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Overstorey evapotranspiration in a seasonally dry Mediterranean eucalypt forest: Response to groundwater and mining

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Abstract

Groundwater levels in the northern jarrah forest have declined at rates up to 0.5 m year^{-1} owing to increased aridity in south-western Australia in the last 40 years. The forest has also been mined and rehabilitated resulting in significant areas of postmining forest. We tested the impact of declining groundwater levels and mining on evapotranspiration by jarrah forest overstorey. We hypothesized that trees in jarrah forest are facultative phreatophytes (will use groundwater where available but are not reliant on it) and water use per unit overstorey leaf area index (L_{os}) of postmining forest is the same as that of postharvest forest. We measured sapflow at 7 sites in the northern jarrah forest and measured rainfall interception by the canopy at 9 sites. Stemflow was measured at 3 sites. Shallow depth to groundwater was associated with a larger ratio of transpiration per unit leaf area (E_{os}/L_{os}), but there was little difference in E_{os}/L_{os} between postmining and postharvest jarrah forest. E_{os}/L_{os} ranged from 250 - 340 mm year^{-1} (m^2 m^{-2})$^{-1}$ at sites where depth to groundwater was >15 m but was up to 400–500 mm year^{-1} (m^2 m^{-2})$^{-1}$ at *some* sites with shallow groundwater. Based on relationships between transpiration, rainfall interception, and L_{os}, it is possible to estimate overstorey evapotranspiration in jarrah forest from L_{os}, especially if spatial layers are available for depth to groundwater. We conclude that jarrah forest is conservative in its water use and likely to be resilient to a drying climate. Management implications for the northern jarrah forest are briefly discussed.

KEYWORDS

evapotranspiration, groundwater, leaf area index, mining, rainfall interception, sapflow

1 | INTRODUCTION

Groundwater-dependent ecosystems (GDEs) are those that rely on the surface or subsurface expression of groundwater to meet all or some of their life cycle requirements (Eamus, Froend, Loomes, Hose, & Murray, 2006). Ecosystems may be obligate GDEs, with a continuous or entire dependence on groundwater, or facultative GDEs, with an infrequent or partial dependence on groundwater (Zencich, Froend, Turner, & Gailitis, 2002). Plants that depend solely on moisture held within the soil profile are known as vadophytes and are not groundwater dependent whereas plants with deep root systems that access groundwater are known as phreatophytes (Sommer & Froend, 2010). The dependence of GDEs on groundwater varies both spatially and temporally (Eamus, Froend, et al., 2006). Factors such as the rooting depth of a particular species (Canadell et al., 1996), climate (Taylor et al., 2013), and groundwater depth and salinity (Eamus, Hatton, Cook, & Colvin, 2006) all impact on groundwater use by vegetation.

It has been speculated that the jarrah (*Eucalyptus marginata* Donn. ex Smith) tree, the dominant tree species in the jarrah forest of south-western Australia, may be a facultative phreatophyte. Soils in the jarrah forest are typically derived from deeply weathered granitic parent material up to 30 m deep (Churchward & Dimmock, 1989), and roots of jarrah trees have been observed at depths of up to 40 m (Dell, Bartle, & Tacey, 1983). Jarrah roots have been observed at watertables with depths ranging from 15 m (Carbon, Bartle, Murray, & Macpherson, 1980) to 35 m (Silberstein, Held, Hatton, Viney, & Sivapalan, 2001). The jarrah forest's Mediterranean climate consists of cool, wet winters and hot dry summers (Gentilli, 1989). The excess of rainfall over evaporation in winter allows for possible groundwater recharge whereas the large rainfall deficit in summer creates the conditions in which deep-rooted vegetation is likely to draw on groundwater or the deep unsaturated zone.

Several authors have observed that jarrah trees can maintain high rates of transpiration during summer despite the lack of summer rainfall (Carbon, Bartle, & Murray, 1981; Colquhoun, Ridge, Bell, Loneragan, & Kuo, 1984; Doley, 1967; Grieve, 1956; Silberstein et al., 2001), which may reflect the ability of this species' root system to either access groundwater during summer or to expand into the deep unsaturated regolith. Crombie (1997) concluded that a general increase in water potentials and stomatal conductances during summer drought, as seedlings grew to mature jarrah trees, was consistent with expansion of mature roots into deeper soil. Bleby (2003) found that stomatal conductance declined and daily water use fell well below potential during the late summer and autumn, indicating that soil moisture availability was strongly limiting during the dry season for young regrowth stands of jarrah. A study of regrowth and old-growth jarrah trees also concluded that jarrah was subject to substantial summer soil water deficits (Macfarlane et al., 2010). Based on ratios of stable isotopes in twigs, rainwater, soil water, and groundwater, it was concluded (Farrington, Turner, & Gailitis, 1996) that jarrah trees were not using groundwater at sites where groundwater was at 14–30 m depth below the surface.

There has been interest in the hydrology of the jarrah forest dating back at least 30 years (Schofield, Stoneman, & Loh, 1989; Stoneman & Schofield, 1989). During those 30 years, the climate of south-western Australia has become increasingly dry. This trend is predicted to continue throughout the 21st century as a result of global climate change (CSIRO, 2007) and is attributed to factors including natural variability, and changes in land use, ocean temperatures, and atmospheric circulation (van Ommen & Morgan, 2010). Depths to groundwater have been increasing at average rates up to 0.5 m year^{-1} (Hughes, Petrone, & Silberstein, 2012), and during the local drought of 2001–2002, some streams in the jarrah forest ceased flowing for the first time in living memory (Water Corporation, 2005) owing to disconnection from permanent groundwater (Kinal & Stoneman, 2012). During the extreme drought and heatwave of 2010–2011, deaths of jarrah trees were recorded across areas of limited soil moisture holding capacity (Brouwers, Matusick, Ruthrof, Lyons, & Hardy, 2013). To predict the impact that future climate change and falling watertables will have on the persistence and productivity of jarrah forest, it is important to understand the groundwater use of jarrah trees.

The jarrah forest also contains extensive bauxite deposits that have been mined since the early 1960s (Hickman, Smurthwaite, Brown, & Davy, 1992). Jarrah forest catchments that have been mined typically display increased streamflows following mining but return to premining streamflows as the rehabilitated vegetation develops (Bari & Ruprecht, 2003; Grigg, 2017). In some cases, streamflows decline below premine levels (Croton & Reed, 2007) and there has been speculation about the impact of mining on the water balance of the jarrah forest (Croton & Reed, 2007). Possible causes of altered hydrology relate either to modified soils or to changes in stand structure and associated hydraulic traits. A study of young (<10 y) trees on restored sites found that they grew three times faster and used four times more water per unit leaf area than similar sized trees in unmined forest, which the authors (Bleby, Colquhoun, & Adams, 2012) attributed to greater light, water, and nutrient availability on restored sites. However, their results also suggested a declining water availability in restored sites as trees grew to 10 m in height. Increased water use by postmining forest could also result from greater tree density or greater leaf area index as a consequence of greater root penetration into subsoil or fertilizer application; a stand with more sapwood area or greater leaf area index would be expected not only to transpire more but could also intercept more rainfall (Hall, 2003). Rainfall interception can account for 8–16% of rainfall in jarrah forest (Croton & Norton, 2001; Jones, 2009; Schofield et al., 1989; Wallace et al., 2013).

It is also possible that postmining forest may have different functional traits to unmined jarrah forest. Macfarlane, Bond, et al. (2010) found that water use per unit leaf area index in an old-growth jarrah stand was less than that in an adjacent unmined, regrowth stand, primarily due to structural changes in sapwood area with tree age and size. The stand with old trees contained less sapwood area despite a greater stand basal area because of a rapidly declining ratio of sapwood to basal area with increasing tree size. Similar structural changes have been reported for other *Eucalyptus* forests where declines in water use associated with aging of regrowth stands have been identified (Buckley, Turnbull, Pfautsch, Gharun, & Adams, 2012; Roberts, Vertessy, & Grayson, 2001; Vertessy, Watson, & O'Sullivan, 2001). It might, therefore, be expected that stands with large numbers of small trees will have a higher proportion of sapwood for a given stand basal area than stands of fewer, larger trees. However, there was no difference in the ratio of sapwood area to basal area in experimental postmining jarrah stands planted at densities from 600 to 10,000 trees ha^{-1} (Grigg, Macfarlane, Evangelista, Eamus, & Adams, 2008). In young jarrah trees, Bleby et al. (2012) concluded that architectural and physiological plasticity are important for maintaining hydraulic compatibility with soil and growth conditions as jarrah trees increased in age and size in both unmined and postmining environments. Over the course of a decade, regrowth trees on postmining sites reduced leaf area/sapwood area ratios, increased sapwood permeability, and reduced canopy stomatal conductance to offset increases in height and leaf area.

Evapotranspiration forms the major loss component of the jarrah forest water balance, estimated in some studies to exceed 90% of annual rainfall (Ruprecht & Stoneman, 1993). We investigated the evapotranspiration of jarrah forest overstorey in south-western Australia in relation to groundwater depth and mining. We present sapflow data and/or rainfall interception data from nine previously unreported sites, and combine these with data from previous studies, to investigate whether depth to groundwater and altered hydrology after mining affect overstorey transpiration rates. We tested the hypotheses that (a) trees in jarrah forest are facultative phreatophytes, that is, they will use groundwater where available but are not reliant on it and (b) water use per unit leaf area index of postmining forest is the same as that of postharvest forest.

