

ORIGINAL PAPER

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Sources of water used by riparian *Eucalyptus camaldulensis* overlying highly saline groundwater

Received: 11 August 1993/Accepted: 14 May 1994

Abstract Water sources of *Eucalyptus camaldulensis* Dehn. trees were investigated on a semiarid floodplain in south-eastern Australia. The trees investigated ranged in distance from 0.5 to 40 m from a stream, with electrical conductivity 0.8 dS m^{-1} , and grew over groundwater with electrical conductivity ranging from 30 to 50 dS m^{-1} . The sources of water being used by the trees were investigated using the naturally occurring stable isotopes of water and measurements of soil water potential. Xylem water potential and leaf conductance were also examined to identify the trees' response to using these sources of water. Trees at distances greater than about 15 m from the stream used no stream water. The trees used groundwater in summer and a combination of groundwater and rain-derived surface-soil water (0.05–0.15 m depth) in winter. In doing so they suffered water stress at electrical conductivities higher than approximately 40 dS m^{-1} (equivalent to approximately -1.4 MPa). Trees adjacent to the stream used stream water directly in summer, but may have used stream water from the soil profile in winter, after the stream had risen and recharged the soil water. *E. camaldulensis* appeared to be partially opportunistic in the sources of water they used.

Key words Stable water isotopes · Groundwater · Water sources · *Eucalyptus camaldulensis* · Salinity

Introduction

The ecology of riparian environments is dominated by water, with periods of excess water availability, associated with floods, alternating with periods of water deficit (Breen et al. 1988). This is especially the case in semi-arid environments such as the floodplains of the Murray and Darling Rivers of Australia. *Eucalyptus camaldulensis* Dehn. (river red gum), one of the dominant tree species on the floodplains, can inhabit a wide range of environments (Sena Gomes and Kozlowski 1980) due to its tolerance of salinity (Marcar and Termaat 1990), waterlogging (Van der Moezel et al. 1989), and drought (Gibson et al. 1991). By virtue of a deep root system (Dexter 1978; Awe et al. 1976), *E. camaldulensis* can transpire at high rates during dry periods (Pereira and Kozlowski 1976; Quraishi and Kramer 1970). Despite these tolerances *E. camaldulensis* is naturally restricted to the fringes of waterways. The distribution of *E. camaldulensis* suggests that rivers and streams may be important sources of water.

Recent studies using naturally occurring stable isotopes of water have found that trees adjacent to streams do not necessarily use the stream water (Dawson and Ehleringer 1991; Smith et al. 1991). *E. camaldulensis* adjacent to an ephemeral stream transpired groundwater in preference to stream water in an area where the groundwater was moderately saline (electrical conductivity of 10 dS m^{-1} ; Thorburn and Walker 1993). However it is not known whether trees will resort to using stream water if groundwater is saline enough to cause water stress. Additionally, the streamside trees investigated by Thorburn and Walker (1993) were situated on an ephemeral stream and so did not have continuous access to stream water. Trees that have access to a permanent stream may have a reduced dependence on groundwater.

The aims of the study were to examine the sources of water used by *E. camaldulensis* where groundwater

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salinity was high and where a permanent source of fresh stream water was available. This knowledge would contribute to an understanding of the water use characteristics of *E. camaldulensis* in saline environments. The study was conducted during two seasons when environmental conditions and soil moisture regimes differed. Plant water relations and leaf conductance were also measured to gauge the tree's response to the source of water.

Materials and methods

Site description

The study was conducted on the Chowilla anabranch system of the River Murray in eastern South Australia (140° 52' E, 33° 59' S). The floodplain of the anabranch covers an area 200 km². The region has a semi-arid climate with mean rainfall of 260 mm year⁻¹ and potential evaporation of approximately 2000 mm year⁻¹. The soils of the Chowilla floodplain generally consist of a grey cracking clay overlying an unconsolidated alluvial sand deposit (Hollingsworth et al. 1990). The floodplain communities consist of a woodland of *E. camaldulensis* and *E. largiflorens* (black box), with an understorey of grasses and shrubs (O'Malley 1990). *E. camaldulensis* tends to occupy the lowest and most frequently flooded communities.

