

RESEARCH ARTICLE

How important is groundwater availability and stream perenniality to riparian and floodplain tree growth?

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Abstract

Riparian vegetation is important for stream functioning and as a major landscape feature. For many riparian plants, shallow groundwater is an important source of water, particularly in areas where rainfall is low, either annually or seasonally, and when extended dry conditions prevail for all or part of the year. The nature of tree water relationships is highly complex. Therefore, we used multiple lines of evidence to determine the water sources used by the dominant tree species *Eucalyptus camaldulensis* (river red gum), growing in riparian and floodplain areas with varying depth to groundwater and stream perenniality. Dendrometer bands were used to measure diel, seasonal, and annual patterns of tree water use and growth. Water stable isotopes ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) in plant xylem, soil water, and groundwater were measured to determine spatial and temporal patterns in plant water source use. Our results indicated riparian trees located on relatively shallow groundwater had greater growth rates, larger diel responses in stem diameter, and were less reactive to extended dry periods, than trees in areas of deep groundwater. These results were supported by isotope analysis that suggested all trees used groundwater when soil water stores were depleted at the end of the dry season, and this was most pronounced for trees with shallow groundwater. Trees may experience more frequent periods of water deficit stress and undergo reduced productivity in scenarios where water table accessibility is reduced, such as drawdown from groundwater pumping activities or periods of reduced rainfall recharge. The ability of trees to adapt to changing groundwater conditions may depend on the speed of change, the local hydrologic and soil conditions as well as the species involved. Our results suggest that *E. camaldulensis* growing at our study site is capable of utilizing groundwater even to depths >10 m, and stream perenniality is likely to be a useful indicator of riparian tree use of groundwater.

KEYWORDS

groundwater-dependent vegetation, phreatophytes, plant functional traits, plant hydrotypes, tree water use, water isotopes

1 | INTRODUCTION

Riparian vegetation is a fundamental structural and ecological component of all streams and rivers, and loss of riparian vegetation can drastically alter the ecological functioning of a stream and the surrounding

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vegetation (Naiman, Décamps, & McClain, 2005). The riparian zone is a pervasive and important landscape feature that regulates stream ecological processes and acts as the interface or “ecotone” between terrestrial and aquatic systems (Naiman & Décamps, 1997). Riparian tree species tend to be phreatophytic in the presence of shallow groundwater and are adapted to accessing water from a variety of sources including in-stream surface water, soil moisture, and shallow groundwater (Holland, Tyerman, Mensforth, & Walker, 2006; Meinzer, 1927; Stromberg, Tiller, & Richter, 1996; Thorburn & Walker, 1994). Long-term reliability of accessible groundwater may encourage riparian trees to develop roots predominantly in the capillary fringe and saturated zone rather than throughout the soil profile, especially if precipitation during the growing season is unreliable (Ehleringer & Dawson, 1992). However, many riparian trees have dimorphic root systems, including shallow roots to improve stability in floods, nutrient uptake, and rapid uptake of surface soil water after rainfall events, as well as deeper sinker roots that can access the capillary fringe of groundwater (David et al., 2013; Eamus, Froend, Loomes, Hose, & Murray, 2006; Pinto et al., 2014). Species that are adapted to exploiting water from a number of sources are likely to be drought avoiders (Levitt, 1980; Lo Gullo & Salleo, 1988) and, therefore, poorly adapted to prolonged periods of drought. This can result in significantly poorer canopy condition in trees occurring where groundwater depths exceed identified thresholds and support the contention that access to groundwater provides a critical resource for these drought avoider species (Kath et al., 2014). Understanding the dynamics of plant interactions with available water sources is important for managing plant communities dependent on groundwater resources.

The impacts of climate change, agricultural development, and coal seam gas extraction on native vegetation health are difficult to predict due to plant interactions that can also affect health and floristic composition. Studies have shown links between groundwater decline and the degradation of dependent habitats (Busch & Smith, 1995; Stromberg et al., 1996). Understanding how keystone species of riparian vegetation use groundwater is particularly important to predict resilience to climate change and other factors affecting declining groundwater levels. Previous studies of trees growing above shallow groundwater have identified a dynamic interaction between deep roots and groundwater (Canham, Froend, & Stock, 2012; Guevara, Giordano, Aranibar, Quiroga, & Villagra, 2010; Vonlanthen, Zhang, & Bruelheide, 2011), suggesting mature trees may have the capacity to adapt to declining water tables (Richardson et al., 2011). Whether this interaction is common to all plants that access groundwater in different biophysical settings and the time scale required for adaption to take place, is not known. Changes in groundwater depth and quality have been linked to differences in canopy condition (e.g., Cunningham, Thomson, MacNally, Read, & Baker, 2011), population characteristics (e.g., recruitment and survivorship [e.g., Horner et al., 2009]), and vegetation community composition (e.g., Elmore, Manning, Mustard, & Craine, 2006; Stromberg et al., 1996), as well as decreased leaf water potential, mortality, and branch dieback (Cooper, D'Amico, & Scott, 2003). In general, there are uncertainties regarding the potential for deleterious impacts on groundwater-dependent vegetation when exposed to reduced groundwater availability (Eamus et al., 2006; Yin et al., 2015).

Due to the highly complex nature of tree water relationships (Dawson & Ehleringer, 1991), providing definitive evidence of whether trees are dependent on groundwater for survival and growth is difficult. In this study, we therefore use multiple lines of evidence to imply groundwater use and dependence by *Eucalyptus camaldulensis* trees growing in riparian and floodplain areas with varying depth to groundwater. Studies show that depth to the water table, fluvial disturbance, and degree of flow permanence are strong influences on dryland riparian community structure and productivity (Gonzalez-Sanchis, Comin, & Muller, 2012; Liu, Chen, Chen, Zhang, & Li, 2005; Merritt & Poff, 2010). In dry landscapes, this raises the question of whether riparian and floodplain trees on perennial streams are more dependent on groundwater than trees on intermittent streams that will use water from a number of different sources. Trees on permanent streams may be more affected by groundwater drawdown, and as these streams transition to intermittent conditions, there may be a corresponding change in the relative importance of groundwater as a tree water source.

The aim of this study was to determine whether near-channel riparian and interior floodplain trees on perennial streams are more dependent on groundwater than riparian and floodplain trees on intermittent sections of the stream, where groundwater is considerably deeper. To test this, we first need to establish where trees are accessing water at different times of the year across this landscape gradient and understand the diurnal, seasonal, and annual water use patterns of trees in different hydrological landscape positions. We examine diel and seasonal fluctuations in stem diameter as an indication of the degree of tree hydration and tree growth (Biondi & Rossi, 2015; Deslauriers, Morin, Urbinati, & Carrer, 2003; Herzog, Hasler, & Thum, 1995; Zweifel, Item, & Häsler, 2001) to determine how the water status of trees is affected by landscape position, depth to groundwater, and seasonal precipitation. The water source partitioning by plants provides evidence for trees using various combinations of groundwater, rainfall-derived shallow soil water, and stream water (Lamontagne, Cook, O'Grady, & Eamus, 2005; O'Grady, Eamus, Cook, & Lamontagne, 2006; Pfausch, Dodson, Madden, & Adams, 2015; Thorburn & Walker, 1994). Water isotope studies have indicated widespread occurrence of incomplete mixing of subsurface water and suggest different water sources can sustain plant transpiration or contribute to groundwater recharge and streamflow (Brooks, Barnard, Coulombe, & McDonnell, 2010; Evaristo, Jasechko, & McDonnell, 2015). In a global review across 162 sites of water isotope studies of plant-groundwater interactions, Evaristo and McDonnell (2017) reported groundwater use by plants in 37% of these studies. They also noted that groundwater source contribution to plants increases with aridity. We measured the spatial variability of the isotopes $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in tree xylem water, soil water, and groundwater along transects spanning the elevation gradient of the riparian zone and the floodplain, in perennial and intermittent sections of a stream.

2 | METHODS

2.1 | Study site

This study was located on riparian and floodplain sites of Maules Creek, a tributary of the Namoi River that flows west from the Great

Dividing Range and is part of the Murray-Darling river system in northern New South Wales (Figure 1). Maules Creek rises in the Mt. Kaputar ranges (a weathered Tertiary era volcano with sedimentary rocks) and flows south across the Namoi River floodplain and into the Namoi River. The Quaternary alluvial floodplain of the Maules Creek catchment comprises gravels and clays overlying Permian volcanics and coal measures at depth. The top 6 m of the regolith is dominated by Holocene clay and silt rich vertosols (Andersen, Meredith, Timms, & Acworth, 2008). Maules Creek is an intermittent, seasonally dry stream, flowing only after rainfall events in the upper reaches and in the lower sections where groundwater is generally too deep to directly influence the stream. In the middle section of the creek, shallow groundwater intersecting the stream creates large permanent pools that continue to exchange water with the hyporheic zone throughout the year. Irrigated cotton farming relies on extracting water from an extensive groundwater aquifer from a palaeochannel of the Namoi River in the lower sections of the catchment. In the upper sections of the catchment, cattle grazing on improved pasture is the principal land use.

