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Determining water requirements for Black Box (*Eucalyptus largiflorens*) floodplain woodlands of high conservation value using drip-irrigation

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Abstract

Black Box (*Eucalyptus largiflorens* F. Muell.), is a keystone tree species of lowland semi-arid floodplain ecosystems in south-eastern Australia. *E. largiflorens* woodlands are of high conservation value and threatened by climate change-induced drought and irrigation water diversions due to their location on upper floodplain areas where flood frequency has declined. Water requirements of *E. largiflorens* have not been well quantified using empirical data. Accordingly, knowledge gaps exist in relation to volumes of environmental water required to maintain and improve ecological condition for disconnected floodplain woodlands. To further assist conservation and water resource management, we tested the use of drip irrigation to provide a variety of water regimes to experimental plots in order to monitor tree responses. Water was provided via irrigation delivery across four regimes representing known volumes of water, referred to as an environmental water provision, applied over a 22-week period for two Austral summers. Benefits to trees were identified by measuring transpiration and plant water status using sap flow sensors and a Scholander pressure chamber, respectively. Results indicate that volumes of 0.3, 0.4, 0.7 and 0.8 ML increased *transpiration* and improved plant water status in comparison to a control, with delivery recommended to commence early autumn. Greater volumes (1.4 ML), substantially increased transpiration and improved water status, especially when delivered at a rate of ~25 mm week^{-1} compared to a monthly 'burst' which broadly represented natural, sporadic summer rainfall in the region. For an environmental watering provision of 25 mm week^{-1}, ~178 ha of *E. largiflorens* woodland can be watered with a 1 GL environmental water allocation. The study methods presented are relevant worldwide and our results further the collective understanding of the benefits environmental water provides to *E. largiflorens*.

KEYWORDS

black box, drought, environmental water, Murray-Darling Basin, transpiration, vegetation health, water potential, water stress

1 | INTRODUCTION

Floodplain ecosystems, particularly in arid and semi-arid regions, continue to be heavily altered by increasing demand for water resources and the effects of climate change (Colloff et al., 2015; Glenn et al., 2013; Stella & Bendix, 2019; Vörösmarty et al., 2010). These alterations, including decline in ecosystem conditon, have stimulated research to understand water requirements, ecological responses and importance of hydrological connectivity for the biotic components of floodplains (Poff & Zimmerman, 2010; Rogers & Ralph, 2011; Sajedipour et al., 2017; Schofield et al., 2018). In particular, a body of research has focused on understanding how managed environmental flows can be used to combat ecosystem decline to conserve ecosystems and biodiversity (Acreman et al., 2014; Arthington et al., 2018; Poff et al., 2017). However, there remains a lack of empirical data on water requirements or volumes of water that need to be delivered to maintain floodplain woodlands and shrubland communities of high conservation value in a healthy condition, especially in the Murray-Darling Basin (MDB) of south-eastern Australia. Previously, studies have been undertaken using remote sensing and hydrological flood frequency data to elucidate vegetation water requirements; however, few studies exist in the MDB that directly and robustly measure water use of vegetation to assist with determination of water requirements.

With continued reductions in river flows and overbank flooding, a major challenge for conserving floodplain ecosystems is how environmental flows of sufficient magnitudes can be delivered to vegetation communities on elevated, disconnected floodplain locations. In the MDB, such disconnected upper floodplain areas can no longer be managed using in-channel environmental flow releases as the water volumes required to inundate these areas exceeds what is currently possible. Release of large environmental flow volumes is constrained by weirs and locks to reduce the risk of flood damage to infrastructure, crops and private property. As an example, along South Australian reaches of the River Murray, floodplain areas requiring flows of more than 80 000 ML day^{-1} to flood, are well outside what is considered manageable under the current constraints and these floodplains are likely at greater risk of further decline. A survey undertaken between 1987 and 1988, indicated that even then, *Eucalyptus largiflorens* communities were in poor condition with only 56% of trees sampled along the length of the River Murray in good health (Smith & Smith, 2014). Since then, *E. largiflorens* has been shown to maintain poorer condition than *E. camaldulensis* (River Red Gum; Smith & Kenny, 2005; Cunningham et al., 2009) which lines riverbanks and is within the zone of management intervention.

There are several management options to address this challenge, including the use of infrastructure to move water to wetland areas passively or by pump (Stewardson & Guarino, 2018); raising the height of weir pools (Clarke et al., 2015; Gehrig et al., 2016) and creation of artificial freshwater lenses by recharging groundwater bores and subsurface pumping to draw freshwater from the river into the root zone of vegetation (Berens et al., 2009; Doody et al., 2009).

1.1 | Woody vegetation of semi-arid and arid floodplains in south-East Australia

Woody vegetation of arid and semi-arid floodplain ecosystems includes trees that function as keystone species and are responsible for multiple ecosystem processes and services. These processes include provision of habitat and food resources, diversion of flooding flows, redistribution of soil water, sequestration and distribution of carbon, nutrients and organic matter and the provision of shade and shelter for humans and livestock (Capon et al., 2013; Colloff, 2014; Sweeney et al., 2004).

In south-east Australia, three eucalypt tree species, *E. camaldulensis*, *E. coolabah* (Coolibah) and *E. largiflorens* (Black Box) are found on lowland inland floodplains. These trees have evolved multiple adaptations to withstand prolonged droughts and floods and extremes of temperature and salinity (Costelloe, 2016; Costelloe & Strang, 2016; Roberts, 1993). However, they require access to adequate fresh water for growth, reproduction and maintenance. Their adaptation to extremes of wet and dry conditions includes the ability to switch between use of different water sources including lateral flows from rivers, soil water, rainfall and groundwater reserves (Costelloe, 2016; Costelloe & Strang, 2016; Doody et al., 2009; Holland et al., 2006; Slavich et al., 1999). Salt and drought tolerance vary, with *E. largiflorens* and *E. coolibah* being more drought and salt-tolerant than *E. camaldulensis* (Costelloe et al., 2008; Roberts & Marston, 2011).

E. largiflorens is widely distributed in the MDB, forming open woodlands (Roberts & Marston, 2011) and often disconnected from surface water resources for long periods of time. Woodland location on the floodplain, community structure and composition are driven by former inundation history, with recruitment and regeneration linked to floods (George et al., 2005). Tree water requirements vary for different life cycle stages such as recruitment, establishment, growth and reproduction if mixed-aged stands are to develop and provide habitats of high biodiversity value (McGinness et al., 2018; Moxham et al., 2018). Adaptations for survival in semi-arid and arid environments include drought-resistance via slow growth and low transpiration (Akeroyd et al., 1998; Costelloe et al., 2008; Doody et al., 2009; Jolly & Walker, 1996; Slavich et al., 1999); opportunistic use of different water sources, including highly saline groundwater (Doody et al., 2009; Holland et al., 2006; Streeter et al., 1996), leaf excision to reduce transpiration when water stressed and an ability to recover to reproduce rapidly following flooding (Moxham et al., 2018; Parsons & Zubrinich, 2010). Due to its slow growth, trees are typically 10–20 m tall, with a diameter at breast height > 10 cm achieved only after about 100 years (George et al., 2005).

1.2 | Flood characteristics

E. largiflorens woodlands occur over a wide range of flood regimes (Roberts & Marston, 2011). They tend to be located on the higher parts of these lowland floodplains (Holland et al., 2006; Margules &

Partners et al., 1990; Smith & Smith, 2014) and consequently, are inundated less often than *E. camaldulensis*. Historically, *E. largiflorens* woodlands received 10–50 floods per century compared with 45–90 for *E. camaldulensis* communities (Roberts, 2004). The position of *E. largiflorens* woodlands often marks a floodplain-upland boundary between flood-dependent vegetation and terrestrial communities, including agricultural land. Consequently, large areas of *E. largiflorens* woodland has been cleared for agriculture, particularly in the upper and central Murray regions, and remnants are subject to grazing pressure from livestock (Keith, 2004). Woodlands are considered of high conservation value due to their high structural and biotic diversity (Sommerville, 1999; Wassens et al., 2005).

The Millennium Drought (1997–2010) drove substantial dieback of floodplain eucalypt communities in the southern MDB (Cunningham et al., 2009; Mac Nally et al., 2011). Managed environmental watering has been used to counter declines in condition (Doody et al., 2009; Fernando et al., 2018; Holland et al., 2009; Moxham et al., 2018), prompting research into response of trees to different flood regimes. Moxham et al., (2018) highlighted broader age-class ranges of *E. largiflorens* at frequently flooded sites, with fewer dead trees, better canopy condition and higher growth and reproduction than at sites not flooded for 24 years. McGinness et al., (2018) found *E. largiflorens* woodlands that were flooded at least every 1 in 10 years had structurally complex understorey vegetation, supporting greater abundance and diversity of migratory small-bodied birds and had less dieback than sites that were less frequently flooded. As little as 1 week of inundation was found to trigger improved nutritional status and physiological responses, including rapid reduction in water stress (Fernando et al., 2018).

Nonetheless, there remains a lack of long-term empirical data on tree water use of *E. largiflorens*. Flood-gradient studies, such as that undertaken for *E. camaldulensis* (Doody, Colloff, et al., 2015), are difficult to replicate for *E. largiflorens* woodlands due to their position beyond the limits of managed environmental flows. Novel techniques therefore need to be designed to provide environmental water to disconnected tree communities to identify appropriate volumes of water which will help to achieve ecosystem and management outcomes. These outcomes include maintaining the current extent of *E. largiflorens* across the MDB (MDBA, 2014), prevent further decline, increase recruitment and build resilience to future perturbations. One way of delivering environmental water is via drip irrigation, although the rate and frequency at which water should be applied to generate a benefit to the trees via improved tree water status is unknown. It is also suggested that watering over multiple years ('follow-up' watering), can provide additional benefits, and more so when delivered over successive years (Wallace, Gehrig, Doody, Davies, et al., 2021).