Trees were examined at four sites in an *E. camaldulensis* woodland beside Punkah Creek, an outer stream of the Chowilla anabranch system (Fig. 1), and beside Chowilla Creek on the western side of the floodplain. Site characteristics are outlined in Table 1. The possible sources of water for trees were considered to be groundwater (both in the unsaturated and the saturated regions of the soil), rainfall as surface soil water (0–0.2 m), and stream water. The stream could be

a source of water for trees 15–30 m from the stream since the canopy of some of the trees extended to the stream edge.

Plant and soil measurements

The concentration of stable isotopes of water in both soil and plants were measured, along with soil water potential, xylem water potential and leaf conductance. Samples for soil and plant analysis were taken in summer (12–20 March) and winter (1–9 July), to encompass differences in soil moisture regimes and climate.

Differences in the isotopic composition of water may occur through the soil profile (Allison et al. 1983) and between stream water and soil water. Provided there is no fractionation of isotopes as water is taken up by plants the isotopic composition of xylem water should match that of the water source. This assumption has been validated for young plants of *E. camaldulensis* by Thorburn et al. (1993a).

Soil was sampled in 0.1-m increments to 0.4 m depth, 0.2-m increments to 2 m, and from there every 0.5 m to the groundwater, with every depth increment being represented by the midpoint value. One soil profile was sampled at each site in summer and winter. Stream water was sampled next to visible roots at site C, and 0.5 m from the bank near sites A and M, once each season. Three twigs were sampled from each of the three trees at each site giving nine readings per site per season. Water extracted, using azeotropic distillation according to the method of Revesz and Woods (1990) for soils and Thorburn et al. (1993a) for plant material, was analysed by mass spectrometry for deuterium (²H) and oxygen-18 (¹⁸O). Results are expressed as $\delta^2\text{H}$ and $\delta^{18}\text{O}$.¹ The error of analysis is $\pm 1.3\%$ for

¹ Isotope concentrations are expressed as delta notation: $\delta(\text{‰}) = (R_i/R_s - 1) 1000$, where R is the ratio of heavy:light isotope, i indicates the isotope sample and s the standard "V-SMOW". $\delta^2\text{H}$ refers to ²H, while $\delta^{18}\text{O}$ refers to ¹⁸O

Fig. 1 The Punkah Creek site layout indicating sites A, B and C and distance from the stream

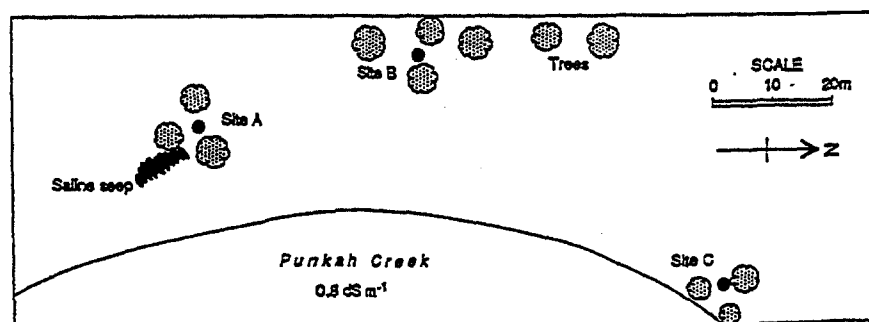


Table 1 Environmental characteristics of sites A, B, M, and C during the two sampling periods in summer (March 1992) and winter (July 1992). Soil type A is sandy clay over sand and soil type B is reworked clay over sand

Site characteristics		Site A	Site B	Site M	Site C
Stream		Punkah	Punkah	Chowilla	Punkah
Distance from stream (m)		15–20	25–30	35–40	0.5–3
Stream salinity (dS/m)	Summer	0.9	0.9	0.7	0.9
	Winter	0.8	0.8	0.5	0.8
Groundwater depth (m)	Summer	2.3	2.8	2.7	1.7
	Winter	2.5	2.9	2.9	1.3
Groundwater salinity (dS/m)	Summer	30	39	10	50
	Winter	28	36	8	33
Soil type		A	A	A	B
Flood frequency (approx.)		1 in 3 years	1 in 3 years	1 in 3 years	1 in 1 year

