

Tree Water Use and Sources of Transpired Water in Riparian Vegetation along the Daly River, Northern Territory

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Executive Summary

Introduction

Throughout northern Australia, agricultural and industrial development is increasing. Horticultural and pastoral industries, in particular, are developing rapidly and are becoming increasingly important export earners for the Northern Territory. Major large-scale land developments are planned for the Daly River region and the Darwin Region and it is expected that the Ord River irrigation scheme will be extended into the Northern Territory. In the Daly River region 194545 ha have already been cleared, 63% has occurred on pastoral leases, 29% on freehold and 8% on other land tenures (Hosking 2002). Water resource managers are faced with an urgent requirement to better understand the water regimes of tropical ecosystems in order to allocate water sustainably, thereby maintaining important environmental resources, services and values.

Much of the proposed development will result in large-scale clearance of native vegetation for improved pasture or irrigated agriculture. These large-scale changes in land use are expected to have a significant impact on regional water balances and resources. Under the terms of the 1994 Council of Australian Governments agreement between states and territories, managers must ensure that sufficient water is allocated to maintain environmental integrity.

Importance of riparian and rainforest vegetation

Riparian vegetation is an integral component of river systems and is vital for maintaining a number of key ecosystem services. Vegetation along waterways protects water quality by filtering runoff water moving across the soil surface, as well as lateral sub-surface water moving through the soil to the river. Thus riparian vegetation reduces turbidity (by protecting against erosion and acting as traps for debris in surface flows) but also maintains bank stability (Askey-Doran et al. 1999). In addition riparian communities often have higher species diversity, are more productive than communities in the adjacent uplands (Askey-Dorin et al. 1999) and are important as wildlife corridors and in maintaining bio-diversity (Catterall 1993). Riparian communities are an important source of both terrestrial and in-stream habitat.

Despite the importance of riparian vegetation to catchment management there is a paucity of information relating to the water use requirements. Indeed, an as yet unrecognised problem may be that widespread re-vegetation in catchments to combat rising salinity could result in reduced flow to rivers in catchments where water is already over-allocated. Heron et al. (2001), in a modelling study, found that large-scale "blanket" re-vegetation would have long-term impacts in terms of lower stream salinities but this was at the expense of large flow losses. Further, they also noted that reduction in salt loads may not be realised for up to 200 years and that other tree planting scenarios, ie targeted tree planting etc, had little impact on stream salt loads. It is well recognised that forested catchments have higher rates of evapotranspiration than grassed catchments resulting in lower surface runoff, groundwater recharge and interflow. This results in lower mean annual stream flow.

In the Northern Territory, regional groundwater discharge maintains dry season flow of many of the major river systems. Significant extraction of groundwater for any number of proposed developments may seriously disrupt this key process resulting in a decline in groundwater discharge into rivers and a subsequent decline in river flows and health. Clearly there is an urgent requirement to understand the flow requirements of riparian ecosystems, particularly where flows are being, or will be (in the case of several northern Australian rivers), altered through river regulation and water extraction. Ecosystem services (water filtration, erosion control, nutrient cycling, C storage, salinity amelioration) provided by riparian vegetation may be impossible or extremely costly to replace.

Water use by riparian vegetation

Despite the importance of riparian communities to the hydrological regimes of river systems there has been very little work examining the water use of riparian vegetation. In Australia, the published work is mainly restricted to studies of the water use of eucalypts on the Chowilla floodplain in South Australia (Bacon et al. 1993, Thorburn et al. 1994, Mensforth et al. 1994).

The environmental water requirements of a system have been defined as the "water regime required to sustain key ecological values of groundwater dependent ecosystems at a low level of risk" (Waters and Rivers Commission 1999). Environmental water requirements are analogous to environmental flow requirements and include both surface and sub-surface components (Clifton and Evans 2001).

The structural complexity of riparian vegetation presents a range of problems for defining its water requirements. Water use is likely to vary with geomorphology, position in the landscape, different flow regimes and under varying seasonal conditions. Further, water sources will vary spatially and temporally (Dawson and Ehleringer 1991, Thorburn et al. 1994). In order to better address the environmental and flow requirements of riparian vegetation greater attention must be paid to the sources and amount of water used by the vegetation.

Groundwater dependence of vegetation

Several groundwater dependent ecosystems have been identified within Australia and include vegetation communities that have seasonal or episodic dependence on groundwater. Groundwater-dependent ecosystems include riparian vegetation adjacent to streams fed by groundwater discharge, aquifer or cave ecosystems, wetlands, and estuarine or near shore ecosystems (SKM 2000). Determination of the groundwater dependence of riparian vegetation is a significant and under-represented component of environmental flow regime assessments. Consumptive uses of groundwater by agricultural, urban and other commercial land users have altered the hydrologic regime of many Australian landscapes and river systems (Clifton and Evans 2001) and are considered to be key threatening processes to sustaining groundwater resources.

Key objectives of this project

The main aims of this research were to characterise the seasonal and spatial patterns of water use in riparian vegetation. This information will be particularly useful in quantifying the water requirements of riparian vegetation along the Daly River in the Northern Territory.

Specifically the project aimed:

- to characterise the seasonal and spatial patterns of water use in the dominant tree species of the Daly River;
- to determine the relationships between tree water use and functional parameters such as sapwood area, basal area and DBH, on a temporal and spatial basis in order to facilitate scaling of measures of individual tree water use to estimates of stand and community water use;
- to determine the seasonal sources of water for the dominant tree species using stable isotope ratios ($^{18}\text{O}:^{16}\text{O}$ and $^2\text{H}:^1\text{H}$);
- to assess the groundwater dependence and environmental water requirement of riparian vegetation along the Daly River.