The aim of our study was therefore to test if drip irrigation supplied to disconnected floodplain regions could be used to determine the water use (transpiration) and water status trends of mature drought-stressed *E. largiflorens* woodland trees. In addition, we endeavoured to test the feasibility of supplying water to measure tree responses to a variety of water application rates across four treatment plots. We sought to understand if increased water availability increased transpiration as well as reduced tree water stress by measuring shoot/stem pre-dawn potential, reported as plant water status response. The study was continuously measured to include two Austral summers when evaporative demand was highest and trees at higher risk of water stress. The purpose of the study was to provide field-based empirical data to inform conservation policy and environmental flow delivery in the MDB. Our focus was to further our understanding of water volumes required (water requirements) to generate ecological benefits for *E. largiflorens* such as improved plant water status and increased transpiration.

Over the first irrigation period, we endeavoured to determine which irrigation volumes led to increased transpiration and improved plant water status relative to a control plot. Plots were irrigated approximately weekly using four irrigation rates. Rates of irrigation were altered for all treatment plots for the second irrigation season to improve our understanding of tree response to varying water delivery frequency and the benefit of watering consecutive years. While application of drip irrigation is common for irrigated agriculture, its use as a method to identify environmental water volumes required to benefit disconnected woodland communities, is unique.

2 | METHODS

2.1 | Site details

The Markaranka Floodplain research site (139°53′22″E, 34°05′28″S), adjacent to a large vineyard (Treasury Wine Estates Pty Ltd), is located on the River Murray ca. 25 km north-west and downstream of Waikerie in the Riverland region of South Australia (Figure 1). The Riverland is the main irrigation region in the state, with many horticultural properties lining the river.

The region is semi-arid, with mean rainfall of ~250 mm year^{-1} and potential pan evaporation of 1900 mm year^{-1} (site 024029; Bureau of Meteorology, 2017), hence, an environment of severe water-deficit. Rainfall is typically higher during winter and spring than summer, which generally has at least one 20–40 mm event as the region is characterized by large episodic summer rainfall events. (Figure 2). Mean daily temperature range is 6–33°C and summer maxima may exceed 40°C for several days. Evaporative demand increases from early spring (September), indicating vegetation water requirements will also increase (Figure 2).

Dominant woodland vegetation in the region is related to proximity to water, elevation and, to some extent, depth to groundwater. On the Markaranka Floodplain, *E. camaldulensis* is the dominant tree species adjacent to water, while *E. largiflorens* woodland occupies more distant, elevated areas of floodplain which are flooded less frequently. The study site consisted of an open *E. largiflorens* woodland with a sparse understorey of salt-tolerant plants including Tangled Lignum (*Duma florulenta*) and Saltbush (*Atriplex* spp.; Gehrig, 2013). Research plots were located 300–500 m from the main channel (Figure 1) over low-permeability Coonambidgal clay up to 5 m thick (Jolly, 1994).

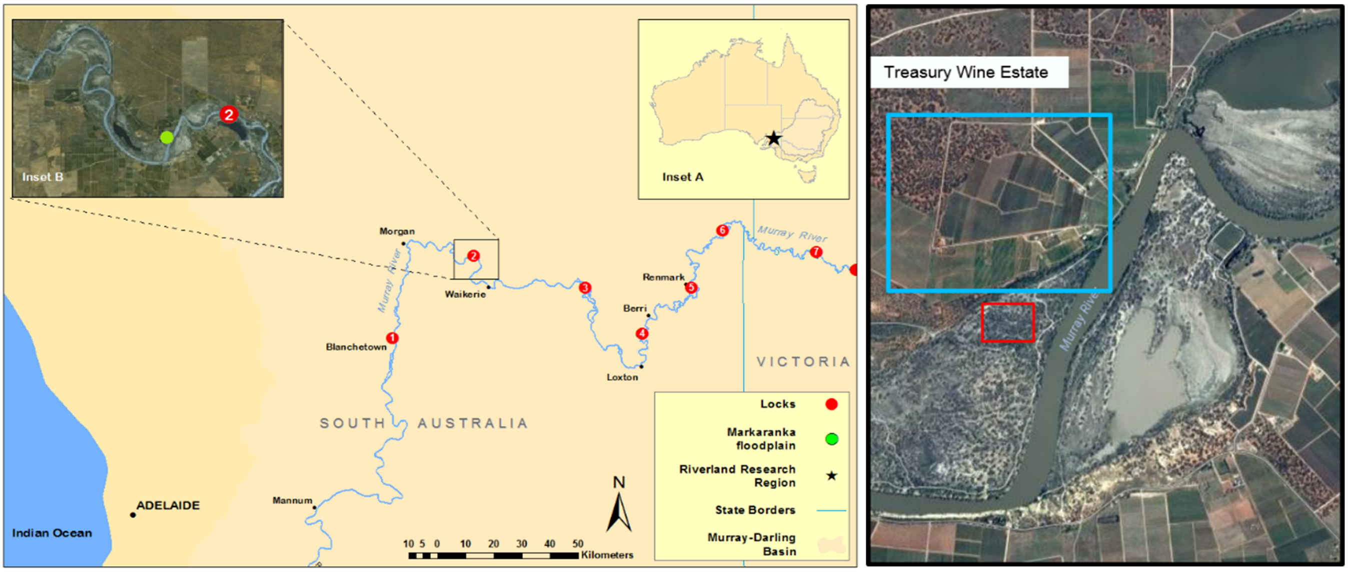

FIGURE 1 Location of the Markaranka floodplain along the River Murray in the Riverland region of South Australia. Inset (a) highlights the field location in the Murray-Darling Basin. Inset (b) pinpoints the Markaranka Floodplain research area, while the adjacent image distinguishes between the adjoining vineyard (blue outline), the research floodplain (red outline) and the river and associated wetlands

Doody, Pritchard, et al. (2015) found the depth to groundwater is approximately 5 m with a soil chloride content between 9000 and 25 000 μS cm^{-1} prior to drip irrigation. This level of salinity is within the tolerance zone for *E. largiflorens* and if within the reach of tree roots, the groundwater is available for tree consumption (Doody et al., 2009; Overton et al., 2018). Prior to watering, the stand structure of *E. largiflorens* within the experimental area was variable, ranging from large, single-stemmed individuals to numerous multi-stemmed trees that showed signs of coppicing. The population structure was unbalanced with no evidence of young growth stages (i.e., no seedlings and one sapling <5 cm, diameter at 1.3 m above ground).

2.2 | Flood and rainfall history

A water volume of ∼60 GL day^{-1} is required to initiate overbank flows in this region and up to 145 GL day^{-1} to inundate the *E. largiflorens* study woodland according to the River Murray Flood Inundation Model (RiM-FiM; Overton, 2005; Overton et al., 2006). Consequently, the site has not been inundated since major floods during 1974–76 (Figure 3a) and trees otherwise rely on rainfall and groundwater where possible. Trees at this location are unlikely to access lateral bank recharge, given their location beyond 100 m from the river channel and zone of influence (Doody et al., 2014).

A dry decade occurred from 1999 to 2008 (Figure 3b; Bureau of Meteorology, Station 024029) during the Millennium Drought followed by a wet decade from 2009 to 2018, encompassing the study period (2014–2015). Seasonal rainfall averages for the dry decade were 147 mm in 'winter' (winter–spring; May–October) and 107 mm in 'summer' (summer-autumn; November–April) and 140 and 143 mm, respectively, for the wet decade. The higher summer average rainfall in the wet decade was caused by very wet summers in 2010 and 2011, with widespread flooding of lower elevations. For the purposes of this study, 'summer' rainfall in 2013/14 is representative of that of the wet decade (169 mm), while rainfall in 2014/15 was similar to a dry decade (118 mm). By early 2013, study trees were in poor condition prior to application of drip irrigation, with sparse canopies and a large proportion of dead branches (Gehrig, 2013).

2.3 | Field irrigation design

This research forms part of a larger drip irrigation study to artificially water *E. largiflorens* (for further detail, see Gehrig, 2013, 2014; Gehrig & Frahn, 2015). For the purpose of this study, four irrigation treatment plots and one control plot were randomly selected from a total of 15 plots, located within an experimental area of 4.5 ha (Figure 1). Plots were 50 × 50 m and had a 5 m buffer between adjacent plots.

Water delivery via drip irrigation was managed by Treasury Wine Estates Pty Ltd (see Gehrig, 2013 for details), with water delivered during the vineyard irrigation season (November–May). Water was piped to rows of polytube dripper lines at 3 m intervals (17 rows per plot). Drippers were installed at 50 cm intervals along each line (see Gehrig, 2013 for details). Valves attached to the main water source allowed water delivery to each plot at rate of 1.1 L s^{-1} for a specified period (e.g. 12 h). The period of delivery was directly related to a specific flow volume regime (cf. Gehrig & Frahn, 2015 for details) and water was delivered for 22 weeks over two irrigation seasons in 2013/14 and 2014/15 (Table 1).

