3.1 Analysis approach

For the 2020 analysis, the new dynamic joint species distribution model was applied to the full seven years of data to evaluate both the effects of the current environmental watering regime and the unmanaged state. The analysis approach is described in detail in Gwinn *et al.* (in preparation). The basic approach was to evaluate the response of individual species occurrence to winter and summer rainfall and flooding (and interactions), capturing the current and historical low-flow and high-flow periods. Species responses were then summarised to examine the responses of multiple plant community metrics and functional groups. To demonstrate the value of our modelling approach, the fitted model was used to predict the occurrence and inter-annual population growth rates for species and functional groups for the managed state (i.e. observed flooding) and for the theoretical unmanaged state (i.e. observed flooding minus environmental watering). This allowed for a statistical evaluation of environmental flow deliveries between 2014 to 2020.

Plant community metrics

The analyses described and evaluated patterns in several key plant community metrics and a selection of plant species determined to be major community drivers (Moxham *et al.* 2019a). These metrics included:

- **Plant origin**: native and exotic plant abundance.
- **Water Plant Functional Groups** (Table 2) – to enable the findings to align with, and be used as a comparison, with other TLM program outcomes. This analysis had a strong focus on the two dominant plant groups of the Hattah Lakes system: Terrestrial Dry and Terrestrial Damp.
- **Influential plant species cover**: previous analyses highlighted that some dominant species of the system were key drivers of community dynamics and may be more informative than plant functional groups (e.g. water plant functional group). These included: (i) Water responsive species - Common Sneezeweed *Centipeda cunninghamii* (ATl, Campbell *et al.* 2014), Spiny Flat-sedge *Cyperus gymnocaulos* (ATe, Campbell *et al.* 2014), Spreading Nut-heads *Sphaeromorphaea littoralis* (Tda, Campbell *et al.* 2014) and *Stemodia* spp. (Tda, Campbell *et al.* 2014), (ii) Terrestrial dry species - Clammy Goosefoot *Dysphania pumilio* (Tdr, Casanova and Brock 2011; Campbell *et al.* 2014), Ruby Saltbush *Enchylaena tomentosa* var. *tomentosa* (Tdr, Campbell *et al.* 2014), and (iii) Exotic species - Mediterranean Turnip *Brassica tournefortii* (Tdr, Campbell *et al.* 2014) and Common Heliotrope *Heliotropium europaeum* (Tda, Campbell *et al.* 2014).

Table 2. Water plant functional groups (Brock and Casanova 1997; Casanova 2011; Campbell *et al.* 2014).

Water plant functional groups	Description
Terrestrial Dry (Tdr)	Plant taxa which are not dependent on flooding but will respond to rainfall or flooding events
Terrestrial Damp (Tda)	Plant taxa which germinate in moist soil, but cannot tolerate water saturation in a vegetative state
Amphibious Fluctuation Responder – plastic (ARp)	Plant taxa which respond to changes in water levels morphologically (e.g. rapid growth) and can survive on damp and drying soil
Amphibious Fluctuation Tolerator – low-growing (ATl)	Plant taxa which germinate under water or on damp soil
Amphibious Fluctuation Tolerator – emergent (ATe)	Plant taxa which inhabit saturated soil or shallow water, but require most of their vegetative parts to remain above water
Amphibious Fluctuation Tolerator – woody (ATw)	Plant taxa which are perennial with an aerial seed bank (seed held in the canopy) which required a moist root zone throughout the year and will germinate under moist soil conditions or in shallow water

The results for this annual report are provided in two sections:

- descriptive overview; and
- modelled system wide outcomes (2014-2020) from the new dynamic joint species distribution model.

3.2 Results: descriptive overview

Floristics overview

Two hundred and twenty-eight plant species have been recorded over the seven years of monitoring (Appendix 3). Of these, 186 were native and 42 were exotic species (Figure 7). Exotic species richness was lowest in 2019 (12 species) while native species richness was highest in 2014 (117 species).

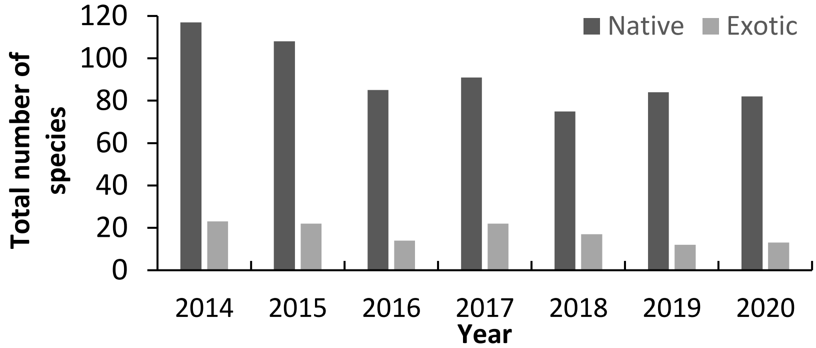

Figure 7. The total number of native and exotic plant species recorded between 2014 and 2020.

Since 2014, 33 rare or threatened plant species have been recorded, including the Curly Flat-sedge (*Cyperus rigidellus*), which is also listed under the Flora and Fauna Guarantee Amendment Act 2019 (Appendix 3). Three new rare or threatened species were recorded in 2020: the poorly known Native Verbena (*Verbena officinalis* var. *gaudichaudii*), the rare Yellow Garland Lily (*Calostemma luteum*) and the vulnerable Lagoon Spurge (*Phyllanthus lacunaris*).

Invasive animal damage

Browsing damage was recorded at 12 of the 16 monitored sites in 2020. While this was generally by native species (e.g. kangaroos), goat browsing was evident at more sites than in previous years. Evidence of pig damage was highest in 2018 (Table 3, Figure 8).

Table 3. The number of monitoring sites (x/20) with evidence of pig and goat damage for each year.

	2014	2015	2016	2017	2018	2019	2020
Evidence of pigs	1	1	1	2	6	2	1
Evidence of goats	0	0	0	0	0	1	3

Figure 8. Monitoring site disturbed by pig damage.

Visual changes in plant communities

Changes in plant community composition were visible within each EVC (Figure 9). The wet-drying-dry cycle was especially evident on the lake bed influencing plant composition. In 2014 and 2017, the 'green flush' seen following the retreat of flood waters and/or high rainfall was particularly noticeable within Intermittent Swampy Woodland (Figure 9). In contrast, the effect of below-average rainfall was most apparent in 2016, 2019 and 2020, following a dry spring and summer in both Intermittent Swampy Woodland and Riverine Chenopod Woodland. In addition, Riverine Chenopod Woodland occurs on the upper floodplain which is less influenced by environmental watering.

Figure 9. Visual vegetation changes in Riverine Chenopod Woodland (Lake Konardin), Intermittent Swampy Woodland (Lake Nip Nip) and Lake Bed Herbland (Lake Tullamook) from 2014 to 2020.

3.3 Results: modelled system wide outcomes

The water-dependant plant species and functional groups at Hattah Lakes responded positively to environmental water management. For instance, 82 plant species demonstrated higher population growth rates (e.g. occurrences) under environmental water management relative to the predicted unmanaged state, while only 66 species responded negatively to water management (Figure 10). That is, the dryland terrestrial species and functional groups that habit the higher floodplain that aren't adapted to flood regimes (e.g. long dry floodplain) declined in occurrence with increased flooding and were likely replaced by water-dependant species.

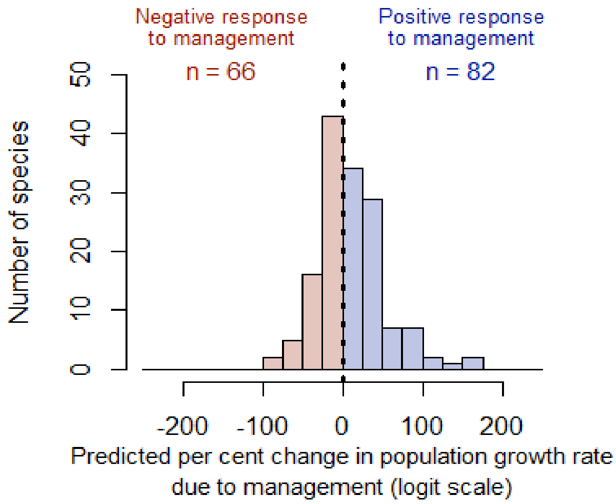

Figure 10. System-wide (%) increase in plant growth rates due to environmental water management. Negative (%) on the x-axis indicate negative change in growth rates due to water management. Y-axis is the number of species in each column.

3.3.1 Responses of functional groups

Overall, native and exotic taxa had similar responses to environmental water management. Both groups contained similar proportions of species responding positively and negatively to water management, with the most common response being positive (54% and 61% positive responses by natives and exotics, respectively).

The Water Plant Functional Groups responded as expected. For example, nearly all species in the Amphibious functional groups (i.e. ARp, ATe, and ATl) responded positively to environmental flow management (Figure 11). The Terrestrial damp group and the Terrestrial dry group demonstrated a variable response, with the Terrestrial damp group generally showing positive responses (5 and 30 species with negative and positive responses, respectively) and the Terrestrial dry group generally showing negative responses (57 and 30 species with negative and positive responses, respectively).