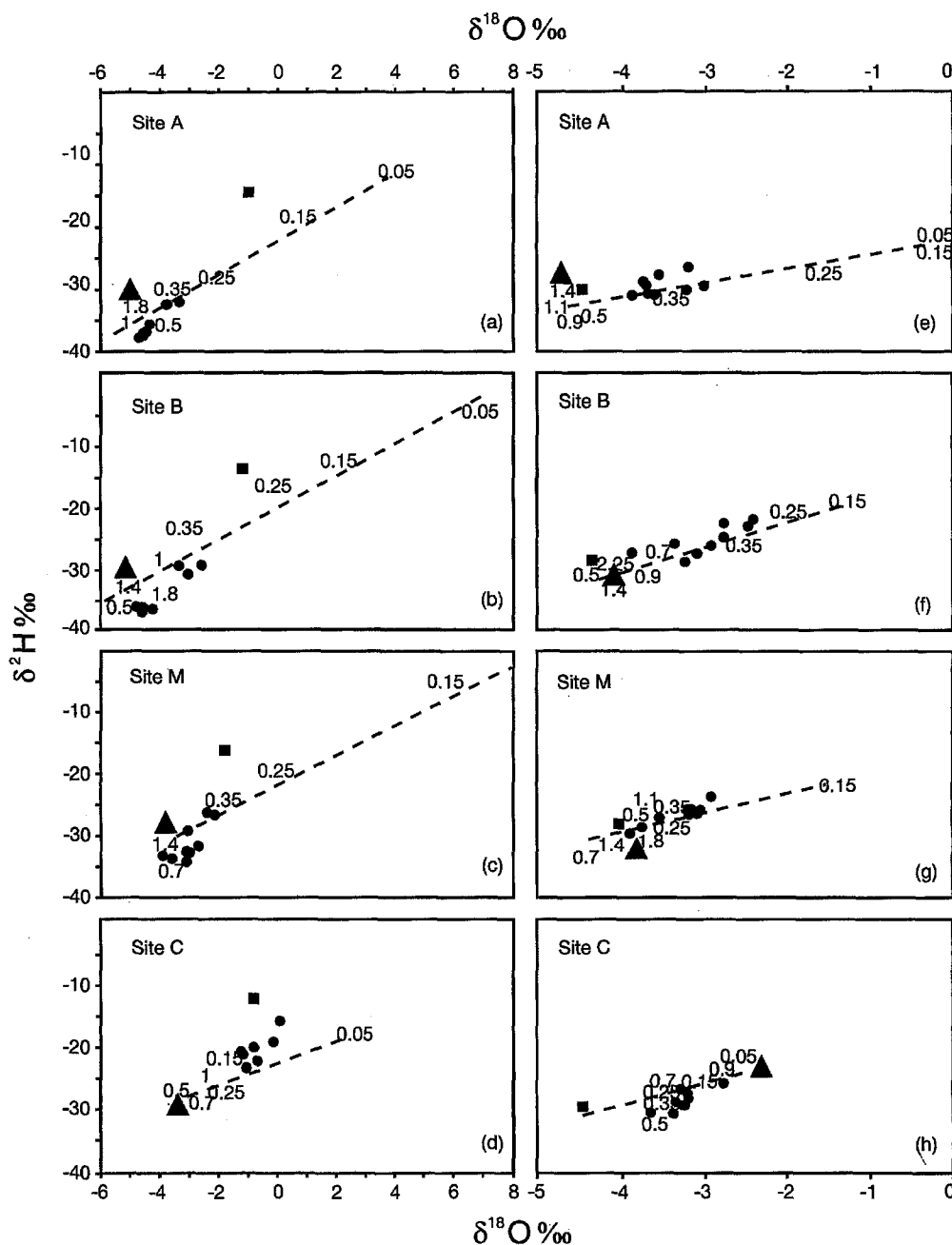
$\delta^2\text{H}$ and $\pm 0.3\text{‰}$ for $\delta^{18}\text{O}$ (Thorburn et al. 1993a). The source of water present in the twig was identified by plotting the $\delta^2\text{H}$ values of the possible source waters at a site against their corresponding $\delta^{18}\text{O}$ values and matching the isotopic composition of the individual twig water with this plot (Fig. 2) as in Thorburn et al. (1993b).

Matric potential was measured on each soil sample using the "filter paper" technique (Greacen et al. 1989). Also, total chloride (grams of chloride per kilogram of dry soil) was measured colorimetrically in water extracts (Taras et al. 1975) and converted to the concentration in the soil solution using gravimetric water content. The osmotic potential was estimated from the Cl^- content of the soil solution by assuming that all salts were present as NaCl in the soil solution. The total soil water potential was determined by summing matric and osmotic potentials.