Vegetation and site descriptions

The Daly River catchment is dominated by *Eucalyptus* woodlands and open-forests. However, other communities occur within this matrix including closed forests, riparian vegetation, *Melaleuca* communities, floodplains and mangroves. Riparian vegetation varies in width from a single line of trees to dense closed forests along the levee banks and contains many species typical of monsoon-closed forests such as *Nauclea orientalis* and *Barringtonia acutangula* (Faulkes 1998). The riparian vegetation along the Daly River exhibits distinct zonation. The riverbanks are steep and rise in a series of terraces from the river. *Melaleuca argentea* and *Melaleuca leucadendra* trees occur on the lower terraces along the river itself. Behind this strip of *Melaleuca* trees the terraces are often dominated by closed monsoon forest communities dominated by trees such as *Casuarina cunninghamiana*, *Nauclea orientalis*, *Barringtonia acutangula*, *Ficus racemosa*, *Cathormion umbellatum* and *Strichnos lucida*. *Eucalyptus* communities occur along the levee banks and tend to be dominated by *Eucalyptus bella*, although other species commonly found in savanna woodlands also occur including *Eucalyptus tectifera*, *Erythrophloeum chlorostachys*, *Planchonia careya* and *Terminalia ferdinandiana*. Faulkes (1998) mapped in detail the cross sectional vegetation profiles within all major rivers and tributaries in the Daly River catchment. Two large patches of closed monsoon forest occur at the confluence of the Douglas and Daly Rivers and at the confluence of the Fergusson and Daly Rivers (Faulkes 1998).

Three sites along the river were selected. First, the Claravale/Dorisvale crossing, second a site down-stream of Ooloo crossing (Ooloo) and third, the confluence of the Douglas and Daly Rivers. These sites were selected principally because they were: (a) all underlain by the Ooloo limestone aquifer, a major source of groundwater inflow during the dry season (P. Jolly pers. comm.); (b) were representative of the vegetation communities along the river; and (c) were accessible during most of the year. Site access can be particularly problematic for large lengths of the river due to remoteness and the impact of the wet season.

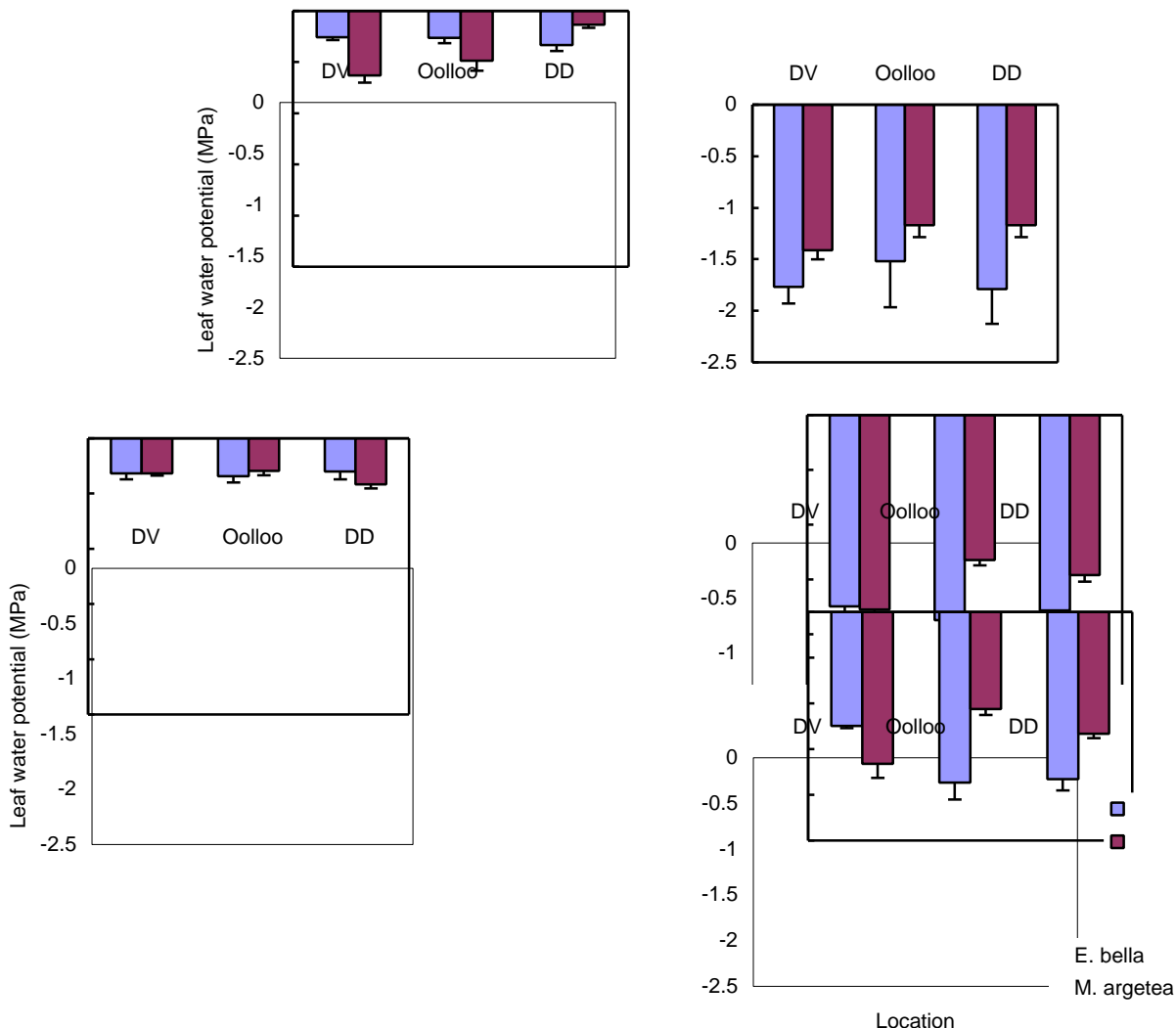
Forty-four tree species were recorded during the vegetation surveys. Of these, three were unidentified, as they had no leaves during the surveys and three were introduced species (Poinciana, Mahogany, and Kalope). Mean (\pm SE) basal area for the riparian vegetation was $71 \pm 13.1 \text{ m}^2 \text{ ha}^{-1}$ but ranged from $9 \text{ m}^2 \text{ ha}^{-1}$ to $286 \text{ m}^2 \text{ ha}^{-1}$. Mean tree density (\pm SE) was 1219.6 ± 164.7 stems per ha^{-1} . Six species contributed 82% of the standing basal area (*M. leucadendra*, *E. bella*, *M. argentea*, *C. umbellatum*, *N. orientalis*, *C. cunninghamiana*).