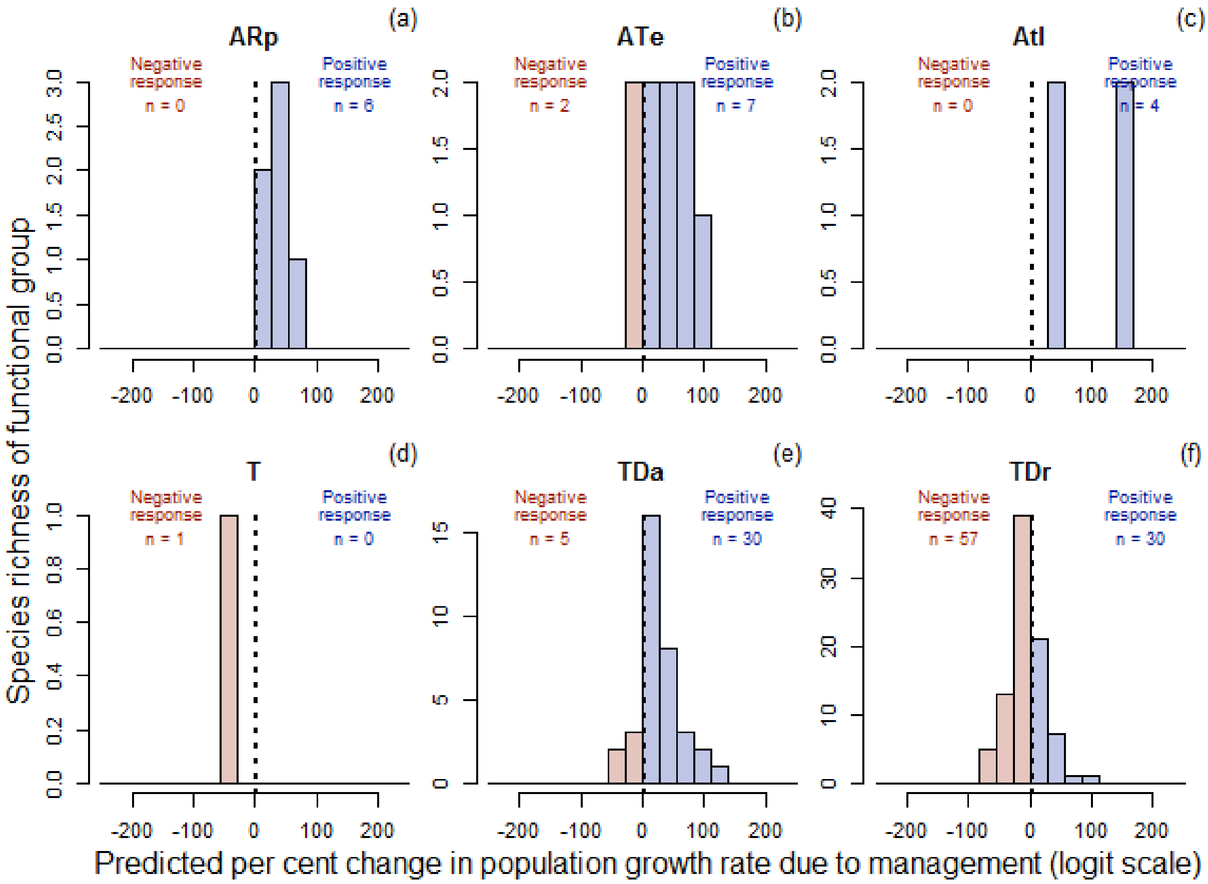

Figure 11. System-wide percent increase in growth rates of water plant functional groups due to water management (ARp = Amphibious Fluctuation Responder – plastic, ATe = Amphibious Fluctuation Tolerator – emergent, ATl = Amphibious Fluctuation Tolerator – low-growing, T =trees Amphibious Fluctuation Tolerator, Tda = Terrestrial Damp, Tdr = Terrestrial Dry). Negative per cents on the x-axis indicate negative change in growth rates due to water management. The y-axis is the number of plant species that experience each response.

The predicted trends in species richness of each functional group gave insight into how the species responses to water management determine the aggregate response of the functional group. Figure 12 shows these trends with the estimated slopes across the years of floristic data collection.

The greatest difference between the trends under water management and no management was experienced by the Amphibious Fluctuation Tolerator – low-growing functional group (unmanaged – managed = 0.282), indicating the strongest positive response to management (Figure 12c). The ARp, ATe and Tda water plant functional groups demonstrated lesser but still positive responses to water management (unmanaged – managed = 0.121, 0.086, and 0.048, respectively, Figure 12a, b, e). Alternatively, the Amphibious Fluctuation Tolerator and Terrestrial dry functional groups both demonstrated a negative aggregate response to water management, with the single T species having the strongest negative response (unmanaged – managed = -0.186, -0.048, respectively, Figure 12d, f).

These results indicate that management of Hattah Lakes with environmental water has met the primary management objective of advantaging water-dependent plant species while disadvantaging dryland species. However, over the time period of study, all functional groups demonstrated a decline in species richness.

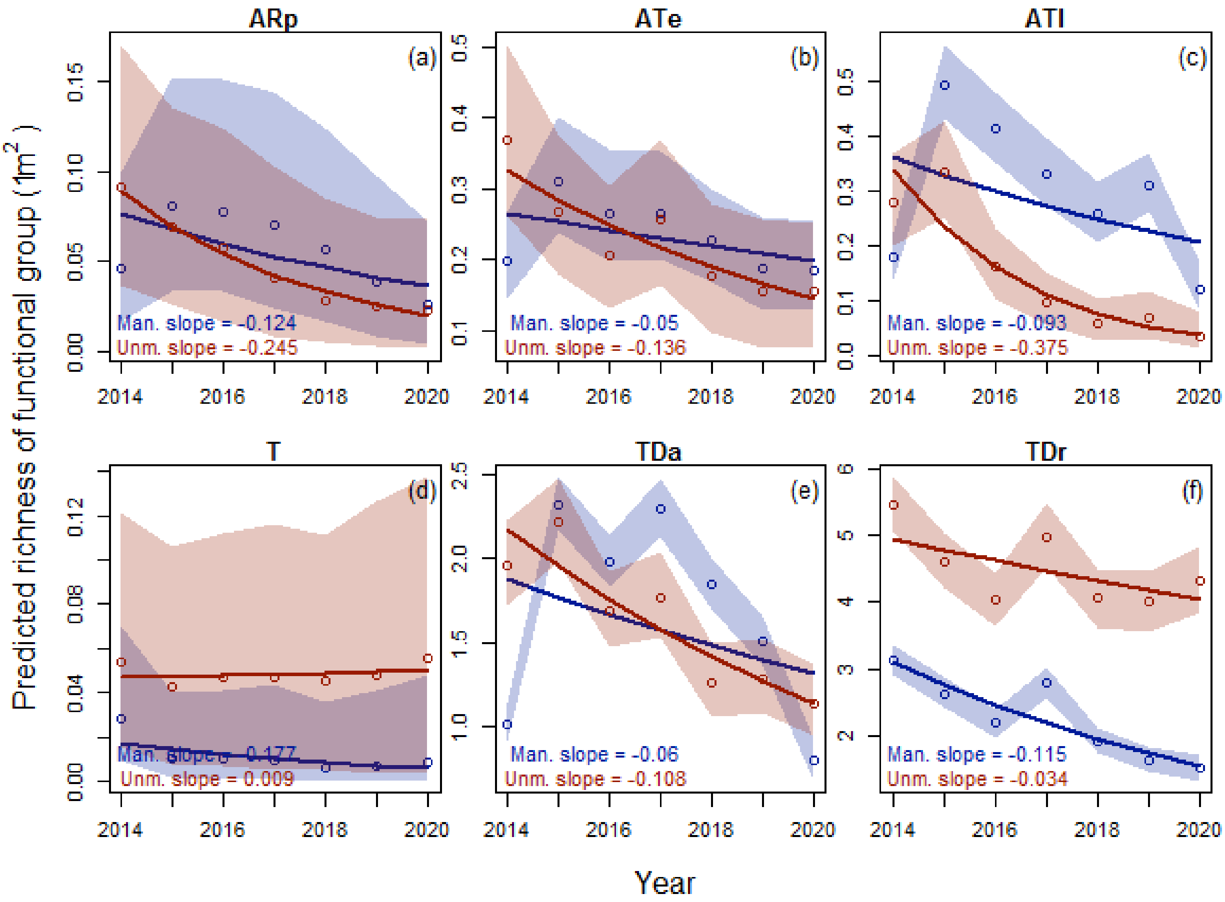

Figure 12. Model predicted species richness of water plant functional groups under environmental water management (blue) and no water management (red). Water plant functional groups: ARp = Amphibious Fluctuation Responder – plastic, ATe = Amphibious Fluctuation Tolerator – emergent, ATl = Amphibious Fluctuation Tolerator – low-growing, T =trees Amphibious Fluctuation Tolerator, Tda = Terrestrial Damp, Tdr = Terrestrial Dry. The open circles indicate the species richness predictions with 95% Bayesian credible intervals, while the lines depict the log-linear trend.

3.3.2 Responses of Influential plant species

The analysis of Moxham *et al.* (2018) determined eight taxa that disproportionately influenced the aggregate functional group responses to flow management. In the current analysis, these plant species showed variable responses to management, with the majority of native water-dependent taxa (e.g. *Centipeda cunninghamii, Cyperus gymnocaulos, Sphaeromorphaea littoralis;* Campbell *et al.* 2014) showing an increase in occurrence with environmental water management (Figure 13a-c).