As continual 'flooding' per se did not occur, we report the drip irrigation regimes as a 'watering provision' in ML of total water delivered,

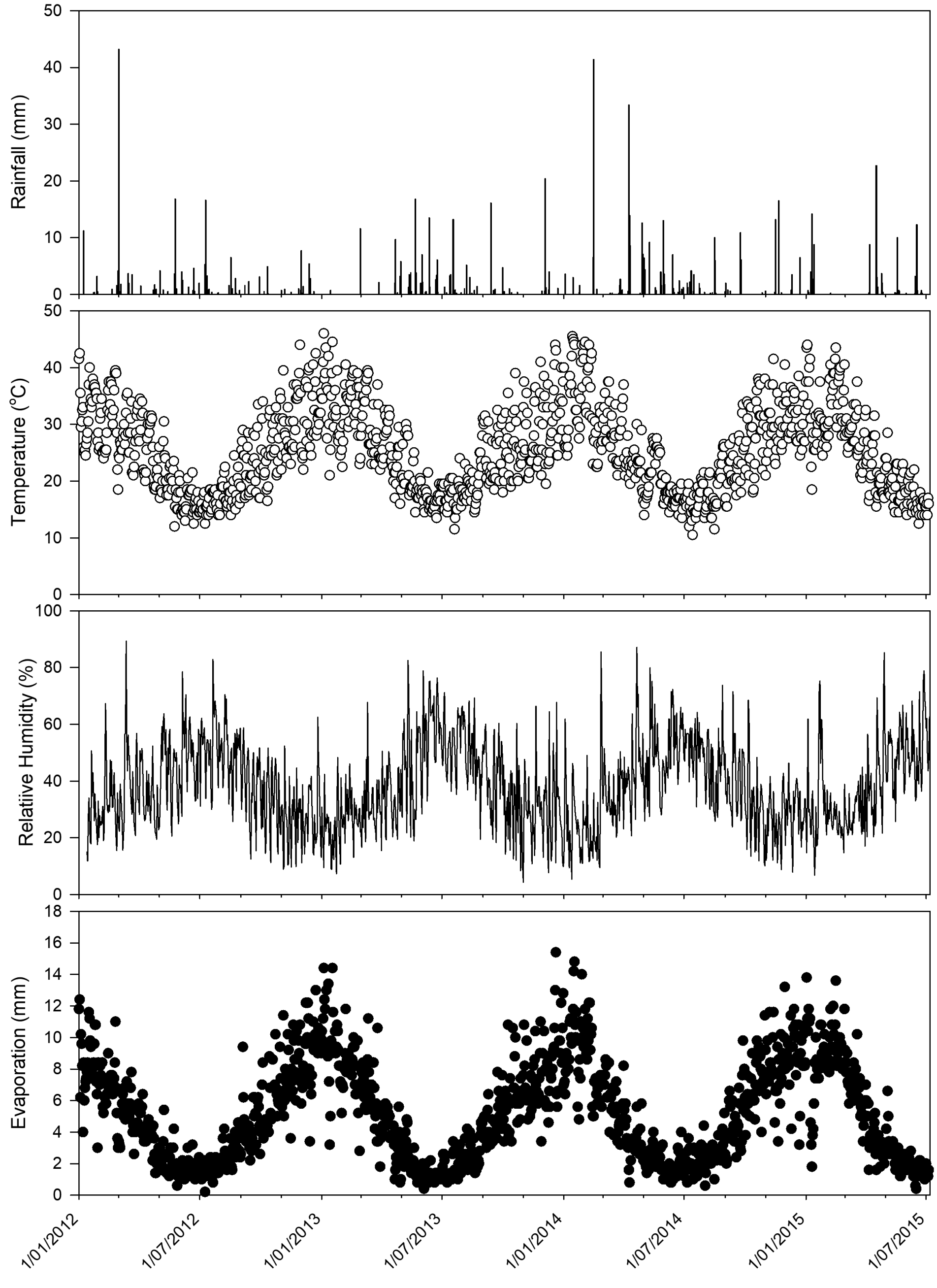

FIGURE 2 Daily trends in rainfall (mm), temperature (°C), relative humidity (%) and evaporation (mm) between 1 January 2012 and 5 July 2015 at weather station 024029, Waikerie

converted to millimetres delivered each week or 'rainfall equivalent' (Table 1). Data is reported per treatment plot as Wi_{w_5}, Wi_{w_15}, $Wi_{w\_12.5}$, $Wi_{w\_7.5}$ as well as a control plot for the 2013/14 irrigation season, where W indicates a water treatment plot, *i* represents the first irrigation season of 2013/14, w represents a weekly water application rate, designated by the number following it (e.g. Wi_{w_5} is a plot irrigated in 2013/14 at a rate of 5 mm rainfall equivalent each week over the irrigation season). Plot codes for 2014/15 represent altered dripper regimes with plots reported as $Wii_{2m\_50\ (i5)}$, $Wii_{w\_26(i15)}$, $Wii_{w\_0\ (12.5)}$, $Wii_{m\_100(i7.5)}$ and a control (Table 1). These codes use *ii* to represent the second irrigation season (2014/15), m represents a water application rate of once a month and 2m represents volume of water applied once every 2 months. The information in brackets beginning with *i*, indicates the previous irrigation season regime for ease of cognizance. It is important to note that this project was managed adaptively to suit additional but limited resources that became available for the 2014/15 irrigation season and as such, has a less rigorous project design than otherwise desired. We were also required to work within the operational watering schedule of the vineyard.

Low volumes delivered once a week created a wet sphere of influence around each dripper, but moisture did not cover the whole plot. Larger volume regimes, such as 25 mm $week^{-1}$, saturated the soil surface across most of the plot. The plots and measured trees remain the same each year, only the treatment irrigation rate changes. Soil moisture measurements, although desirable, were out of scope.

In 2013/14, water was delivered weekly to monitor tree response to small volumes applied at regular intervals to begin to understand the benefits different application rates had on tree transpiration and

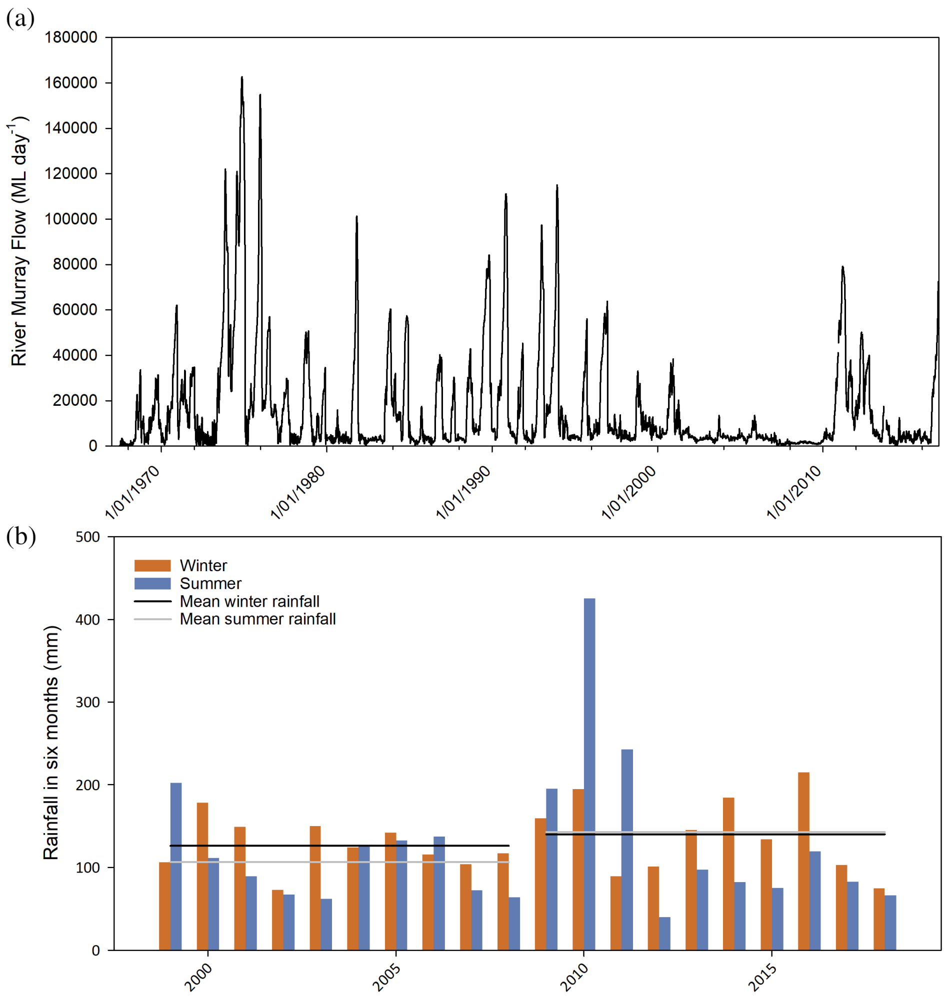

FIGURE 3 (a). Hydrograph of River Murray flow (ML day^{-1}) at Morgan, South Australia, from 1967 to 017; (b). Rainfall at Waikerie (024029) in winter (May to October) and summer (November to April) for the decades 1999–2008 inclusive, representing a recent dry decade, and 2009 to 2018 inclusive, representing a recent wetter decade. Average decadal winter and summer rainfall is also shown

plant water status, particularly when all plots received water at the same time (Table 1). Water application rates in 2014/15 were altered to vary volume and frequency of delivery to investigate responses to natural conditions, such as sporadic rainfall (Table 1). One treatment included withholding water to monitor if a sustained benefit could be detected over the second irrigation season (Table 1). The control provided an opportunity to monitor transpiration rates under a 'do-nothing' water management scenario, where environmental flows are not provided (Table 1).