Measurements of xylem water potential and leaf conductance were made during 1-week periods in winter and summer with all

sites being measured within a 7-day period. Weather conditions were generally constant except for the summer period when temperatures were higher on the day that site M was investigated. Xylem water potential (nine replicate twigs per site taken at 2–3 m from the ground) was measured before dawn and at midday, at all sites, using a Scholander pressure bomb (Ritchie and Hinckley 1975). At each site leaf conductance was measured on the abaxial side of 15 mature leaves (five per tree on three trees) using a Delta T AP4 cycling porometer from before dawn to evening at hourly intervals. An average daily conductance value was obtained through integration of the curve obtained from a daily set of leaf conductance readings (Simpson's Rule applied to a smoothed curve). The integration was performed to obtain a true average leaf conductance over the day. Seasonal and site differences in pre-dawn xylem water potential, midday xylem water potential, midday leaf conductance and average daily conductance were subjected to a two-way analysis of variance.

Fig. 2a–h The plot of all $\delta^2\text{H}$ against corresponding $\delta^{18}\text{O}$ values for soil water (numbers overlie data points and indicate depth, m), groundwater (\blacktriangle), stream water (\blacksquare) and twig water (\bullet) for all sites in **a–d** summer (March 1992) and **e–h** winter (July 1992). The dotted line represents the regression line for all soil and groundwater values



Results

Stable isotopes of water

During summer the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of soil water at all sites were generally high at the surface (0.05–0.15 m samples) and then decreased with depth (see Fig. 2a–d). The stream water (squares in Fig. 2a–d) was more enriched in $\delta^2\text{H}$ than the soil water, resulting in strong distinction between stream water and soil water at all sites. At sites A, B, and M the twig water $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values were within analytical error ($\pm 1.3\text{‰}$ for $\delta^2\text{H}$ and $\pm 0.3\text{‰}$ for $\delta^{18}\text{O}$) of the soil values between the depth 0.35 m and the groundwater, indicating uptake from this region in the soil. Furthermore, there was no indication that the trees were using stream water, which had higher $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values than those appearing in the twig water. At site C (creek-side; Fig. 2d) the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of most of the twigs were within, or close to, analytical error of the soil values from 0.05–0.25 m depth (Fig. 2d). However, all the twig δ values were displaced towards the stream δ values. This distribution of all the twig water δ values between the stream and the soil values suggests that there was mixing of stream water and soil water within the trees at site C during summer.

The winter soil profiles of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ at all sites was similar to those observed in summer (Fig. 2e–h). However, the stream water in winter was not as isotopically distinct from the groundwater and soil water making it difficult to determine water sources for the trees. The isotope values of twig water from trees at sites A, B, C and M matched that of the soil water at numerous depths between 0.25 m and the groundwater (Fig. 2e–h). In particular, the twig $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values at sites B and M (Fig. 2f, g) varied considerably between individual twigs, unlike the summer data. This may indicate that different sources of water, or combinations of sources, were taken up by separate parts of the root system and not mixed completely in the trunk prior to reaching the twig, resulting in a range of values in individual twigs (to be discussed further in the next section). At site C the depth at which twig and soil δ values matched (0.25–0.95 m) had an isotopic composition which lay between the stream water and the surface soil water and groundwater $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values (Fig. 2h), indicating that the adjacent stream may have recharged the soil water at this depth.

Soil and plant water potential

During summer the total soil water potential was very low at the surface (less than -6 MPa in the top 0.1 m) and increased with depth to the water table at all sites (Fig. 3a–d). Reduction in total soil water potential nearer the water table was mainly due to the low