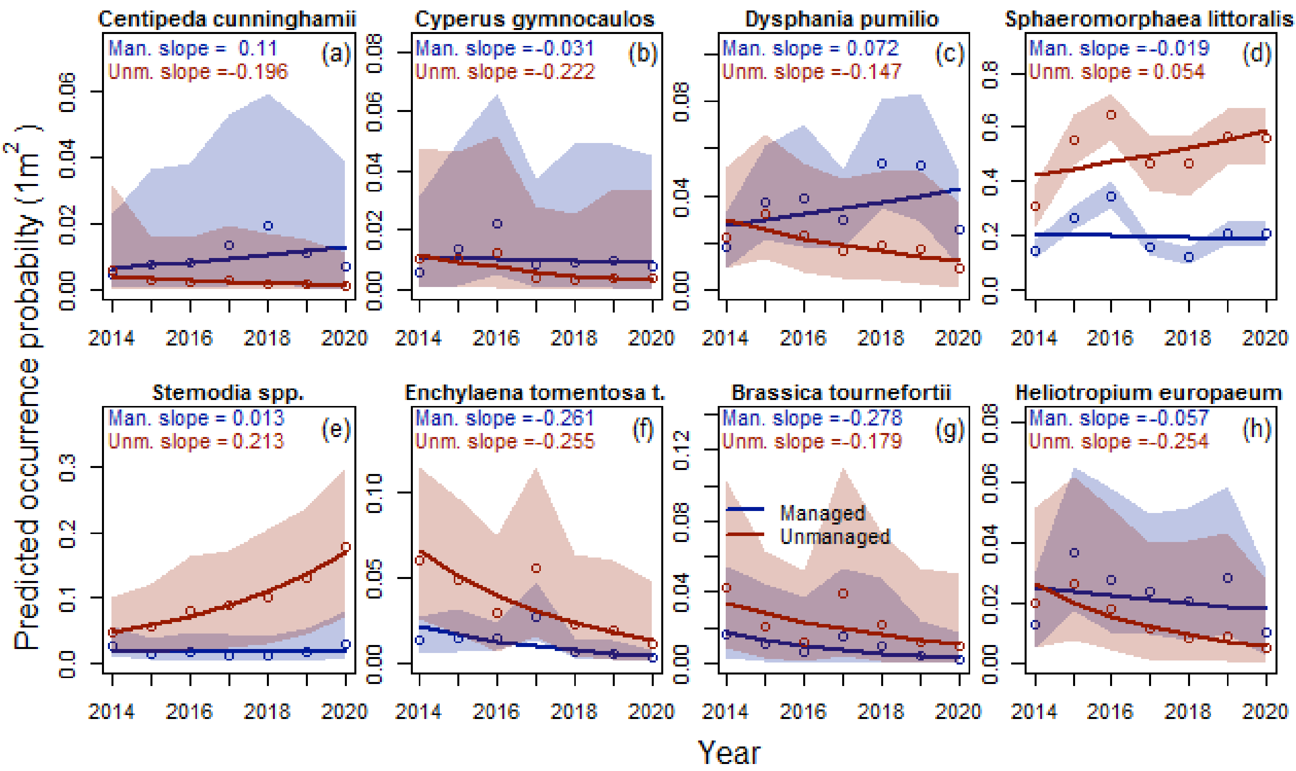

Figure 13. Model predicted occurrence probability of influential plant species under environmental water management (blue) and no water management (red). The open circles indicate the species richness predictions with 95% Bayesian credible intervals, while the lines depict the log-linear trend.

4 Synthesis

This monitoring program has shown that the delivery of environmental watering is important to maintain and improve the native water-dependent plant community of Hattah Lakes. This was one of the main objectives of environmental watering program at Hattah Lakes (MDBA 2012). Furthermore, the success of the new dynamic joint species distribution model to determine the influence of both rainfall and flooding on multiple levels of the plant community suggests that the monitoring program can support more refined analyses to inform management.

The main modelling outcomes for 2020 were:

- Environmental watering at Hattah Lakes has successfully increased the occurrence of most native riparian plant species from 2014 to 2020:
  - native water-dependent plant species increased.
  - native dryland plant species declined due to inundation.
  - Exotic species also benefited from environmental watering; however, this benefit was subdued relative to that of native water-dependent plant species.
- Overall most plant species and functional groups experienced declines in occurrence and richness from 2014 to 2020; this decline was greater under the no environmental watering scenario; highlighting the importance of long-term monitoring data and the essential role of environmental watering in maintaining the semi-floodplain system of the Hattah Lakes Icon site. This finding likely reflects the impacts of several external drivers of floodplain systems including the long-lasting impacts of the 'Millennium Drought' (1999 to 2009), flood regimes, climate change and variation in annual rainfall before monitoring.

The main findings of the overall monitoring program included a range of information in relation to vegetation responses to environmental watering including:

- Vegetation responses differed at multiple scales from individual plant species to functional groups and system wide changes.
- Individual *plant taxa* models provided more useful response indicators than *plant functional group* metrics.
- Plant taxa favouring the lake edge had positive responses to environmental watering, whereas plant taxa favouring the floodplain had a more even mix of both positive and negative responses.
- Overall terrestrial dry taxa decreased, and water respondent taxa increased in relation to environmental watering.
- Multiple environmental watering events affected water plant functional groups differently:
  - two environmental watering events decreased terrestrial dry species abundance;
  - one and two environmental watering events increased terrestrial damp species abundance;
  - emergent and low-growing amphibious fluctuation-tolerator functional groups abundance increased with the increasing number of environmental watering events.
- Native water-dependent species responses to environmental watering events are time bound with short (e.g. < 6 months) and longer-term responses (e.g. > 12 months) evident.
- Eight dominant species of the system were identified as key drivers of community dynamics.
- Species responses were driven by water availability in the form of both rainfall and flooding.

This monitoring program has greatly increased our knowledge base on semi-arid floodplain plant species and community responses to environmental watering. This has enabled reporting on the effectiveness of the current environmental watering strategy in maintaining or improving the water-dependent native vegetation of the Hattah Lakes Icon site. In addition, it has created a modelling tool that can be used to refine future environmental water delivery to improve biodiversity outcomes and program efficiency and effectiveness. These findings highlight the benefits of applying a counterfactual model-based approach to evaluating environmental water management and is a significant advancement for this program. The results can be used to demonstrate the value of past environmental-flow deliveries and meet the increasing demands on managers to justify their management choices and provide evidence on which to refine management regimes.

4.1 Vegetation responses to environmental watering

Overall, most native water-dependent plant community metrics (e.g. water plant functional groups and key taxa) displayed a positive response to environmental watering. Whereas, the more terrestrial dryland taxa and functional groups displayed more negative responses. These findings are supported by the scientific literature and are reflective of the wet-drying-dry cycle of these semi-arid floodplains (Casanova and Brock 2000; Capon 2003; Nishihiro *et al.* 2004; Raulings *et al.* 2010; Moxham *et al*. 2019b). However, the medium-term nature of this monitoring program dataset has enabled us to tease apart the more intricate workings of the wet-drying-dry floodplain cycle to refine our management approaches. For example, we now know that there are influential species in the system, whose responses are known to a range of environmental watering scenarios (and responses to further scenarios can be modelled) and used as system indicators to measure our management objectives. In addition, two interesting outcomes of the monitoring program that have not been undertaken before were:

1) the ability to tease apart the effect of water management versus no water management scenarios; and

2) the ability to examine multiple scales of the plant community (i.e. species to functional groups and system wide outcomes) to refine our understanding of system responses in relation to various aspects of the flood regime (e.g. temporal, multiple events).

4.2 Rainfall and flooding effects on management scenarios

The model outcomes contained evidence of interactions between water availability in the form of rainfall and flooding. These interactions suggest that water received in the form of rainfall or flooding can moderate the influence of the other. For example, for some species, winter rainfall can reduce the positive effects of summer flooding. Similarly, summer rainfall can reduce the positive effects of summer flooding. There was also evidence that the positive effects of flooding could be disproportionately enhanced when flooding occurs in both summer and winter. These interactions require careful consideration because historical flooding at Hattah Lakes occurred in spring/summer (SKM 2004), whereas the current delivery of environmental water has predominantly occurred in winter/spring. These interactions require further investigation, but suggest two important processes for water managers to consider:

1) Firstly, these results suggest that there can be an optimal amount and form (rainfall versus flooding) of water for the maintenance of each plant species, where the response to greater water availability can be positive up to a certain level and then become negative as water availability increases (or vice versa).

2) Secondly, these results suggest that the optimal environmental water delivery for a given species or functional group can vary depending on antecedent conditions (rainfall and previous flooding history).

5 Management implications

5.1 TLM ecological objectives

The overarching ecological objective of the TLM program related to the vegetation of the Hattah Lakes Icon Site is to 'restore a mosaic of healthy wetland and floodplain communities to maintain the ecological character of the Ramsar site' (MDBA 2012, p. 16). This monitoring program has demonstrated that the three large environmental watering events over a seven-year period have maintained or improved the water dependent semi-arid floodplain plant communities of the Hattah Lakes Icon Site. However, many uncertainties about the best environmental watering strategies for the system remain. For example, although the benefit of the last three environmental watering events were evident, the optimal timing of different flood regimes or aspects of the flood regime (e.g. duration, depth, frequency) is unknown. Furthermore, the overall decreasing trend of plant richness and abundance remains a concern. This trend likely reflects the impacts of several external drivers of floodplain systems including the long-lasting impacts of 'The Millennium Drought' (1999 and 2009), historical alteration of flooding regimes, climate change/variation and rainfall variation immediately prior to monitoring. Thus, indicating that a long-term approach is required to fully refine management strategies to maintain and improve this semi-arid floodplain system.

5.2 Management implications

Environmental water delivery is maintaining and improving the water dependent plant community at Hattah Lakes. From the current findings, recommendations for environmental watering include:

- Environmental water delivery is required to maintain the wet-drying-dry cycle of this semi-arid floodplain into the future.
- A larger response from the floodplain system can be achieved with lower-volume water delivery by leveraging rainfall and natural flooding during and prior to environmental water delivery. For example, environmental water delivery may be reduced during times of high rainfall with similar effects. Future research is needed in this area to determine optimal environmental deliveries given rainfall and natural flooding at the time and prior to environmental water delivery.
- Environmental water delivery at times of below average annual rainfall, is most beneficial for water-dependent vegetation. This is when environmental water may deliver its greatest effect on the floodplain system per unit volume.