2 | MATERIALS AND METHODS

2.1 | Site descriptions

Evapotranspiration measurements were made at nine sites in the high (>1,000 mm) rainfall zone of the northern jarrah forest of south-western Australia Schofield et al, 1989), a biodiverse region supporting jarrah and marri (*Corymbia calophylla* [Lindl.] K.D. Hill & L.A.S. Johnson) as the dominant overstorey species, and *c*. 800 understorey species (Bell & Heddle, 1989). Jarrah forest is managed for multiple uses, including conservation and recreation, wood production, bauxite mining, and water supply for the nearby metropolitan city of Perth. The climate is hot-summer Mediterranean (Köppen climate classification *Csa*), characterized by hot dry summers and cool wet winters with most rain falling between May and October (Gentilli, 1989). Soils are typically sandy gravels of inherently low fertility derived from deeply weathered granitic parent material up to 30 m deep (Churchward & Dimmock, 1989). Five sites (Lewis R, Lewis F, Bates, Warren, and Huntly 5) were located near Dwellingup, Western Australia, and four sites (A5, B1, C2, and C5) were located in the 31 Mile Brook catchment, approximately 50 km north of Dwellingup (Figure 1, Table 1). The landforms, vegetation, soils, and climate of the 31 Mile Brook catchment are described in detail by Havel (1975).

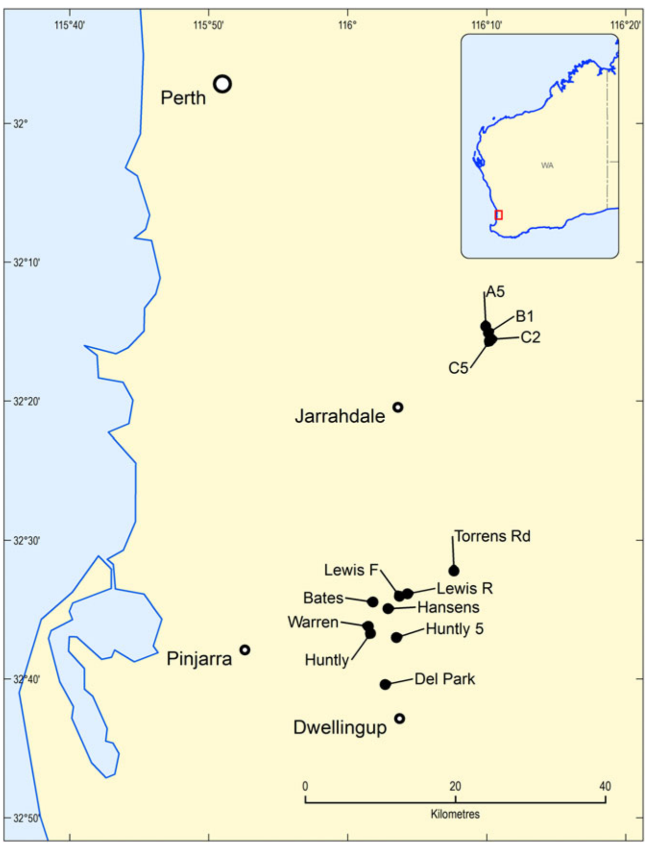

FIGURE 1 Location of study sites within the northern jarrah forest of south-western Australia

Stands of young postmining jarrah forest (Lewis R—established 1999), older postmining forest (Huntly 5—established 1979), and postharvest jarrah forests (Bates, Lewis F, and Warren—mixed age) were selected to compare young jarrah trees on rehabilitated mines and older regenerating jarrah trees in postmining and postharvest forest (Dwellingup sites; Table 1). The Bates and Lewis F sites were regrowth stands from past timber harvesting operations containing a variable proportion of larger diameter individuals, retained as habitat trees or future crop trees. No midstorey vegetation was present, and the understorey consisted of low stature shrubs that comprised only a minor component of the stand. The Warren site was heavily affected by *Phytophthora* dieback and supported only a sparse stand with a higher proportion of marri, which is more resistant to the disease than jarrah. The Lewis R and Huntly 5 sites were established postmining and were necessarily even-aged in structure. Both were dominated by jarrah with a variable presence of marri. In addition, Huntly 5 contained two species from eastern Australia, *Eucalyptus resinifera* Sm. (32% of stand basal area) and *Corymbia maculata* (Hook.) K.D. Hill & L.A.S. Johnson (9% of stand basal area). The Huntly 5 site had been burnt by a cool prescribed fire 1.5 years prior to the study; virtually all understorey was removed by the fire and regrowth over the course of the study was negligible. In contrast, the unburnt Lewis R site supported a very dense understorey of mainly *Bossiaea aquifolium* Benth. and *Acacia* spp. up to approximately 2.2 m in height.

Four stands of postharvest jarrah forest (31 Mile Brook sites; Table 1) were selected as part of a parallel study on the effects of forest density on catchment run-off (Macfarlane, Ogden, & Silberstein, 2012). Two sites (Table 1) were located on upper slopes (B1 and C2) and two on lower slopes (A5 and C5). The overstorey at the sites was dominated by jarrah except at C5 that was dominated by blackbutt (*Eucalyptus patens* Benth.). Similar to the Bates site, all these sites were mixed-age regrowth stands from past timber harvesting operations and contained a proportion of larger diameter individuals. Other species including marri, bullich (*Eucalyptus megacarpa* F. Muell.), and sheoak (*Allocasuarina fraseriana* [Miq.] L.A.S. Johnson) were minor components of the overstorey. The midstorey was sparse and consisted of scattered small trees of *Banksia* spp. Understorey foliage cover at the sites ranged from 15% to 25%.

During rehabilitation, the shallow (3–4 m deep) mine pits are landscaped to form an undulating terrain that blends with the natural landform and the pit floor is ripped using a winged tine to an approximate depth of 1.5 m. Ripping relieves compaction (Kew, Mengler, & Gilkes, 2007), aids later root exploration (Szota, Veneklaas, Koch, & Lambers, 2007), and may assist in reconnecting "root channels" that provide preferential pathways for infiltrating rainfall to the deep groundwater (Churchward & Dimmock, 1989; Dell et al., 1983). Salvaged subsoil and topsoil are returned to the landscaped pits, and the surface is ripped a second time on the contour to approximately 0.8 m depth, to prepare a seedbed, assist surface infiltration, and reduce potential erosion. A single application of fertilizer replaces

TABLE 1 Description of each study site

Site	Age (years)	Lat. (S)	Long. (E)	Stocking (stems/ha)	Basal area (m^2/ha)	Codominant height (m)
Dwellingup sites						
Lewis R	8	32°33′53″	116°04′18″	2,100	24	8
Huntly 5	30	32°37′01″	116°03′30″	810	27	14
Lewis F	mixed	32°34′03″	116°03′43″	670	29	15
Warren	mixed	32°36′13″	116°01′29″	97	8	16
Bates	mixed	32°34′28″	116°01′50″	925	29	12–16
31 Mile Brook sites						
A5	mixed	32°14′39″	116°09′56″	1,100	32	16–20
B1	mixed	32°15′06″	116°10′08″	988	38	12–16
C2	mixed	32°15′34″	116°10′20″	1,156	29	12–16
C5	mixed	32°15′42″	116°10′12″	394	20	16–20

nutrients lost in the mining process and assists early vegetation growth (Koch, 2007; Ward, 2000). Hence, mine rehabilitation typically results in fast growing, even-aged stands in postmining forest. In contrast, unmined, postharvest jarrah forest contains cohorts of different age occurring as a mosaic that result from silviculture and disturbance. Silvicultural methods applied in jarrah forest include gaps with retained habitat, group selection, shelterwood with retained habitat, and thinning with retained habitat (Stoneman, 2007). The multiage structure of jarrah forest is also maintained by disturbances including fire, insects, disease, and windstorm (Stoneman, 2007).

In our synthesis of sapflow data from jarrah forest, we also include results from three previous studies (shown in Figure 1) at Huntly and Hansens (Bleby, 2003), Del Park (Marshall & Chester, 1992), and Torrens postharvest (Macfarlane, Bond, et al., 2010). In our synthesis of throughfall data from jarrah forest, we include results from three previous studies (not shown; Croton & Norton, 2001; Jones, 2009; Schofield et al., 1989).

2.2 | Measurement of stand structure, sapwood area, wood density, and water content

At each site, a 40 × 40 m (0.16 ha) plot was established (except Huntly 5 and Warren, where plots were 30 × 30 m and 60 × 60 m, respectively). The height, diameter at breast height over bark (*D*) and bark thickness of all trees in each plot was measured, and for all sites except Lewis F and Warren, wood cores were collected for sapwood depth and sapwood area measurements. At least two stem-wood cores (either 5 or 12 mm diameter) were collected, using a motorized or hand corer, at breast height (1.3 m) from trees of a range of sizes (including the trees used for sapflow measurement) at each plot. Cores were at least 40 mm long to ensure that they contained the sapwood–heartwood boundary. The bark thickness was also recorded on these sample trees. The dates of measurements at each site are given in Table 2.