Leaf Water Potential

Leaf water potential is a measure of the water status of a leaf and hence the plant. A plant that is fully hydrated may exhibit a water potential close to zero. As a leaf loses water and water availability declines, leaf water potential declines. However, declines in leaf water potential occur during the morning everyday, followed by an increase in leaf water potential during the late afternoon and nighttime.

Pre-dawn water potential is an approximate measure of soil water potential. It is assumed that leaf water potential equilibrates overnight to a value determined by the soil water potential where most of a tree's roots are located.

Seasonal patterns of pre-dawn leaf water potential and midday leaf water potential are shown in Figure 1. Pre-dawn leaf water potential remained high (close to zero) during the dry season for both species at all sites. There were no significant differences between sites or seasons. Mid-day leaf water potential declined compared to pre-dawn leaf water potential at all sites, seasons and in both species. The decline in midday leaf water potential was larger in *E. bella* than in *M. argentea*.



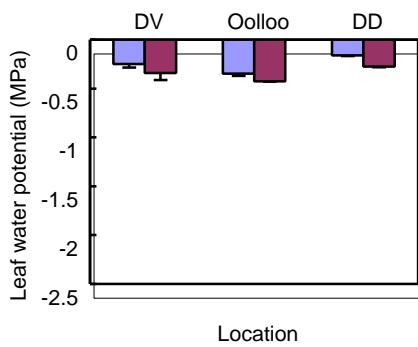


Figure 1. Predawn and midday leaf water potential for July/August 2000 (top), October 2000 (middle) and May 2001 (bottom). Data represents the mean (\pm SE) leaf water potential of four trees at each site along the Daly River.

Soilwater Availability

Despite variability in soil matric potential, a number of trends were evident. Surface soil, within the range of 0.1 - 0.5 m was extremely dry during both seasons and soil matric potential became less negative (increased water availability) with depth. Soil matric potential for soils in the top metre were low and lower than the pre-dawn leaf water potential for both *E. bella* and *M. argentea*, suggesting that trees were using water at depths greater than 1 m. During May, samples collected along the levee at 3 m reflected pre-dawn leaf water potential. Soils close to the river were generally very shallow and were often saturated at about one metre. However, above the water table these soils were very sandy in texture and hold very little moisture and therefore tended to have low matric potential. Soils on the levee banks however contained higher clay content and tended to hold more moisture within the soil profile. As expected, May (wet season) soil matric potential was higher than at the end of the dry season (September). Mean matric potentials are shown in Table 1.

Table 1 Mean (\pm SE) soil matric potential along the Daly River

Location	Habitat	Depth (m)	September (MPa)	May (MPa)
DV	Levee	0.1	-41.1 \pm 1.6	-55.2 \pm 21.5
		0.5	-10.4 \pm 4.5	-3.3 \pm 2.4
		1	-3.3 \pm 2.6	-0.5 \pm 0.4
		3		-0.6 \pm 0.3
	Riverbank	0.1	-89.2 \pm 7.6	-1.0 \pm 7.5
		0.5	-7.4 \pm 6.3	-5.5 \pm 2.7
		1	-1.2 \pm 1.2	-0.4 \pm 1.8
		3		
Oolloo	Levee	0.1	-125.7 \pm 43.9	-65.9 \pm 5.4
		0.5	-24.8 \pm 9.2	-10.4 \pm 2.8
		1	-4.0 \pm 2.4	-4.3 \pm 1.2
		3		-0.5 \pm 0.22
	Riverbank	0.1	0.0 \pm 0.0	-19.8 \pm 0.0
		0.5	0.0 \pm 0.0	-8.50 \pm 0.0
		1	-0.6 \pm 0.6	-1.2 \pm 0.5
		3		
DD	Levee	0.1	-48.8 \pm 1.6	-16.7 \pm 8.0

	0.5	-39.8±4.6	-9.5±3.1
	1	-27.6±13.7	-6.4±1.1
	3		
Riverbank	0.1	-42.2±0.0	-1.9±0.9
	0.5	-2.5±0.3	-2.3±1.0
	1	-3.3±0.6	-6.9±5.1
	3		

Tree water use

Spatial and temporal patterns of water use were examined in *Eucalyptus bella* and *Melaleuca argentea* at three locations along the river; Dorisvale crossing, Ooloo and at the confluence of the Douglas and Daly Rivers. Water use was estimated using the heat pulse technique. These two species were chosen for an initial study to determine important sources of variability in the spatial and temporal patterns of tree water use, as they are found along the length of the river and occupy different niches. *Eucalyptus bella* was found principally along the tops of the levee banks often forming the boundary with the surrounding savannas. *Melaleuca argentea*, in contrast, was found along the riverbanks.

There were no differences between sites or seasons in daily tree water use. Tree water use along the Daly River varied as a function of species, tree size and time of day. Diurnal patterns of tree water use in *E. bella* exhibited a similar pattern to the diurnal pattern of radiation and vapour pressure deficit. Tree water use increased rapidly during the morning reaching a peak late in the morning. Water use declined late in the afternoon. In contrast *M. argentea* trees, often exhibited a distinct plateau in tree water use, usually between 10 am and 3 pm. As a result, daily water use was lower (for any given tree size) in *M. argentea* trees by the river than in *E. bella* trees along the levee banks (ANCOVA $F=9.08$, $df=1,31$, $p<0.01$), (Fig 2). Overall mean water use (\pm SE), normalised by sapwood area in *E. bella* was 2.7 ± 0.2 m³ m⁻² day⁻¹ and in *M. argentea* 2.3 ± 0.2 m³ m⁻² day⁻¹. Daily water use, normalised by sapwood area at each sampling period is shown in Table 3.1. Examples of diurnal curves for each species are shown in Figure 2.