5.3 Conclusion

Monitoring of understorey plant community dynamics across a hydrologic elevation gradient from lake bed to floodplain has contributed to key ecological knowledge gaps at the Hattah Lakes Icon Site. Since its inception in 2014 the monitoring program has generated ecological evidence that will aid improvements in management practices to either maintain or improve the health of water dependent plant communities following environmental watering events. This work, together with EWKR and WetMAP, makes an important contribution to better informing the management of the Hattah Lakes semi-arid floodplain system and has the potential to be extrapolated to other floodplain systems within the Murray-Darling Basin. Furthermore, this report and the publication in preparation, Gwinn *et al*. (in preparation), can be cited as definitive proof of the positive impacts of this environmental flow program. Thus, proponents of environmental flow management and water managers can use these documents to justify the contentious use of this valuable water.

Lastly, although environmental watering benefited the native plant community, most plant species and functional groups experienced declines in occurrence and richness from 2014 to 2020. This finding likely reflects the impacts of several external drivers of floodplain systems including the long-lasting impacts of 'The Millennium Drought' (1999 to 2009), flood regimes, climate change and variation in annual rainfall before monitoring. It also highlights the importance of long-term monitoring data and the essential role of environmental watering in maintaining the semi-floodplain system of the Hattah Lakes Icon site.

6 Future directions

The continuation of the Hattah Lakes vegetation monitoring program is recommended. In this report, the data enabled the statistical evaluation of the relationships of plant community metrics to both rainfall and flooding; however, as this dataset continues to grow, so does our ability to evaluate more refined management questions. In the near future, this data set will be useful for answering questions about optimal flood volumes, duration, timing and periodicity. Furthermore, a longer temporal data set will enable the description of longer-term patterns of flood and recovery cycles that are difficult to capture within short time frames. This sort of detailed information can help water managers refine their environmental flow delivery strategies to greatest benefit. Additionally, the Hattah Lakes monitoring program provides an annual measure of the state of the plant community that can alert managers to when the system is declining and trigger management.

It is recommended that:

- Ideally, the monitoring program should continue, and the next monitoring period is scheduled for April 2021. The next stage of the monitoring program should involve using the model to predict future vegetation responses to environmental watering followed by on ground monitoring to evaluate the accuracy of the model predictions.
- Predict vegetation responses to a range of environmental watering management strategies.
- Develop semi-arid water plant functional groups classification that can be applied across a range of environmental water management scenarios and riparian systems (e.g. other icon sites and assets).
- Using existing data to accurately model floodplain tree condition and hydrological regimes to determine floodplain tree maintenance requirements and recovery trajectories.
- A plant trait database could be developed and incorporated into the model to enable application across a wide range of riparian systems. Additionally, plant traits can be used to elucidate how water management strategies can influence ecosystem function and system resilience, which can be incorporated into management objectives.

6.1 Predicting vegetation responses to environmental watering

Predictive models allow for the evaluation of the management interventions that have been implemented; however, they can also allow us to go beyond the data to predict the outcomes of hypothetical management interventions that may occur. This can greatly speed up the learning process because management experiments, that can take years to conduct and evaluate, can be essentially performed as desk-top experiments in short time frames and at low cost. Furthermore, predictive models are a platform that can be continually updated as new data are added to the existing dataset so that management decisions are always supported by the best available science.

The new dynamic joint species distribution model provides a framework for future applications and evaluations to refine our understanding of vegetation responses to environmental watering across a range of different riparian systems and management scenarios. These evaluations can include the predicted outcomes of any number of hypothetical environmental watering regimes. Predicting counterfactuals is only one potential use of a predictive model. Thus, other potential applications of the model include:

- Predicting vegetation responses to a range of hypothetical environmental watering management strategies.
- Defining plant functional groups to aid management - prediction of plant response functional groups to environmental water management that is applicable across a range of management scenarios and riparian systems (e.g. other icon sites and assets).

Evaluating environmental watering management scenarios

In actively managed natural systems, managers must choose the best management option to move the system towards a desired state; however, the best management option is not always easily identifiable. For example, we have demonstrated that the Hattah Lake riparian vegetation benefits from management with environmental flows, but we continue to build our understanding and optimise the regime to deliver water to the system (e.g. timing, duration, magnitude) to obtain the greatest conservation value.

For the current project, the model was used to predict the outcome of one alternative management approach (i.e. no management); however, the model could be tailored to predict the outcomes of a variety of management strategies available to water managers. Using models in this way can resolve uncertainties among management strategies at low costs and little risk of mismanagement of the system, which the Hattah Lakes water management program could benefit from. As such a logical next step for model application is predicting vegetation responses to a range of management scenarios including water deliveries (timing, duration, magnitude), climatic influences (natural flooding, rainfall, drought) and management objectives (e.g. competing objectives: understorey vegetation, fish etc). Initially this could be undertaken in the Hattah Lakes context and then expanded to other similar semi-arid riparian systems (e.g. Lindsay-Mulcra floodplain, wetlands and waterways). That is, in the Hattah Lakes context we could predict future vegetation responses to planned watering regimes and then collect on-ground data to evaluate the accuracy of these predictions.

Recommendation: Tailor the model to predict the outcomes of a range of environmental watering management strategies.

Develop a set of nuanced plant functional groups for semi-arid riparian systems

Because applied vegetation ecology research often deals with numerous taxa, interpretation is often simplified by summarising taxa into function groups, as done here. The water plant function groups used for Hattah Lakes have been developed based on plant ecological theory in other systems but have never been empirically validated. A species-specific response model will enable the grouping of plant taxa based on empirical evidence of their response to rainfall and flooding, thus providing scientifically supported and validated functional groupings with which to summarise community dynamics. Developing such functional groups specific to Hattah Lakes will help refine future water management in the system. In addition, these plant functional groups then allow us to apply the model to evaluate the effectiveness of environmental water delivery in other semi-arid riparian systems (e.g. Icon sites, wetland and waterway assets).

Recommendation: Develop semi-arid water plant functional group classification that can be applied in semi-arid riparian systems to refine water management practices.

6.2 Validating floodplain tree recovery trajectories

The flood regime required to maintain floodplain tree health (e.g. River Red Gum and Black Box) and the expected recovery trajectories of those trees in poor health remains a key knowledge gap. This information is essential to inform optimal management scenarios. Although current monitoring programs and models are starting to fill these knowledge gaps, further work is required. One priority investigation should be to validate existing models of tree health maintenance and recovery requirements, in different condition states, in relation to aspects of the flood regime and climatic influences. This could be undertaken utilising the existing TLM tree condition monitoring dataset. We propose adjusting the model for the tree condition data and incorporating accurate hydrological history for the site locations to model response trajectories.

Recommendation: Using existing data accurately model floodplain tree condition and hydrological regimes to determine floodplain tree maintenance requirements and recovery trajectories.

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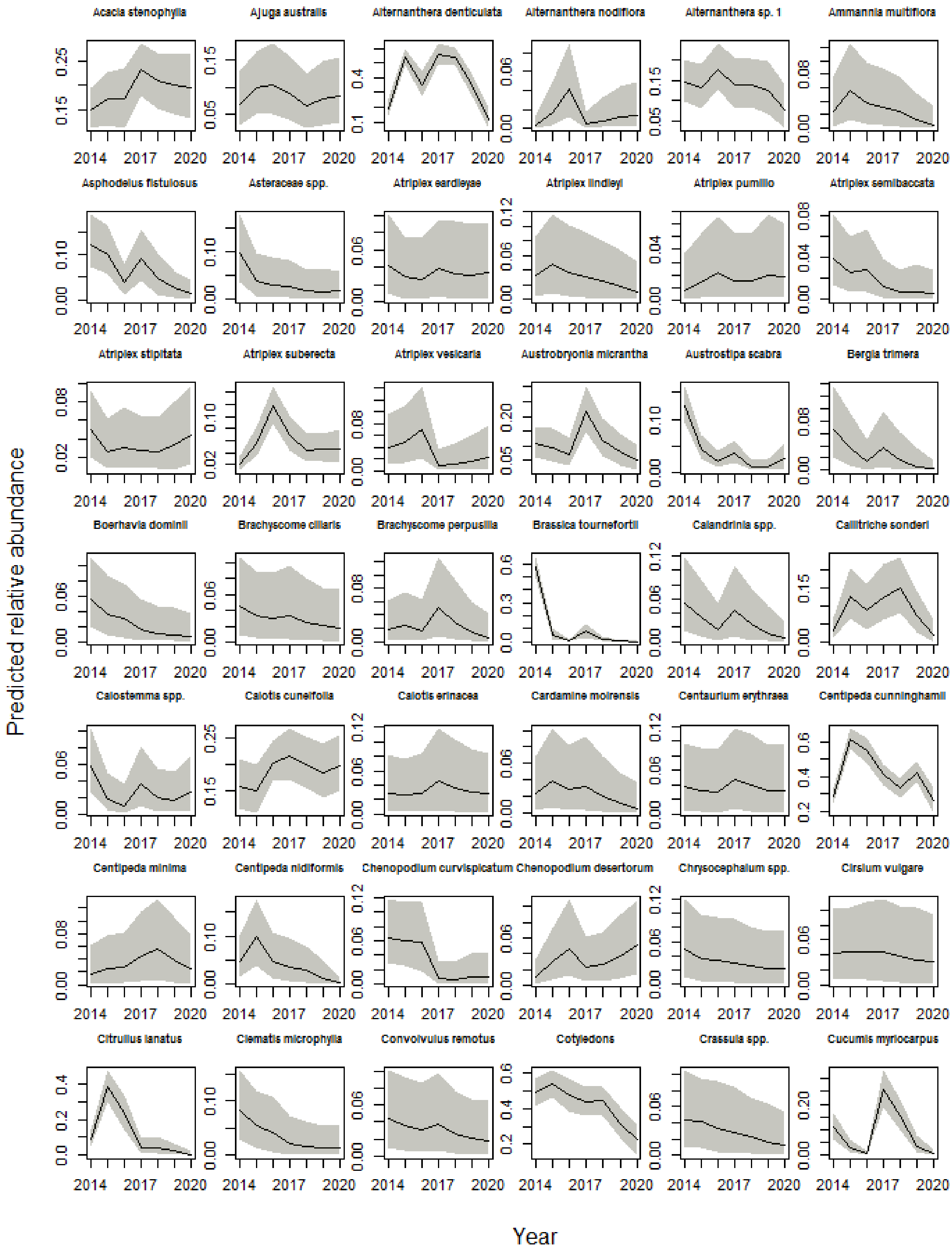
Appendix 1. Monitoring site locations and vegetation types