The sapwood–heartwood boundary along the wood cores was identified by the natural colour difference after fine sanding, which was further enhanced by staining with 1% methyl orange. We have compared this method against microscopic inspection for blocked xylem vessels on these and other species and found it to produce equivalent results (Pfautsch, Macfarlane, Ebdon, & Meder, 2012). The sapwood depth was measured with an electronic calliper, the sapwood removed from the rest of the core, and the fresh weight of the sapwood sample recorded. Although care was taken to use very little methyl orange for staining, it is possible that this may have introduced a small positive bias to calculated moisture contents of the sapwood. The volume of the samples was estimated by measuring the mass of water displaced when they were fully immersed in a beaker of water on a tared balance (Chave et al., 2005). The sapwood was then oven dried and its dry weight recorded. The water content and basic density of sapwood were calculated for use in sap velocity calculations. For

TABLE 2 Dates of measurements at each study site (month/year)

Site	Sapflow	Tree *D*	Wood cores	L_{os}	Interception
Lewis R	10/07–11/09	12/07 and 12/08	07/08	01/08	06/07–03/09
Huntly 5	05/09–01/11	02/10	01/09 and 02/10	03/10 and 04/11	04/09–01/10
Bates	10/07–01/11	05/08	06/08	09/08	04/08–12/09
Lewis F[a]	—	07/07	—	06/07	06/07–04/08
Warren[a]	—	08/10	—	04/10	04/10–11/10
A5	10/08–06/10	01/09	12/09	02/09 and 11/09	03/09–05/10
B1	10/08–05/10	01/09	12/09	02/09 and 11/09	03/09–05/10
C2	10/08–01/10	01/09	12/09	02/09 and 11/09	03/09–05/10
C5	09/08–12/09	01/09	12/09	02/09 and 11/09	03/09–05/10

Note. *D* = diameter at breast height (over bark).

[a]Sapflow measurements and wood cores were not collected from the Lewis F and Warren sites.

each tree, sapwood area (A_s) was calculated from the basal area, bark thickness, and sapwood depth.

Data obtained specifically for this study were pooled with data from other published and unpublished studies to derive robust allometric relationships between A_s and D. In total, data from 379 trees were used. We used analysis of covariance to test whether regressions of A_s versus D differed between jarrah trees from postmining forest (n = 121), postharvest forest (n = 138), and old-growth forest (n = 14). A single regression was calculated for other overstorey trees (n = 82), which formed a minor component of stand overstorey and appeared to have similar relationships between A_s and D (see Section 3). A single regression was also calculated for the midstorey *Banksia* spp. (n = 18). Pooled data from these studies were also used to investigate relationships between sapwood density and water content.

2.3 | Measurement of leaf area index

At all sites, we measured understorey cover, overstorey cover, and leaf area index (L_{os}) using digital cover photography and assuming a light extinction coefficient of 0.5 (Macfarlane, Grigg, & Evangelista, 2007). Image acquisition dates are given in Table 2. All digital cover photographs were collected as Fine JPEG images with maximum resolution (10 megapixels) using either a Nikon D80 SLR camera and 50 mm lens (31 Mile Brook sites), or a Nikon CoolPix 4500 with a maximum resolution of 3.9 megapixels (Dwellingup sites). In each case, the camera was mounted on a tripod and positioned approximately 1.5 m above the ground. The cameras were set to aperture-priority mode, autofocus, and automatic exposure. The lens was pointed directly upwards, and the camera lens was levelled using a bubble level either on the lens cap or on the tripod. Cover images were collected during the day in calm conditions either when the sky was free of clouds or there was uniform cloud cover. A total of 25 cover photographs (49 cover photographs at Warren) were collected on a 10 × 10 m grid (7.5 × 7.5 m grid at Huntly 5).

Cover images were analysed using WinSCANOPY Pro 2008a (Regent instrument, Ste Foy, Quebec). The blue channel of the sharpened (medium) RGB images was analysed. The sky pixels were separated from canopy pixels using a threshold brightness value that was automatically determined by algorithms within the software. WinSCANOPY separated large gaps from small gaps based on their area; gaps larger than 1.3% of the total image area were classified as large gaps (Macfarlane, Grigg, et al., 2007; Macfarlane, Hoffman, et al., 2007). WinSCANOPY calculated foliage cover, crown cover, crown porosity, and leaf area index (Macfarlane, Grigg, et al., 2007). We also estimated understorey leaf area index (L_{us}) at sites where this layer was substantial and contributed to rainfall interception losses using a variety of approaches (Macfarlane, Grigg, & Daws, 2017).

2.4 | Measurement of sap velocity

At each sapflow site (Table 2), five to 10 trees were selected to represent the range of tree sizes and species present. Sapflow measurement dates are given in Table 2. Two probes were installed at breast height (1.3 m) on opposite sides of each tree. We used heat ratio method (Burgess et al., 2001) probes (HRM30) produced by ICT International (Armidale, Australia) to measure sapflow. The sensors were carefully installed with 5 mm spacing between the heater and upstream and downstream probes. The sapwood was only 10–15 mm deep on most trees sampled, therefore sap velocity was only measured at one depth. The inner thermocouple was switched off because it lay in, or very near, the heartwood. We determined from initial tests that the inner thermocouples were recording zero or near zero flow. Needle-type probes such as these typically average sapwood temperature over a radial distance of 10 mm (Bleby, 2003; Dye & Olbrich, 1993; Hatton, Catchpole, & Vertessey, 1990; Swanson, 1983); hence, we installed the probes with the outer thermocouple at a precise distance of 5 mm from the cambium. This distance provided an average estimate of sap velocity in the outer 10 mm of sapwood (from the cambium to a depth of 10 mm) and also located the thermocouple near the depth of maximum sap velocity as recommended (Nadezhdina, Cermak, & Ceulemans, 2002) to maximize the sensitivity of the measurements to changes in sap flow and to reduce errors associated with installation. Farrington, Bartle, Watson, and Salama (1994) noted that maximum sap velocity was recorded at a depth of 5 mm in the sapwood of *Eucalyptus wandoo* and *Eucalyptus salmonophloia*. Similarly, maximum sap velocity was recorded at 5 mm depth in *Fraxinus* sp. which has similarly thin sapwood (Gebauer, Horna, & Leuschner, 2008).

The raw output from the HRM30 sensors was half-hourly heat pulse velocity (cm hr^{-1}). Raw data were quality controlled and gap filled using the OzFluxQC (Version 2.9.5) suite of Python scripts (Isaac et al., 2016), which were originally developed to process eddy covariance flux data. The following workflow was applied:

1. Ingest the raw heat pulse velocities and save as netCDF format files. This corresponds to Level 1 described in Isaac et al. (2016).
2. Quality control the data using range checks for plausible data and manual rejection of date ranges and apply baseline corrections for probe asymmetry to the data so that each sensor had a minimum heat pulse velocity of zero at predawn during winter when the assumption of zero sapflow at predawn would be satisfied. This corresponds to Level 2 described in Isaac et al. (2016).
3. Gap fill the heat pulse velocities. For gaps shorter than 3 hr, values were linearly interpolated; data within longer gaps were modelled using climate drivers and a self-organizing linear output (SOLO) model based upon a self-organizing feature map. This corresponds to Level 5 described in Isaac et al. (2016).

Data from individual sapflow probes were gap filled using SOLO. This type of artificial neural network is used in hydrology for its small error and resistance to overtraining (Hsu, Gupta, Gao, Sorooshian, & Imam, 2002). Details of the SOLO neural network design and operation are given in (Abramowitz, 2005). Application of SOLO to gap filling fluxes is described in Isaac et al. (2016). A 10-day window was used with only net radiation (F_n) and vapour pressure deficit (*VPD*) as climate drivers. Soil moisture (θ) was assumed to have minimal impact on sap velocities using such a short window. F_n and *VPD* were chosen because they were obvious strong drivers of evaporation and transpiration

(Monteith, 1965; Penman, 1948). Climate drivers were obtained from multiple sources:

- Hourly climate data were obtained for the Dwellingup (009538) Bureau of Meteorology automatic weather station for the years 2006 to 2013; encompassing several years either side of the sapflow sampling period. The data composed of air temperature, relative humidity, wind speed, wind direction, and atmospheric pressure. Half-hourly values of all data were interpolated as the mean of adjacent hourly values. VPD was calculated from air temperature and humidity.
- Six-hourly radiation data were obtained for 2006–2013 from the ERA interim reanalysis data set from the European Centre for Medium Range Weather Forecasting (Dee et al., 2011). For radiation data, the ERA-I provides similar gap-filling performance to the Australian Community Climate Earth System 5 Simulator (Bi et al., 2013) numerical weather prediction (NWP) model run by the Bureau of Meteorology. Australian Community Climate Earth System 5 Simulator model output was not available prior to 2011. ERA-I data were obtained for the 75 × 75 km grid square nearest the sample sites. The 6-hourly ERA-I data were interpolated to provide half-hourly data as described by Isaac et al. (2016).

Gaps were only filled if more than 50% of data were present within the window. Following gap filling, a linear correction for wounding was then applied (Burgess et al., 2001). Based on previous experience with jarrah and examination of cores extracted at the end of sapflow measurements, we used a wound size of 3 mm in calculations. Wound sizes reported for eucalypts from other studies range from as little as ~2 mm (Farrington et al., 1994; Medhurst, Battaglia, & Beadle, 2002) to more than 3 mm (Dye & Olbrich, 1993; Mitchell, Veneklaas, Lambers, & Burgess, 2009; O'Grady et al., 2009). The density and water content of the sapwood were used together with the specific heat capacity of wood and water to convert the corrected heat pulse velocities to sap velocities (Burgess et al., 2001). To account for the smaller sap velocity in deeper sapwood close to the heartwood boundary, we assumed that sap velocity decreased linearly to zero from 10 mm depth to the sapwood–heartwood boundary (Macfarlane, Bond, et al., 2010); that is, we assumed that the sap velocity in the “inner sapwood ring” (A_i, 10 mm to the heartwood) was half that of the “outer sapwood ring” (A_o). The area of sapwood in the inner ring typically accounted for only 10–40% of total sapwood area in trees with sapwood deeper than 10 mm. The sapwood-area-weighted mean sap velocity (V_m) of each tree was therefore calculated from sap velocity in the outer ring (V_o) as (Equation 1):

$$V_m = (A_o V_o + A_i V_o/2)/(A_o + A_i). \tag{1}$$

2.5 | Modelling of transpiration

Transpiration of overstorey trees at each sapflow site was modelled using multiple linear regression, after confirming that there was no clear relationship between V_m and tree diameter. First, the sap velocities derived from the first stage of gap filling were used to derive a multiple regression model of daily sap velocity. Each day's mean sap velocity (V_s) for each sapflow probe was treated as an observation to derive constants in the following model (Equation 2):

$$V_s = a \times \theta \times F_n + b \times \theta \times VPD + c, \tag{2}$$

where a, b, and c are constants, θ is the soil moisture fraction (0–6 m), F_n is daily mean net radiation, and VPD is daily mean VPD. The form of this model is based on the strong link between potential evaporation and F_n and VPD (Monteith, 1965; Penman, 1948). In the Penman–Monteith equation, θ was included as a “modifier” of potential evaporation and performs an analogous role to canopy conductance. This yielded mean V_s for each site for the whole modelled period. This was multiplied by the sapwood area of the plot to calculate stand overstorey transpiration. Annual averages of V_s and stand transpiration were calculated from July to June for years with good data coverage. The period of July to June was used to best capture the seasonal pattern of sapflow, as has been done for streamflow analysis in the northern jarrah forest region (Hughes et al., 2012).