Climate and groundwater levels for the study period were obtained from the nearest weather station—Narrabri Post Office (Australian Government Bureau of Meteorology, 2017). The climate is semiarid with hot summers (highest daily maximum temperatures in January of 33.8 °C) and cool winters (lowest daily maximum temperature in July of 18 °C). Rainfall is fairly evenly spread across the year with a slightly higher proportion (56%, November to April) in the summer months (Figure 2a). Relative humidity is on average highest in winter (June, 52%) and lowest in summer (December, 38%). Annual rainfall over the study period (October 2015 to September 2016) was 21% above the long-term average (620 mm). However, this varied across the study period with the late summer, early autumn period (February to April) 56% below the long-term average (132 mm) for these months (Figure 2a). In contrast, June to September was 214%

above the long-term average for these months (124 mm). Although groundwater levels did rise appreciably at the riparian intermittent (upstream) site in winter 2015, levels did not vary greatly across sites during the study period (October 2015–September 2016; Figure 2b). Stream flow data was available at the lower perennial site only. Over 47 years of records (1973–2017) flow was recorded in all months with no flow recorded on 16 occasions across all months. Highest maximum monthly flows were recorded in December, January, and February (34,602, 52,310, and 78,920 ML, respectively). There was no stream discharge data for the upstream site. For most of the year, the stream is dry as there is no groundwater interaction with the streambed at this site. The stream flows episodically for only a short period after large rainfall events, and pools dry out fairly rapidly (2–4 weeks) in this semiarid climate.

The riparian vegetation was dominated by river red gum (*E. camaldulensis*) and contained river oak (*Casuarina cunninghamiana*) with a midstorey of black tea tree (*Melaleuca bracteata*) in near-channel riparian areas, with a sedge and grass understorey. On the interior floodplain, the vegetation consisted of *E. camaldulensis*, Blakely gum (*Eucalyptus blakelyi*), and Wilga (*Geijera parviflora*), with a mixed grassy understorey. *E. camaldulensis* was the dominant tree species at all study sites, although at the upstream floodplain site, native cypress pine (*Callitris glaucophylla*) was a codominant overstorey tree. *E. camaldulensis* are the most common and widespread riparian and floodplain tree on mainland Australia (Good, Smith, & Pettit, 2017) and are able to tolerate high water tables and flooded conditions, as well as extended periods of drought (Smith, Renton, & Reid, 2017).

2.2 | Site selection and vegetation measurements

The rationale for choosing sites was to measure trees that occur across a gradient of groundwater depth. At each of two sites,

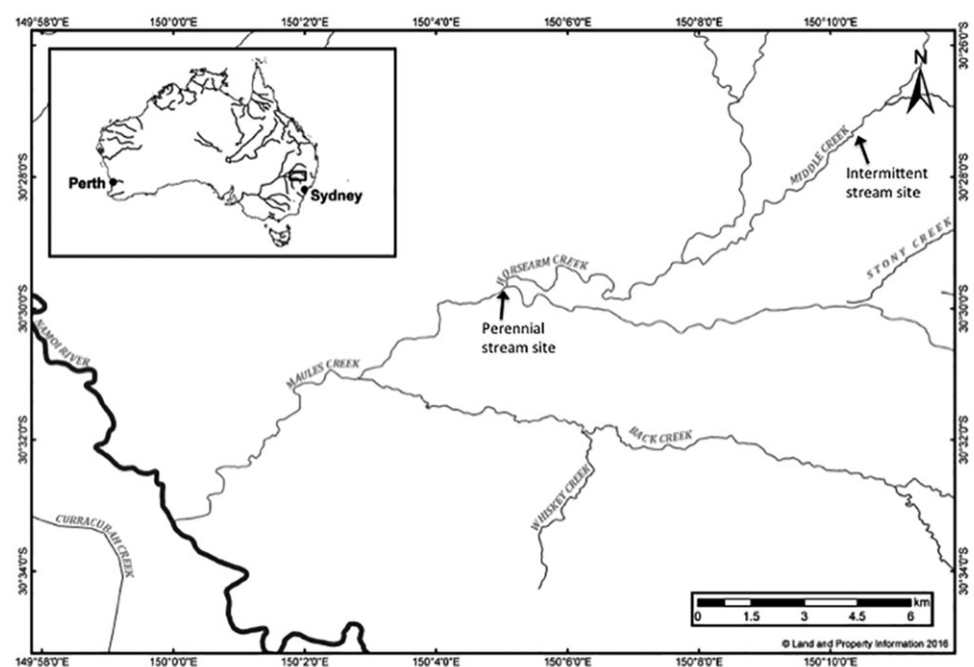


FIGURE 1 Location of the study sites on Maules Creek, a tributary of the Namoi River in northern New South Wales, Australia

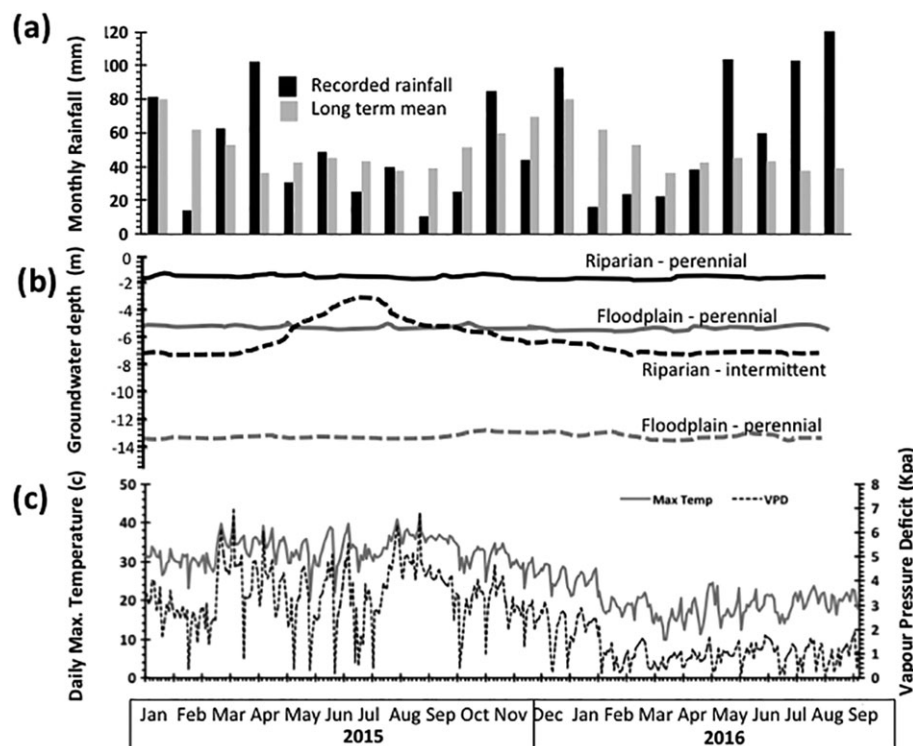


FIGURE 2 (a) Monthly rainfall recorded during the study period (dark bars) and long-term average monthly rainfall (light bars), for Narrabri, NSW. (b) Groundwater depth from groundwater bores located near each landscape position. (c) Maximum daily temperature and vapour pressure deficit before and during the study period (October 2015 to September 2016). Rainfall and temperature data obtained from Australian Government Bureau of Meteorology (2017), groundwater data from M. Andersen (UNSW)

naturally occurring trees were selected from two landscape positions: the near-channel riparian bank directly adjacent to the Maules Creek and on the interior floodplain approximately 100 m from the riparian bank and the stream. The first site was on the middle section of Maules Creek where groundwater at the near channel site is shallow (2–3 m depth), indicated by the water level in the perennial stream pools at this site. Interior floodplain sites adjacent to the perennial stream were considered to have the next shallowest groundwater (5–7 m). We refer to these sites as the riparian and floodplain perennial stream sites throughout this article. A second site in the upstream section of the creek had deeper near-channel riparian groundwater between 3 and 8 m, and at the nearby interior floodplain sites, the groundwater was 14–18 m deep. The groundwater at the riparian site does not intersect the stream and stream flows, and pools persist for only short periods after rainfall events (Andersen et al., 2017). These sites are therefore referred to as riparian and floodplain intermittent stream sites.

At each of the four landscape positions, a 20 m × 20 m overstorey plot was placed alongside each measured *E. camaldulensis*, providing a representation of local riparian conditions. Within each plot, the stem diameter at breast height (dbh) of all woody species with a dbh > 2 cm was recorded, and basal area per hectare for each site was calculated from dbh measurements in these plots. Canopy cover for each site was estimated by taking nine tree canopy photos in a grid pattern across a 10 × 10 m plot and converted to canopy and foliage cover with MatLab Image Processing Toolbox (MacFarlane & Ogden, 2012).

2.3 | Stem diameter measurements

In order to assess the diel and seasonal hydrological state and growth of *E. camaldulensis* trees in the different landscape positions, dendrometer bands with an attached data logger were fitted to the trunks of three *E. camaldulensis* trees at the riparian perennial (dbh 17.4, 25.8, 38.8 cm), floodplain perennial (dbh 18.5, 22.0, 24.0 cm), riparian intermittent (dbh 24.5, 27.7, 40.0 cm), and the floodplain intermittent (20.9, 24.5, 58.0 cm) stream sites. Stem diameter changes (mm) were measured at 30-min intervals, with initial stem diameters adjusted to zero. All study trees were selected as mature healthy trees with a leaf area representative of trees within the forest in which they occur. Although there is range of diameters for our study trees, we were careful to select mature healthy trees to minimize any effect young or senescent trees may have on stem increments. Initial differences in tree diameter did not influence the final measured stem increment with no relationship between tree diameter and annual stem increment ($r = 0.003$, $p > .1$).