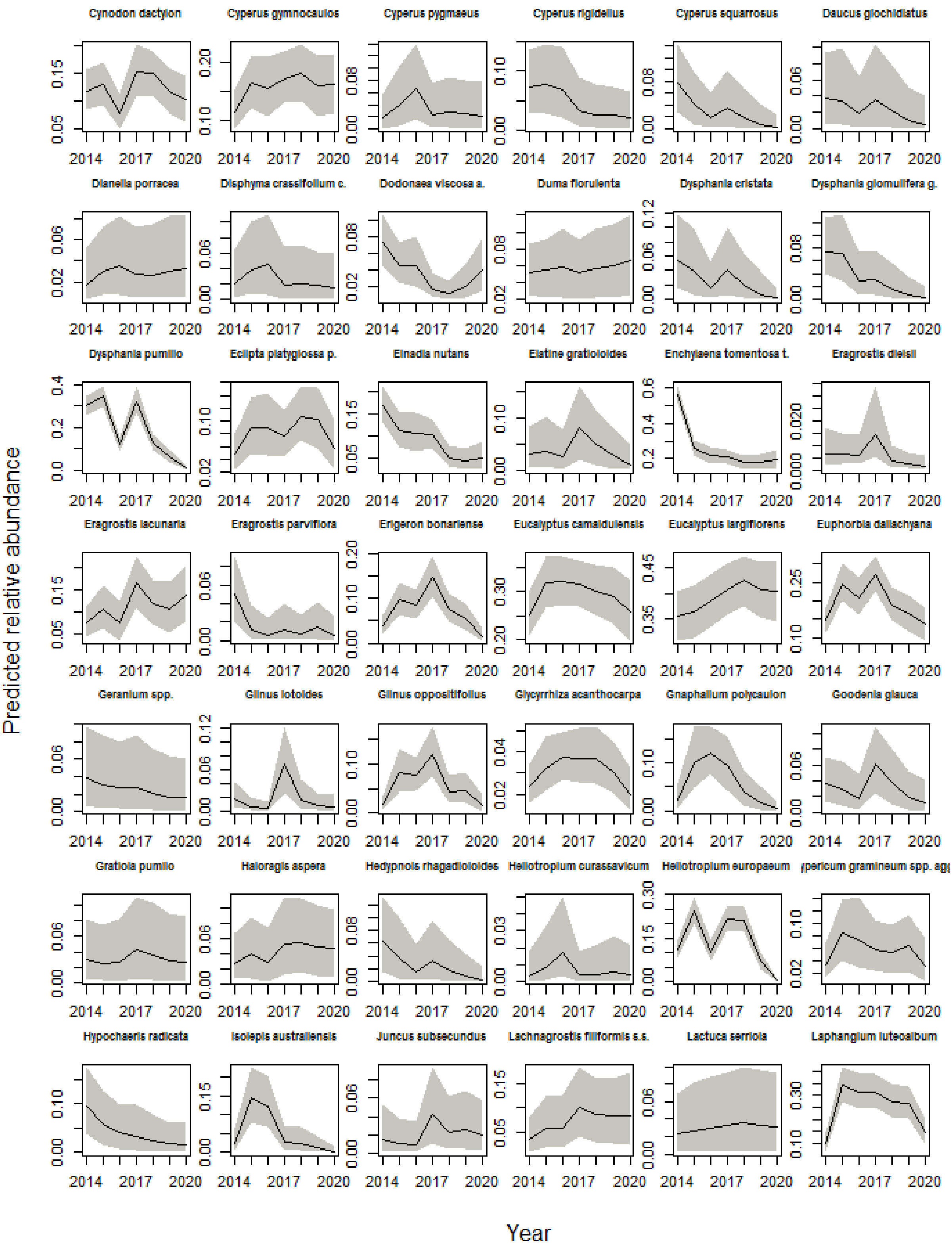
Table A1. The 20 monitoring site locations including transect length and the vegetation zone sampled. Note 'LB' = lake bed and 'F' = floodplain. '(NS)' was not monitored in 2020 and '(45 m F)' indicates that 45 m of the floodplain was monitored in 2020. GPS coordinates are in GDA94, MGA zone 54 and recorded at the lake edge in April 2014. Lake type is taken from SKM (2004) and MDBA (2012).

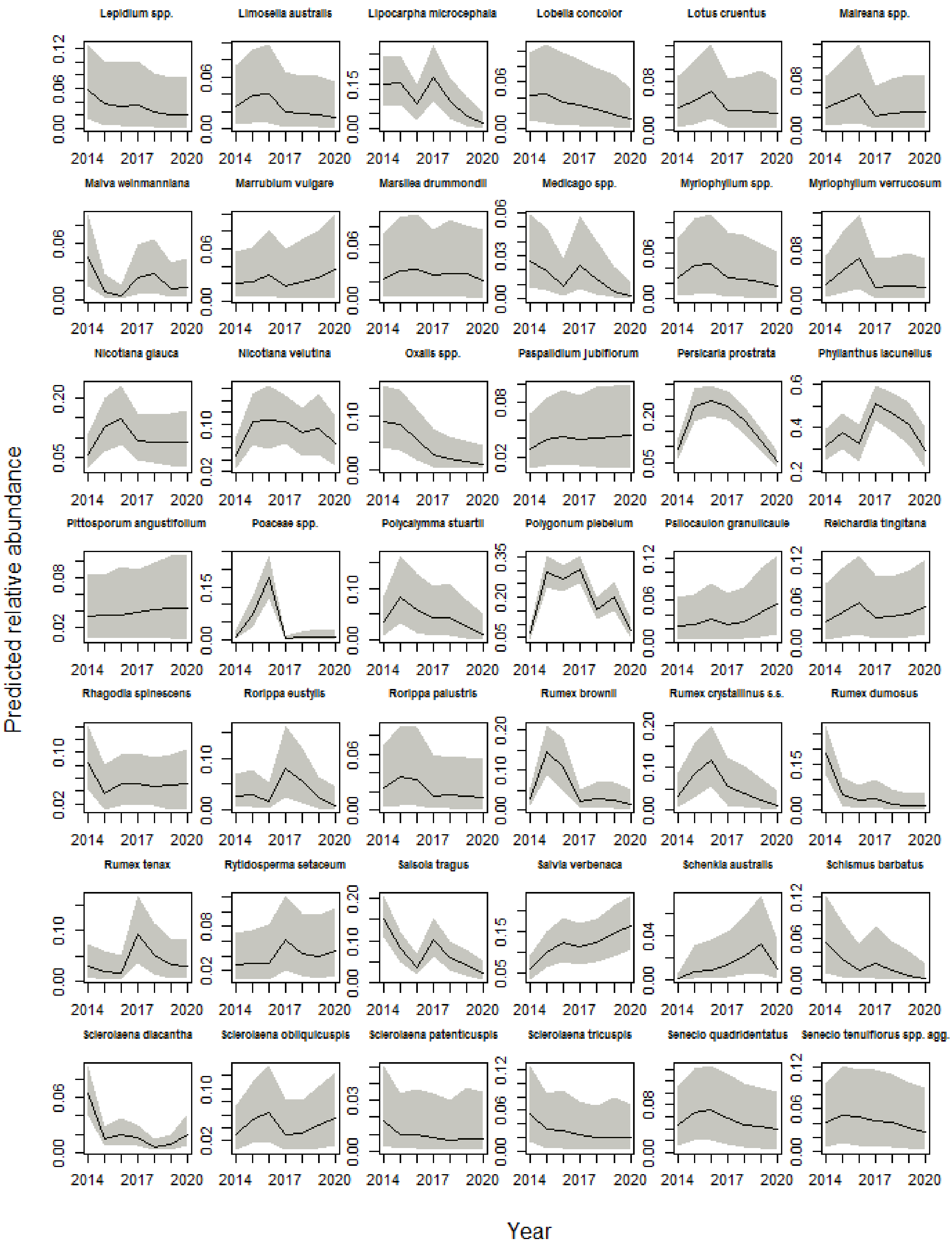
Lake	Lake type	Site number	Transect length (m)	Zone sampled	Easting	Northing
Lake Hattah	Semi-permanent	1	100	LB – F	623702	6152714
		2	100	LB – F	623796	6152759
Lake Arawak		3	100	LB – F	624419	6152696
		4	100	LB – F	624376	6152411
Lake Marramook	Persistent temporary	5	100	LB – F	625443	6152406
Lake Nip Nip		6	100	LB – F	627985	6153763
		7	100	LB – F	328118	6153868
Lake Tullamook		8	150	LB – F	627543	6153870
Lake Yellwell		9	100	LB – F	625795	6159277
		10	150	LB – F	625797	6159449
Lake Bitterang		11	100	LB – F	626472	6163266
		12	150	LB – F	626853	6163505
Lake Woterap		13	100	LB – F	623740	6162672
		14	150	LB – F	623713	6162355
Lake Konardin		15	100	LB – F	624025	6160489
Lake Kramen	Episodic	16	150 (NS)	LB – F	634355	6150392
		17	150 (NS)	LB – F	634051	6150575
		18	100 (45 m F)	LB – F	634048	6149852
		19	100 (NS)	LB – F	633339	6151019
		20	100 (NS)	LB – F	633249	6150809