Daily soil moisture data (θ, soil moisture fraction from 0 to 6 m depth) were obtained from the Australia Landscape Water Balance (Hafeez et al., 2015). These data are based on the Australian Water Resources Assessment Landscape model (AWRA-L v5.0) described in Viney et al. (2015). AWRA-L data were obtained for the 5 × 5 km grid square nearest the sample sites. The daily AWRA-L data were converted to half-hourly data by assuming the soil moisture fraction was constant for a calendar day.

We tested the significance of each individual climate driver using the following main effects model (Equation 3):

$$V_s = a \times \theta + b \times F_n + c \times VPD. \tag{3}$$

2.6 | Rainfall, throughfall, and stemflow

All interception measurements were undertaken between June 2007 and May 2010 (Table 2). Total daily rainfall for the 31 Mile Brook sites was measured using a research quality rain gauge in a clearing at Hakea Rd supplied by the WA Department of Water (Bureau of Meteorology 509610). For the Dwellingup sites, single or dual Rainwise© Model 111 300 mm diameter tipping bucket logging rain gauges with a 0.25 mm bucket capacity were installed in open areas at distances of 200–600 m from each site. Tips were logged to 1 min resolution.

We measured throughfall at each site using 16 fixed gauges installed on regular 7.5 m (Huntly 5) or 10 m (all other sites) grids. At all Dwellingup sites except Warren, the fixed gauges were supplemented with two to four roving gauges at randomly selected points within the fixed grid. Roving gauges were moved to new locations every 6–8 weeks during the winter months. We used Rainwise© Model 111 rain gauges mounted on square plywood sheets and placed on the ground surface. Tipping bucket rain gauges were cleaned and recalibrated in the laboratory annually. Due to the sparse and clumped tree cover at Warren, a larger plot of 60 × 60 m was established to obtain a better estimate of mean throughfall. Here, a total of 49 rain gauges were established on the 10 × 10 m grid, consisting of 13 tipping bucket logging rain gauges, as described above, and 36 storage gauges (Nylex© 280 mm storage capacity, 105 mm diameter) affixed to timber stakes and positioned with the opening approximately 30 cm above the ground. Storage gauges were read and emptied after each storm event. At the 31 Mile Brook sites, we used Nylex© Rain Gauge 1000 storage gauges affixed to timber stakes and positioned with the opening approximately 30 cm above the ground. Storage gauges were read and emptied approximately monthly during the winter months.

We measured stemflow on 20 trees at Bates, 10 trees at Lewis R, and 19 trees at Huntly 5, selected to cover the range of sizes and species present; stemflow was not measured at Lewis F and Warren, nor at any of the 31 Mile Brook sites. On each tree, stemflow was intercepted by flexible polycarbonate collars attached to the tree trunk and sealed with waterproof silicon sealant and directed via hoses (internal diameter 15 mm) into sealed storage containers. Multiple storage containers per tree and large containers up to 200 L capacity on the larger trees were used to reduce the incidence of overflow. Collected stemflow was recorded approximately fortnightly (longer in the dry summer months) and the containers emptied.

For each site, throughfall was averaged across all gauges and the average compared with total rainfall recorded in the open area gauge. Missing data due to logger malfunction or blockages were estimated from regression of the individual gauge against the open gauge. Linear regression models were developed between stemflow recorded for individual trees and rainfall recorded at the open gauge for each site. Non-linear models were then developed between tree diameter and the slope and intercepts of the linear regressions for each species at each site. These non-linear models were subsequently applied to all trees measured in the plot to derive an estimate of total plot stemflow for each collection period, expressed as a depth over the plot area. For the 31 Mile Brook sites, Lewis F, and Warren, the regression models developed for the Bates site were applied to all the trees in each plot as follows: The model for jarrah was applied to both jarrah and blackbutt, whereas the model for marri was applied to marri and all other non-jarrah species. For a given site, plot-scale stemflow estimates were correlated with rain event size, the slope of which yielded an estimate of total stemflow as a percentage of rainfall for the period of records.

Interception (c_I) was calculated as (Equation 4):

$$c_I = (100 - c_{TF}) - c_{SF}, \tag{4}$$

where c_{TF} is throughfall (%) and c_{SF} is plot stemflow (%).

2.7 | Depth to groundwater

Where deep bores were present within 50 m of a sapflow site, observed groundwater depths for up to eight bores per site were averaged over the period of sapflow measurements. At Site B1 in 31 Mile Brook, the bore was dry at 16 m depth throughout the measurement period, with drill records indicating that this depth was at or close to bedrock. In this instance, 16 m has been assumed as the depth to groundwater.

For sapflow sites where no deep bores were in close proximity—C2 and Huntly 5 (this study), Huntly (Bleby, 2003) and Torrens Rd (Macfarlane, Bond, et al., 2010), groundwater depths were estimated by establishing a relationship between depth to groundwater at deep bores in the local area and UPNESS, a topographic wetness index variable within the FLAG model (Roberts, Dowling, & Walker, 1997). An UPNESS value describes in absolute terms a position within a landscape calculated as the number of grid cells connected by a monotonic continuous uphill path, with small values indicating positions high in the landscape and increasingly larger values indicating positions in valley locations moving progressively downstream. For this study, UPNESS values were generated on a 25 m grid using a 5-m digital elevation model. At 31 Mile Brook, mean annual depth to groundwater for a total of 11 deep bores in 2009, the year covering the majority of sapflow measurements, formed a log normal relationship with UPNESS (Figure 2a). The fitted curve provided the estimated depth to groundwater for site C2. For the Dwellingup sites, similar relationships were derived between UPNESS and groundwater information for 57–85 deep bores, with the number of bores available depending

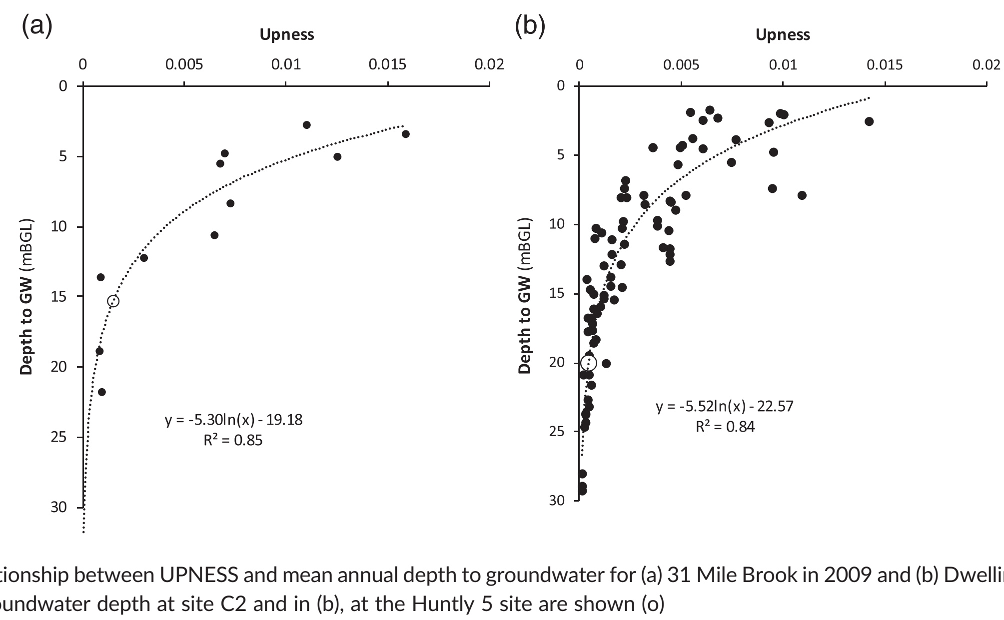

FIGURE 2 Relationship between UPNESS and mean annual depth to groundwater for (a) 31 Mile Brook in 2009 and (b) Dwellingup in 2010. In (a), the estimated groundwater depth at site C2 and in (b), at the Huntly 5 site are shown (o)

on the year of sapflow measurement. The curve for 2010, in which the majority of sapflow measurements at Huntly 5 were undertaken, is shown in Figure 2b. Correlation coefficients for all relationships were in the range 0.83–0.85.