To understand the differences in tree response to rainfall events, we calculated metrics for each stem diameter increment trace during or following high rainfall periods or extended periods of no rainfall. The high rainfall event (73 mm) occurred between November 2 and November 5, 2015, and the dry period was from February 12 to March 31, 2016 (50 days where no rain was recorded). The mean differences in the slope of stem increment traces of each three trees, the peak response, and decline slope of the increment curve were determined. To assess the responsiveness of tree stem increments to

sustained rainfall, we also calculated variability of the stem increments as the standard deviation of the increment curve during an extended rainfall period from December 17, 2015 to February 4, 2016, where 147 mm of rain fell across 20 rain days. Comparisons of stem increment changes between trees in different landscape position were analysed using a one-way analysis of variance (ANOVA), followed by Fisher's least significant difference tests and Bonferroni correction.

2.4 | Stable isotope sampling and analysis

To determine what water sources were used by *E. camaldulensis* trees on riparian and floodplain sites at Maules Creek, the natural abundance of stable isotopes of oxygen ($\delta^{18}\text{O}$) and hydrogen ($\delta^2\text{H}$) were measured from xylem water of tree branches, and soil samples of the unsaturated soil layers, as well as groundwater and stream pool water. The uptake of water by roots is generally considered a nonfractionating process (Dawson & Ehleringer, 1991), and the isotopic composition of xylem water represents an integrated signal of water source, such as from the soil and/or groundwater (Dawson & Pate, 1996). However, there needs to be consideration of the potential for fractionation confounding water isotope results (Evaristo, McDonnell, & Clemens, 2017). Samples for stable isotope analysis were taken at each tree in October 2015, March and June 2016, where small tree branches (5 mm dia. \times 100 mm length) from the northern midcanopy were collected. Samples were taken from the part of the branches with mature bark that were closest to the main branch to minimize the effect of evaporative enrichment by water loss through green stems. At this time, soil samples (~5 g) were also collected near each tree at 0.25 m intervals through the soil profile to 1.5 m, where possible. Stem and soil samples were collected and placed in a vial, sealed with parafilm, put on ice and taken back to the laboratory, and stored in a freezer until water was extracted from samples via cryogenic distillation (Turner, Farrington, & Gailitis, 2001). Each soil sample was divided in two with one sample analysed for water stable isotopes and the other gravimetric water content was measured, where samples were weighed, then dried in the oven at 105 °C for 24 hr then reweighed so that percentage soil moisture can be calculated. Extracted water from soil and stems was analysed for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotopes to compare isotope ratios of plant and soil water with values for rainwater, stream pool water, and groundwater. A local meteorological water line (LMWL) of best fit for rainfall isotope values in the area was taken from Andersen et al. (2008). Groundwater samples are from six to 10 monitoring bores located as near as possible to each landscape position where sample trees were located. The stable isotope composition ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) of all water samples was analysed using a L1102-isotopic Liquid Water Analyser (Picarro, Sunnyvale, CA, USA). Raw values of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ samples were normalized to the Vienna Standard Mean Ocean Water scale, based on three laboratory standards, each replicated twice and reported in per mil (‰). The long-term analytical uncertainty (one standard deviation) was determined as 0.8‰ for $\delta^2\text{H}$ and 0.06‰ for $\delta^{18}\text{O}$ (Skrzypek & Ford, 2014).

Water samples with similar isotope ratios are likely to come from the same source and therefore provide insight to whether the tree's

xylem water is sourced from soil water (rainfall) or groundwater. Stream pool water isotope values were not included in the analysis as water was available only once (October 2015) at the intermittent stream site and never at the floodplain sites. To test for evaporative isotopic enrichment, we calculated the line conditioned excess (lc-excess*; Landwehr & Coplen, 2006) or precipitation offset (Evaristo et al., 2015) of soil water, xylem water, and groundwater:

$$\text{lc excess}^* = [\delta^2\text{H} - a \delta^{18}\text{O} - b] / S, \quad (1)$$

where a and b are the slope and intercept of the LMWL and S is the standard deviation of both $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values. The lc excess* describes the difference in the isotopic composition of environmental waters from that of local precipitation (offset = 0) given as the LMWL (Evaristo, McDonnell, Scholl, Bruijnzeel, & Chun, 2016). Therefore, lc-excess* values close to zero are similar to rainfall isotope values and have not been affected by high rates of evaporation. By comparing the lc excess* for soil and xylem water, and groundwater, we can identify which are significantly different from each other and therefore likely come from a different source.

For all landscape positions, daily maximum stem diameter expansion of each *E. camaldulensis* tree was calculated at October 2015, March and June 2016, and compared with measured $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of tree xylem water for that time. Daily maximum stem expansion provided a measure of daily tree hydration that could then compared with xylem isotope values measured for each tree at that time.

3 | RESULTS

3.1 | Tree measurements

General measurements of the study sites indicated that tree canopy cover was similar for the perennial and intermittent stream sites but differed between riparian ($64 \pm 2\%$ perennial and $62 \pm 12\%$ intermittent) and floodplain ($48 \pm 5\%$ perennial and $38 \pm 6\%$ intermittent) landscape positions (ANOVA; $F = 6.4$, $p = .04$). Tree basal area at the perennial riparian site ($22.3 \pm 8 \text{ m}^2/\text{ha}$) was greater than at the other landscape positions (ranging from $12.2 \pm 4.2 \text{ m}^2/\text{ha}$ for floodplain perennial, $12.4 \pm 3.5 \text{ m}^2/\text{ha}$ for riparian intermittent, and $11.8 \text{ m}^2/\text{ha}$ for floodplain intermittent sites). However, the basal area was not statistically significant different between landscape positions due to high variability (ANOVA; $F = 2.1$, $p = .08$). Tree densities were similar across the sites, ranging from 475 to 575 stems ha^{-1} .

Long-term changes in stem diameter of *E. camaldulensis* indicated seasonal variation in hydrological state and growth among trees in the different landscape positions (Figure 3). There was little stem diameter increase for trees at all locations in the late autumn and summer period, with trees at the intermittent stream site showing negative growth at this time. Stem growth rates increased for all trees in the late autumn summer period (Figure 3), corresponding to a drop in daily maximum temperature and vapour pressure deficit (Figure 2). There was a significant difference in annual growth rates during the study period for trees in the different landscape positions ($F = 10.3$, $p = .004$). Riparian trees on the perennial section of Maules Creek had the highest growth rates ($8.4 \pm 1.7 \text{ mm/year}$), followed by trees

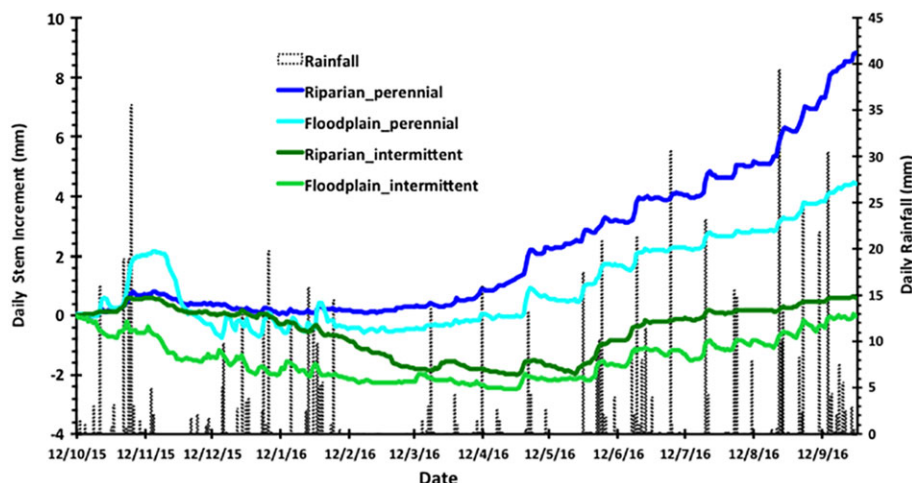


FIGURE 3 Daily rainfall (bars) and mean stem diameter increment (lines) of *Eucalyptus camaldulensis* trees ($n = 3$) in different landscape positions at Maules Creek, New South Wales, Australia

on the adjacent floodplain (4.1 ± 1.1 mm/year). At the upstream site where stream flow is intermittent, annual stem growth rates were significantly less, 0.12 ± 0.9 mm/year for riparian and -0.02 ± 1.4 mm/year for floodplain trees (Figure 3).