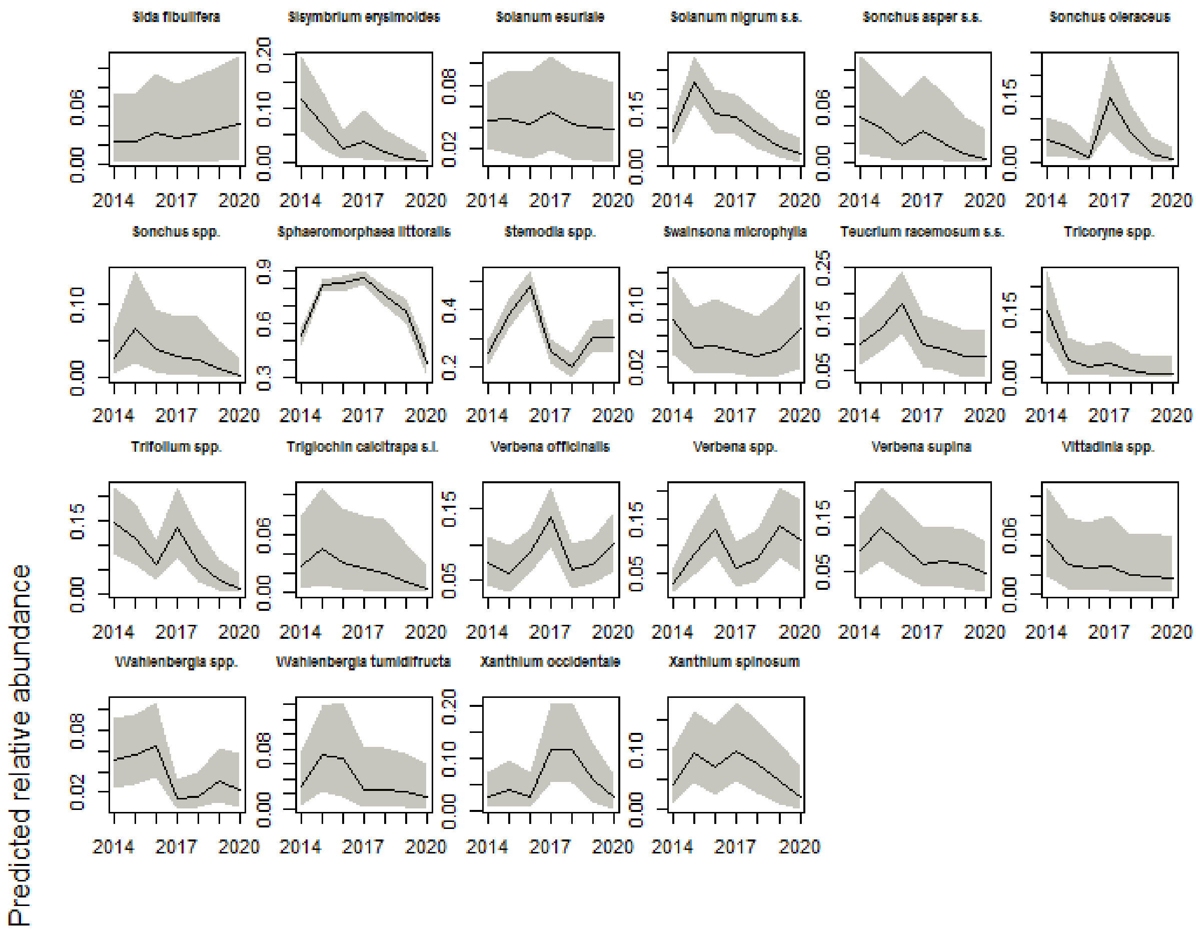
Appendix 2. Model outcomes

Individual species responses




Cynodon dactylon
Cyperus gymnocaulos
Cyperus pygmaeus
Cyperus rigidellus
Cyperus squarrosus
Daucus glochidiatus
Dianella porracea
Disphyma crassifolium c.
Dodonaea viscosa a.
Duma florulenta
Dysphania cristata
Dysphania glomulifera g.
Dysphania pumilio
Eclipta platyglossa p.
Einadia nutans
Elatine gratioloides
Enchylaena tomentosa t.
Eragrostis dielsii
Eragrostis lacunaria
Eragrostis parviflora
Erigeron bonariense
Eucalyptus camaldulensis
Eucalyptus largiflorens
Euphorbia dallachyana
Geranium spp.
Glinus lotoides
Glinus oppositifolius
Glycyrrhiza acanthocarpa
Gnaphalium polycaulon
Goodenia glauca
Gratiola pumilio
Haloragis aspera
Hedypnois rhagadioloides
Heliotropium curassavicum
Heliotropium europaeum
ypericum gramineum spp. ag
Hypochaeris radicata
Isolepis australiensis
Juncus subsecundus
Lachnagrostis filiformis s.s.
Lactuca serriola
Laphangium luteoalbum
Predicted relative abundance
Year
2014 2017 2020


Lepidium spp.
Limosella australis
Lipocarpha microcephala
Lobelia concolor
Lotus cruentus
Maireana spp.
Malva weinmanniana
Marrubium vulgare
Marsilea drummondii
Medicago spp.
Myriophyllum spp.
Myriophyllum verrucosum
Nicotiana glauca
Nicotiana velutina
Oxalis spp.
Paspalidium jubiflorum
Persicaria prostrata
Phyllanthus lacunellus
Pittosporum angustifolium
Poaceae spp.
Polycalymma stuartii
Polygonum plebeium
Psilocaulon granulicaule
Reichardia tingitana
Rhagodia spinescens
Rorippa eustylis
Rorippa palustris
Rumex brownii
Rumex crystallinus s.s.
Rumex dumosus
Rumex tenax
Rytidosperma setaceum
Salsola tragus
Salvia verbenaca
Schenkia australis
Schismus barbatus
Sclerolaena diacantha
Sclerolaena obliquicuspis
Sclerolaena patenticuspis
Sclerolaena tricuspis
Senecio quadridentatus
Senecio tenuiflorus spp. agg.
Predicted relative abundance
Year
2014
2017
2020


Sida fibulifera
Sisymbrium erysimoides
Solanum esuriale
Solanum nigrum s.s.
Sonchus asper s.s.
Sonchus oleraceus
Sonchus spp.
Sphaeromorphaea littoralis
Stemodia spp.
Swainsona microphylla
Teucrium racemosum s.s.
Tricoryne spp.
Trifolium spp.
Triglochin calcitrapa s.l.
Verbena officinalis
Verbena spp.
Verbena supina
Vittadinia spp.
Wahlenbergia spp.
Wahlenbergia tumidifructa
Xanthium occidentale
Xanthium spinosum
Predicted relative abundance
2014
2017
2020

Appendix 3. Species lists

Table A3. Plant species recorded at the Hattah Lakes Icon Site monitoring sites between 2014 and 2020. Note under 'Status', '*' = exotic (Walsh and Entwisle 1994, 1996, 1999; Royal Botanic Gardens Board Victoria (2015)), 'v' = vulnerable, 'r' = rare, 'e' = endangered, 'k' = poorly known (DEPI 2014) and 'L' = listed under the Flora and Fauna Guarantee Amendment Act 2019. 'WPFG' = water plant functional group where 'ATw' = amphibious fluctuation tolerator – woody, Tdr = terrestrial dry, Tda = terrestrial damp, ARp = amphibious fluctuation responder – plastic, T = terrestrial species, ATl = amphibious fluctuation tolerator – low-growing and ATe = amphibious fluctuation tolerator – emergent (see Table 1 for more detail).

Common name	Scientific name	Status	WPFG	2014	2015	2016	2017	2018	2019	2020
Eumong	*Acacia stenophylla*		ATw	✓	✓	✓	✓	✓	✓	✓
Austral Bugle	*Ajuga australis*		Tdr	✓	✓	✓	✓	✓	✓	✓
Bugle	*Ajuga* spp.		Tdr		✓					
Lesser Joyweed	*Alternanthera denticulata* s.s.		Tda	✓	✓	✓	✓	✓	✓	✓
Common Joyweed	*Alternanthera nodiflora*	k	Tda			✓			✓	✓
Joyweed	*Alternanthera sp.* 1	k	Tda	✓	✓	✓	✓	✓	✓	✓
Joyweed	*Alternanthera* spp.		Tda			✓			✓	
Jerry-jerry	*Ammannia multiflora*	v	ARp		✓					
Common Wheat-grass	*Anthosachne scabra* s.l.		Tdr	✓			✓			
Onion Weed	*Asphodelus fistulosus*	*	Tdr	✓	✓	✓	✓	✓	✓	✓
Composite	Asteraceae spp.		T	✓						
Small Saltbush	*Atriplex eardleyae*		Tdr	✓			✓		✓	✓
Slender-fruit Saltbush	*Atriplex leptocarpa*		Tdr							✓
Flat-top Saltbush	*Atriplex lindleyi*		Tdr	✓			✓		✓	
Corky Saltbush	*Atriplex lindleyi* subsp. *inflata*		Tdr			✓				
Flat-top Saltbush	*Atriplex lindleyi* subsp. *lindleyi*	k	Tdr		✓		✓			
Mat Saltbush	*Atriplex pumilio*		Tdr			✓	✓		✓	✓
Berry Saltbush	*Atriplex semibaccata*		Tdr	✓	✓	✓	✓	✓	✓	✓
Saltbush	*Atriplex* spp.		Tdr	✓	✓	✓			✓	✓
Kidney Saltbush	*Atriplex stipitata*		Tdr	✓	✓	✓	✓	✓	✓	✓
Sprawling Saltbush	*Atriplex suberecta*		Tdr	✓	✓	✓	✓	✓	✓	✓
Bladder Saltbush	*Atriplex vesicaria*		Tdr	✓	✓	✓		✓	✓	