3 | RESULTS

3.1 | Sapwood area and leaf area index of the plots

Sapwood area of the plots ranged from 3.6 to 7.9 m^2 ha^{-1} and was dominated by jarrah except at C5 (Table 3). Sapwood areas, and the ratios of sapwood to basal area, were largest at the two postmining sites, which was partly the result of trees at these two sites being smaller on average but also having deeper sapwood on average (Figure 3a). Based on the analysis of covariance, we developed separate regressions for postmining, postharvest, and old-growth jarrah trees. The postmining jarrah trees had noticeably more sapwood area for a given sized tree than the postharvest or old-growth jarrah trees. The regression for the other overstorey species (Figure 3b) was similar to that of the postharvest jarrah trees. L_{os} ranged from 1.1 to 1.9 and the leaf area to sapwood area ratio ranged from 0.23 to 0.37.

The larger sapwood area of the postmining trees was the result of thicker sapwood, whereas old-growth trees had thin sapwood independent of tree diameter (Figure 4a). Postmining forest also tended to have less dense sapwood with higher water content than postharvest forest, although there was a large variation in sapwood density and water content for all forest types. Old-growth forest (Macfarlane, Bond, et al., 2010) appeared to have both consistently low density and water content (Figure 4b,c).

3.2 | Rainfall, throughfall, and stemflow

Annual rainfall at 31 Mile Brook was 1,145 mm in 2007, 1,023 mm in 2008, and 1,094 mm in 2009. For the Dwellingup sites, annual rainfall varied from 1,206 mm in 2009 to only 520 mm at Warren in 2010. Throughfall varied between 73% and 92% of gross rainfall across the nine sites in this study (Table 4). When combined with other published studies, throughfall was linearly related to total (overstorey and understorey) leaf area index (L_{total}), reducing by 9% of rainfall per unit L (Figure 5a).

TABLE 3 Sapwood area by species, total sapwood area (m^2 ha^{-1}), overstorey leaf area index (L_{os}), and ratios (L_{os}/A_s, cm^2 m^{-2} and A_s/A_b, m^2 m^{-2})

Site	A_s total	A_s jarrah	A_s other	L_{os}[a]	L_{os}/A_s	A_s/A_b
Lewis R	6.9–7.9	5.8–6.6	1.1–1.3	1.6–1.9	0.23–0.24	0.28
Huntly 5	6.7	3.5	3.2	1.7	0.26	0.25
Bates	5.0	3.0	2.0	1.6	0.32	0.17
A5	5.0	3.0	2.0	1.3	0.26	0.19
B1	5.4	3.9	1.5	1.5–1.9	0.29–0.34	0.14
C2	4.6	3.1	1.3	1.6	0.37	0.16
C5	3.6	0.4	3.2	1.2	0.30	0.18

[a]Where more than one estimate of L_{os} was available, the estimate that best represents the sapwood measurement period was used.

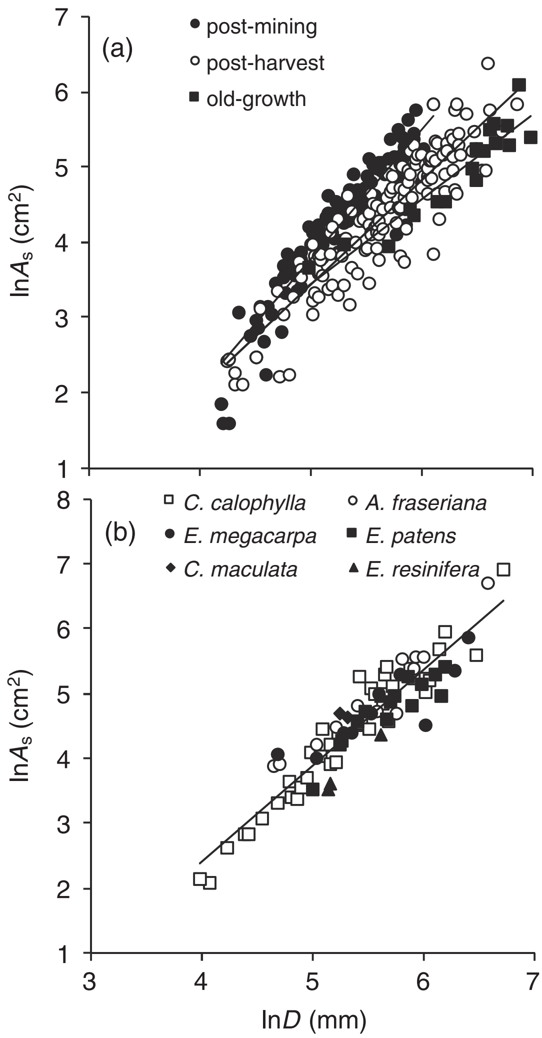

FIGURE 3 Sapwood area (A_s) versus tree diameter over bark at breast height (D) of (a) *Eucalyptus marginata* trees in three different stand types and (b) minor overstorey species

There was a linear relationship between stemflow volume and rainfall and correlation coefficients for all trees across all sites varied between 0.77 and 0.99, with an average of 0.92 (data not presented). For these linear relationships, regression slopes increased and intercepts became more negative as tree size increased, generally conforming to power relationships with tree diameter for each species at each site. The power relationship evident for trees at Bates was also observed at Lewis R and Huntly 5 although model coefficients differed between sites. Measured or estimated stemflow at each site varied from 0.6% to 12.2% (Table 4) across a range of L_{total} from 0.7 to 2.9; on average c_{SF} increased by 3% of rainfall per unit L_{total}. Calculated rainfall interception (Equation 4) was in the range 7–18% (Table 4) and was closely related to L (Figure 5b), increasing at 6.5% of rainfall per unit L, based on our data and data from other jarrah forest studies (Croton & Norton, 2001; Jones, 2009; Schofield et al., 1989).

3.3 | Sap velocity and overstorey transpiration

Other than at Huntly 5, there was no relationship between tree size and sap velocity (Figure 6); hence, we judged that it was reasonable

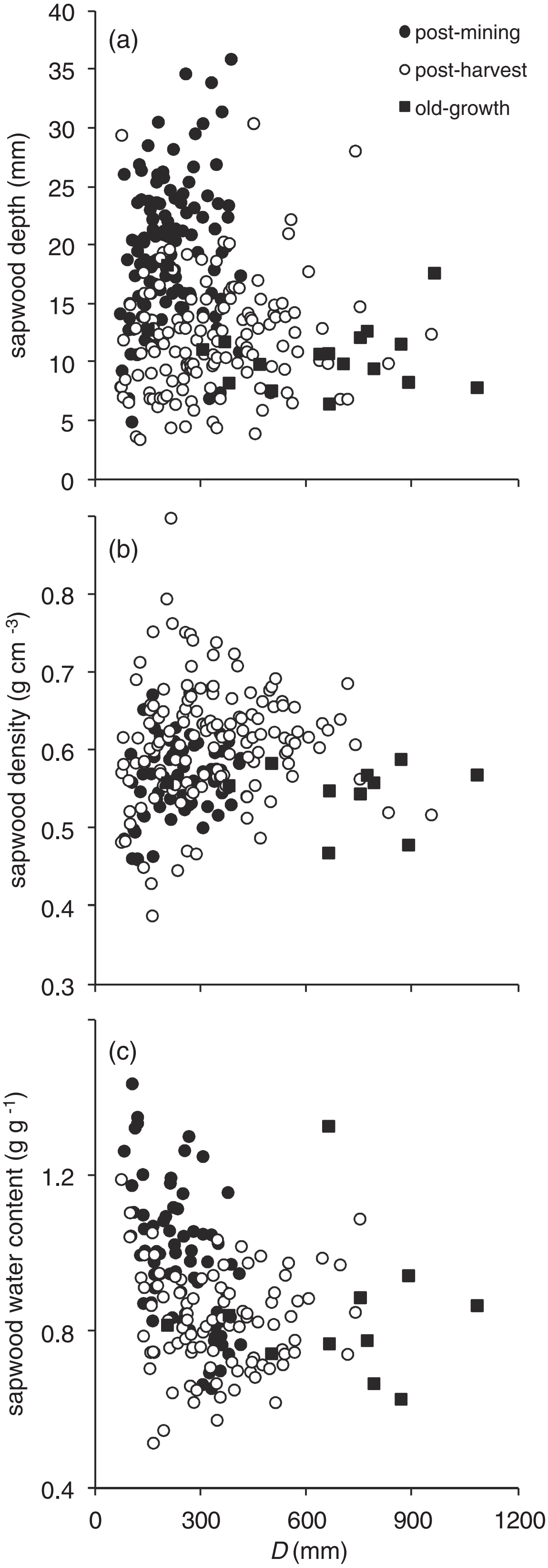

FIGURE 4 (a) Sapwood depth, (b) sapwood density, and (c) water content versus tree diameter over bark at breast height (*D*) of *Eucalyptus marginata* trees in three different stand types

to treat each sapflow sensor as an independent sample regardless of the size of the tree it was installed in. Similarly, only weak, nonsignificant relationships existed between tree size and sap velocity in

TABLE 4 Canopy leaf area index (L_{os}), combined canopy and understorey leaf area index (L_{total}), canopy cover (f_f), throughfall (c_{TF}), stemflow (c_{SF}), and interception (c_I) at each site

Site	L_{os}[a]	L_{total}	f_f	c_{TF} (%)	c_{SF} (%)	c_I (%)
Bates	1.6	1.8	0.42	83	5.3	11
Lewis R	1.5	2.9	0.31	73	12.2	15
Huntly 5	2.1	2.1	0.51	76	8.1	16
Lewis F	1.3	1.6	0.34	83	5.5	12
Warren	0.65	0.7	0.17	92	0.6	7
A5	1.3	2.1	0.36	86	5.3	9
B1	1.5	2.1	0.42	75	6.7	18
C2	1.3	2.1	0.35	80	5.3	14
C5	1.0	1.6	0.30	89	2.4	9

[a]Where more than one estimate of was L_{os} was available, the estimate that best represents the throughfall measurement period was used.