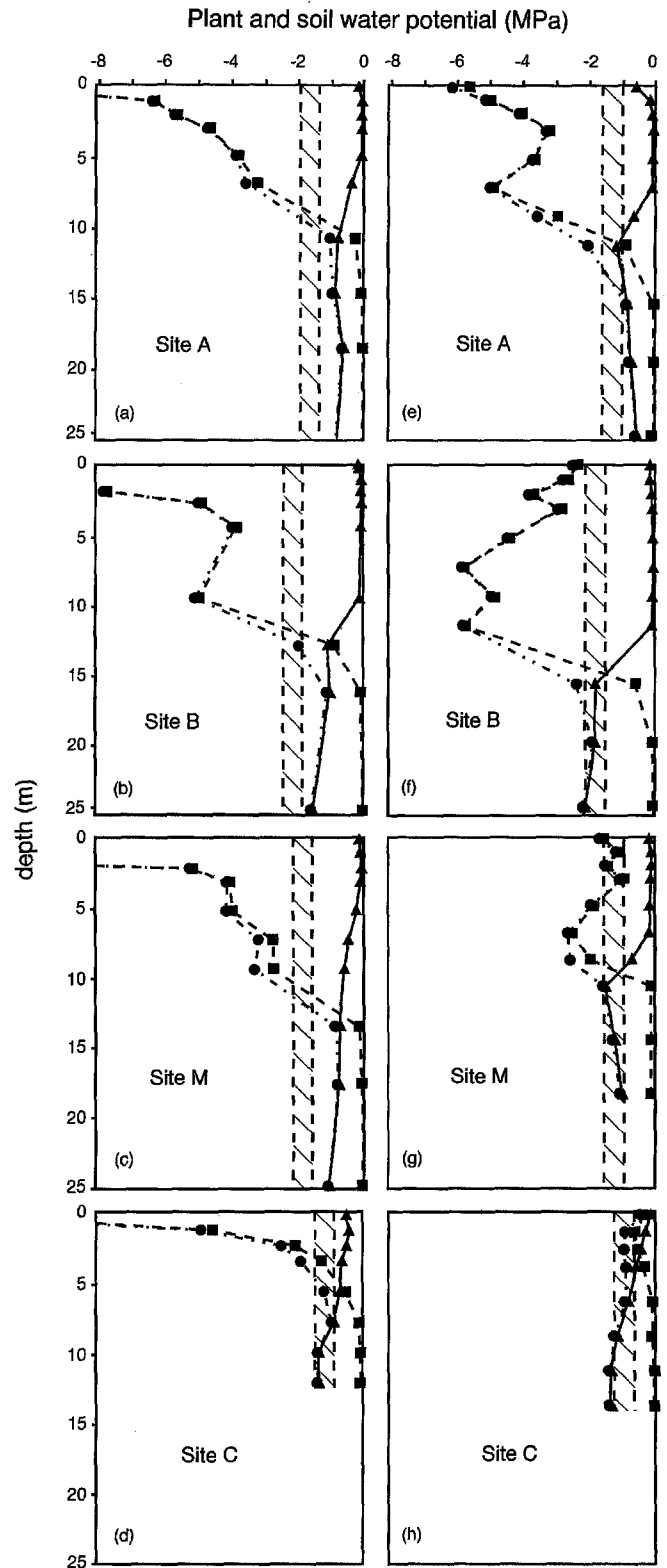


Fig. 3a–h Total soil water potential (●), matric soil water potential (■), and osmotic soil water potential (▲) at all sites in a–d summer (March 1992) and e–h winter (July 1992). The 95% confidence interval of the mean pre-dawn xylem water potential (hatched area; $n = 9$) for trees at each site is shown

osmotic potential of the groundwater. The osmotic potential at site M was slightly higher than at the other sites (Fig. 3c), reflecting the lower groundwater salinity at this site.

The pre-dawn xylem water potentials during summer differed among almost all sites (Table 2; $F = 39.12$, $P < 0.05$), the exception being sites B and M. Trees at sites B and M showed the lowest pre-dawn xylem water potentials and trees at site C (creek side) showed the highest pre-dawn xylem water potentials (Table 2). The pre-dawn water potential at sites A, B, C and M matched with the total soil water potential of the soil at a depth of 1–1.5 m (Fig. 3a–d). This region was at the drying front, that is, the area where soil water potential suddenly decreases from that of the groundwater, probably due to water uptake by roots. The midday xylem water potentials during summer did not differ significantly between sites (Table 2; $F = 3.15$, $P > 0.05$) despite the differences in pre-dawn water potential.