The annual growth rate accorded with average depth to groundwater at each site, so that perennial stream sites with shallower depth to groundwater (2 to 7 m) had more rapid growth than trees at the intermittent stream sites (Figures 2b and 3). There was a reduction in girth of floodplain intermittent trees where depth to groundwater was much greater (~14 m depth) than other sites (Figure 2b). There was a general reduction in growth rates in April, which was the driest month during the study (22 mm rainfall), but monthly growth rates of trees at different landscape positions were still significantly different ($F = 5.17$, $p = .03$). Stem increments for April in riparian trees on the perennial stream were 0.94 mm/month that were significantly higher than floodplain trees (0.24 mm/month), which were in turn greater than trees at the intermittent stream riparian (0.05 mm/month) and floodplain (0.09 mm/month) sites. However, trees at the floodplain intermittent site showed some recovery in stem diameter in the latter stages of the study when there was above-average rainfall in the area of Maules Creek, suggesting dependence of the trees on rainfall recharge of soil water (Figure 3). During the wettest month (September, 117 mm of rain), stem increment growth was positive for trees at all site. However, there continued to be a significant difference between sites ($F = 18.1$, $p = .006$), with riparian trees on the perennial

stream (2.44 mm/month) greater than the floodplain trees (1.03 mm/month) and in turn greater than trees at the intermittent stream riparian (0.18 mm/month) and floodplain (0.53 mm/month) sites. There was a significant difference in stem increment between the driest and wettest months for all landscape positions ($F = 22.7$, $p = .002$).

Trees in the riparian and floodplain perennial sites had greater responses to a large rainfall event than for trees at the intermittent stream sites, in terms of the rate, size, and duration of the stem increment (Table 1). During a sustained rainfall period, perennial stream riparian trees showed the least variation in response to rainfall compared with trees at the other locations. In contrast, during a sustained period of no rainfall, trees at the perennial riparian site showed a lower rate of decline (drought slope) in stem diameter than trees at the other sites (Table 1). These differences in stem diameter responses are also evident when considering diel traces for trees in each landscape position during a period immediately before and after a rainfall event (Figure 4a,b). Diel traces indicated that all trees responded to a large rainfall event in early November 2015, with a step increase in stem increment that was maintained for some days (Figure 4a,b and Table 1). In contrast, during an extended dry period (38 days of no rain), diel traces showed a much-reduced amplitude of the stem increment changes for all trees (reflected in the order of magnitude reduction in y-axis scale in Figure 4c,d). This emphasizes the large differences in diel stem increment changes between the wet and dry periods. During this dry period, trees at all sites still maintained a

TABLE 1 Average stem diameter increment responses (\pm SE) of *Eucalyptus camaldulensis* in each landscape position to high rainfall event (November 2–5, 2015; response slope, response maximum, period of response, and decline slope), a period of sustained rainfall (December 17, 2015 to February 4, 2016; standard deviation for rainfall period), and a sustained period of no rainfall (February 12 to March 31, 2016)

Stream site	High rainfall event				Frequent rainfall	Dry period
	Response slope	Response max. (mm/day)	Period of response (days)	Decline slope	SD for rain period	Drought slope
Perennial stream						
Riparian	0.09 ± 0.03	0.85 ± 0.18	18	-0.03 ± 0.01	0.18 ± 0.07	0.0003 ± 0.0002
Floodplain	0.26 ± 0.06	1.40 ± 0.34	16	-0.12 ± 0.04	0.28 ± 0.11	-0.0058 ± 0.004
Intermittent stream						
Riparian	0.06 ± 0.04	0.33 ± 0.21	9	-0.05 ± 0.02	0.25 ± 0.02	-0.022 ± 0.01
Floodplain	0.05 ± 0.01	0.39 ± 0.11	10	-0.08 ± 0.03	0.27 ± 0.09	-0.034 ± 0.04

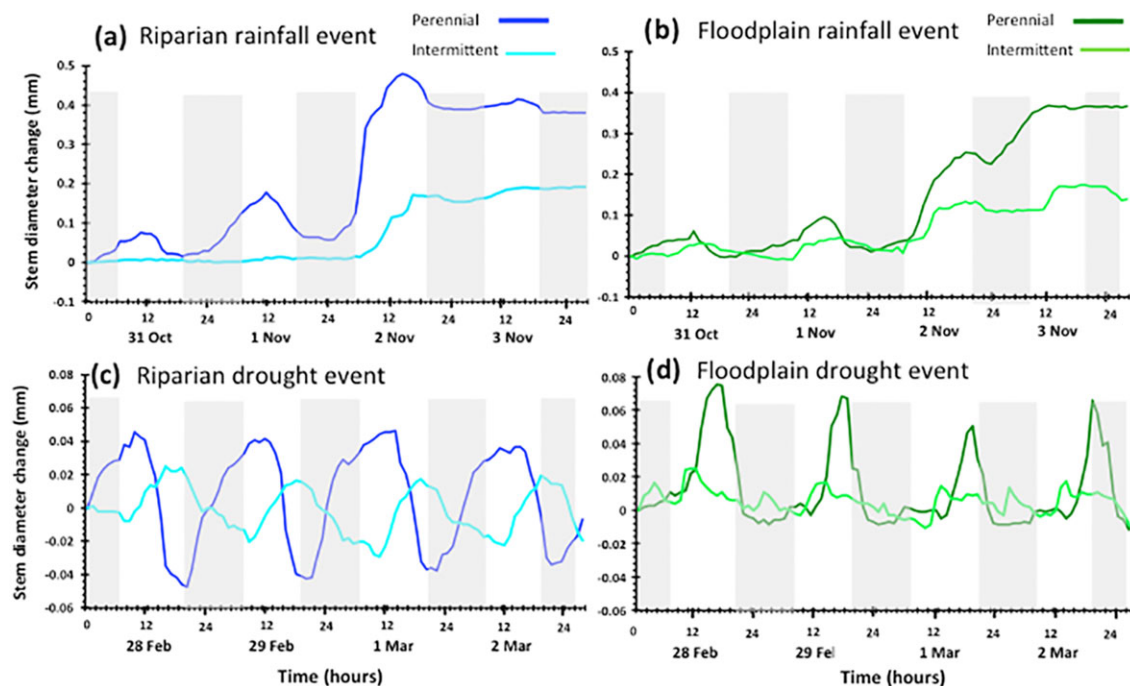


FIGURE 4 Diel stem diameter responses of *Eucalyptus camaldulensis* trees in the different landscape positions at Maules Creek, New South Wales, Australia, to a heavy rainfall event of 36 mm rain over 48 hr. (a) Riparian perennial and intermittent trees and (b) floodplain perennial stream and intermittent stream trees. And response to a sustained period of no rainfall (38 days of no rain) for (c) riparian perennial stream and intermittent stream trees and (d) floodplain perennial stream and intermittent stream trees. Note the order of magnitude difference in vertical scales (stem increment) for figures a and b (rainfall event) compared with figures c and d (drought period)

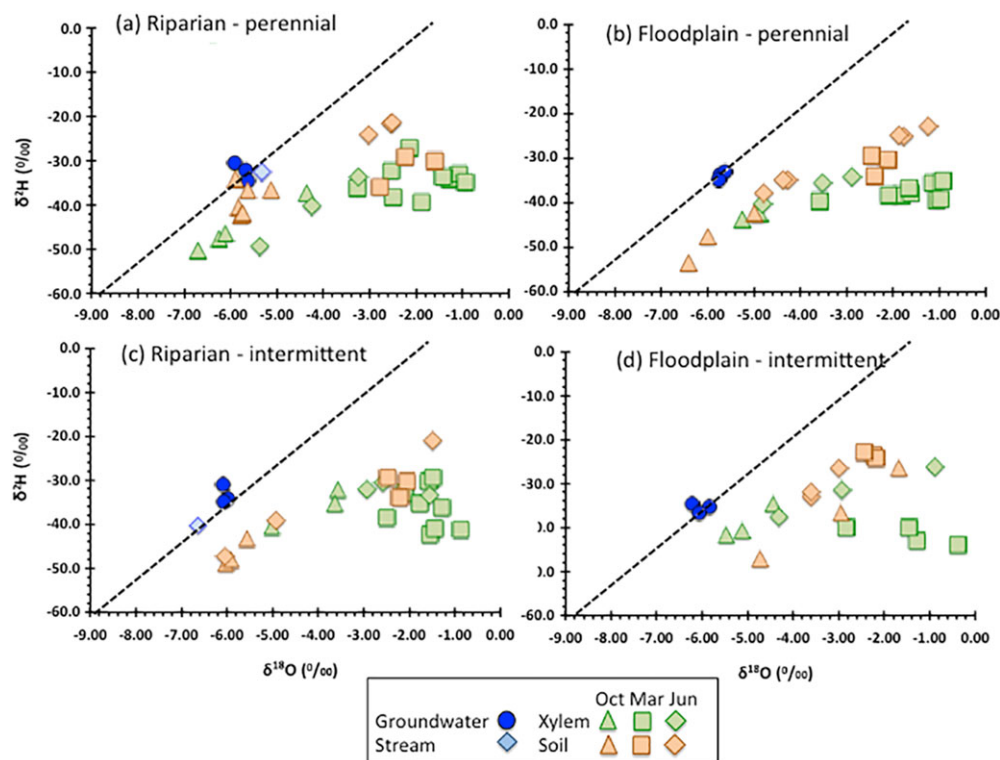


FIGURE 5 Biplots of water stable isotope (SI) composition ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) from water in *Eucalyptus camaldulensis* xylem and soil water from Maules Creek, New South Wales, Australia: (a) riparian perennial stream site, (b) floodplain perennial stream site, (c) riparian intermittent stream site, and (d) floodplain intermittent stream site. Dotted line indicates the local meteorological water line ($y = 8.436x + 14.546$, $r^2 = 0.9906$) for rainfall isotope values in the area (taken from Andersen et al., 2008). Isotope values for xylem water are a mean of three samples from three trees at each site for each sampling time. Soil samples are means of three samples for each soil depth (cm) and each sampling time. Groundwater samples are from monitoring bores near the study sites

regular diel cycle of expansion and contraction of their stems. Trees at the perennial stream sites showed greater variability in stem increment over a 24-hr cycle as trees transpired during day and rehydrated at night (Figure 4c,d). In contrast, trees at the intermittent stream sites had flatter traces indicating, particularly for the floodplain trees, transpiration and stem recovery was restricted by reduced access to water.