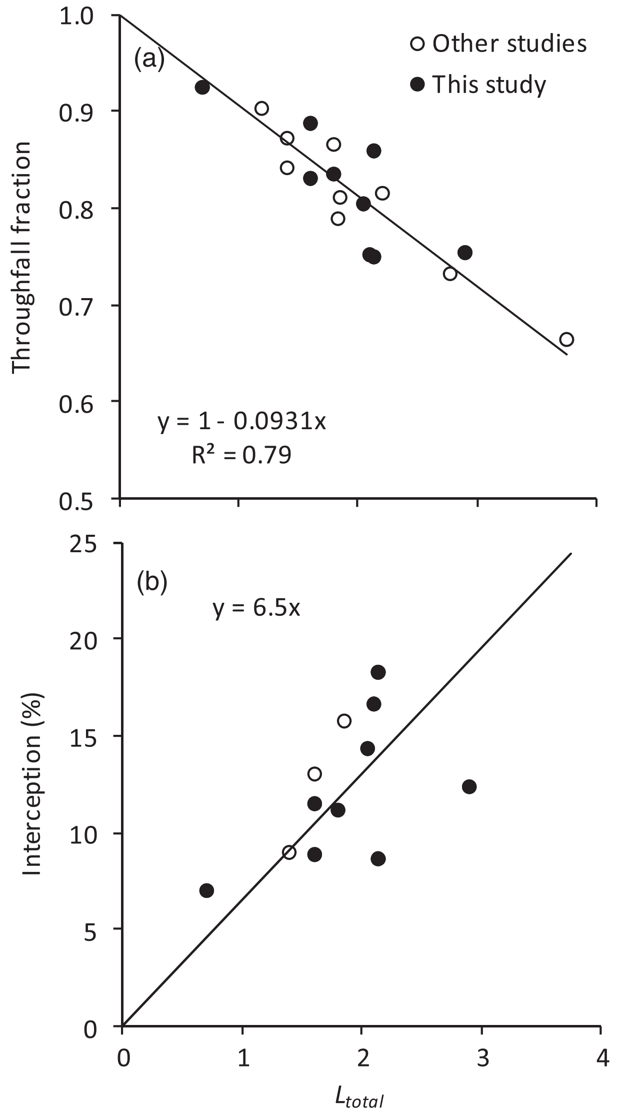

FIGURE 5 (a) Throughfall and (b) rainfall interception in jarrah forest stands in relation to combined canopy and understorey leaf area index from (●) this study and (○) other published jarrah forest studies (Croton & Norton, 2001; Jones, 2009; Schofield et al., 1989)

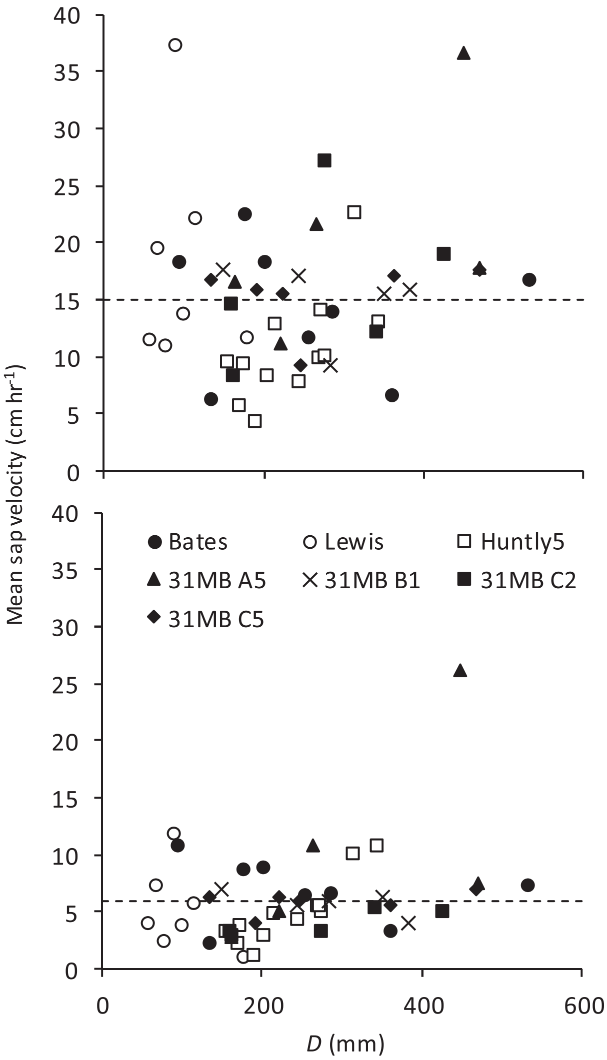

FIGURE 6 Relationship between tree size and mean sap velocity in January (top) and July (bottom) for each site. The average for all sites is shown as a dashed line

Eucalyptus regnans (Benyon, Nolan, Hawthorn, & Lane, 2017). Based on the main effects model (Equation 3), all three climate drivers were significant predictors (p < .001) of mean daily sap velocity at all sites except for soil moisture fraction that was not significant at C5 and only weakly significant (p = .05) at Lewis R (data not presented). Separate multiple regressions (Equation 2) were developed to model mean daily sap velocity for each site (not shown). All intercepts and slopes were highly significant (p < .001). Correlation coefficients were generally small (0.17–0.55), which reflected the large variation in the magnitude of sap velocity between different sensors at a site. Large slopes in the multiple regressions to model mean daily sap velocity indicate greater sensitivity to evaporative demand and, thus, may indicate access to either groundwater or a large store of soil water in the unsaturated zone. Three sites had large slopes for both the $\theta \times F_n$ and $\theta \times$ VPD terms: Lewis R, A5, and C2. Site C5 had a large slope for the $\theta \times$ VPD term only. Sites Bates, Huntly 5, and B1 were relatively insensitive to evaporative demand.

Across all sites and years, mean daily sap velocities (for a whole year) ranged from 8.9–14.4 cm hr^{-1} but were 10–12 cm hr^{-1} at most sites (Table 5). There was no clear evidence that sap velocities were higher in postmining forest (Huntly 5 and Lewis R) than in postharvest forest (Figure 7). The seasonal pattern of sap velocity found here was similar to previous studies of jarrah forest (e.g., Macfarlane, Bond, et al., 2010); sap velocity was greatest in the summer months and least in the winter months (Figure 7). Mean sap velocities from other published studies of jarrah forest (Table 6) were generally lower than the data presented here, which presumably is due in part to the wide range of field methods and data postprocessing applied in the earlier studies.

Annual overstorey transpiration ranged from just 322 mm at C5 to over 700 mm at Lewis R; which is similar to the range in previously published studies (Table 7) if sites with very low leaf area (Worsley and Hansens) are excluded. The ratio of overstorey transpiration to sapwood area is directly proportional to mean daily sap velocity and

TABLE 5 Summary of overstorey transpiration estimated from sap velocity measured using the heat ratio method and modelled using multiple regression from data subjected to Stage 1 of gap filling only

Site	Year (July–June)	D_{GW} mBGL	V_s cm hr^{-1}	E_{os} mm day^{-1}	E_{os} mm year^{-1}	E_{os}/L_{os} mm year^{-1} (m^2 m^{-2})$^{-1}$	E_{os}/A_s mm year^{-1} (m^2 ha^{-1})$^{-1}$
Huntly 5	09–10	20.1	8.9	1.4	525	300	78
Lewis R	07–08	7.7	11.7	2.0	715	447	103
Lewis R	08–09	7.7	11.8	2.2	818	431	103
Bates	07–08	16.2	11.0	1.4	504	315	101
Bates	08–09	16.2	11.1	1.4	503	315	101
Bates	09–10	16.2	11.2	1.4	512	320	103
A5	08–09	6.0	14.2	1.7	622	471	124
A5	09–10	6.0	14.4	1.7	628	483	126
B1	08–09	16.0	11.2	1.4	526	319	98
B1	09–10	16.0	11.3	1.5	532	339	99
C2	08–09	15.3	10.2	1.1	413	253	89
C5	08–09	8.1	10.2	0.9	322	261	89

Note. Sap velocity (V_s) and overstorey transpiration (E_{os}) are annual averages. Depth to groundwater (D_{GW}) at each site in each year is also given.