During winter the soil water potential was higher at the surface (more than -6 MPa in top 0.1 m; Fig. 3e–h) than during summer at all sites as a result of rain in May. The xylem pre-dawn water potential at sites A, B and M was significantly higher in winter than in summer (Table 2; $F = 46.15$, $P < 0.05$) but did not differ between seasons at site C. The pre-dawn xylem water potential also differed significantly between sites ($F = 39.12$, $P < 0.05$) in winter. Trees at site B showed a lower pre-dawn water potential than trees at sites A, C and M and trees at site C had a higher pre-dawn water potential than the other sites (Table 2). At sites B and M the xylem pre-dawn water potential matched both the soil water potential of the surface soil (0–0.4 m depth) and the deeper unsaturated zone (Fig. 3f, g). For site A a match occurred with the soil water potential of the unsaturated zone (1.2–1.5 m depth; Fig. 3e) and for site C a match occurred at 0.2–0.8 m depth in the soil profile (Fig. 3h). The midday xylem water potentials were not significantly different from those in March at all sites ($F = 1.25$, $P > 0.05$) and did not differ significantly between sites (Table 2; $F = 3.15$, $P > 0.05$).

Table 2 Mean ($n = 9$) xylem water potential for all sites in summer (March) and winter (July). Significantly different xylem water potentials between sites and seasons are represented by different letters for both pre-dawn measurements (lower case) and midday measurements (upper case). (LSD least significant difference)

Site	Pre-dawn	LSD = 0.2	Midday	LSD = 0.5
	Summer	Winter	Summer	Winter
A	-1.6^a	-1.3^d	-2.2^F	-2.5^F
B	-2.0^b	-1.6^c	-2.5^F	-2.6^F
C	-1.0^c	-0.8^c	-2.1^F	-2.3^F
M	-1.9^b	-1.2^d	-2.6^F	-2.3^F

Leaf conductance

Midday leaf conductance and averaged total daily values of leaf conductance were statistically analysed for both seasonal (summer and winter) differences and site differences. Despite some apparent differences in patterns of leaf conductance throughout the day between sites there was no significant difference in midday leaf conductance or averaged total values between sites ($F = 1.45$, $P > 0.05$). This was a result of large within-site variability. However, there was a significant site-season interaction in daily averaged values ($F = 4.78$, $P < 0.05$) which may have been caused by a tendency for low leaf conductance at site M in summer and high leaf conductance in winter (both midday and total daily values).

The mean midday stomatal conductance of all sites was significantly higher in winter than summer ($F = 5.28$, $P > 0.05$). There was, however, no significant difference in total average daily values between the two seasons ($F = 1.99$, $P < 0.05$). This difference in results between midday values and average daily values may have been a result of midday stomatal closure in summer leading to a lower mean midday leaf conductance, but which did not affect total values. Midday depression in stomatal conductance has been used as an indication of tree water stress (Sinclair 1980).

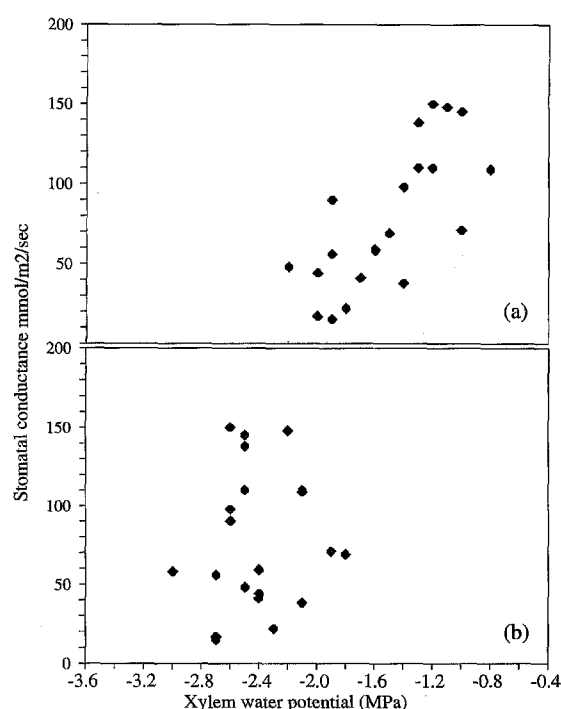


Fig. 4a, b The positive correlation ($r = 0.74$, $P < 0.05$) of midday stomatal conductance with xylem pre-dawn water potential (a) for all trees during summer and winter. Midday stomatal conductance and midday xylem water potential (b) were not significantly correlated ($r = 0.1$, $P > 0.05$).