2.4 | Transpiration

Sap flow sensors (SF300, Greenspan Technology, Warwick, Queensland, Australia) were installed in five plots in late January 2014 to determine tree transpiration (*T*). Methods of installation, detection of conducting wood area, scaling to plot level and error correction followed those of Doody et al., (2015a). Sap flow was measured continuously in six trees per plot, with two probe heads per tree, from 25 January 2014 to 5 July 2015. Small, medium and large trees were randomly selected for measurement of *T* based on tree basal area classes to represent a cross-section of tree sizes in each plot. Plot basal area and conducting wood area (determined using sap flow probes; Doody, Colloff, et al., 2015), were measured in mid-January 2014 and mid-March 2015 (Table 2). Trees had undergone drought stress, as demonstrated by very thin conducting wood, often less than 15 mm thick. Plot daily transpiration (mm day^{-1}) was calculated as the product of plot conducting wood area and mean daily plot sap velocity (Doody, Colloff, et al., 2015).

2.5 | Shoot water potential

Shoot/stem water potential (Ψ_{shoot}) provides a quantitative measure of tree water status in relation to water availability in the soil. This provides an indication of whether plants are increasingly water stressed, particularly during hotter and drier months from late spring to early autumn when evaporative demand increases and soil water availability decreases. Water stress becomes evident from increasingly negative values of Ψ_{shoot} and reported as a decline or reduction in plant water status.

Within each plot, four trees were randomly selected every survey period for measures of Ψ_{shoot}. Two shoots per tree were collected before sunrise ($\Psi_{predawn}$) to reduce many of the confounding variables

TABLE 1 Plot codes and irrigation water treatments during 2013/14 and 2014/15

	Plot code	Weekly irrigation (mm)	Total volume delivered (ML)	Total irrigation delivered (mm)	Design rationale
7/11/13-3/4/14	Control	0.0	0.0	0.0	Comparison and 'do-nothing' watering scenario
	Wi_{w_5}	5.0	0.3	105.0	Investigate *T* trends and plant water status to 5 mm week^{-1}
	$Wi_{w\_7.5}$	7.5	0.4	158.0	Investigate *T* trends and plant water status to 7.5 mm week^{-1}
	$Wi_{w\_12.5}$	12.5	0.7	263.0	Investigate *T* trends and plant water status to 12.5 mm week^{-1}
	Wi_{w_15}	15.0	0.8	315.0	Investigate *T* trends and plant water status to 15 mm week^{-1}
18/12/14-13/5/15	Control	0.0	0.0	0.0	Comparison and 'do-nothing' watering scenario
	$Wii_{w\_0(i12.5)}$	0.0	0.0	0.0	Investigate sustained benefit after one irrigation season
	$Wii_{2m\_50(i5)}$	50.0[a]	0.3	150.0	Investigate effect of sporadic moderate rainfall bi-monthly
	$Wii_{w\_26(i15)}$	26.0	1.4	546.0	Investigate effect of high-volume irrigation delivered weekly
	$Wii_{m\_100(i7.5)}$	100.0[b]	1.4	500.0	Investigate effect of sporadic high rainfall monthly

Note: T is transpiration. Weekly irrigation is presented as a rainfall equivalent in mm per delivery period (i.e., weekly, monthly, bi-monthly). The design rationale for each regime is presented. Tree transpiration and plant water status was measured over each irrigation season.
[a]bimonthly and [b]monthly: water delivered all at once to investigate large 'bursts' of rainfall, characteristic of summer.

TABLE 2 Plot tree characteristics measured on 14 January 2014 and 23 March 2015

Plot	Plot BAOB m^2 ha 2014	Plot BAOB m^2 ha 2015	Plot CWA m^2 ha 2014	Plot CWA m^2 ha 2015
Control	10.01	9.64	1.73	1.64↓
Wi_{w_5}/Wii_{2m_50}	6.28	6.47	1.11	1.10↓
$Wi_{w\_7.5}$/Wii_{m_100}	12.15	11.69	2.04	1.93↓
$Wi_{w\_12.5}$/Wii_{w_0}	5.00	5.12	1.02	1.21↑
Wi_{w_15}/Wii_{w_26}	15.20	15.50	2.78	3.15↑

Note: BAOB is plot total basal area over bark (m^2 ha), CWA is total plot conducting wood area (m^2 ha).

associated with variability in evapotranspiration and photosynthetic rates (e.g. sunny/overcast and or shaded/not-shaded conditions). Samples were immediately placed in snap lock bags with Ψ_{shoot} measured within 10 min. A shoot was defined as a terminal branchlet bearing 5–10 leaves. Ψ_{shoot} was determined using a pressure chamber instrument (Model 1000, PMS Instrument Company, Oregon, USA; Scholander et al., 1965). The pressure required for water to exude from the petiole is proportional to the degree of water stress of the tree. Measurements were made ~ three monthly to include periods before, during and after irrigation. Mean plot $\Psi_{predawn}$ is reported.

2.6 | Statistical analyses

Transpiration data during the dates of overlap between the 2 years (January 25 to June 30) were combined with daily observations of rainfall, minimum and maximum vapour pressure deficit (vpd_{min}, vpd_{max}), potential evapotranspiration (*pET*) and accumulated volumes of irrigation at each delivery date, for each of the treatments. Accumulated irrigation volumes were restarted at 0 for the second year of the treatments, as was the control.

A generalized linear model was fitted to analyse the difference in the treatments taking into account differences in climate and accumulated irrigation volumes:

$$g(\text{Transpiration}) \sim \text{Treatment} + \text{rainfall} + vpd_{\min} + vpd_{\max} + \text{total}pET + \text{irrigation} + corAR1(\epsilon) \quad (1)$$

In Equation (1), g() is a link function, where we used a square root transformation of the transpiration data after analysis of the residuals in the non-transformed model. The function corAR1(ϵ) applies a first order autocorrelation model to the residuals, as it was assumed that the transpiration data would be autocorrelated in time.

The model was run for all data (across the two treatment years) and for the individual treatment years. In the first case, the assumption was that the treatments of the first year can in some way influence the treatments of the second year, while in the second case the treatments are considered independent. As the result from the combined analysis was not materially different from the independent year analysis, we only report the results from the individual year analysis. After fitting the model, the autocorrelation structure of the residuals was analysed, which indicated that the first order regressive model removed most of the autocorrelation structure in the residuals.

3 | RESULTS

3.1 | Rainfall and irrigation

During the Austral summer (December–February), average and maximum temperature in 2014 and 2015 were 32°C (0.5°C above average) and 46, and 32 and 44°C, respectively. Annual rainfall was below average in 2013 and 2015 (192 and 210 mm, respectively) and above average in 2014 (294 mm).

Irrigation commenced on 7 November 2013 for the 2013/14 measurement period. Due to operational issues with delivery of irrigation water, a regular watering regime was not established until early January 2014, coinciding with installation of sap flow sensors. Irrigation commenced on December 18 for the 2014/15 measurement period and was provided for 22 weeks in both years.

3.2 | Response of *E. largiflorens* to drip irrigation and climate variables

Transpiration was measured continuously in all plots for 527 days (Figure 4). As shown via the generalized linear model (Tables 3 and 4) all treatment plots maintained significantly higher *T* rates than the control plot over both years of irrigation ($P < 0.001$; Figure 4). Of note, $Wii_{w\_0(i12.5)}$ maintained higher *T* than the control even though water was withheld during the second irrigation season ($P < 0.001$).

During the first irrigation season, there was a distinct separation in *T* rates between plots that received 5 and 7.5 mm week^{-1} and 12.5 and 15 mm week^{-1}. Hence, trees receiving higher rates of irrigation water maintained higher *T* rates (Table 3). When irrigation regimes were varied in frequency and volume of application across the treatments over the second irrigation season, all treatment plots had similar *T* rates in comparison to the control except $Wii_{w\_26(i15)}$ which had higher *T* (see Figure 4). This result suggests that 'follow-up' watering in large bursts (i.e., $Wii_{2m\_50(i5)}$ and $Wii_{m\_100(i7.5)}$) may not be as effective as weekly delivery ($Wii_{w\_26(i15)}$). Changing irrigation frequency to bi-monthly but maintaining a similar total volume over the 22 weeks was not as effective as weekly irrigation ($Wii_{2m\_50(i5)}$). The control plot increased *T* in response to rainfall events during both irrigation seasons but continued to reduce *T* rate over the course of monitoring (Figure 4).