Bladder Saltbush	*Atriplex vesicaria* subsp. *variabilis*		Tdr			✓				
Mallee Cucumber	*Austrobryonia micrantha*	r	Tda	✓	✓	✓	✓	✓		
Knotty Spear-grass	*Austrostipa nodosa*		Tdr	✓						
Rough Spear-grass	*Austrostipa scabra*		Tdr		✓					✓
Rough Spear-grass	*Austrostipa scabra* subsp. *falcata*		Tdr						✓	
Spear Grass	*Austrostipa* spp.		Tdr	✓	✓	✓	✓	✓	✓	✓
Small Water-fire	*Bergia trimera*	v	Tda	✓						
Tah-vine	*Boerhavia dominii*		Tdr	✓	✓	✓	✓			
Variable Daisy	*Brachyscome ciliaris*		Tdr	✓						
Variable Daisy	*Brachyscome ciliaris* var. *ciliaris*		Tdr		✓					
Rayless Daisy	*Brachyscome perpusilla*		Tdr				✓			
Mediterranean Turnip	*Brassica tournefortii*	*	Tdr	✓			✓			
Crucifer	Brassicaceae spp.		T	✓						
Purslane	*Calandrinia* spp.		Tdr	✓			✓			
Matted Water-starwort	*Callitriche sonderi*		Tda		✓		✓	✓		✓
Yellow Garland-lily	*Calostemma luteum*	v	Tda							✓
Garland Lily	*Calostemma* spp.		Tda	✓	✓	✓	✓			✓
Blue Burr-daisy	*Calotis cuneifolia*	r	Tdr	✓	✓	✓	✓	✓	✓	✓
Tangled Burr-daisy	*Calotis erinacea*		Tdr			✓	✓			
Riverina Bitter-cress	*Cardamine moirensis*	r	Tda		✓					
Pigface	*Carpobrotus* spp.		Tdr	✓						
Malta Thistle	*Centaurea melitensis*	*	Tdr				✓	✓		
Common Centaury	*Centaurium erythraea*	*	Tdr				✓			
Common Sneezeweed	*Centipeda cunninghamii*		ATl	✓	✓	✓	✓	✓	✓	✓
Spreading Sneezeweed	*Centipeda minima* subsp. *minima* s.s.		ATl					✓		
Cotton Sneezeweed	*Centipeda nidiformis*	r	ATl	✓	✓					
Chenopod	Chenopodiaceae spp.		Tdr		✓	✓				✓
Cottony Saltbush	*Chenopodium curvispicatum*		Tdr	✓	✓	✓	✓	✓	✓	✓
Frosted Goosefoot	*Chenopodium desertorum*		Tdr	✓	✓	✓	✓	✓	✓	✓
Frosted Goosefoot	*Chenopodium desertorum* subsp. *desertorum*	r	Tdr			✓	✓		✓	
Goosefoot	*Chenopodium* spp.		Tdr						✓	✓

Everlasting	*Chrysocephalum* spp.		Tdr	✓						
Chicory	*Cichorium intybus*	*	Tdr	✓						
Spear Thistle	*Cirsium vulgare*	*	Tdr		✓		✓		✓	
Camel Melon	*Citrullus lanatus*	*	Tdr	✓	✓	✓				
Small-leaved Clematis	*Clematis microphylla* s.s.		Tdr	✓	✓					✓
Grass Bindweed	*Convolvulus remotus*		Tdr	✓	✓		✓			
Bindweed	*Convolvulus* spp.		Tdr	✓	✓					
Crassula	*Crassula* spp.		Tda	✓	✓					
Paddy Melon	*Cucumis myriocarpus* subsp. *myriocarpus*	*	Tdr	✓			✓	✓	✓	✓
Couch	*Cynodon dactylon*		Tdr	✓	✓	✓	✓	✓	✓	
Couch	*Cynodon dactylon* var. *dactylon*	*	Tdr					✓		
Native Couch	*Cynodon dactylon* var. *pulchellus*	k	Tdr	✓	✓	✓	✓	✓		✓
Spiny Flat-sedge	*Cyperus gymnocaulos*		ATe	✓	✓	✓	✓	✓	✓	✓
Dwarf Flat-sedge	*Cyperus pygmaeus*	v	ATe			✓				
Curly Flat-sedge	*Cyperus rigidellus*	e, L	ATe	✓	✓	✓				
Flat Sedge	*Cyperus* spp.		ATe	✓						
Bearded Flat-sedge	*Cyperus squarrosus*	v	ATe	✓						
Recurved Thorn-apple	*Datura inoxia*	*	Tdr		✓					
Australian Carrot	*Daucus glochidiatus*		Tdr	✓						
Riverine Flax-lily	*Dianella porracea*	v	Tdr	✓	✓	✓	✓	✓	✓	✓
Rounded Noon-flower	*Disphyma crassifolium* subsp. *clavellatum*		Tdr		✓	✓				
Hard-head Saltbush	*Dissocarpus paradoxus*		Tdr						✓	
Slender Hop-bush	*Dodonaea viscosa* subsp. *angustissima*		Tdr	✓	✓	✓	✓	✓	✓	✓
Tangled Lignum	*Duma florulenta*		ATe	✓	✓	✓	✓	✓	✓	✓
Crested Goosefoot	*Dysphania cristata*		Tdr	✓						
Globular Pigweed	*Dysphania glomulifera* subsp. *glomulifera*		Tdr	✓	✓					✓
Clammy Goosefoot	*Dysphania pumilio*		Tdr	✓	✓	✓	✓	✓	✓	✓
Pigweed	*Dysphania* spp.		Tdr			✓		✓		
Yellow Twin-heads	*Eclipta platyglossa* subsp. *platyglossa*		Tda	✓	✓	✓	✓	✓	✓	✓
Nodding Saltbush	*Einadia nutans*		Tdr	✓	✓	✓	✓	✓	✓	✓
Waterwort	*Elatine gratioloides*		ARp				✓			

Ruby Saltbush	*Enchylaena tomentosa* var. *tomentosa*		Tdr	✓	✓	✓	✓	✓	✓	✓
Mallee Love-grass	*Eragrostis dielsii*		Tdr	✓	✓	✓	✓	✓	✓	✓
Purple Love-grass	*Eragrostis lacunaria*	v	Tdr	✓	✓	✓	✓	✓	✓	✓
Weeping Love-grass	*Eragrostis parviflora*		Tdr	✓					✓	
Love Grass	*Eragrostis* spp.		Tdr		✓	✓			✓	✓
Common Emu-bush	*Eremophila glabra*		Tdr	✓		✓	✓			
Flaxleaf Fleabane	*Erigeron bonariense*	*	Tdr	✓	✓	✓	✓	✓	✓	✓
Tall Fleabane	*Erigeron sumatrensis* var. *sumatrensis*	*	Tdr					✓		
Blue Heron's-bill	*Erodium crinitum*		Tdr	✓						
River Red-gum	*Eucalyptus camaldulensis*		ATw	✓	✓	✓	✓	✓	✓	✓
Black Box	*Eucalyptus largiflorens*		ATw	✓	✓	✓	✓	✓	✓	✓
Eucalypt	*Eucalyptus* spp.		ATw	✓	✓	✓	✓	✓	✓	✓
Flat Spurge	*Euphorbia dallachyana*		Tdr	✓	✓	✓	✓	✓	✓	✓
Crane's Bill	*Geranium* spp.		Tdr	✓						
Hairy Carpet-weed	*Glinus lotoides*		Tda	✓		✓	✓		✓	
Slender Carpet-weed	*Glinus oppositifolius*		Tda	✓	✓	✓	✓		✓	✓
Carpet Weed	*Glinus* spp.		Tda		✓					
Southern Liquorice	*Glycyrrhiza acanthocarpa*		Tda	✓	✓	✓	✓	✓	✓	✓
Indian Cudweed	*Gnaphalium polycaulon*		Tda		✓	✓	✓	✓		
Pale Goodenia	*Goodenia glauca*		Tda	✓	✓		✓	✓		✓
Goodenia	*Goodenia* spp.		Tda		✓			✓		
Dwarf Brooklime	*Gratiola pumilo*	r	Tda				✓			
Rough Raspwort	*Haloragis aspera*		Tda	✓	✓		✓	✓	✓	✓
Hedypnois	*Hedypnois rhagadioloides*	*	Tdr	✓						
Smooth Heliotrope	*Heliotropium curassavicum*		Tda			✓	✓		✓	
Common Heliotrope	*Heliotropium europaeum*	*	Tda	✓	✓	✓	✓	✓	✓	✓
Small St John's Wort	*Hypericum gramineum* spp. agg.		Tdr	✓	✓	✓	✓	✓	✓	
Flatweed	*Hypochaeris radicata*	*	Tdr	✓	✓					
Cat's Ear	*Hypochaeris* spp.	*	Tdr		✓					
Inland Club-sedge	*Isolepis australiensis*	k	ATe		✓	✓				
Club Sedge	*Isolepis* spp.		ATe		✓			✓	✓	