The pre-dawn xylem water potential was significantly positively correlated ($r = 0.74$, $P > 0.05$) with the midday leaf conductance for trees at all sites in summer and winter (Fig. 4a). Correlation between the midday leaf conductance and the midday xylem water potential ($r = 0.1$, $P < 0.05$; Fig. 4) was low and not significant (Fig. 4b).

Discussion

Effect of groundwater salinity on the sources of water

To examine the influence of groundwater salinity on the sources of water used by *E. camaldulensis*, trees at site A and site B, where groundwater salinity was high ($> 30 \text{ dS m}^{-1}$), were compared with trees at site M where groundwater salinity was lower [electrical conductance (EC) approximately 10 dS m^{-1}].

During summer the isotopic composition of water from twigs at sites A, B and M all matched the isotopic composition of soil water from 0.35 m depth to the groundwater (Fig. 2a–c). This water would have been derived from the groundwater as a result of capillary rise into the unsaturated zone. Therefore, despite the differences in groundwater salinity, trees at all sites used groundwater. Further support for this conclusion comes from the pre-dawn xylem water potentials of trees at sites A, B and M. These matched the soil water potentials at depths from 1 m to the groundwater (Fig. 3a–c) indicating the trees were taking water from these depths.

During winter the results indicated that more than one source of water may have been used by *E. camaldulensis* at sites A, B and M. The isotopic composition of twig water at site B matched soil values around 0.35–0.7 m depth (Fig. 2f). However, this match did not necessarily indicate uptake from 0.35–0.7 m depth. As opposed to summer, when the twig water had exceptionally low values of $\delta^2\text{H}$ and $\delta^{18}\text{O}$, the isotopic composition of the twigs in winter was between all the possible sources and so could indicate simultaneous uptake from a number of sources, such as surface soil water (high δ), groundwater (low δ) and stream water (low δ), and mixing within the tree. More information was obtained from soil and plant water potential data.

The soil water potential in the surface soils at site B were low (-2 to -3 MPa at 0.05 and 0.15 m) and near the limit of water uptake for *E. camaldulensis* (-2.5 MPa) based on the fact that midday xylem water potential did not on average fall below this (Table 2). Considering that the errors in measurement of matric water potential are quite high at low water potentials ($< 2 \text{ MPa}$) and potentials tend to be underestimated (Greacen et al. 1989), it is possible that some water may have been taken from these depths. Water was also available in the deeper soil profile, from 1.5 m

to the groundwater (Fig. 3e), as well as from the stream. Therefore, the isotopic composition of the twigs from site B could have been a result of mixing of water from the surface soil (high δ values at 0.15 m depth) and either groundwater or stream water (both with low δ values).

The pre-dawn xylem water potentials of trees from site B (Table 2) were similar to those of the soil water at a depth of 1.50 m (the end of the drying front) (Fig. 3f), indicating that groundwater was one of the sources. If stream water was the primary source of water we would have expected the xylem water potential to be higher. The water potential of the other source (the surface soil water) was more negative than the pre-dawn xylem water potentials but was within the range of available soil water. It can therefore be concluded that trees at site B in winter were simultaneously taking water from two sources, one of them being the surface soil water at 0.05–0.15 m depth (rain-derived) and the other probably being groundwater. The contribution from groundwater, calculated using the mixing model of Thorburn and Walker (1993), averaged 27% ($\pm 21\%$ SD) of the twig water. Similar conclusions were obtained for trees at site A, where it was considered that despite the low soil water potentials in the surface soil (-4 MPa at 0.25 m) some water would have been obtained, and site M.

Effect of permanent fresh stream water on tree water sources

To examine the influence of availability of water from the permanent stream on the source of water used, stream-side trees (site C) were compared with trees at sites A and B which were 15–30 m from the stream.

During summer the isotopic composition of some twig water from site C had $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values in between the stream water and the soil surface water (0.05–0.25 m depth; Fig. 2d). The proportion of stream water used by the trees at site C was calculated using the mixing model of Thorburn and Walker (1993) which showed that none of the twigs contained more than 30% stream water. Pre-dawn water potentials at site C were higher than the other sites during both summer and winter (Table 2) also indicating that stream water could be a source. Apparently the contribution of stream water was enough to maintain a higher water status in these trees.