Soil moisture at 100-cm soil depth was highest during June 2016 for all sites, after substantial rains during the month preceding sampling. Soil moisture was highest in June ranging from $10.2 \pm 1.7\%$ at the riparian perennial stream landscape position, $9.6 \pm 3.4\%$ in floodplain perennial stream site, $7.5 \pm 1.5\%$ at the riparian intermittent site, and $8.8 \pm 3.3\%$ at the floodplain intermittent site. The lowest soil moisture for all sites occurred in March 2016 after a sustained dry, hot period of 36 days of no rainfall and maximum temperatures above 34°C (mean 36.5°C) and varied across sites from $5.6 \pm 0.2\%$ at the riparian perennial stream site, $5.2 \pm 0.4\%$ in floodplain perennial stream site, $4.2 \pm 1.1\%$ at the riparian intermittent site, and $3.9 \pm 0.5\%$ at the floodplain intermittent site.

3.2 | Water source partitioning

Water isotope values for xylem, soil, and groundwater showed variability across sites and sample times (Figure 5). For all landscape positions, xylem water isotope values were most similar to groundwater and deep soil water in October 2015 when rainfall for the previous 2 months had been well below average. $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values for xylem water were very different than groundwater for samples taken in March 2016 during a time of extended dry, hot conditions

(Figure 5). Isotope values of soil water and xylem water showed similar trends, for the different landscape positions and sampling times, although the seasonal changes in soil water isotope values were smaller (Figure 5c,d). There was a strong evaporative signal for xylem and soil water isotope values at all sites (Figure 5). In October, after the driest part of the year, trees on both floodplain and intermittent riparian sites have isotope values close to groundwater and may have relied more on this source at this time of year (Figure 5). Trees at the perennial riparian site are also close to isotope values of the soil water but less enriched. This may indicate that they are using groundwater and fractionated against deuterium. Isotope samples for the March sampling time are highly enriched indicating possible extreme evaporation effects. Weather conditions during these days were extreme with hot dry conditions with maximum temperatures $>40^\circ\text{C}$ and relative humidity $<20\%$. There was also some variability in the values of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ for xylem water and the different water sources. For example, the $\delta^2\text{H}$ values show more overlap between xylem water and groundwater values. In contrast, the $\delta^{18}\text{O}$ values show a clear difference of several per mil between xylem water and groundwater (Figure 5).

For all sampling times, the lc-excess^* values of groundwater are near zero and therefore show close affinity with rainfall values (LMWL) and are therefore not affected by evaporation. In contrast, the lc-excess^* values for soil and plant xylem water were distinct from groundwater at all sites and sampling times (all ANOVA; $F > 8.6$, $p < .03$; Figure 6). This was particularly apparent during the dry period of the March sampling time. These soil and plant xylem water lc-excess^* patterns indicate that the variability of soil water isotopic composition during the wet and the dry period, respectively, can be

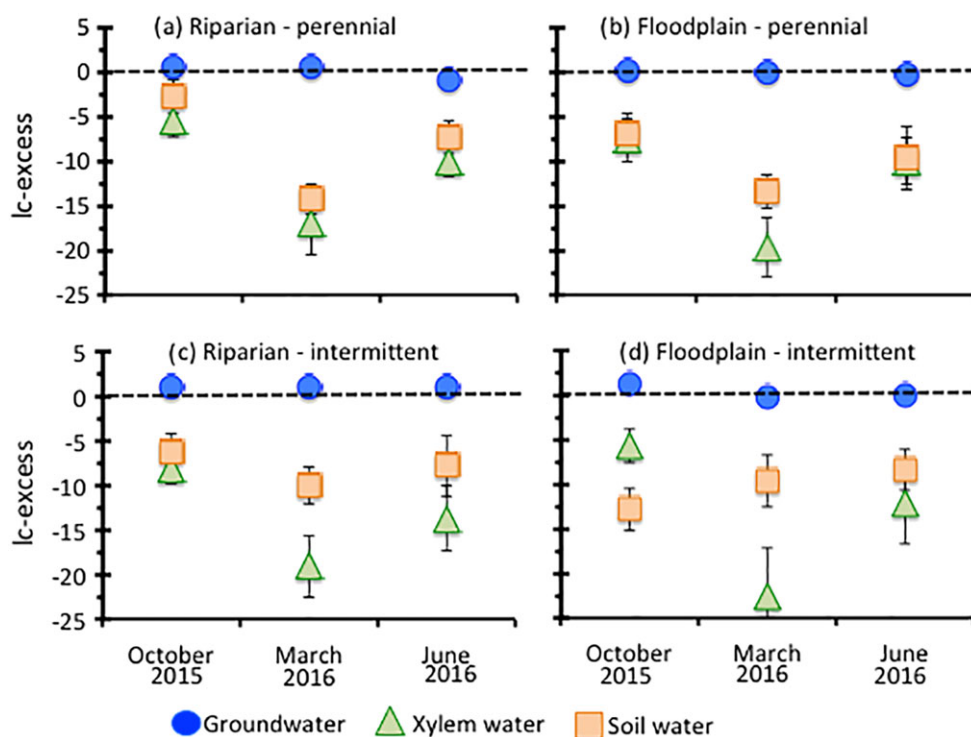


FIGURE 6 Comparison of line-conditioned excess values for xylem, soil, and groundwater at each landscape position and for each of the sampling time. The lc-excess^* values that are close to zero are similar to rainfall isotope values and have not been affected by high rates of isotopic fractionation due to evaporation

related to the variability in xylem water composition. The $\delta^{18}\text{O}$ -excess* values for xylem and soil were most similar to groundwater values during the October sampling time at the riparian perennial site (ANOVA; $F = 8.6$, $p = .03$) and to a lesser extent the riparian intermittent site (ANOVA; $F = 12.2$, $p = .009$; Figure 6).

Comparing xylem water $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values with maximum daily stem expansion at each sampling time showed the relationship of tree hydration with tree water isotope values. Seasonal changes in water source availability that produced enriched $\delta^{18}\text{O}$ values of the xylem water were generally accompanied by higher maximum stem expansion values for all landscape positions (Figure 7). This figure also shows that trees at the perennial site in both landscape positions grew more and to some extent used all available source waters. The broad range of $\delta^2\text{H}$ values indicate large fractionation due most likely to strong evaporative effects. The $\delta^{18}\text{O}$ values therefore appear more reliable in tracing tree water sources and the relationship with tree daily stem increments (Figure 7).

For all landscape positions, daily maximum stem expansion showed highest values in the wettest part of the year (June) and lowest values in the dry period (March). Trees at the riparian perennial stream landscape position showed the highest stem expansion across all dates, even during the driest period (March) than the other landscape positions (Figure 7). For all landscape positions, xylem water $\delta^{18}\text{O}$ values were more enriched in March than at the other sampling times and maximum diel stem expansion was greater in June and at the perennial stream sites compared with intermittent stream sites. For the October and June sampling times, there was a significant correlation between stem increment and xylem water $\delta^{18}\text{O}$ values for perennial ($r = 0.522$, $p < .5$) and intermittent stream sites ($r = 0.639$, $p < .05$). This indicated that $\delta^{18}\text{O}$ values became more enriched as maximum daily stem increment was larger (indicating greater hydration).

4 | DISCUSSION

This study provides new insights into groundwater dependence of trees growing in riparian and floodplain sites with different patterns of groundwater availability and stream perenniality. Phreatophytic

E. camaldulensis appear to use groundwater opportunistically throughout the different seasons, particularly when soil water stores were depleted at the end of the dry season, irrespective of their landscape position. The relative importance of groundwater as a plant water source increased when soil water stores were depleted at the end of the dry season. Isotope values (omitting values for the March sampling time) somewhat support the idea that these trees use a greater proportion of groundwater. As would be expected, stream perenniality would seem to define sites that have shallow groundwater. Our results also suggest that surface expression of groundwater (i.e., perenniality of groundwater-sourced baseflow) is a likely indicator of riparian and floodplain tree groundwater use, provided water tables are accessible. However, trees may undergo more frequent periods of water deficit stress and reduced productivity in scenarios where water table accessibility is reduced, such as drawdown from groundwater pumping activities or periods of reduced rainfall recharge. Similar conclusions were made for studies of *E. camaldulensis* trees growing in various landscapes in eastern Australia where groundwater access influences the growth and distribution of this species (Lamontagne et al., 2005; Mensforth, Thorburn, Tyerman, & Walker, 1994; Smith et al., 2017; Thorburn & Walker, 1994). Our analysis provides an approach to quantify the effects of spatial and temporal variation in groundwater availability using readily available biomonitoring data.