Maximum *T* of 0.474 mm day^{-1} for the control plot was recorded on 14 April 2014 in response to high rainfall in the preceding days. Treatment $Wi_{w\_12.5}$ recorded maximum *T* of 0.594 mm day^{-1} on 12 February 2014, while $Wii_{w\_26(i15)}$ peaked at 1.184 mm day^{-1} on 3 March 2015 during an extended dry period. This maximum (1.184 mm day^{-1}) is the highest rate recorded for *E. largiflorens* to date. Maxima of 0.86 and 0.52 mm day^{-1} have been recorded in the flushed zone of the Bookpurnong floodplain (Doody et al., 2009) and

TABLE 3 Results of the generalized model analysis for the 2013/2014 season

Factor	Value (relative to control)	*p*-value
Wi_{w_5}	0.16	< 0.001
$Wi_{w\_7.5}$	0.17	< 0.001
$Wi_{w\_12.5}$	0.42	< 0.001
Wi_{w_15}	0.38	< 0.001
vpd_{max}	0.03	0.01
vpd_{min}	0.03	0.05
pET	0.01	0.11
Rainfall	-2.23×10^{-3}	0.01
Irrigation volume	-0.48×10^{-3}	< 0.001

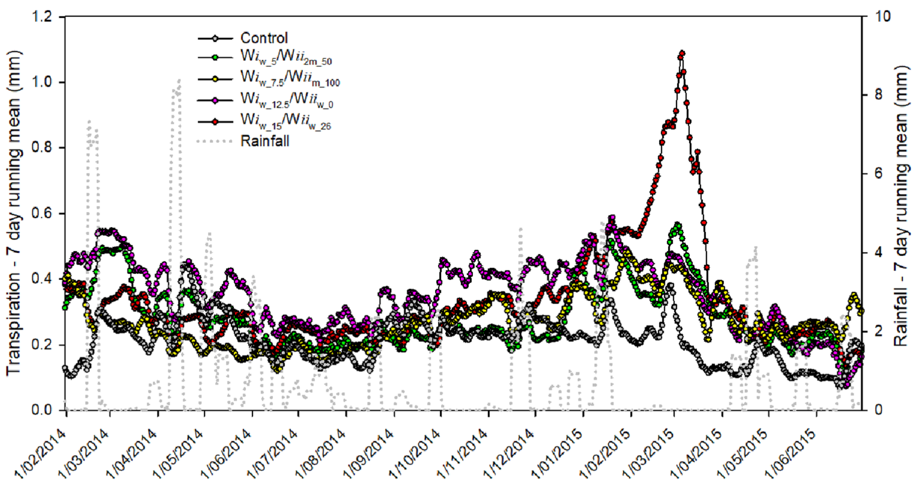

FIGURE 4 7-day running mean of transpiration (mm) - control, treatment plots and rainfall

TABLE 4 Results of the generalized model analysis for the 2014/15 season

Factor	Value (relative to control)	*p*-value
$Wii_{w\_0\ (i12.5)}$	0.14	< 0.001
$Wii_{2m\_50(i5)}$	0.13	< 0.001
$Wii_{w\_26(i15)}$	0.20	< 0.001
$Wii_{m\_100(i7.5)}$	0.14	< 0.001
vpd_{max}	0.03	0.19
vpd_{min}	0.04	0.21
pET	0.06	< 0.001
Rainfall	1.04 × 10–3	0.56
Irrigation volume	1.43 × 10–5	0.05

beyond the flushed zone at Yanga National Park in 2011 (unpublished data), respectively.

Over both irrigation seasons, irrigation was a significant variable, given a specific treatment plot *T* (Tables 3 and 4; $P < 0.001$ and $P = 0.05$ for 2013/14 and 2014/15, respectively). It might seem curious that the impact of irrigation (and rainfall) in 2013/2014 is negative, but this simply means that after accounting for the difference in irrigation treatments, adding further irrigation (or rainfall) slightly reduces transpiration. Potential ET in 2014/15 was the only significant climate variable ($P < 0.001$; Table 4), and rainfall was not significant. In this season, further irrigation had a positive effect on *T* (after accounting for the treatment, Table 4). Overall these results indicate that the main factor explaining the difference in *T* is the irrigation treatment, followed by some of the other factors, which varied by season (Tables 3 and 4).

3.3 | Water potential

Over both summer periods prior to irrigation, plant water status varied with most plots having mean $\Psi_{predawn}$ of > − 3.0 MPa. The control however, was often not the most water stressed for unknown reasons which could indicate some ability to access and use groundwater. Once irrigation began in 2013/14, plant water status was lowest (i.e. more negative $\Psi_{predawn}$) in the control plot and only alleviated with Autumn rainfall and reduced evaporative demand (Figure 5a).

With irrigation, treatment plots substantially increased plant water status (i.e. less negative $\Psi_{predawn}$) in both years (Figure 5a,b). There were significant differences between the December 2013 and January 2014 measurements for $Wi_{w\_7.5}$ ($P = 0.02$, paired *t*-test) and $Wi_{w\_12.5}$ ($P < 0.001$, paired *t*-test; Figure 5a). Likewise, significant differences between December 2014 and February 2015 were detected for $Wii_{m\_100(i7.5)}$ ($P = 0.002$, paired *t*-test) and $Wii_{w\_26(i15)}$ ($p = <0.001$, paired *t*-test; Figure 5b). Water stress of $Wii_{2m\_50\ (i5)}$ improved marginally (Figure 5b).

Of importance is the reduced water status in October and December 2014 (Figure 5a) compared to April 2014 (Figure 5b), prior to irrigation commencing for the 2014/15 summer. All treatment plots significantly

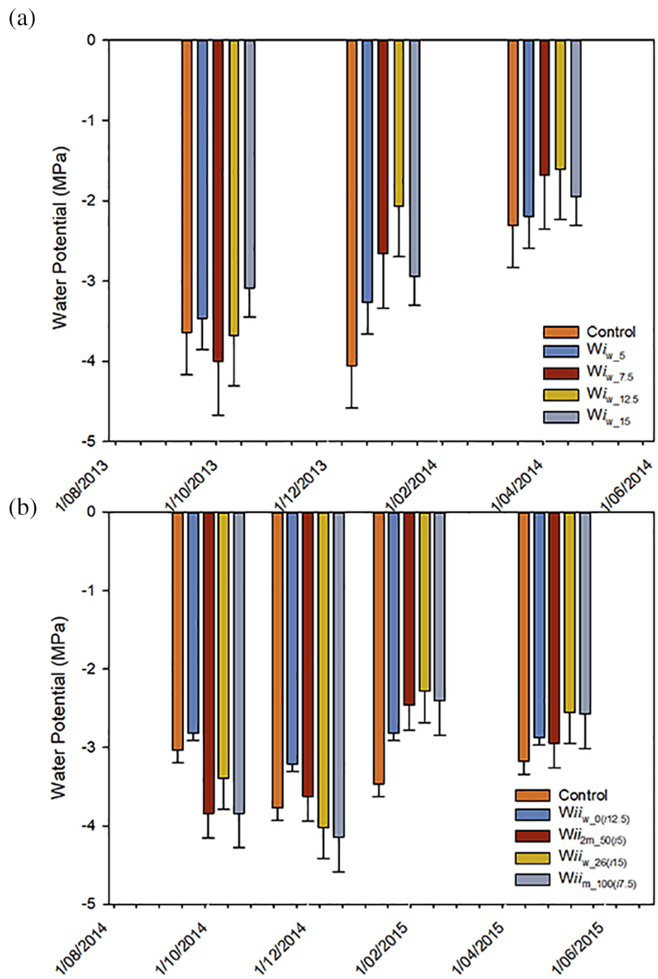

FIGURE 5 Mean plot *E. largiflorens* pre-dawn shoot water potentials (MPa; mean ± S.E. n = 4 per plot) in (a) 2013/14 and (b) 2014/15, for the control plot and four irrigation treatments. Irrigation occurred between 7 November 2013 and 3 April 2014 (a) and 13 December 2014 and 13 May 2015 (b)

decreased water status indicating increased water stress (Wi_{w_5}, $P = 0.008$; $Wi_{w\_7.5}$, $P < 0.001$; $Wi_{w\_12.5}$, $P = 0.002$; Wi_{w_15}, $P < 0.001$, paired *t*-test). This suggests that provision of irrigation earlier would have likely prevented increased water stress to the degree measured.

Although $Wi_{w\_12.5}$ and Wi_{w_15} demonstrated higher *T* rates than Wi_{w_5} and $Wi_{w\_7.5}$ (Table 3), $Wi_{w\_12.5}$ and $Wi_{w\_7.5}$ showed increased water status from $\Psi_{predawn}$ measurements (Figure 5a). It is unclear why Wi_{w_15} has a more negative $\Psi_{predawn}$ but likely related to rabbits interfering with dripper pipe, leading to inconsistent pressure and irrigation disruption. Both plots receiving 100 mm month^{-1} ($Wii_{w\_26(i15)}$ and $Wii_{m\_100(i7.5)}$) showed improved water status even though *T* rates were lower for $Wii_{m\_100(i7.5)}$ (Figure 5b). The plot with second year watering withheld ($Wii_{w\_0\ (i15)}$), maintained improved water status compared to the control but a poorer water status compared to the other treatments in February 2015 (Figure 5b). An extended drought period in 2015 may explain the lower water status across all plots in April that year, compared to the previous year, demonstrating the benefit of rainfall to supplement irrigation (Figure 5a,b).

3.4 | Conducting wood area

Increase or decrease in conducting wood area (CWA) can provide some additional insights related to tree response, potentially indicating portioning of resources to leaf, root and conducting wood growth. Without additional soil and plant measurements this is difficult to quantify. CWA measurements undertaken at monitoring commencement and completion, exhibit a decline of 5% for the control plot which is not surprising (Table 2). A similar decline is noted for $Wii_{m\_100(i7.5)}$, while $Wii_{w\_0\ (i15)}$ where water was withheld during the second irrigation season, increased CWA by 16%, the reason for this is unknown. CWA of $Wii_{2m\_50\ (i5)}$ remained the same, perhaps reflecting the same volume of water received both irrigation seasons, albeit at different frequencies of delivery. Not surprising, CWA of $Wii_{w\_26(i15)}$ increased by 12%, related to higher volumes of water received weekly over both irrigation seasons.