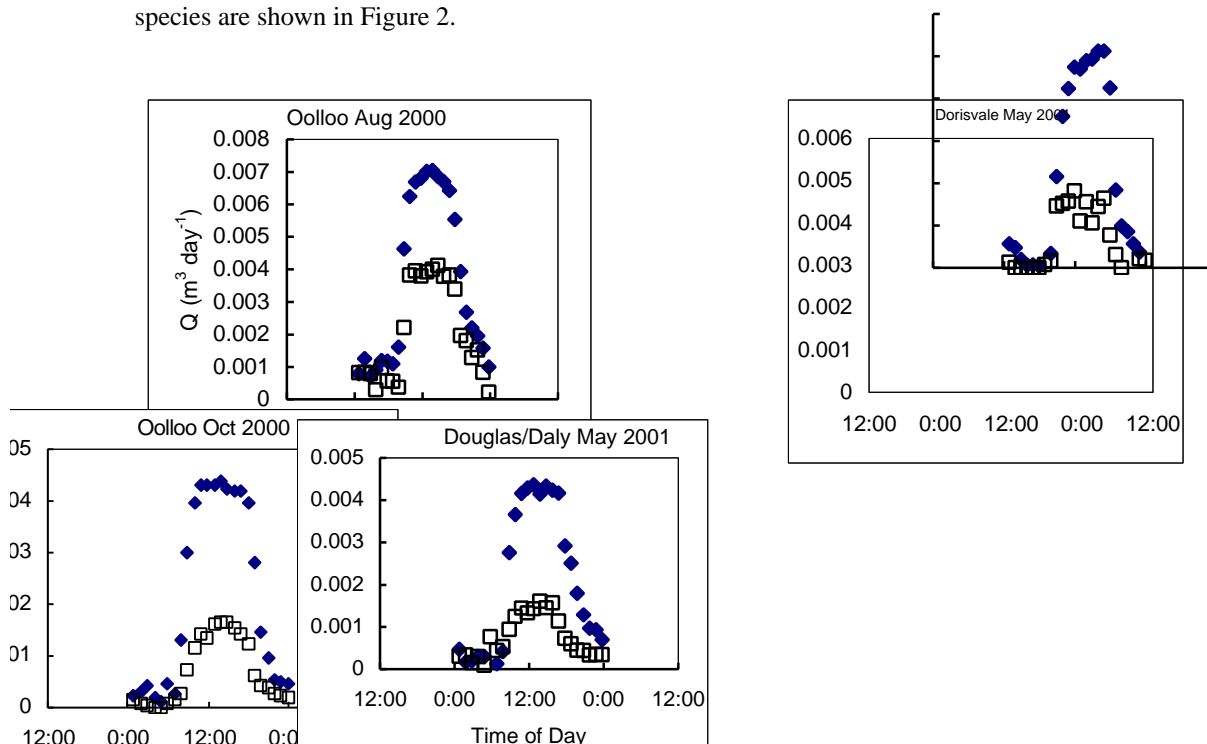


Figure 2 Examples of diurnal curves for selected *E. bella* (♦) and *M. argentea* (?) trees along the Daly River during each sampling period. Data are presented for trees from each sampling period that are approximately the same size.

Tree water use was correlated well with tree size. However, the relationship was more variable for *M. argentea* trees than for *E. bella* trees. The relationship between tree water use and tree size was best described by power functions. Within any given site there were generally strong correlations between tree water use and tree size. For pooled data however, the strength (r^2) of the relationship was more variable. Figure 3 demonstrates the relationship between tree water use and DBH for all trees sampled along the Daly River. As there were no significant differences in tree water use between sites and seasons, tree water use data for each species were pooled to demonstrate the overall relationship between tree size and water use and to capture the variability.

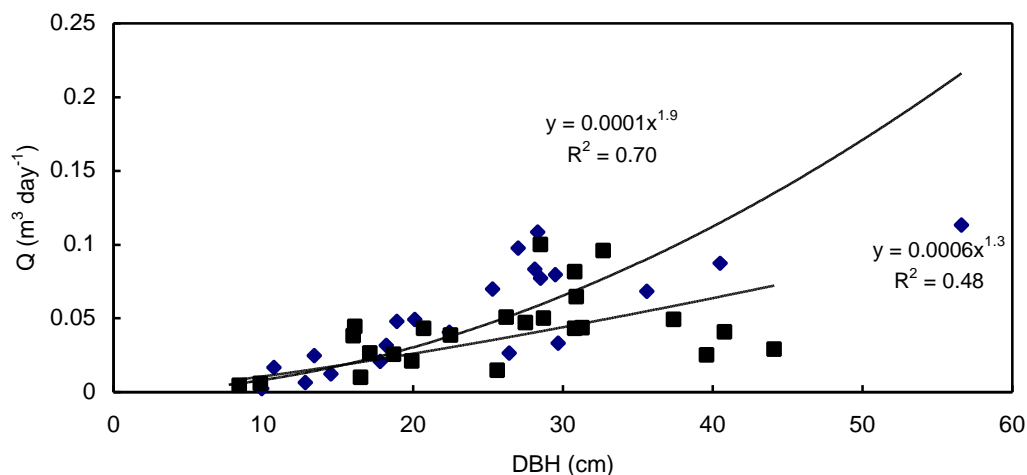


Figure 3 Daily tree water use in *E. bella* (♦) and *M. argentea* (◼) along the Daly River. Data from sites and seasons have been pooled, as there were no significant differences in water use attributable to site or season.

Water use by trees, within a site, are usually strongly correlated with each other. In addition, studies of the water use of several tree species in north Australian savanna found that there were no significant differences between species in the relationship between water use and tree size (Hatton et al 1998, O’Grady et al. 1999, O’Grady 2000). However, this does not appear to be the case in riparian vegetation. Tree water use by *Melaleuca* trees along the river was lower than eucalypt trees along the levees and the riparian strip contains a high number of deciduous and semi-deciduous species that have highly seasonal water use.

Table 2 Mean water use (\pm SE) expressed on a sapwood area basis during each of the sampling periods

Season	Water Use ($\text{m}^3 \text{m}^{-2} \text{day}^{-1}$)	
	<i>E. bella</i>	<i>M. argentea</i>
August 2001	2.2±0.29	1.9±0.41
September 2001	3.0±0.43	2.8±0.36
May 2002	3.2±0.38	2.3±0.38

Sources of water transpired by riparian vegetation

Until recently it has been difficult to determine from where plants obtained their water, particularly where there is more than one source of water available (e.g. where groundwater is shallow or streams are nearby). However, there has been a recent increase in the number of vegetation studies that have used measurements of the stable isotope composition of soilwater, groundwater and xylem water to determine the most likely sources of water exploited by vegetation (Jackson et al. 1999, Burgess et al. 2000, Adams and Grierson 2001, Zencich et al. 2002).