Although stable isotope analysis is a powerful tool in ecological studies, of itself, it is frequently not enough to disentangle complex ecological interactions (Fry, 2013). Here, we have used a combination of techniques to understand water resource partitioning by riparian and floodplain trees. Considered together, the stem diameter and stable isotope data provide evidence of what water these *E. camaldulensis* trees are sourcing to fulfil their water requirements. The degree of groundwater use varied between locations and times of year and for individual trees. Riparian trees at the downstream site, with shallow groundwater, had greater growth rates, larger diel responses in stem diameter, and were less reactive to rainfall and extended periods of no rainfall. At the upstream site where the stream was intermittent with deeper, fluctuating groundwater sources, trees had lower growth, smaller diel responses, and were more reactive to climate. This was evidenced by trees at the upstream sites having increased stem

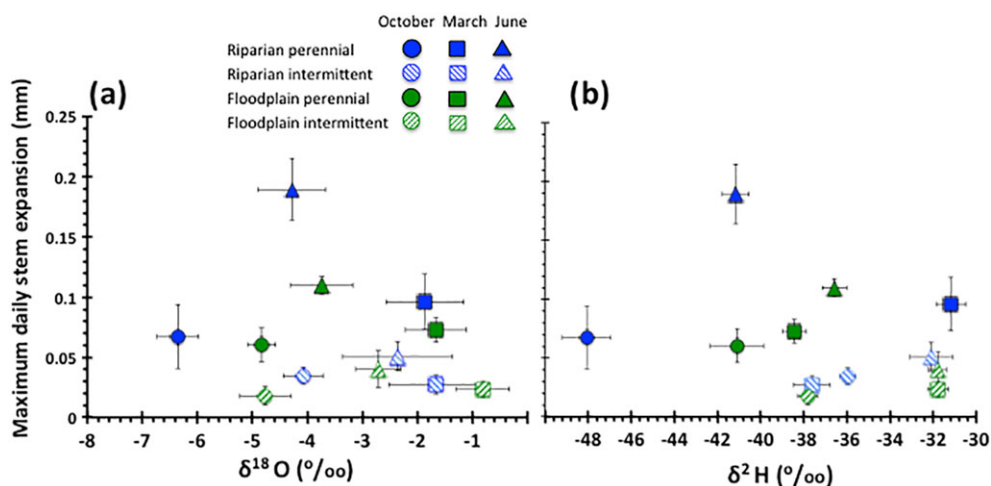


FIGURE 7 Comparison of mean (\pm SE) daily maximum stem diameter expansion compared with $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of xylem water for *Eucalyptus camaldulensis* trees ($n = 3$) in the different landscape positions

increment response in the latter part of the study period when rainfall and soil moisture increased, suggesting water was the main limiting factor to growth and access to groundwater was limited. We therefore suggest that access to groundwater is likely to be a major factor in lower growth rates of trees at the upstream site, given that the rainfall, soils, geomorphic, and landscape conditions are similar for the different sites.

Although stable isotope analysis of plant water sources was highly variable between landscape positions and sampling times, it does suggest that trees access groundwater as a water source and that the relative importance of groundwater is variable over time and space. It is generally suggested that many tree species are facultative with respect to the use of groundwater, that is, individual plants that access groundwater develop a degree of dependence. Therefore, phreatophytic behaviour may be more related to the prevailing environmental conditions than to the capabilities of a given plant species or type (Thomas, 2014). In addition, phreatophytic trees are likely to maximize the exploitation of the environmental resources by using the topsoil water during most of the year and groundwater in the dry summer (David et al., 2013). Although groundwater may constitute a small proportion of water use in facultative phreatophytes such as the trees at the upstream sites in this study, it is probably still important for their long-term survival. Some trees may only revert to groundwater use during drought periods, when all other sources are unavailable (Dawson & Pate, 1996; Mensforth et al., 1994; Zencich, Froend, Turner, & Gailitis, 2002). Dimorphic root distribution is therefore advantageous for this strategy to work for *E. camaldulensis* (Gibson, Bachelard, & Hubick, 1994; Thorburn & Walker, 1994) and other eucalypts (Dawson & Pate, 1996), as well as oaks (*Quercus robur*; Pinto et al., 2014) and poplars (*Populus* sp.; Snyder & Williams, 2000). Groundwater depth thresholds have been identified for *E. camaldulensis* in the range from 12.1 to 22.6 m, beyond which canopy condition declines (Kath et al., 2014). Our study tree the river red gum (*E. camaldulensis*) occurs throughout the temperate, subtropical, and semiarid regions of Australia and has developed a range of adaptations to cope with droughts and floods, and in particular, the root system of river red gums allows this species to switch between water sources depending on availability (Mensforth et al., 1994).

Our water isotope results showed a lack of an evaporative signature of both groundwater and streams at the study sites. This suggests that rainfall water is transported quickly to deeper subsurface storage in the groundwater (Evaristo et al., 2016), and water that evaporates from the permanent stream pools is quickly replenished by groundwater. In contrast, across all sites, stable isotope data for tree xylem and soil water showed strong evaporative signals and are evaporatively enriched relative to the sampled source waters. This was particularly apparent for the March 2016 samples with the xylem water samples very different than the soil water and groundwater isotope values, which suggests a nonsoil profile water source. However, this may be soil water from a much earlier rainfall event that is tightly bound within the soil matrix and is taken up in the xylem during hot dry summer periods when other water is not available (Brooks et al., 2010). The extreme hot dry conditions that were experienced during the March sampling time may also have created high isotope fractionation in the xylem and soil water due to very high evaporation rates.

Although great care was taken with removal, packaging, and storage of samples, there may also have been some evaporative loss during handling in these extreme conditions.

There appears to be some inconsistency in the hydrogen and oxygen water isotope data, with the hydrogen isotope data showing strong overlap between xylem water and groundwater values, but this is inconsistent for oxygen. The hydrogen isotopic may be a poor tracer of water sources to plants because of its higher energy state and tendency to fractionate (Singer et al., 2014), with evidence for deuterium fractionation in a wide variety of tree species (Evaristo et al., 2017). This suggests that the $\delta^{18}\text{O}$ data can be more reliable for water source tracing for these trees. The use of $\delta^{18}\text{O}$ analysis of cellulose within tree rings is commonly used for annual and longer term (decadal) studies of tree water use (Sargent & Singer, 2016).

Stem increment measures combined with stable isotope analysis provide some evidence of links to groundwater for trees in the riparian area at the site of a perennial pool, as well for trees on the nearby floodplain where groundwater is deeper (5–7 m). At the sites further up the catchment where stream flow and shallow groundwater are seasonally intermittent, trees may access groundwater periodically when there is little rainfall and groundwater levels are at their lowest. For all landscape positions, xylem water isotope values were most similar to groundwater and deep soil water in October but very different for samples taken in March, at a time of extended dry hot conditions and fractionation is high due to high evaporation rates. Other studies have shown the opportunistic changes of water sources in trees such as oaks (*Quercus ilex*) on a floodplain in south-west USA where the isotope composition of xylem water tracked changes in the soil water during the first 2 months of drought but began to depart from soil values after 3 months (Del Castillo, Comas, Voltas, & Ferrio, 2015). Other studies have shown a switch to greater dependence on groundwater by trees in the dry season (45–75%) for *Populus euphratica* in desert floodplains in China decreasing to 4–12% during the wet period (Yin et al., 2015), and in central Portugal groundwater uptake accounts for 73% of *Quercus suber* needs during the dry summer period (Pinto et al., 2014).

Our results indicate the importance of both antecedent and current climate conditions (rainfall, temperature, and vapour pressure deficit) for the hydrated state of the trees and the water sources they use. Climatic and hydrologic shifts alter water distribution to riparian trees and are influenced by annual (wet vs. dry years) and seasonal hydrologic conditions (Singer et al., 2014). Following periods of abundant rainfall and stream flow, the trees are well-hydrated and drawing water predominately from the unsaturated soil profile. Annual rainfall over the study period was 21% above the long-term average (620 mm) for the Maules Creek area. However, this rainfall varied across the study period with the late summer-early autumn period (February to April) below average and June to September was 214% above the long-term average for these months. Reduced water availability was likely responsible for the stem shrinking and negative growth observed at the intermittent stream sites during the extended dry period in summer. Timing and magnitude of daily variations in stem size are mainly determined by transpiration and soil water content (Kozlowski, 1976; Zweifel, Zimmermann, Zeugin, & Newbery, 2006). If water available to the trees is not sufficient to replenish the stem,

then recovery will be limited and positive stem increments are unlikely to occur (Vieira, Rossi, Campelo, Freitas, & Nabais, 2013). As a consequence, the stem would progressively contract over period of low water availability. In contrast, at the perennial stream site where a shallow water table is accessible, trees were not water-limited and able to maintain positive stem increments and therefore adequate recovery and growth during the dry summer period. This was further supported by significant daytime contraction (transpiration) and nighttime expansion (recovery) diel patterns of tree trunk movements. During the dry part of the year, trees that are not accessing groundwater, the recovery phase is not likely to be sufficient to replenish the water from the stem lost during the day, and stem shrinkage observed as negative growth (Vieira et al., 2013). Near-stream riparian trees are also likely influenced by hyporheic water flow via the stream (Singer et al., 2013), whereas the interior floodplain trees are reliant on rainfall derived soil water, in the absence of groundwater access.