During winter the isotopic composition of twig water at site C matched soil water at depths of 0.25–0.95 m (Fig. 2h). The sources of water used by the trees could be considered to be from the depths of 0.25–0.95 m or from a combination of water sources with a low $\delta^2\text{H}$ and $\delta^{18}\text{O}$ (the stream) and a high $\delta^2\text{H}$ and $\delta^{18}\text{O}$ (the groundwater or surface soil water). The soil water from 0.25 m to 0.75 m was partially stream-derived, as indicated by the plot of these soil values between the

stream and the groundwater values (Fig. 2h). A lack of strong soil water potential gradients in the profile (Fig. 3h) did not allow a match between the pre-dawn xylem water potentials and soil water potentials at a particular depth. However the xylem pre-dawn water potentials from trees at site C were not significantly different from those during summer indicating that water of a similar potential might have been used. It is not possible to distinguish clearly between the possible water sources based on the results available. However it is possible to ascertain that trees at site C were using some stream water in summer and may have been using stream water, either resident in the unsaturated zone or directly from the stream, in winter. This use of stream water may explain the maintenance of a more favourable water status in these trees.

Ecological implications of sources of water used

E. camaldulensis at sites A, B and M were using groundwater in summer and winter but were combining it with rain-derived surface soil water in winter. Despite the high groundwater salinity under trees at the sites investigated, *E. camaldulensis* still used groundwater in preference to the fresh stream water within a distance of 30 m of the stream and did not cease using saline groundwater when fresh water was available at the soil surface (0.05–0.15 m). The use of groundwater in preference to stream water has been suggested for riparian trees in the USA overlying fresh groundwater (Dawson and Ehleringer 1991), and also for *E. camaldulensis* overlying moderately saline groundwater (Thorburn and Walker 1993).

High (40 dS m^{-1}) groundwater salinity did not prevent the trees from using groundwater. However the lower pre-dawn xylem water potential at site B in winter compared to other sites may indicate some water stress in these trees. The positive correlation between midday leaf conductance and pre-dawn water potential for trees at all sites (Fig. 4) indicates that the drier or more saline soil from which water was drawn may have influenced transpiration via indirect or direct effects on stomatal aperture. The closure of stomata in response to a falling plant water potential (-0.8 to -1.2 MPa) has been observed with *E. camaldulensis* in pot experiments (Pereira and Kozlowski 1976). This response differs among provenances of *E. camaldulensis* (Gibson et al., 1991) and occurs at lower leaf water potentials than in other Eucalypt species (Quraishi and Kramer 1970; Pereira and Kozlowski 1976). Since transpiration and photosynthesis within a species is correlated this suggests that the trees that used groundwater in preference to creek water were doing so at a cost to growth. At present we do not have enough information as to the reasons for this but we may speculate that root growth patterns and long term preference for a more permanent groundwater are factors to be considered.

The sources of water used by *E. camaldulensis* at all sites changed in response to the soil moisture conditions in the two seasons tested. Trees at sites A, B and M used solely groundwater in summer but in winter were able to take some water from the surface soil (0.05–0.15 m) because of heavy rains at the end of autumn. This use of two spatially separate sources of water during winter may have been achieved by the use of surface roots along with the deep tap root, as has been observed in *E. camaldulensis* grown in controlled conditions (Awe et al. 1976). The dry soil conditions during summer may have inactivated these surface roots. The use of surface roots in semi-arid and arid environments allows the plant to be opportunistic with respect to water and nutrient acquisition (Rundel and Nobel 1991). In a 2-year study at site M, Thorburn et al. (1993b) found that *E. camaldulensis* consistently used surface soil water combined with groundwater except during the summer period of this study, March 1992, when surface soil was substantially drier than at other times investigated. *E. camaldulensis* investigated therefore were able to be partially opportunistic in their sources of water, using less saline sources as they became available.

Acknowledgements Technical assistance with isotope analysis provided by John Dighton, Fred Leaney, and Kerry McEwan is gratefully acknowledged, as is field assistance provided by Jack Seekamp and Tatia Zubrinich. The second author acknowledges the support of an Australian Postgraduate Priority Research Award and a Centre for Groundwater Studies Bursary during this work, which was conducted while on leave from the Queensland Department of Primary Industries. This work was partially supported by LRWWDC grant No 88/44.

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