The isotopic signature of water (expressed as the deuterium concentration (‰)) in the upper soil profile differs from that of groundwater. Frequently the isotopic signature of groundwater differs from that of river water. Therefore, since roots do not alter the isotopic signature of the water they absorb, an examination of the water inside the xylem of plants can often be used to infer the source of the water being absorbed by plants.

Sources of water used by riparian vegetation along the Daly River were assessed by examining the isotopic composition, (the concentration of deuterium), in river water, groundwater, soilwater and xylem water (Table 3). There were distinct differences in deuterium signatures of groundwater and soilwater. However, there were no differences in the composition of the groundwater and river water, supporting the proposition that groundwater discharge was a significant component of dry season base flow. Soilwater was depleted in deuterium in comparison to groundwater. Further, there was considerable variability in the isotopic composition of soilwater. This variability was probably driven by large event-to-event variability in the isotopic composition of rainfall. The isotopic composition of xylem water was principally a function of position in the landscape. Trees along the river had isotopic signatures very similar to groundwater or riverwater. In contrast, trees further away from the river and *E. bella* along the levee banks had isotopic signatures similar to that of soilwater.

Table 3 Deuterium concentration (‰) in *M. argentea*, *E. bella* and the Daly River between May 2000 and October 2001. Mean ± SD for three samples (unless otherwise noted).

Site	Date	<i>M. argentea</i> (‰)	<i>E. bella</i> (‰)	Daly River (‰)
Dorisvale	May 2000	-55.9 ± 3.8	-100.1 ± 4.2	-52.5 ± 0.2 (2)
	Sep 2000	-56.4 ± 2.6	-85.3 ± 5.0	-45.4
Oolloo	May 2000	-45.2 ± 1.4	-70.0 ± 8.6	-46.4 ± 2.6 (6)
	Sep 2000	-45.6 ± 2.4	-63.3 ± 6.6	-44.2 ± 0.8 (5)

Daly River NT, Riparian Vegetation Water Use.

Aug 2001	-47.5 ± 1.1 (2)	–	-45.9 ± 0.9
Oct 2001	-45.1 ± 5.0	-58.3 ± 2.4	–

Although water use by riparian vegetation varied principally with tree size, distance from the river was also a very important factor. Trees at different elevations in the landscape had access to different sources of water, depending principally on distance from and height above the river. *Melaleuca* trees growing along the rivers edge used less water (Table 2) and sourced water directly from the river or groundwater (Table 3) whereas *Eucalyptus* trees along the levee banks had a higher water use for any given DBH and were principally using soilwater (Tables 2 and 3).

Stand water use

Mean daily stand water use of all trees was summed at each site to determine water use by the stand. At Oolloo water use was relatively constant throughout the year. At Douglas/Daly, however, there was a marked increase in stand water use from August to December. Overall, stand water use varied from approximately 1.5 mm day^{-1} (Transect 2, December) to more than 4.9 mm day^{-1} (Transect 1, October) and mean water use increased slightly from August (2.9 mm day^{-1}) to December (3.3 mm day^{-1}). Average daily stand water use for each site and sampling period is shown in Table 4. Stand water use increased during the dry-wet transition in transect one and at the Douglas/Daly site as deciduous trees flushed in response to improved soilwater availability and declining leaf to air vapour pressure deficits. Although large evergreen trees dominated basal area at all sites, deciduous and semi-deciduous species are an important component of all stands. Thus the large increase in water use at the Douglas/Daly rainforest site from August to December was directly attributed to the increase in leaf area associated with leaf flush in *Strichnos lucida*, a deciduous rainforest species. Water use increased from approximately 2 mm day^{-1} during the dry season to over 4 mm day^{-1} during the wet season. Seasonal changes at the two Oolloo sites were small in comparison as water use in these transects were dominated by a few large evergreen trees (Table 4).

Overall stand water use by riparian vegetation along the Daly River was estimated to be 3.2 mm day^{-1} .

Table 4 Stand water use (mm day^{-1}) by riparian vegetation at three sites along the Daly River

Plot	Basal area ($\text{m}^2 \text{ ha}^{-1}$)	August 2001	October 2001	December 2001
T1 (Oolloo)	98.17	4.22	4.89	4.28
T2 (Oolloo)	25.76	1.98	1.88	1.46
Douglas/Daly	52.88	2.32	2.54	4.32

Despite the inherent variability of water use within the riparian community, there was a good relationship between stand water use expressed on a ground area basis (mm day^{-1}) and basal area ($\text{m}^2 \text{ ha}^{-1}$) (Fig. 3). This was especially so during the dry season. Indeed, dry season water use from a number of sites throughout the Territory is strongly correlated with basal area (Fig. 4).

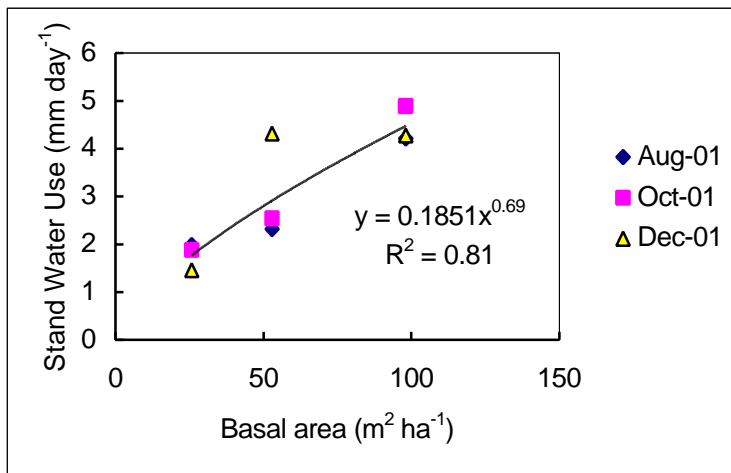


Figure 3 The relationship between stand water use (mm day⁻¹) and stand basal area (m² ha⁻¹) at three sites along the Daly River