Rush	*Juncus* spp.		ATe		✓				✓	
Finger Rush	*Juncus subsecundus*		ATe	✓			✓		✓	✓
Common Blown-grass	*Lachnagrostis filiformis* s.s.		Tda		✓		✓		✓	✓
Blown Grass	*Lachnagrostis* spp.		Tda		✓					
Prickly Lettuce	*Lactuca serriola*	*	Tdr				✓		✓	
Jersey Cudweed	*Laphangium luteoalbum*		Tda	✓	✓	✓	✓	✓	✓	✓
Common Peppercress	*Lepidium africanum*	*	Tdr	✓						
Peppercress	*Lepidium* spp.		Tdr	✓						✓
Austral Mudwort	*Limosella australis*		ARp		✓					
Button Rush	*Lipocarpha microcephala*	v	ATe	✓	✓		✓			
Poison Pratia	*Lobelia concolor*		Tda	✓	✓					
Austral Trefoil	*Lotus australis* var. *australis*	k	Tdr	✓						
Red Bird's-foot Trefoil	*Lotus cruentus*		Tdr	✓		✓				
Trefoil	*Lotus* spp.		Tdr						✓	
Short-leaf Bluebush	*Maireana brevifolia*		Tdr	✓	✓	✓	✓	✓	✓	✓
Sago Bush	*Maireana pyramidata*		Tdr							✓
Radiant Bluebush	*Maireana radiata*		Tdr			✓				
Bluebush	*Maireana* spp.		Tdr	✓	✓		✓		✓	
Australian Hollyhock	*Malva weinmanniana*		Tdr	✓			✓	✓	✓	✓
Horehound	*Marrubium vulgare*	*	Tdr	✓	✓	✓	✓	✓	✓	✓
Common Nardoo	*Marsilea drummondii*		ARp		✓		✓		✓	✓
Burr Medic	*Medicago polymorpha*	*	Tdr				✓			
Medic	*Medicago* spp.	*	Tdr	✓	✓	✓	✓	✓		✓
Creeping Myoporum	*Myoporum parvifolium*		Tdr					✓	✓	
Water Milfoil	*Myriophyllum* spp.		ARp		✓					
Red Water-milfoil	*Myriophyllum verrucosum*		ARp			✓				
Tree Tobacco	*Nicotiana glauca*	*	Tda		✓	✓	✓	✓		✓
Tobacco	*Nicotiana* spp.		Tda		✓					
Velvet Tobacco	*Nicotiana velutina*		Tda	✓	✓	✓	✓	✓	✓	✓
Prickly pear	*Opuntia* spp.	*	Tdr	✓	✓	✓	✓			
Bonefruit	*Osteocarpum salsuginosum*		Tdr				✓			

Grassland Wood-sorrel	*Oxalis perennans*		Tdr	✓	✓		✓			✓
Wood Sorrel	*Oxalis* spp.		Tdr	✓	✓					
Warrego Summer-grass	*Paspalidium jubiflorum*		Tda	✓	✓	✓	✓	✓	✓	✓
Creeping Knotweed	*Persicaria prostrata*		ATl	✓	✓	✓	✓	✓	✓	✓
Lagoon Spurge	*Phyllanthus lacunarius*	v	Tda							✓
Sandhill Spurge	*Phyllanthus lacunellus*	r	Tdr	✓	✓	✓	✓	✓	✓	
Weeping Pittosporum	*Pittosporum angustifolium*		Tdr	✓	✓	✓	✓	✓	✓	✓
Winged Plains-bush	*Pluchea rubelliflora*	e	Tdr					✓		
Grass	Poaceae spp.		T	✓	✓	✓			✓	
Poached-eggs Daisy	*Polycalymma stuartii*		Tdr		✓			✓		
Small Knotweed	*Polygonum plebeium*		Tda	✓	✓	✓	✓	✓	✓	✓
Wiry Noon-flower	*Psilocaulon granulicaule*	*	Tdr	✓	✓	✓	✓	✓	✓	✓
False Sow-thistle	*Reichardia tingitana*	*	Tdr			✓				✓
Hedge Saltbush	*Rhagodia spinescens*		Tdr	✓		✓	✓	✓	✓	✓
Shrubby Twin-leaf	*Roepera aurantiaca* subsp. *aurantiaca*		Tdr		✓					
Pale Twin-leaf	*Roepera glauca*		Tdr	✓						✓
Twin-leaf	*Roepera* spp.		Tdr						✓	✓
Dwarf Bitter-cress	*Rorippa eustylis*	r	Tda	✓			✓	✓		
Marsh Yellow-cress	*Rorippa palustris*	*	Tda		✓					
Slender Dock	*Rumex brownii*		Tda		✓	✓	✓		✓	✓
Glistening Dock	*Rumex crystallinus* s.s.	v	Tda			✓				
Wiry Dock	*Rumex dumosus*		Tda	✓						
Dock	*Rumex* spp.		Tda	✓			✓	✓		
Narrow-leaf Dock	*Rumex tenax*		Tda		✓		✓	✓		
Bristly Wallaby-grass	*Rytidosperma setaceum*		Tdr	✓						✓
Wallaby Grass	*Rytidosperma* spp.		Tdr	✓	✓		✓	✓		
Prickly Saltwort	*Salsola tragus*		Tdr	✓	✓	✓	✓	✓	✓	✓
Wild Sage	*Salvia verbenaca*	*	Tdr		✓	✓	✓	✓	✓	✓
Wild Sage	*Salvia verbenaca* var. *vernalis*	*	Tdr	✓						
Spiked Centaury	*Schenkia australis*		Tdr						✓	
Arabian Grass	*Schismus barbatus*	*	Tdr	✓						

Grey Copperburr	*Sclerolaena diacantha*		Tdr	✓	✓	✓	✓	✓	✓	✓
Limestone Copperburr	*Sclerolaena obliquicuspis*		Tdr		✓	✓		✓	✓	✓
Spear-fruit Copperburr	*Sclerolaena patenticuspis*	v	Tdr	✓	✓	✓	✓	✓	✓	
Streaked Copperburr	*Sclerolaena tricuspis*		Tdr	✓			✓	✓		
Cotton Fireweed	*Senecio quadridentatus*		Tdr		✓		✓	✓		
Mallee Groundsel	*Senecio spanomerus*		Tdr							✓
Groundsel	*Senecio* spp.		Tdr	✓	✓					
Slender Fireweed	*Senecio tenuiflorus* spp. agg.		Tdr		✓		✓			
Variable Sida	*Sida corrugata*		Tdr						✓	
Pin Sida	*Sida fibulifera*		Tdr	✓			✓		✓	
Smooth Mustard	*Sisymbrium erysimoides*	*	Tdr	✓	✓					
London Rocket	*Sisymbrium irio*	*	Tdr	✓						
Mustard	*Sisymbrium* spp.	*	Tdr							✓
Hairy Nightshade	*Solanum eremophilum*	k	Tdr	✓						
Quena	*Solanum esuriale*		Tdr	✓	✓	✓	✓	✓	✓	✓
Black Nightshade	*Solanum nigrum* s.s.	*	Tdr	✓	✓	✓	✓	✓	✓	
Oondoroo	*Solanum simile*		Tdr			✓				
Rough Sow-thistle	*Sonchus asper* s.s.	*	Tdr	✓						
Common Sow-thistle	*Sonchus oleraceus*	*	Tdr	✓	✓		✓	✓		
Sow Thistle	*Sonchus* spp.	*	Tdr		✓					
Spreading Nut-heads	*Sphaeromorphaea littoralis*		Tda	✓	✓	✓	✓	✓	✓	✓
Blue Rod	*Stemodia florulenta*		Tda							✓
Blue Rod	*Stemodia* spp.		Tda	✓	✓	✓	✓	✓	✓	
Small-leaf Swainson-pea	*Swainsona microphylla*	r	Tdr	✓	✓	✓	✓	✓	✓	✓
Swainson Pea	*Swainsona* spp.		Tdr		✓					
Native Spinach	*Tetragonia* spp.		Tdr	✓						
Grey Germander	*Teucrium racemosum* s.s.		Tdr	✓	✓	✓	✓	✓	✓	✓
Caltrop	*Tribulus terrestris*		Tdr	✓						✓
Rush Lily	*Tricoryne* spp.		Tdr	✓						
Clover	*Trifolium* spp.	*	Tdr	✓	✓	✓	✓		✓	
Spurred Arrowgrass	*Triglochin calcitrapa* s.l.		ATe		✓					

Needle Grass	*Triraphis mollis*	r	Tdr		✓					
Common Verbena	*Verbena officinalis* s.l.		Tdr	✓				✓	✓	
Inland Verbena	*Verbena officinalis* var. *africana*	k	Tdr	✓		✓	✓	✓		✓
Native Verbena	*Verbena officinalis* var. *gaudichaudii*	k	Tdr							✓
Verbena	*Verbena officinalis* var. *halei*	*	Tdr							✓
Verbena	*Verbena officinalis* var. *officinalis*		Tdr	✓	✓					
Verbena	*Verbena* spp.		Tdr	✓	✓	✓	✓	✓	✓	✓
Trailing Verbena	*Verbena supina*	*	Tda		✓		✓	✓	✓	✓
Trailing Verbena	*Verbena supina* var. *supina*	*	Tda	✓						
Annual New Holland Daisy	*Vittadinia cervicularis*		Tdr	✓				✓		
Fuzzy New Holland Daisy	*Vittadinia cuneata*		Tdr							✓
Fuzzy New Holland Daisy	*Vittadinia cuneata* var. *cuneata*		Tdr	✓						
Dissected New Holland Daisy	*Vittadinia dissecta* var. *hirta*		Tdr	✓	✓	✓	✓	✓	✓	✓
Woolly New Holland Daisy	*Vittadinia gracilis*		Tdr	✓	✓				✓	
New Holland Daisy	*Vittadinia* spp.		Tdr	✓	✓	✓		✓		
River Bluebell	*Wahlenbergia fluminalis*		Tda	✓		✓	✓			✓
Bluebell	*Wahlenbergia* spp.		Tdr	✓	✓	✓		✓	✓	✓
Mallee Annual-bluebell	*Wahlenbergia tumidifructa*	r	Tdr		✓					
Noogoora Burr	*Xanthium occidentale*	*	Tdr				✓	✓		
Bathurst Burr	*Xanthium spinosum*	*	Tdr		✓	✓	✓	✓		

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