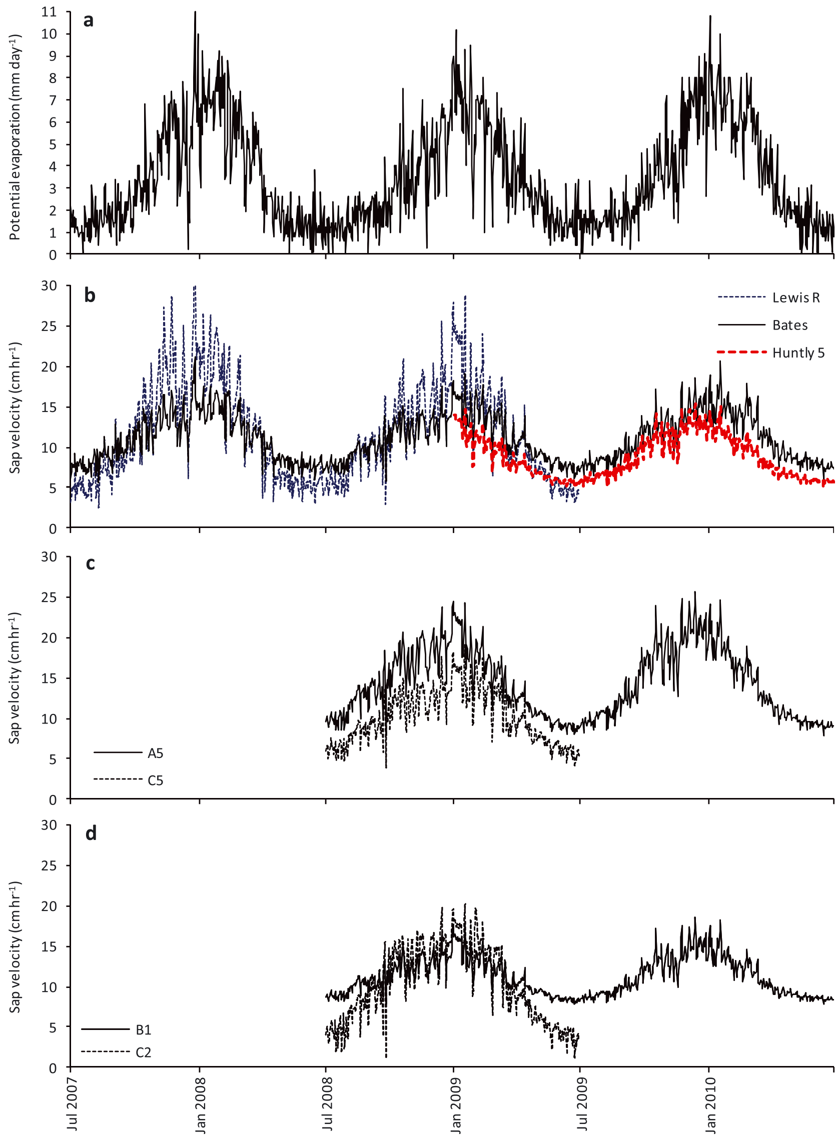

FIGURE 7 Seasonal pattern of (a) potential evaporation; (b) sap velocity at three sites near Dwellingup: Bates (postharvest), Lewis R (postmining), and Huntly 5 (postmining); (c) sap velocity at two postharvest sites at 31 Mile Brook with deep groundwater; (d) sap velocity at two postharvest sites at 31 Mile Brook with shallow groundwater. Data have been gap filled with modelled data

TABLE 6 Summary of overstorey transpiration estimated from sap velocity in previous studies of jarrah forest

Site	A_s m^2 ha^{-1}	L_{os}	D_{GW} mBGL	V_s cm hr^{-1}	E_{os} mm day^{-1}	E_{os} mm $year^{-1}$	E_{os}/L_{os} mm $year^{-1}$ $(m^2\ m^{-2})^{-1}$	E_{os}/A_s mm $year^{-1}$ $(m^2\ ha^{-1})^{-1}$
Huntly[a]	7.2	3.1	17.3	12.7	2.2	803	259	111
Hansens[b]	1.8	0.4	7.9	10.1	0.4	161	402	88
Del Park[b]	10.1	1.8	19.1	5.4	1.3	485	262	48
Torrens postharvest[c]	7.0	1.9	7.5	8.5	1.4	502	267	72

[a](Bleby, 2003).

[b](Marshall & Chester, 1992).

[c](Macfarlane, Bond, et al., 2010).

was in the range 76–126 mm $year^{-1}$ $(m^2\ ha^{-1})^{-1}$, slightly higher than previously published. The ratio of overstorey transpiration to L (E_{os}/L_{os}) is highly susceptible to uncertainties in estimates of L_{os} and is more variable than the ratio of transpiration to sapwood area (Table 5). In our data set, E_{os}/L_{os} ranged from 244 to 482 mm $year^{-1}$ $(m^2\ m^{-2})^{-1}$ (Table 5), somewhat less variable and with a higher mean value than the range of 128–420 mm $year^{-1}$ $(m^2\ m^{-2})^{-1}$ found in previous studies (Table 6).

There was a clear tendency for sites with greater depth to groundwater to have a lower E_{os}/L_{os} than sites with shallower groundwater (Figure 8). E_{os}/L_{os} of sites with depth to groundwater >15 m ranged from 250 to 340 mm $year^{-1}$ $(m^2\ m^{-2})^{-1}$. There was a much wider range of E_{os}/L_{os} for sites with depth to groundwater <10 m. Three sites with shallow groundwater, Lewis R, A5, and Hansens, had E_{os}/L_{os} of 400 to 500 mm $year^{-1}$ $(m^2\ m^{-2})^{-1}$. Two sites with shallow groundwater, Torrens Rd regrowth and C5, had small

TABLE 7 Rainfall and overstorey evapotranspiration (mm year^{-1}) at each site

Site	Year	Rainfall (P)	Transpiration (E_{os})	Interception[a]	Total evapo-transpiration (ET_{os})	ET_{os}/P
Huntly 5	09–10	996	525	159	684	0.69
Lewis R	07–08	1,031	715	155	870	0.84
Lewis R	08–09	1,332	818	200	1,018	0.76
Bates	07–08	1,031	504	113	617	0.60
Bates	08–09	1,332	503	147	650	0.49
Bates	09–10	996	512	110	622	0.62
A5	08–09	1,249	622	109	731	0.59
A5	09–10	914	628	80	688	0.75
B1	08–09	1,249	526	229	755	0.60
B1	09–10	914	532	167	699	0.76
C2	08–09	1,249	413	170	583	0.47
C5	08–09	1,249	322	111	433	0.35

[a]Interception calculated from % interception for each site in Table 5.

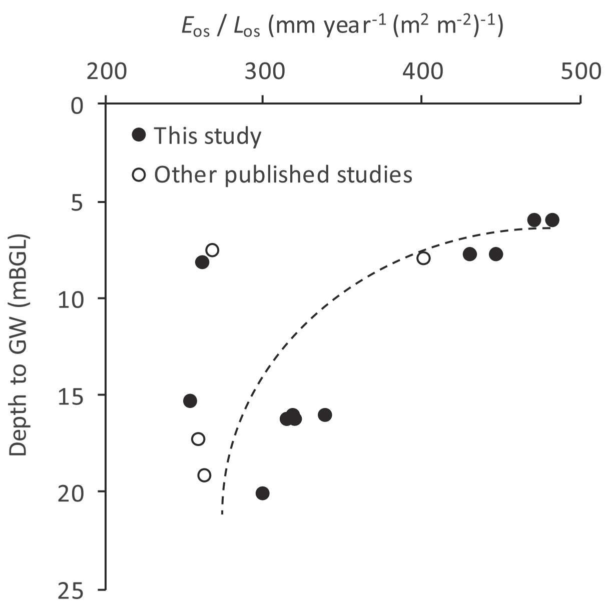

FIGURE 8 Relationship of transpiration per unit leaf area (E_{os}/L_{os}) to depth to groundwater for sites from this study and other published studies. The dashed line indicates the general trend and is not a fitted line

(260–270 mm year^{-1} [m^2 m^{-2}]$^{-1}$) values of E_{os}/L_{os}. One of these sites, C5, was not dominated by jarrah, which may explain the unusual result. No groundwater measurements were available for the Torrens Rd regrowth site, and it is possible that the estimated groundwater depth from the UPNESS model we developed is not adequate and that groundwater is in fact deeper at this site. There was no evidence that postmining forest had a larger E_{os}/L_{os} than unmined forest; two of the three sites with large values of E_{os}/L_{os} were unmined forest. The postmining site with a large value of E_{os}/L_{os} also had access to shallow groundwater.

Rainfall (July–June) ranged from 914 mm in 2009–2010 at 31 Mile Brook to 1,249 mm in 2008–2009 at Dwellingup (Table 7). Total overstorey evapotranspiration as a fraction of rainfall (ET_{os}/P) ranged from as little as 0.35 at C5 to 0.84 at Lewis R in 2007–2008. Although ET_{os}/P was generally high for the postmining sites (Lewis R and Huntly 5), there were postharvest sites (A5 and B1) with equally high ET_{os}/P in some years (Table 7). ET_{os}/P was larger in years of low rainfall than in years of high rainfall.

4 | DISCUSSION

Our study of sapflow at 11 jarrah forest sites strongly supports the hypothesis that jarrah forest trees are facultative phreatophytes. Where depth to groundwater is less than 10 m, it is likely that trees will access groundwater to supplement the store of water in the unsaturated zone and increase rates of transpiration per unit leaf area (E_{os}/L_{os}) by as much as 50% more than those trees with no access to groundwater, or access to much deeper groundwater. Our estimated rates of E_{os}/L_{os} of "vadophyte jarrah" are 250 to 340 mm year^{-1} (m^2 m^{-2})$^{-1}$, substantially less than the 400 to 500 mm year^{-1} (m^2 m^{-2})$^{-1}$ estimated for "phreatophyte jarrah." This conclusion is consistent with the finding that jarrah forest above a watertable at 6 m depth was using groundwater but jarrah forest above a watertable at 14 and 30 m was not (Farrington et al., 1996). In general, transpiration of groundwater is expected to decline as the depth to groundwater increases, but there is very limited evidence within Australia to support this assumption. The results of our study are in broad agreement with a review of estimates of groundwater discharge in Australia (O'Grady, Carter, & Holland, 2010), which concluded that there is considerable variation in the relationship between transpiration of groundwater and depth to groundwater but that groundwater use by vegetation was largest where depth to groundwater was less than 5 m.