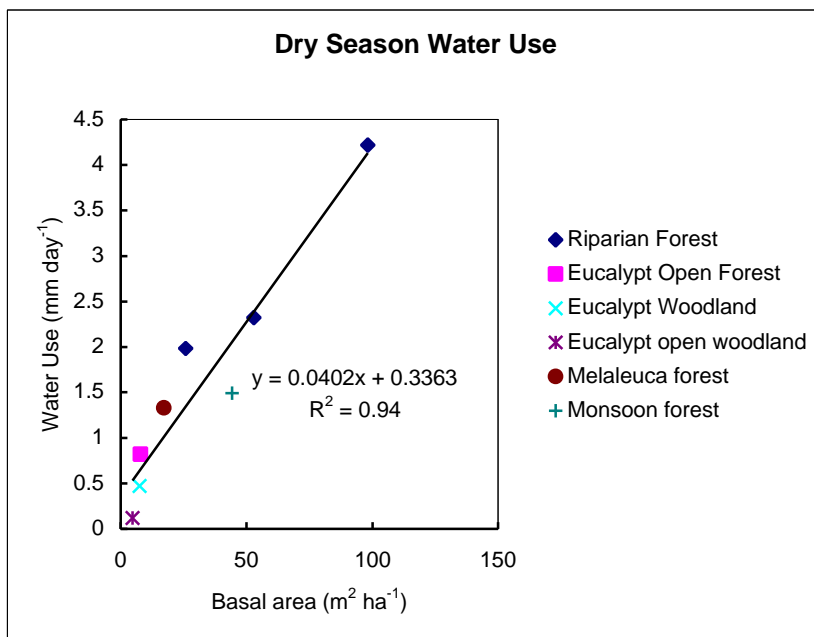


Figure 4 Stand water use during the dry season in relation to stand basal at four sites in the Northern Territory. Data from: Hatton et al. (1998), Hutley et al. (2000), Hutley et al. (2001), Kelley (2002). The three points for the riparian forest represent the three transects in this study.

Daily stand water use during the wet season at the Douglas/Daly site was similar to that for transect 1 at the Oolloo site despite the large difference in basal area (approximately $50 \text{ m}^2 \text{ ha}^{-1}$ and $90 \text{ m}^2 \text{ ha}^{-1}$ respectively). This suggests that stand water use during the wet season was at a maximum at a basal area of about $50 \text{ m}^2 \text{ ha}^{-1}$. Potential evaporation rates for the area are approximately 6 mm day^{-1} . Leaf area index at these sites during the wet season was probably between 3 and 4, however LAI was not measured. Schulze et al. (1994) demonstrated that for ecosystems where LAI is less than 4, understorey evapotranspiration can contribute up to 30% of site E_t , suggesting that the total vegetation water use along the Daly is running at close to potential E_t during the wet season (overstorey and estimated understorey).

Figure 4 demonstrates a very good relationship between stand basal area and stand water at a number of sites throughout the Northern Territory and gives added confidence to the data for the Daly River. Clearly stand basal area is a major determinate of stand water use. This relationship does not, however, take into account understorey and soil evaporation, both of which can be significant contributors to E_t in tropical savannas (Hutley *et al.* 2000, Hutley *et al.* 2001). Seasonality in stand water use along the Daly River was generally small, as a significant component of the stand basal area consisted of large evergreen trees. However, deciduous and semi-deciduous trees were important and can be significant contributors to stand water use during the wet season when they are a significant component of the stand basal area (eg Daly).

Patterns of water use were also examined in the *M. viridiflora* forests and monsoon rainforest within the Howard East Catchment. *Melaleuca* forests occurred in drainage depressions throughout the catchment area, often forming monospecific stands. Although at the tree-scale, when analysed for the entire 2 y period of study, water use per tree was aseasonal, scaled estimates of stand water use was significantly larger during the wet season than the dry and late dry seasons during both 1998 and 1999 for *M. viridiflora* ($P < 0.01$; Figure 5). Mean E_t for the wet season was 1.7 mm d^{-1} , while mean E_t was 1.0 mm d^{-1} for both dry and late dry seasons. In the monsoon forest scaling of individual tree transpiration to E_t was based on a plot census rather than use of a scalar as for the other communities. Dry season E_t was 0.4 mm d^{-1} , and significantly lower than E_t during either wet (1.5 mm d^{-1}) or late dry seasons (2.5 mm d^{-1} ; $P < 0.01$), which did not differ significantly.

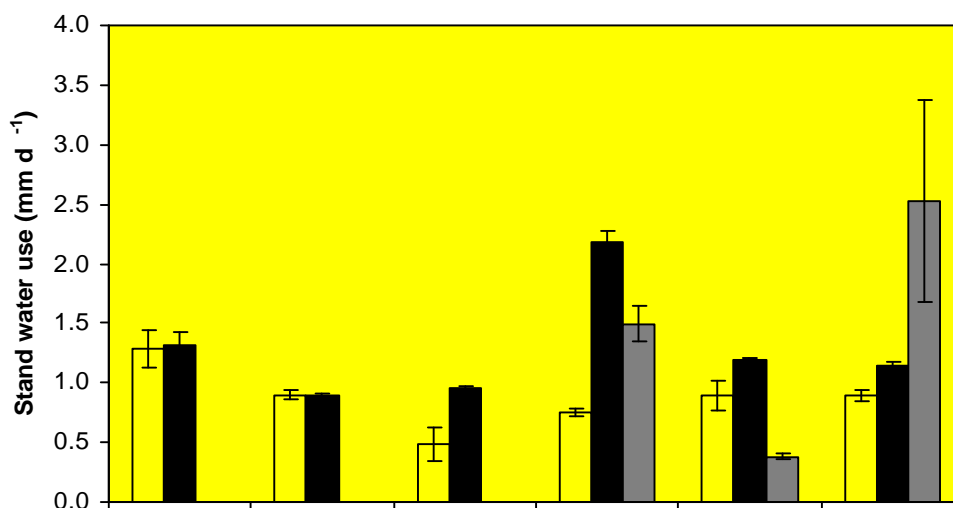


Figure 5 Stand water use in *Melaleuca* forest (black bars) and Monsoon Forests (grey bars) within the Howard East Catchment. Water use in the *E. miniata/E.tetrodonta* savannas (open bars) are included for comparison (Kelley 2002).