4 | DISCUSSION

A review of *E. largiflorens* water requirements (Casanova, 2015) indicates a flood frequency of every three to seven years is required for trees to have vigorous growth, with a duration of inundation somewhere between three to six months. The timing of inundation may not be important according to Casanova (2015) while Roberts and Marston (2011) suggest timing of initial water delivery in early spring may supplement winter rainfall and provide increased water availability to support trees during the rise in evaporative demand that occurs thereafter. By 12–16 years without inundation, trees will be in a poor condition with a reduced capacity to respond (Bond et al., 2018; Casanova, 2015). A noticeable absence in the literature is quantified volumes of environmental water required to generate tree and ecosystem benefits. This is because reported water requirements or tree community responses are related to flood regimes (Casanova, 2015; McGinness et al., 2018; Moxham et al., 2018; Roberts & Marston, 2011) or estimated volumes of water storage to riverbanks (e.g. Holland et al., 2009) rather than in-situ measurements of tree transpiration and plant water status. This study is therefore the first to apply drip irrigation to investigate rapid response indicators, such as transpiration and plant water status of flood dependent tree species *E. largiflorens* to increased water availability. The results provide insights into how trees might benefit from environmental water of differing volumes and frequency of water application, should current constraints be overcome to deliver water to higher floodplain elevations.

4.1 | New knowledge to inform environmental flow delivery to disconnected arid and semi-arid floodplains

For *E. largiflorens*, flow volume, frequency, timing and duration of environmental watering will depend on whether the objective is to maintain or improve tree condition, trigger reproduction and sustain/improve population demographics or improve habitat complexity (Bond et al., 2018; McGinness et al., 2018; Roberts & Marston, 2011) from a floodplain and water management perspective. Further considerations relate to antecedent conditions, particularly years since last flood and flood regime characteristics, as well as rainfall received during inter-flood periods. Accordingly, environmental watering needs to be designed to take account of the full range of hydrological processes that influence tree condition. This study provides some preliminary indicative volumes of water that could be delivered to provide benefits to mature drought stressed woodlands (summarized in Table 5) and which might instigate future innovation to overcome current constraints to water delivery to disconnected floodplain regions.

Addition of water via drip irrigation led to higher *T* rates in all treatment plots in comparison to the control. Similar benefits have been observed for *E. camaldulensis* in response to natural (Doody, Colloff, et al., 2015) and artificial flooding (Holland et al., 2009). Plant water status was improved for all treatments plots in the first irrigation season, but more variable in the second due to changes in timing of watering (i.e. from weekly to monthly or bi-monthly 'bursts', in line with seasonal rainfall volumes). Likewise, water status increased for *E. largiflorens* after increased water availability via artificial means (Doody et al., 2009; Fernando et al., 2018; Holland et al., 2009). It was also evident from the first irrigation season, that higher volumes of water (0.7 and 0.8 ML) led to higher *T* rates but did not necessarily reduce water stress considerably. This could be related to tree resource partitioning which requires further investigation.

To achieve appreciable increases in *T* rates and increased water status in mature drought stressed woodlands, a total volume of 1.4 ML delivered weekly, ($Wii_{w\_26}(_{i15})$) could be trialled further as a baseline to future water management planning In addition, a higher weekly delivery regime the preceding irrigation season may have a substantial influence (0.7 ML; Wi_{w_15}). When delivered in monthly bursts in this study ($Wii_{m\_100}(_{i7.5})$, 1.4 ML was effective at reducing water stress and maintaining statistically higher *T* rates than the control ($P < 0.001$). Additionally, provision of water in the consecutive year appeared more effective at reducing tree water stress when delivered in higher volumes such as 1.4 ML .

Of note, *T* rates during the consecutive year of watering remained similar when compared to the control (except for $Wii_{w\_26(i15)}$), indicating there is unlikely a 'right' formula for how water volumes should be delivered and in what combination unless a response such as that seen by $Wii_{w\_26(i15)}$ is sought. Ultimately, any water added to disconnected floodplain regions provides a benefit to *E. largiflorens*, including rainfall which drove a reduction in tree water stress for the control site. A similar result for this species was also identified by Fernando et al., (2018) where only 7 days after wetland flooding, increased water status was measurable. When irrigation was available, *T* rates were likely driven by irrigation over both watering seasons, rather than rainfall, however this requires further investigation. This contrasts with findings of Wen and Saintilin (2015) who found via remote sensing that *E. camaldulensis* recovery to drought breaking floods could be explained by rainfall, rather than inundation.

TABLE 5 Summary of new knowledge that has been derived using drip irrigation as a method to deliver environmental water provisions to drought stressed, disconnected floodplain *E. largiflorens* communities

New knowledge	Volume magnitude (ML per irrigation season)	Duration	Timing of delivery	Water status
Increased *T* relative to control with weekly water delivery (2013/14)	0.3, 0.4, 0.7, 0.8	~ 6 months	Weekly	Improved
Higher rates of *T* with higher volumes (2013/14)	0.7 and 0.8	~ 6 months	Weekly	Variable
Follow-up watering was more effective when delivered weekly rather than in 'bursts'	0.8/1.4 ($Wii_{w\_26(i15)}$)	~ 6 months	Weekly	Improved
Follow-up watering was more effective when delivered in higher magnitudes	1.4 ML ($Wii_{w\_26(i15)}$ and $Wii_{m\_100(i7.5)}$)	~ 6 months	Weekly and monthly	Improved
Rainfall improved control tree water status	—	—	—	Improved
Withholding follow-up watering was not detrimental to tree water status	—	—	—	Maintained
Combinations of weekly delivery followed by bi-monthly, monthly and 0 'follow-up' irrigation of variable volumes, maintained similar *T* rates in 2014/15	0.7/0 ($Wii_{w\_0(i12.5)}$) 0.3/0.3 ($Wii_{2m\_50(i5)}$) 0.4/1.4 ($Wii_{m\_100(i7.5)}$)	-~1 week each time ~2–3 weeks each time	0 2 monthly 'bursts' monthly 'bursts'	Maintained Improved Improved
December delivery of follow-up water led to decreased plant water status after first irrigation season			Late winter/ spring	Declined from previous autumn (2014)

It was also apparent that delivery of water in weekly instalments is more likely to be beneficial to trees rather than 'bursts', as tree roots are constantly exposed to moist soil in contrast to episodic wetting and drying. Weekly water delivery to some extent likely mimicked improved and prolonged soil water availability provided by persistent floods or environmental flow to a wetland. A six-month duration of increased soil moisture does not appear to be detrimental to *E. largiflorens* which was also demonstrated by Akeroyd et al., 1998.

With delivery of a total volume of 0.4 ML in 12.5 mm week^{-1} intervals over 6 months, followed by withholding water the consecutive year, *E. largiflorens* maintained similar *T* rates to other plots receiving monthly or bi-monthly irrigation, demonstrating a sustained benefit from the first irrigation season (Table 5). Such sustained benefit is often overlooked when canopy condition monitoring is relied on as reduction in tree water stress may not have been realized via canopy cover change (Wallace, Gehrig, Doody, Davies, et al., 2021). It is noted that this plot ($Wi_{w\_12.5}$) may have also had higher intrinsic *T* rates which aided maintenance of improved water status over the second irrigation season, where ~10 weeks of drought was experienced. Thus, monitoring using sap flow sensors and shoot water potential provide important rapid tree responses not otherwise visible. Accordingly, a multiple-lines-of-evidence approach is suggested, to provide robust information to water management (Wallace, Gehrig, & Doody, 2020a; Wallace, Gehrig, Doody, Davies, et al., 2021).

The timing of water delivery to support and maintain adult *E. largiflorens* is unclear given complexities with depth to groundwater and salinity where <3.65 m and low salinity (<32 000 μS cm^{-1}) respectively, are optimal (Colloff et al., 2015). Survival on local rainfall is common (Jensen et al., 2008) as is groundwater use (Doody et al., 2009; Holland et al., 2006) and Roberts and Marston (2011) suggest optimum timing is related to historic natural flood regimes which vary from site to site. A study at Yanga National Park indicated that with increased water availability (from flooding, winter rain or both) and increasing evaporative demand, *T* of *E. camaldulensis* begins to increase from late Austral winter in August (Doody, Colloff, et al., 2015). In this study, *T* increases were seen in all plots from early spring, indicating that provision of environmental water at this time, especially to drought stressed regions, would aid in supporting plant water status in the lead up to summer and facilitate spring leaf production. The noticeable decrease in water status in October and December 2014, prior to the second irrigation season, suggests environmental flows delivered late winter/early spring would most likely provide further benefits to these woodlands.

4.2 | Implications for design of environmental watering

New information presented within furthers our understanding of the water volumes that might be required to aid the meeting of environmental objectives of the Murray-Darling Basin Plan (MDBA, 2012. The Basin-wide environmental watering strategy (MDBA, 2014) is the long-term watering plan for the MDB which states the environmental expected outcomes for key ecological assets (e.g. vegetation, birds, fish and river flow and connectivity) across the Basin. Expected Basin-wide outcomes for *E. largiflorens* are specific; 'maintain the current extent of ~409, 000 ha' (MDBA, 2014) of *E. largiflorens*' and 'maintain the current condition of lowland floodplain forests and woodlands' (MDBA, 2014). Meeting these outcomes with limited knowledge of the environmental watering volumes, duration and timing which provide tree benefits, is likely to be a challenge under future climate change and constraints related to moving environmental water to elevated, disconnected floodplain regions. Floodplain water managers are required to plan and prioritize riparian zones and floodplains based on limited water availability for environmental watering. This process is complex and includes consideration of how to maximize environmental benefits of water allocations while accounting for transmission and evaporative losses.