Although jarrah forest may access deep groundwater owing to great tree rooting depths (Carbon et al., 1980), use of deep groundwater is likely to be limited and trees are likely to be largely reliant on soil water stored in the unsaturated zone above the watertable. Water use by jarrah is very likely to be facultative because there have been no reports of jarrah deaths in response to falling watertables in stream zones. Watertables in the northern jarrah forest have been falling at average rates up to 0.5 m year^{-1} (Hughes et al., 2012), but deaths of jarrah trees have been associated with areas of shallow soil near rocky outcrops, high elevations, and steep slopes (Brouwers et al., 2013), not riparian zones with falling water tables. Hence, although climate change (the driver of falling watertables) is likely to result in decreasing transpiration (and probably productivity) of jarrah trees in low lying areas in the future, it is unlikely that it would result in a change from jarrah forest to some other type of forest or vegetation. A study of the structure and productivity of eucalypt forest across a depth-to-watertable gradient in the upper Nepean catchment in NSW (Zolfaghar et al., 2014) found that where groundwater was shallow, vegetation had significantly higher biomass and productivity than sites where depth to groundwater was greater than approximately 10 m.

Modelling of evaporation from remotely sensed L in jarrah forest may need to account for variable E_{os}/L_{os} in response to watertable depth, both into the future and in the past. Although this study suggests that "vadophyte jarrah" has a typical transpiration rate of 250 to 340 mm year^{-1} (m^2 m^{-2})$^{-1}$, the corresponding rate for "phreatophyte jarrah" is much larger. Given the rate at which watertables have fallen in the past 40 years, it is likely that the mean E_{os}/L_{os} of the northern jarrah forest has declined as the area with shallow groundwater has shrunk. Modelling of transpiration from remotely sensed L would likely be improved if historical groundwater surfaces could be modelled. More accurate modelling of transpiration in the recent past and into the future may be possible with additional remotely sensed data, such as land surface temperature (Zhang, Chiew, Zhang, Leuning, & Cleugh, 2008). Where such data are available at a fine enough spatial scale, it may be possible to map the changing area of forest that has access to shallow groundwater based on the disparate E_{os}/L_{os} of phreatophyte and vadophyte jarrah.

We found no evidence that rates of E_{os}/L_{os} of postmining jarrah forest were larger than those of postharvest jarrah forest. Both postharvest and postmining forest responded to the presence of shallow groundwater, and rates of E_{os}/L_{os} were similar for postharvest and postmining forest above deep groundwater. Hence, where water use by postmining forest exceeds that of postharvest forest, it is most likely to be the result of greater plant density and leaf area index. Total stand leaf area index can reach as high as three in postmining forest, particularly where vigorous understorey makes a substantial contribution to L_{total} (Macfarlane, Lardner, Patterson, & Grigg, 2010). L_{total} in this study exceeds 2.1 at only one postmining forest site (Lewis R). Water use can also be greater in postmining forest owing to suppression of the dieback disease *Phytophthora cinnamomi* (Koch & Samsa, 2007). Postmining rehabilitation of areas badly affected by dieback with vigorous, healthy forest will result in greater water use than postharvest forest.

We found some evidence that trees in postmining forest have deeper sapwood and a larger ratio of sapwood area to basal area (A_s/A_b) than trees in unmined forest (Table 3). Lewis R and Huntly 5 both had larger A_s/A_b (0.25–0.28) than the postharvest forest (0.14–0.19); however, this probably reflects tree age and size rather than the effects of mining versus harvesting. The postmining forest is younger than the postharvest forest and, as demonstrated in postharvest jarrah forest (Macfarlane, Bond, et al., 2010), younger, smaller jarrah trees have a smaller A_s/A_b than older, larger trees. The postmining sites, Lewis R and Huntly 5, also had smaller L_{os}/A_s (0.23–0.26 m^2 cm^{-2}) than the postharvest forest (0.26–0.37 m^2 cm^{-2}). The range of L_{os}/A_s observed in postharvest forest in our study is similar to that observed in postharvest jarrah forest by Macfarlane, Bond, et al. (2010), and our finding that young postmining forest has a smaller L_{os}/A_s than older postharvest forest is consistent with our earlier conclusion (Macfarlane, Bond, et al., 2010) that tree age and size has an important influence on L_{os}/A_s in eucalypts. Similar conclusions were reached for a broader range of angiosperms within Australia (Togashi et al., 2015). The smaller L_{os}/A_s of postmining forest wholly explains the high rates of E_{OS}/L at the Lewis R postmining site; sap velocity at this site was similar to other sites. In contrast, the high rates of E_{os}/L_{os} at the A5 postharvest site are explained by both a small L_{os}/A_s (0.26 m^2 cm^{-2}) and a higher sap velocity (Table 5). Mean daily sap velocities at most sites were similar to previously published estimates for other eucalypt species (Forrester, Collopy, & Morris, 2010; Macfarlane, Bond, et al., 2010; Mitchell, Lane, & Benyon, 2012; Roberts et al., 2001; Vertessy et al., 2001), suggesting that overstorey transpiration can be scaled with reasonable accuracy from sapwood area at many sites, but not from basal area owing to changing A_s/A_b with age.

Existing literature for Australian forest, for which both interception and L_{os} are available (Dunin, O'Loughlin, & Reyenga, 1988; McJannet, Wallace, & Reddell, 2007a, 2007b; Mitchell et al., 2009; Wallace & McJannet, 2008), is heavily biased towards forests with $L_{os} > 3$; only one study reported interception for eucalypt forest with $L_{os} < 1$ (Mitchell et al., 2009). The lack of comprehensive rainfall interception data sets for Australian forests was exemplified in a recent study (Wallace et al., 2013) that relied on rainforest and jarrah forest data sets to derive parameters for a continental-scale model of the landscape water balance. Our study reports interception for 12 additional eucalypt forest sites (all jarrah) with $L_{os} < 3$ and thus greatly increases both the number of Australian forest sites with published rainfall interception data and also the reported range of L_{os} over which it is measured. It was reported (Dunin et al., 1988) that 3–5% of precipitation intercepted per unit L_{os} for mixed forest of *C. maculata* and *Eucalyptus globoidea*, whereas rainfall interception ranged between 5% and 7% per unit L in rainforest (McJannet et al., 2007a, 2007b; Wallace & McJannet, 2008). In our study, rainfall interception ranged from 7% to 18% as L_{os} increased from one to three; hence, 6.5% of rainfall was intercepted for each unit of L_{os}, which is similar to the rainforest studies. The strong correlation between rainfall interception and L_{os} supports previous findings that L_{os} and foliage cover are key inputs into models of rainfall interception (e.g., Gash, Lloyd, & Lachaud, 1995) because they relate to throughfall and canopy storage parameters (e.g., Gómez, Giráldez, & Fereres, 2001; Keim, Skaugset, & Weiler, 2006). However, some studies found weak relationships between L and rainfall interception (e.g., Benyon & Doody, 2015) that was attributed to local rainfall characteristics. In that study, rainfall interception was 5.0–5.5% per unit of L_{os} for *Eucalyptus globulus* and *Pinus radiata*. Stemflow at the five sites where measurements were made ranged from 0.6% to 12.2% of rainfall and was positively correlated with L_{os} and negatively correlated with throughfall, as expected. The large range in stemflow likely reflected variable stand structure in which stocking differed by almost two orders of magnitude across sites (Table 1). Stocking was closely related to L_{os} in these stands (Tables 1 and 3). Overall, our results suggest that catchment-scale rainfall interception in the northern jarrah forest can be modelled using L_{os} alone with some confidence.

Total overstorey evapotranspiration (ET_{os}) ranged from 433 to 1,018 mm year^{-1}, of which on average, 21% (range 11–31%) was rainfall interception. As a fraction of annual rainfall, ET_{os} ranged from 0.35 to 0.84 and was smaller in years of high rainfall and at sites with less leaf area. The relationship between L_{os} and ET_{os} was weaker than that between L_{os} and rainfall interception owing to the more variable ratio of E_{os}/L_{os} discussed previously. We recommend that, where catchment-scale *ET* needs to be calculated from L_{os}, rainfall interception be calculated separately using the relationship in Figure 5b and that transpiration be modelled from ET_{os}/L_{os}. The estimate of ET_{os} should incorporate knowledge of the depth to groundwater if this is available.

Based on the fraction of annual rainfall accounted for by ET_{os}, we calculate that 16–65% of annual rainfall is lost from bare soil evaporation, understorey evaporation, and catchment run-off. The latter has decreased dramatically owing to the increased aridity in south-western Australia in the last 30 years. As a result of groundwater disconnecting from stream beds in the northern jarrah, catchment run-off as a proportion of annual rainfall forest has decreased to as little as 0.03 in many catchments (Hughes et al., 2012). Hence, much of the 16–65% rainfall not accounted for by ET_{os} must be accounted for by understorey water use and bare soil evaporation. It was reported (Greenwood, Klein, Beresford, Watson, & Wright, 1985) that 360–410 mm of evaporation from combined understorey, ground flora, and bare soil in northern jarrah forest (32–36% of annual rainfall), suggesting that the contribution of the nonoverstorey component to total stand evaporation may be quite significant. It is possible that nonoverstorey sources of evaporation could be even more than this at sites with sparse overstorey (Hutley, O'Grady, & Eamus, 2000), such as the sites with small leaf area index in our study.

We conclude that jarrah forest is conservative in its water use characteristics where access to deep groundwater is limited and is therefore likely to be resilient to a drying climatic trend and associated declines in groundwater levels. There is no discernible difference in the ratio of transpiration per unit L_{os} between postmining and postharvest jarrah forest, suggesting that both forest types may be managed consistently in an ecohydrological context. We also conclude that evaporation from understorey, ground flora, and bare soil make an important contribution to the overall stand and catchment water balance in the northern jarrah forest, and this should be taken into account in forest management planning. At the catchment scale, it is possible to estimate transpiration and rainfall interception in jarrah forest from leaf area index with reasonable accuracy, especially if spatial layers are available that show depth to groundwater.

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