Stand water use was higher in the *Melaleuca* forest during the dry season than in the monsoon forest during the dry season, although stand water use in the monsoon forest was higher than the *Melaleuca* forest by the late dry/wet season. Stand water use is strongly related to LAI and evaporative demand. Leaf area index within the *Melaleuca* forests is reasonably constant throughout the year ranging from 1.46 to 1.93 (Hatton et al. 1998, Kelly 2002). During the dry season this is probably higher than the monsoon forest. However by the late dry season LAI in monsoon forests increases rapidly and can be higher than 4.0. Further, for any given tree diameter sapwood area is higher in monsoon forest trees than for *Melaleuca* trees (Kelley 2002). Water use in both monsoon forests and *Melaleuca* forests is typically greater than the water use of the surrounding savannas. Table 5 gives a comparison of community water use for each ecosystem.

Table 5 Seasonal rates of water use (mm season⁻¹), representative values of leaf area index and total annual water use (mm y⁻¹) calculated from stand water use for each community.

	Eucalypt open-forest		Melaleuca swamp forest		Wet monsoon forest	
	Seasonal water use	LAI	Seasonal water use	LAI	Seasonal water use	LAI
Wet season	124	1	240	1.9	183	NA
Dry season	94	0.8	119	1.5	41	NA
Late dry season	96	0.7	150	1.4	344	NA
Total Annual water use (mm y ⁻¹)	315		508		568	

In contrast to the Daly River, there was no clear isotopic discrimination between soilwater and groundwater. Despite this it was unlikely that *M. viridiflora* trees were accessing groundwater, as there was sufficient water stored in the shallow soil profile to support transpiration during the dry season.

Table 6 Summary of likely sources of water used by *M. viridiflora* between 1997 and 1999. Mean standing water level (SWL) of the water table is also shown.

Sample time	Mean SWL (m)	Likely water source
Late Dry 1997	1.3	soilwater 0.5 - 1.0 m
Dry 1998	1.2	soilwater 0 - 0.5 m; groundwater?
Late Dry 1998	3.2	soilwater 0 - 0.1 m
Wet 1999	-0.15	soilwater > 0.4 m
Dry 1999	0.8	soilwater 0.3 - 0.75 m
Late Dry 1999	1.7	soilwater 0 - 0.1 m and groundwater

Water use by riparian vegetation – recommendations and management implications

There are a number of trends that emerge relating to water use by riparian vegetation along the Daly River. There were strong gradients in water use with distance and height from the river. This was most clearly illustrated by the comparison of patterns of water use of *Melaleuca* trees along the riverbank and *Eucalyptus* trees along the levee banks. Water use by *Melaleuca* trees was lower, for any given DBH, than for *Eucalyptus* trees. This trend was consistent spatially and temporally throughout the course of this study. Possible explanations for this trend include differing micro-climatic conditions by the river, varying access to different sources of water and differences in the soil-root hydraulic conductivity as a result of differences in soil structure. The seasonal patterns of pre-dawn leaf water potential for both species suggest that significant water stress did not develop over the course of the dry season and that trees of both species had adequate access to water.

There were strong relationships between tree size and tree water use in both species. Within a particular site this relationship was generally stronger than the relationships generated for all sites combined. Pooled relationships were used to increase the sample size and to highlight the variability in tree water along a large stretch of the Daly River. A strong relationship between tree size and tree water use has formed the basis of estimates of stand water use in a number of communities throughout Australia. In areas where site heterogeneity is small, this represents the best possible approach to solving the tree water use component of the site water balance. In general, however, these studies have been limited by small sample sizes and limited time frames. This study is unique in that we have tried to quantify the patterns of water use at larger than normal spatial and temporal scales. O’Grady (2000) consistently demonstrated strong relationships between tree size and water use in Eucalypt savanna and used these relationships to estimate stand water use over a number of seasons. However in a modelling exercise, Cook et al. (2002) demonstrated that the most robust relationship combined three years of data collected by O’Grady (2000), even though the strength of the relationship was lower (r^2 approx 0.6 as opposed to approx 0.9 for individual seasons).

Estimating stand water use in riparian vegetation along the Daly River was complicated by the seasonal and spatial patterns of tree water use. Large gradients in tree water use and water availability within the riparian strip, variability in forest structure and composition and varying leaf phenologies within the riparian strip make such estimates difficult to compile. In this study, we used a census approach to estimating stand water use. From this it was demonstrated that stand basal area is a major source of variability in stand water use along the Daly River (Fig. 3) and indeed the Northern Territory (Fig 4). Stand structure along the Daly River was highly variable. Mean basal area was $72 \text{ m}^2 \text{ ha}^{-1}$, but ranged from less than $10 \text{ m}^2 \text{ ha}^{-1}$ to more than $200 \text{ m}^2 \text{ ha}^{-1}$. Based on figure 4, mean water use by riparian vegetation during the dry season equates to approximately 3.2 mm day^{-1} . Water use during the 'build-up' or late dry season and wet season will be higher as the LAI of the riparian strip increases at this time. However, wet season water use during this study was at a maximum at around 4 mm day^{-1} for stand basal areas greater than $50 \text{ m}^2 \text{ ha}^{-1}$. Wet season water use at both the Douglas/Daly confluence and at Oolloo reached maximum stand water use at about 4 mm day^{-1} . Although understorey/soil evapotranspiration was not accounted for due to the difficulties of making these measurements in the riparian strip, understorey E_t would probably represent a significant fraction of E_t during the wet season. It is likely that total ecosystem wet season E_t was close to potential for the riparian strip.

How much groundwater is used by riparian groundwater?