If the management goal is to maintain or improve current condition from a water stressed state, including an improvement in water status over summer and potentially facilitating soil recharge, then environmental watering of 0.7–0.8 ML (for a 50 x 50 m plot) could be used as a guide, delivered weekly for at least 5 months from late winter to early spring. This volume is the equivalent of 2.5–3 times the average 'dry' decade rainfall (Figure 3b). To water 1 ha requires ~3 ML and 1 GL could water ~333 ha, with environmental watering required for at least two consecutive years (Wallace, Gehrig, & Doody, 2020). To accelerate woodland benefits might require environmental watering of 1.4 ML per year for a 50 × 50 m plot, over consecutive years (as a guide). At this volume, 5.6 ML would be needed to irrigate 1 ha and 1 GL could irrigate ~178 ha for up to 5 months and facilitate soil recharge although further research in this area is also required. Compared with environmental flow volumes to reconnect lakes and ephemeral creeks (e.g. 135 GL to Macquarie Marshes; 112 GL to Hattah Lakes; MDBA, 2019), these are relatively small volumes of water which are likely to help meet objectives. Total volumes could be reduced over time, depending on required outcomes, and using an adaptive management approach (Gunderson, 2015). Neither germination or seed recruitment were noted at these sites (Gehrig & Frahn, 2015), so further investigation of water requirements for improving *E. largiflorens* population demographics is required. In addition, while the primary focus of this research was to examine tree transpiration and status in response to drip irrigation to further our understanding of *E. largiflorens* water requirements, improvements in woodland understorey vegetation species composition and cover in treatment plots were also recorded (data not shown, see Gehrig, 2013; Gehrig, 2014; Gehrig & Frahn, 2015), indicating benefits to woodland communities as a whole.

The new knowledge presented here indicates that with innovative ways to provide water to woodland communities at higher elevations on the floodplain, water stress in *E. largiflorens* woodlands can be reduced. In addition, consecutive water delivery over time could be used to restore cosystem processes such as river-floodplain-connectivity, leading to improved habitat condition and restoration of vegetation communities. While drip irrigation is one way to provide water to disconnected floodplains, it may not necessarily be the most feasible.

As demonstrated by the control plot, continual water deficit due to reduced natural flood frequency and climate change is likely to lead to continual reductions in *T* and reliance on rainfall to improve plant water status over autumn/winter. If an extended drought were to occur soon, the ability of such water stressed woodlands to persist is likely to be uncertain.

5 | CONCLUSION

Climate change continues to drive decreased inflows in the Murray-Darling Basin and other semi-arid and arid river basins around the world. This causes major changes to riverine and floodplains ecosystems, especially in elevated, disconnected locations. Herein, we have shown that environmental watering provisions, applied using drip irrigation, can provide benefits to disconnected woodlands of *E. largiflorens*, a floodplain tree of high conservation value. A multiple-lines-of-evidence approach, using sap flow sensors and shoot water potential was important to elucidate the benefits and responses of varying regimes of environmental water to drought stressed woodlands. While drip irrigation may not be the most economically viable option to conserve *E. largiflorens* woodlands in the future, we have used this water delivery approach to empirically determine the water requirement of this vegetation community. This information can be used to inform environmental water management of mature drought-affected floodplain woodlands in the Murray-Darling Basin. Similar methods of water delivery can be employed across arid and semi-arid floodplains worldwide to provide an improved understanding of floodplain vegetation water requirements and inform environmental water management. It is also hoped that this research will stimulate thought, innovation and planning in how to deliver water to disconnected but critically important floodplain areas in the future.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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REFERENCES

Acreman, M. C., Arthington, A. H., Colloff, M. J., Couch, C. A., Crossman, N., Dyer, F., Overton, I. C., Pollino, C., Stewardson, M. H., & Young, W. J. (2014). Environmental flows for natural, hybrid and novel riverine ecosystems in a changing world. *Frontiers in Ecology and the Environment*, *21*, 466–473.

Akeroyd, M. D., Tyerman, S. D., Walker, G. R., & Jolly, I. D. (1998). Impact of flooding on the water use of semi-arid riparian eucalypts. *Journal of Hydrology*, *206*, 104–117.

Arthington, A. H., Kennen, J. G., Stein, E. D., & Webb, J. A. (2018). Recent advances in environmental flows science and water management – Innovation in the Anthropocene. *Freshwater Biology*, *63*, 1022–1034.

Berens, V., White, M. G., & Souter, N. J. (2009). Injection of fresh river water into a slaine floodplain aquifer in an attempt to improve the condition of river red gum (*Eucalyptus camaldulensis* Dehnh.). *Hydrological Processes*, *23*, 3464–3473.

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

Bureau of Meteorology (2017) Climate data for Waikerie (024029). http://www.bom.gov.au/climate/data/ []

Capon, S. J., Chambers, L. E., Mac Nally, R., Naiman, R. J., Davies, P., Marshall, N., Pittock, J., Reid, M., Capon, T., Douglas, M., Catford, J., Baldwin, D. S., Stewardson, M., Roberts, J., Parsons, M., & Williams, S. E. (2013). Riparian ecosystems in the ^{2}1st century: Hotspots for climate change adaptation? *Ecosystems*, *16*, 359–381.

Casanova MT (2015) Review of water requirements for key floodplain vegetation for the Northern Basin: Literature review and expert knowledge assessment. Charophyte Services, Lake Bolac.

Clarke, K., Segaran, R. R., & Lewis, M. (2015). *Remote sensing of ecological response to 2014 Murray River weir-pool raising, South Australia*. University of Adelaide.

Colloff, M. J. (2014). *Flooded Forest and Desert Creek: Ecology and history of the river red gum*. CSIRO Publishing.

Colloff, M. J., Caley, P., Saintilan, N., Pollino, C. A., & Crossman, N. D. (2015). Long-term ecological trends of flow-dependent ecosystems in a major regulated river basin. *Marine and Freshwater Research*, *66*, 957–969.

Costelloe, J. F. (2016). Water use strategies of a dominant riparian tree species (*eucalyptus coolabah*) in dryland rivers. In J. A. Webb, J. F. Costelloe, R. Casas-Mulet, J. P. Lyon, & M. J. Stewardson (Eds.), *Proceedings 11th international symposium on Ecohydraulics* (26724). University of Melbourne.

Costelloe, J. F., Payne, E., Woodrow, I. A., Irvine, E. C., Western, A. W., & Leaney, F. W. (2008). Water sources accessed by arid zone riparian trees in highly saline environments, Australia. *Oecologia*, *156*, 43–52.

Costelloe, J. F., & Strang, L. J. (2016). Drivers of the distribution of a dominant riparian tree species (*Eucalyptus coolabah*) on a dryland river system, Diamantina River, Australia. In J. A. Webb, J. F. Costelloe, R. Casas-Mulet, J. P. Lyon, & M. J. Stewardson (Eds.), *Proceedings 11th International Symposium on Ecohydraulics* (26667). University of Melbourne.

Cunningham, S. C., Mac Nally, R., Read, J., Baker, P. J., White, M., Thomson, J. R., & Griffioen, P. (2009). A robust technique for mapping vegetation condition across a major river system. *Ecosystems*, *12*, 207–219.

Doody, T. M., Benger, S., Overton, I. C., & Pritchard, J. (2014). Ecological response of *Eucalyptus camaldulensis* (river red gum) to extended drought and flooding along the river Murray, South Australia, 1997-2011. *Australian Journal of Marine and Freshwater Research*, *65*, 1082–1093.

Doody, T. M., Colloff, M. J., Davies, M., Koul, V., Benyon, R. G., & Nagler, P. L. (2015). Quantifying water requirements of riparian river red gum (*Eucalyptus camaldulensis*) in the Murray-Darling basin, Australia – Implications for the management of environmental flows. *Ecohydrology*, *8*, 1471–1487.

Doody, T. M., Holland, K., Benyon, R., & Jolly, I. (2009). Effect of groundwater freshening on riparian vegetation water balance. *Hydrological Processes*, *23*, 3485–3499.

Doody, T. M., Pritchard, J. L., Llewelyn, A., & Holland, K. L. (2015). *Influence of environmental water delivered by drip irrigation on water stressed black box (Eucalyptus largiflorens) communites*. CSIRO.

Fernando, D. R., Lynch, J. P., Reichman, S. M., Clark, G. J., Miller, R. E., & Doody, T. M. (2018). Inundation of a floodplain lake woodlands system: Nutritional profiling and benefit to mature *Eucalyptus largiflorens* (*E. largiflorens*) trees. *Wetlands Ecology and Management*, *26*, 961–975.