Over longer time periods, high resolution measurements of stem diameter variation recorded by logged dendrometers can also provide valuable information on the growth of trees. In this study, stem diameter growth appeared to increase in the period when daily maximum temperature and vapour pressure deficit were lower, that is, in winter and early spring. This suggests that transpirational demand is lower (Kozłowski, 1976) and tree water status is higher at this time, and that trees are able to recover quickly from water loss and stem radial increments are possible (Vieira et al., 2013). On the other hand, as we observed in this study, unless trees have access to groundwater during summer, low rainfall, high temperatures, and high vapour pressure deficits will likely lead to tree stems cycling through contraction through water loss and recovery with no or negative stem increments.

5 | CONCLUSION

Our study indicates that where groundwater is shallow and therefore readily accessible, riparian and floodplain trees will have higher growth rates even in dry summer periods. In contrast, riparian and floodplain trees growing where groundwater is deeper have reduced growth, particularly in the drier periods and are therefore highly dependent on rainfall. However, the water isotope analysis suggests that trees are likely drawing from the groundwater at some period during the year. This intermittent use of groundwater will improve the likelihood of survival of trees during drought periods for this drought avoider species (Canadell & Zedler, 1995). Therefore, all trees in each landscape position may be dependent on groundwater to some extent at particular times of the year. Stream perenniality, on the other hand, is likely to indicate riparian tree dependence on groundwater only in so far as being an indicator of groundwater depth.

The capability of mature trees to adapt to declining water tables will depend on the rate of groundwater decline so that if the decline in groundwater level is greater than the growth rate of deep roots, transpiration and therefore growth of trees will decrease dramatically (Luo & Sophocleous, 2010; Soyulu, Istanbuloglu, Lenters, & Wang, 2011). Root redistribution may afford tolerance to short-term drawdown in water tables but protracted and rapid groundwater declines are known to result in phreatophytes experiencing water deficit stress

and mortality (Barron et al., 2014; Froend & Sommer, 2010; Shafroth, Stromberg, & Patten, 2002), and reducing vegetation resilience (Sommer & Froend, 2011). Understanding the dependence on groundwater relative to other sources of water is important in differentiating tree responses to changes in groundwater availability. Therefore, to assess potential groundwater use by plant communities, we suggest that ideally, sources of tree water must be assessed over several different seasons and years. Clearly, this is rarely practical for environmental impact assessments and a possible compromise is to substitute space for time, so that assessment of groundwater use by trees can be done at different locations with a gradient of groundwater depths. However, if the trajectory of environmental change is faster than vegetation adaptability, plants are likely to have physiological limits to how quickly root extension can keep pace with rapid groundwater drawdown through extraction (Zencich et al., 2002). Our study has demonstrated that we can use these methods to develop models that allow the estimation of relationships between groundwater depth and vegetation resilience in response to changing impacts on groundwater resources.

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REFERENCES

- Andersen, M., Bond, N., Burrows, R., Eberhard, S., Fensham, S., Froend, R., ... Ward, D. (2017). *Research to inform the assessment of ecohydrological responses to coal seam gas extraction and coal mining*. Canberra, Australia: Office of Water Science, Department of Environment.
- Andersen, M. S., Meredith, K., Timms, W., & Acworth, R. I. (2008). *Investigation of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in the Namoi River catchment—Elucidating recharge sources and the extent of surface water/groundwater interaction*. Toyama, Japan: IAH Congress.
- Australian Government Bureau of Meteorology. (2017). <http://www.bom.gov.au/climate/>
- Barron, O., Froend, R. H., Hodgson, G., Ali, R., Dawes, W., Davies, P., & McFarlane, D. (2014). Projected risks to groundwater-dependent terrestrial vegetation caused by changing climate and groundwater abstraction in the Central Perth Basin, Western Australia. *Hydrological Processes*, 28, 5513–5529.
- Biondi, F., & Rossi, S. (2015). Plant-water relationships in the Great Basin Desert of North America derived from *Pinus monophylla* hourly dendrometer records. *International Journal of Biometeorology*, 59, 939–953.
- Brooks, J. R., Barnard, H. R., Coulombe, R., & McDonnell, J. J. (2010). Ecohydrologic separation of water between trees and streams in a Mediterranean climate. *Nature Geoscience*, 3, 100–104.

- Busch, D. E., & Smith, S. D. (1995). Mechanisms associated with decline of woody species in riparian ecosystems of the southwestern U.S. *Ecological Monographs*, 65, 347–370.
- Canadell, J., & Zedler, P. H. (1995). Underground structures of woody plants in Mediterranean ecosystems of Australia, California and Chile. In M. T. K. Arroyo, P. H. Zedler, & M. D. Fox (Eds.), *Ecology and biogeography of Mediterranean ecosystems in Chile* (pp. 177–210). Berlin Heidelberg New York: California and Australia. Springer.
- Canham, C. A., Froend, R. H., & Stock, W. D. (2012). Dynamics of phreatophyte root growth relative to a seasonally fluctuating water table in a Mediterranean-type environment. *Oecologia*, 170, 909–916.
- Cooper, D. J., D'Amico, D. R., & Scott, M. L. (2003). Physiological and morphological response patterns of *Populus deltoides* to alluvial groundwater pumping. *Environmental Management*, 31, 215–226.
- Cunningham, S. C., Thomson, J. R., MacNally, R., Read, J., & Baker, P. (2011). Groundwater change forecasts widespread forest dieback across an extensive floodplain system. *Freshwater Biology*, 56, 1494–1508.
- David, T. S., Pinto, C. A., Nadezhkina, N., Kurz-Besson, C., Henriques, M. O., Quilho, T., ... David, J. S. (2013). Root functioning, tree water use and hydraulic redistribution in *Quercus suber* trees: A modeling approach based on sap flow. *Forest Ecology and Management*, 307, 136–146.
- Dawson, T. E., & Ehleringer, J. R. (1991). Streamside trees that do not use stream water. *Nature*, 350, 335–337.
- Dawson, T. E., & Pate, J. S. (1996). Seasonal water uptake and movement in root systems of Australian phreatophytic plants of dimorphic root morphology: A stable isotope investigation. *Oecologia*, 107, 13–20.
- Del Castillo, J., Comas, C., Voltas, J., & Ferrio, J. P. (2015). Dynamics of competition over water in a mixed oak-pine Mediterranean forest: Spatio-temporal and physiological components. *Forest Ecology and Management*, 382, 214–224.
- Deslauriers, A., Morin, H., Urbinati, C., & Carrer, M. (2003). Daily weather response of balsam fir (*Abies balsamea* (L.) Mill.) stem radius increment from dendrometer analysis in the boreal forests of Québec (Canada). *Trees*, 17, 477–484.
- Eamus, D., Froend, R., Loomes, R., Hose, G., & Murray, B. (2006). A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation. *Australian Journal of Botany*, 54, 97–114.
- Ehleringer, J. R., & Dawson, T. E. (1992). Water uptake by plants: Perspectives from stable isotope composition. *Plant, Cell and Environment*, 15, 1073–1082.
- Elmore, A. J., Manning, S. J., Mustard, J. F., & Craine, J. M. (2006). Decline in alkali meadow vegetation cover in California: The effects of groundwater extraction and drought. *Journal of Applied Ecology*, 43, 770–779.
- Evaristo, J., Jasechko, S., & McDonnell, J. J. (2015). Global separation of plant transpiration from groundwater and streamflow. *Nature*, 525, 91–94.
- Evaristo, J., & McDonnell, J. J. (2017). prevalence and magnitude of groundwater use by vegetation: A global stable isotope meta-analysis. *Scientific Reports*, 7, 44110. <https://doi.org/10.1038/srep44110>
- Evaristo, J., McDonnell, J. J., & Clemens, J. (2017). Plant source water apportionment using stable isotopes: A comparison of simple linear, two compartment mixing model approaches. *Hydrological Processes*, 31, 3750–3758.
- Evaristo, J., McDonnell, J. J., Scholl, M. A., Bruijnzeel, L. A., & Chun, K. P. (2016). Insights into plant water uptake from xylem-water isotope measurements in two tropical catchments with contrasting moisture conditions. *Hydrological Processes*, 30, 3210–3227.
- Froend, R. H., & Sommer, B. (2010). Phreatophytic vegetation response to climatic and abstraction-induced groundwater drawdown: Examples of long-term spatial and temporal variability in community exposure. *Ecological Engineering*, 36, 1191–1200.
- Fry, B. (2013). Alternative approaches for solving undetermined isotope mixing models. *Marine Ecology Progress Series*, 472, 1–13.
- Gibson, A., Bachelard, E. P., & Hubick, K. T. (1994). Growth strategies of *Eucalyptus camaldulensis* Dehn at three sites in northern Australia. *Australian Journal of Plant Physiology*, 212, 653–662.
- Gonzalez-Sanchis, M., Comin, F. A., & Muller, E. (2012). Hydrologic thresholds for riparian forest conservation in a regulated large Mediterranean river. *River Research and Applications*, 28, 71–80.
- Good M., Smith, R., & Pettit, N. E. (2017). Forests and woodlands of Australia's rivers and floodplains. In *Australian vegetation* (Ed D. Keith) (Chp 21, pp. 516–543), Melbourne, Australia: Academic Publishing.
- Guevara, A., Giordano, C. V., Aranibar, J., Quiroga, M., & Villagra, P. E. (2010). Phenotypic plasticity of the coarse root system of *Prosopis flexuosa*, a phreatophyte tree, in the Monte Desert (Argentina). *Plant and Soil*, 330, 447–464.
- Herzog, K. M., Hasler, R., & Thum, R. (1995). Diurnal changes in the radius of a subalpine Norway spruce stem: Their relation to the sap flow and their use to estimate transpiration. *Trees*, 10, 94–101.
- 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.
- Horner, G. J., Baker, P. J., Mac Nally, R., Cunningham, S. C., Thomson, J. R., & Hamilton, F. (2009). Mortality of developing floodplain forests subjected to a drying climate and water extraction. *Global Change Biology*, 15, 2176–2186.
- Kath, J., Reardon-Smith, K., Le Brocq, A. F., Dyer, F. J., Dafny, E., Fritz, L., & Batterham, M. (2014). Groundwater decline and tree change in floodplain landscapes: Identifying non-linear threshold responses in canopy condition. *Global Ecological Conservation*, 2, 148–160.
- Kozłowski, T. T. (1976). Shrinking and swelling of plant tissues. In T. T. Kozłowski (Ed.), *Water deficits and plant growth*. Academic Press, New York (pp. 1–64).
- Lamontagne, S., Cook, P. G., O'Grady, A., & Eamus, D. (2005). Groundwater use by vegetation in a tropical savannah riparian zone (Daly River, Australia). *Journal of Hydrology*, 310, 280–293.
- Landwehr, J., & Coplen, T. (2006). Line conditioned excess: A new method for characterizing stable hydrogen and oxygen isotope ratios in hydrologic systems. In: *Isotopes in environmental studies* pp132–135. IAEA-CN-118/56, International Atomic Energy Agency (IAEA).
- Levitt, J. (1980). *Responses of plants to environmental stresses*. New York: Academic Press.
- Liu, J. Z., Chen, Y., Chen, Y. J., Zhang, N., & Li, W. H. (2005). Degradation of *Populus euphratica* community in the lower reaches of the Tarim River, Xinjiang, China. *Journal of Environmental Sciences*, 17, 740–747.
- Lo Gullo, M. A., & Salleo, S. (1988). Different strategies of drought resistance in three Mediterranean sclerophyllous trees growing in the same environmental conditions. *New Phytologist*, 108, 267–276.
- Luo, Y., & Sophocleous, M. (2010). Seasonal groundwater contribution to crop-water use assessed with lysimeter observations and model simulations. *Journal of Hydrology*, 389, 325–335.
- MacFarlane, C., & Ogden, G. N. (2012). Automated estimation of foliage cover in forest understorey from digital nadir images. *Methods in Ecology and Evolution*, 3, 405–415.
- Meinzer, O. E. (1927). *Plants as indicators of ground water* (Water Supply Paper 577. Washington USA: U.S. Geological Survey and Department of Interior.
- Mensforth, L. J., Thorburn, P. J., Tyerman, S. D., & Walker, G. R. (1994). Sources of water used by riparian *Eucalyptus camaldulensis* overlying highly saline groundwater. *Oecologia*, 100, 21–28.
- Merritt, D. M., & Poff, N. L. (2010). Shifting dominance of riparian *Populus* and *Tamarix* along gradients of flow alteration in western North American rivers. *Ecological Applications*, 20, 135–152.

- Naiman, R. J., & Décamps, H. (1997). The ecology of interfaces: riparian zones. *Annual Review of Ecology and Systematics*, 28, 621–658.
- Naiman, R. J., Décamps, H., & McClain, M. E. (2005). *Riparia: Ecology, conservation and management of streamside communities*. Boston, USA: Elsevier Academic Press.
- O'Grady, A. P., Eamus, D., Cook, P. G., & Lamontagne, S. (2006). Comparative water use by the riparian trees *Melaleuca argentea* and *Corymbia bella* in the wet-dry tropics of northern Australia. *Tree Physiology*, 26, 219–228.
- Pfautsch, S., Dodson, W., Madden, S., & Adams, M. (2015). Assessing the impact of large-scale water table modifications on riparian trees: A case study from Australia. *Ecohydrology*, 8, 642–651.
- Pinto, C. A., Nadezhdina, N., David, J. S., Kurz-Besson, C., Caldeira, M. C., Henriques, M. O., ... David, T. S. (2014). Transpiration in *Quercus suber* trees under shallow water table conditions: The role of soil and groundwater. *Hydrological Processes*, 28, 6067–6079.
- Richardson, S., Irvine, E., Froend, R. H., Boon, P., Barber, S., & Bonneville, B. (2011). Australian groundwater-dependent ecosystems toolbox part 1: Assessment framework. In *Canberra, Australia: Waterlines Report Series 69*. National Water: Commission.
- Sargent, C. I., & Singer, M. B. (2016). Sub-annual variability in historical water source use by Mediterranean riparian trees. *Ecohydrology*, 9, 1328–1345.
- Shafroth, P. B., Stromberg, J. C., & Patten, D. T. (2002). Riparian vegetation response to altered disturbance and stress regimes. *Ecological Applications*, 12, 107–123.
- Singer, M. B., Sargent, C. I., Piégay, H., Riquier, J., Wilson, R. J. S., & Evans, C. M. (2014). Floodplain ecohydrology: Climatic, anthropogenic, and local physical controls on partitioning of water sources to riparian trees. *Water Resources Research*, 50, 4490–4513.
- Singer, M. B., Stella, J. C., Dufour, S., Piégay, H., Wilson, R. J. S., & Johnstone, L. (2013). Contrasting water-uptake and growth responses to drought in co-occurring riparian tree species. *Ecohydrology*, 6, 402–412.
- Skrzypek, G., & Ford, D. (2014). Stable isotope analyses of saline water samples on a cavity ring-down spectroscopy instrument. *Environmental Science and Technology*, 48, 2827–2834.
- Smith, R., Renton, M., & Reid, N. (2017). Growth and carbon sequestration by remnant *Eucalyptus camaldulensis* woodlands in semi-arid Australia during La Nina conditions. *Agricultural and Forest Meteorology*, 232, 1–7.
- Snyder, K. A., & Williams, D. G. (2000). Water sources used by riparian trees varies among stream types on the San Pedro River, Arizona. *Journal of Agricultural and Forest Meteorology*, 105, 227–240.
- Sommer, B., & Froend, R. (2011). Resilience of phreatophytic vegetation to groundwater drawdown: Is recovery possible under a drying climate? *Ecohydrology*, 4, 67–82.
- Soylu, M. E., Istanbuloglu, E., Lenters, J. D., & Wang, T. (2011). Quantifying the impact of groundwater depth on evapotranspiration in a semi-arid grassland region. *Hydrology and Earth System Science*, 15, 787–806.
- Stromberg, J. C., Tiller, R., & Richter, B. (1996). Effects of groundwater decline on riparian vegetation of semiarid regions: The San Pedro, Arizona. *Ecological Applications*, 6, 113–131.
- Thomas, F. M. (2014). Ecology of phreatophytes. In U. Lüttge, W. Beyschlag, & J. Cushman (Eds.), *Progress in botany* (pp. 335–375). Berlin, Germany: Springer-Verlag.
- Thorburn, P. J., & Walker, G. R. (1994). Variations in stream water uptake by *Eucalyptus camaldulensis* with differing access to stream water. *Oecologia*, 100, 293–301.
- Turner, J. V., Farrington, P., & Gailitis, V. (2001). Extraction and analysis of plant water for deuterium isotope measurement and application to field experiments. In M. Unkovic, J. Gibbs, J. S. Pate, & A. M. McNeill (Eds.), *Proceedings of the CLIMA workshop: The practical application of stable isotope techniques to study plant physiology, plant water uptake and nutrient cycling*. Perth, Australia: Kluwer Academic Publishers.
- Vieira, J., Rossi, S., Campelo, F., Freitas, H., & Nabais, C. (2013). Seasonal and daily cycles of stem radial variation of *Pinus pinaster* in a drought-prone environment. *Agricultural and Forest Meteorology*, 180, 173–181.
- Vonlanthen, B., Zhang, X. M., & Bruehlheide, H. (2011). Establishment and early survival of five phreatophytes of the Taklamakan Desert. *Flora*, 206, 100–106.
- Yin, L., Zhou, Y., Huang, J., Wenninger, J., Zhang, E., Hou, G., & Dong, J. (2015). Interaction between groundwater and trees in an arid site: Potential impacts of climate variation and groundwater abstraction on trees. *Journal of Hydrology*, 528, 435–448.
- Zencich, S. J., Froend, R. H., Turner, J. V., & Gailitis, V. (2002). Influence of groundwater depth on the seasonal sources of water accessed by *Banksia* tree species on a shallow sandy coastal aquifer. *Oecologia*, 131, 9–19.
- Zweifel, R., Item, H., & Häslar, R. (2001). Link between diurnal stem radius changes and tree water relations. *Tree Physiology*, 21, 869–877.
- Zweifel, R., Zimmermann, L., Zeugin, F., & Newbery, D. M. (2006). Intra-annual and radial growth and water relations of trees: Implications towards a growth mechanism. *Journal of Experimental Botany*, 57, 1445–1459.

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