Gehrig SL (2013) *Field Trial Investigating use of Drip Irrigation to Improve Condition of E. largiflorens (Eucalyptus largiflorens) Woodlands. Phase I: Infrastructure Test Report*. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Gehrig SL (2014) *Field Trial Investigating use of Drip Irrigation to Improve Condition of E. largiflorens* (*Eucalyptus largiflorens*) *Woodlands*. *Phase II*: *Optimal Watering Regimes*. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Gehrig SL, Frahn K (2015) *Investigating use of Drip Irrigation to Improve Condition of E. largiflorens Woodlands. Phase III: Variable Watering Regimes*. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Gehrig SL, Frahn KA, Nicol JM (2016) Monitoring the response of Littoral and floodplain vegetation and soil moisture flux to weir Pool raising – 2015. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

George, A. K., Walker, K. F., & Lewis, M. M. (2005). Population status of eucalypt trees on the river Murray floodplain, South Australia. *River Research and Applications*, *21*, 271–282.

Glenn, E. P., Flessa, K. W., & Pitt, J. (2013). Restoration potential of the aquatic ecosystems of the Colorado River Delta, Mexico: Introduction to special issues on "wetlands of the Colorado River Delta". *Ecological Engineering*, *59*, 1–6.

Gunderson, L. (2015). Lessons from adaptive management: Obstacles and outcomes. In C. Allen & A. Garmestani (Eds.), *Adaptive management of social-ecological systems* (pp. 27–38). Dordrecht: Springer https://doi.org/10.1007/978-94-017-9682-8_3.

Holland, K. L., Charles, A. H., Jolly, I. D., Overton, I. C., Gehrig, S., & Simmons, C. T. (2009). Effectiveness of artificial watering of a semi-arid saline wetland for managing riparian vegetation health. *Hydrological Processes*, *23*, 3474–3484.

Holland, K. L., Tyerman, S. D., Mensforth, L. J., & Walker, G. R. (2006). Tree water sources over shallow, saline groundwater in the lower river Murray, South-Eastern Australia: Implications for groundwater recharge mechanisms. *Australian Journal of Botany*, *54*, 193–205.

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

Jolly, I. D., Walker, G. R., & Narayan, K. A. (1994). Floodwater recharge processes in the Chowilla Anabranch system, *South Australia. Australian Journal of Soil Research*, *32*, 417–435.

Jolly, I. D., & Walker, G. R. (1996). Is the field water use of *Eucalyptus largiflorens* F. Muell. Affected by short-term flooding? *Australian Journal of Ecology*, *21*, 173–183.

Keith, D. (2004). *Ocean shores to desert dunes: The native vegetation of New South Wales and the ACT*. Department of Environment and Conservation.

Mac Nally, R., Cunningham, S. C., Baker, P. J., Horner, G. J., & Thompson, J. R. (2011). Dynamics of Murray-Darling floodplain forests under multiple stressors: The past, present, and future of an Australian icon. *Water Resources Research*, *47*, W00G05.

Margules and Partners Pty Ltd., P. and J. Smith Ecological Consultants, (1990) Department of Conservation Forests and Lands Victoria. River

Murray riparian vegetation study. Murray-Darling Basin Authority, Canberra.

McGinness, H., Arthur, A. D., & Davies, M. (2018). Flood regimes driving vegetation and bird community transitions in semiarid floodplain woodlands. *Ecohydrology*, *11*, e1954.

MDBA. (2012) Water act 2007 - basin plan 2012. Murray Darling Basin Authority, Canberra, ACT.

MDBA (2014) Basin-wide environmental watering strategy. Murray-Darling Basin Authority, Canberra.

MDBA (2019) Basin environmental watering outlook for 2019–20. Murray-Darling Basin Authority, Canberra.

Moxham, C., Duncan, M., & Moloney, P. (2018). Tree health and regeneration response of *E. largiflorens* (*Eucalyptus largiflorens*) to recent flooding. *Ecological Management and Restoration*, *19*, 58–65.

Overton, I. C. (2005). Modelling floodplain inundation on a regulated river: Integrating GIS, remote sensing and hydrological models. *River Research and Applications*, *21*, 991–1001.

Overton, I. C, Coff, B., Mollison, D., Barling, R., Fels, K. & Boyd, A. (2018) Black Box Management Framework: A Framework for Managing Floodplain and Wetland Black Box Eucalypts in the Murray-Darling Basin. Prepared by Jacobs Group (Australia) Pty Ltd for the Commonwealth Environmental Water Office, Department of the Environment and Energy.

Overton, I. C, McEwan, K., Gabrovsek, C. & Sherrah, J. (2006) The river Murray floodplain inundation model (RiM-FIM). CSIRO Water for a Healthy Country National Research Flagship, Adelaide.

Parsons, R., & Zubrinich, T. M. (2010). The green-leaved variant of *Eucalyptus largiflorens*: A story involving hybridization and observant local people. *Cunninghamia*, *11*, 415–418.

Poff, N. L., Tharme, R. E., & Arthington, A. H. (2017). Chapter 11- Evolution of environmental flows assessment science, priciples and methodologies. In *Water for the Environment* (Vol. 106, pp. 203-236, 704-714), Shaping the 2014 Colorado River Delta pulse flow: Rapid environmental flow design for ecological outcomes and scientific learning. Ecological Engineering. Elsevier.

Poff, N. L., & Zimmerman, J. K. H. (2010). Ecological responses to altered flow regimes: A literature review to inform the science and management of environmental flows. *Freshwater Biology*, *55*, 194–205.

Roberts, J. (1993). Regeneration and growth of Coolibah, *eucalyptus coolabah* subsp. *Arida*, a riparian tree, in the Cooper Creek region of South Australia. *Australian Journal of Ecology*, *18*, 345–350.

Roberts J (2004) Floodplain forests and woodlands in the southern Murray-Darling basin. Australian Conservation Foundation, Canberra.

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

Rogers, K., & Ralph, T. J. (2011). *Floodplain wetland biota in the Murray-Darling basin: Water and habitat requirements*. CSIRO Publishing.

Sajedipour, S., Zarei, H., & Oryan, S. (2017). Estimation of environmental water requirements via an ecological approach: A case study of Bakhtegan Lake, Iran. *Ecological Engineering*, *100*, 246–255.

Schofield, K. A., Alexander, L. C., Ridley, C. E., Vanderhoof, M. K., Fritz, K. M., Autrey, B. C., DeMeester, J. E., Kepner, W. G., Lane, C. R., Leibowitz, S. G., & Pollard, A. I. (2018). Biota connect aquatic habitats throughout freshwater ecosystem mosaics. *Journal of the American Water Resources Association*, *54*(2), 327–399.

Scholander, P. F., Bradstreet, E. D., Hemmingsen, E. A., & Hammel, H. T. (1965). Sap pressure in vascular plants: Negative hydrostatic pressure can be measured in plants. *Science*, *148*, 339–346.

Slavich, P. G., Walker, G. R., Jolly, I. D., Hatton, T. J., & Dawes, W. R. (1999). Dynamics of *Eucalyptus largiflorens* growth and water use in relation to modified watertable and flooding regimes on a saline floodplain. *Agricultural Water Management*, *39*, 245–264.

Smith, F.M. and Kenny, S.K. (2005). Floristic vegetation and tree health mapping, river Murray floodplain, South Australia. Department for Environment and Heritage, Adelaide.

Smith, P., & Smith, J. (2014). Floodplain vegetation of the river Murray in 1987–1988: An important pre-drought benchmark for subsequent studies. *Cunninghamia*, *14*, 97–151.

Sommerville D (1999). Floral resource database for the NSW apiary industry. Report 99/174. Rural Industries Research and Development Corporation.

Stella, J. C., & Bendix, J. (2019). Multiple stressors in riparian ecosystems. In S. Sabatier, A. Elosegi, & R. Ludwig (Eds.), *Multiple stressors in river ecosystems: Status* (pp. 81–110). *Impacts and Prospects for the Future*. Elsevier.

Stewardson, M. J., & Guarino, F. (2018). Basin-scale environmental water delivery in the Murray—Darling, Australia: A hydrological perspective. *Freshwater Biology*, *63*, 969–985.

Streeter, T. C., Tyerman, S. D., & Walker, G. R. (1996). Water-use strategies of *Eucalyptus largiflorens*. In G. R. Walker, I. D. Jolly, & S. D. Jarwal (Eds.), *Salt and water movement in the Chowilla floodplain* (Vol. 15, pp. 78–89). CSIRO Division of Water Resources.

Sweeney, B. W., Bott, T. L., Jackson, J. K., Kaplan, L. A., Newbold, D., Standley, L. J., Hession, W. C., & Horwitz, R. J. (2004). Riparian deforestation, stream narrowing, and loss of stream ecosystem services. *Proceedings of the National Academy of Sciences USA*, *101*, 14132.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Pruesevich, A, Green P., Glidden, S., Bunn, S. E., Sullivan, C. A., Reidy, L. C., & Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, *467*, 555–561.

Wallace, T. A., Gehrig, S. L., & Doody, T. M. (2020). A standardised approach to calculating floodplain tree condition to support environmental watering decisions. *Wetlands Ecology and Management*, *28*, 315–340.

Wallace, T. A., Gehrig, S. L., Doody, T. M., Davies, M. J., Walsh, R., Fulton, C., Cullen, R., & Nolan, M. (2021). A multiple-lines-of-evidence approach for prioritising environmental watering of wetland and floodplain trees. *Ecohydrology*, *14*(3). https://doi.org/10.1002/eco.2272

Wassens, S., Sass, S., & Swan, G. (2005). Reptile communities in vegetation remnants of the Murrumbidgee Irrigation Area, New South Wales. *Herpetofauna*, *35*, 66–72.

Wen, L., & Saintilin, N. (2015). Climate phase drives canopy condition in a large semi-arid floodplain forest. *Journal of Environmental Management*, *159*, 279–287.

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