An absolute figure on the proportion of groundwater water used by riparian vegetation is difficult to determine. The reasons for this are that the resolution of the isotope and tree water use data, spatially and temporally, was very coarse. However, in order to calculate the proportion of groundwater used by riparian vegetation we have assumed two scenarios; a) all trees within 20 m of the riverbank source 100% of their water use requirements from groundwater and b) all trees within 40 m of the riverbank source 100% of their water use requirements from groundwater. The isotopic composition of trees along the transect was used to guide the 20 m and 40 m distances as these distances represent typical minima and maxima for distances where trees were accessing groundwater/riverwater. The Daly River is approximately 80 km long between Dorisvale Crossing and the confluence of the Douglas/Daly River, equating to approximately 1536 ha of riparian forest. The average width of the riparian strip was 96.5 m and the average basal area of the riparian vegetation was $72 \text{ m}^2 \text{ ha}^{-1}$. Applying Figure 3 to each of the surveyed vegetation transects, mean (\pm SD) daily water use by the riparian vegetation was $3.2 \pm 1.9 \text{ mm day}^{-1}$ ($0.62 \text{ ML km}^{-1} \text{ day}^{-1}$). Under scenario a), i.e. trees within 20 m of the river that source 100% of their water use requirements from groundwater, groundwater use by riparian vegetation along the Daly River was 1.9 mm day^{-1} ($0.08 \text{ ML}_{(\text{groundwater})} \text{ km}^{-1} \text{ day}^{-1}$). Under scenario b), i.e. trees within 40 m of the river that source 100% of their water use requirements from groundwater, groundwater use by riparian vegetation along the Daly River was 2.4 mm day^{-1} ($0.24 \text{ ML}_{(\text{groundwater})} \text{ km}^{-1} \text{ day}^{-1}$).

These figures should be applied cautiously, as mentioned above the spatial and temporal resolution upon which these figures are based is very coarse. Hatton et al. (1995) demonstrated that the errors involved in scaling heat pulse velocity to stand water use could be as high as 40 %, although they were commonly less than 20 %. Thus in a worst-case scenario the figures used here as a basis for this scaling exercise may under or over estimate fluxes by up to 40 %. The problems associated with obtaining fluxes in this study have been discussed in detail in chapters

Three and Five of the accompanying full report (O'Grady *et al.* 2002) and need to be considered carefully when assessing these figures. These figures have been calculated using dry season data, as this is when riparian vegetation is probably most reliant on groundwater. However, these data represent water use requirements when regional water tables are high and the riparian vegetation was not developing significant water stress during the course of the dry season. During extended periods of low rainfall groundwater dependence of riparian vegetation may increase as soil water reserves are depleted. However, these data may provide a useful guide for allocating environmental water provisions. During extended dry periods the allocation of groundwater to riparian vegetation should not be decreased.

Groundwater dependence of riparian vegetation

Many tree species found in the riparian zone of the Daly River used groundwater during the dry season. In general, trees located close to the river or over shallow water tables appear to use groundwater more readily than trees at a greater distance from the river or where the water table was deeper. Some tree species (*Acacia auriculiformis* and *Casuarina cunninghamiana*) appeared opportunistic in their use of water rather than specifically targeting a given source. Other species (*M. argentea*) appeared to target specific sources for most of the dry season, but this may have simply been a function of their position in the landscape. Thus, although it is not possible to determine definitively if riparian vegetation along the Daly River is an obligate groundwater dependent system, it is highly likely that there is at least some level of groundwater dependence. *Melaleuca* trees are often associated with shallow water tables, which suggests some level of groundwater dependency. *Melaleuca argentea* trees within the Pilbara region of Western Australia are thought to be declining where water tables have been lowered as a result of mining activities (Graham 2001). Further, while it was not possible to determine, in this study, whether *M. argentea* used stream water or groundwater using stable isotopes, streamside trees do not necessarily use stream water (Dawson and Ehleringer 1991). For example, riparian *Eucalyptus camaldulensis* along the River Murray were found to only use river water when at distance shorter than 15 meters from the river's edge. In addition, streamside *E. camaldulensis* only derived 30% to 50% of their water from the stream. Stream sediments tend to be strongly reduced (i.e., without oxygen) which may impair the ability of trees to access stream water.

The case for tree species occurring at higher elevations in the landscape is more difficult to evaluate in the short-term. Phreatophytic trees can use soil moisture when in large supply and only revert to groundwater use during prolonged drought periods (Dawson and Pate 1996). In Western Australia, it was only realized during a prolonged drought that groundwater extraction from the Gngangara aquifer was impacting the phreatophytic *Banksia* community because of a lowered water table (Water Authority of Western Australia 1992, Zencich *et al.* 2002). White *et al.* (1985) demonstrated that white pine (*Pinus strobus*) in the eastern United States switched between soilwater and groundwater extraction on a seasonal basis. Thus, many plant communities may be strongly groundwater-dependent even if they only use a small amount of groundwater episodically because they are critically dependent on groundwater during prolonged dry periods. Thus, longer-term monitoring of plant communities is required to determine their water requirements under a diversity of climatic conditions. The significant depletion of the soil moisture profile observed during the dry season suggests that in some years, *E. bella* and other tree species may need to use groundwater in the Daly riparian zone. It is important to note that this study was conducted during a

period where groundwater has remained high following a series of above average wet seasons. Indeed many usually intermittent streams maintained significant flows throughout the dry season. Depth to groundwater varies both seasonally and over longer timeframes (years) and is strongly related to the strength of the preceding wet seasons. Groundwater dependence may become evident after a series of poor wet seasons.

Predicting the impact of groundwater extraction on groundwater-dependent ecosystems

There are three basic steps in the management of the impacts of groundwater extraction on groundwater-dependent ecosystems (Hatton and Evans 1997, Clifton and Evans 2001). First, the nature of the dependency must be understood. For the riparian vegetation of the Daly River, we now know that some tree species probably continuously require access to groundwater, whereas others may only need access episodically or not at all. Secondly, the Environmental Water Requirements (EWR) for each species or vegetation type must be determined. The EWR is the “window” of groundwater conditions where a particular ecosystem or species will be able to persist. What defines the window will be very ecosystem and site specific. For phreatophytic vegetation, for example, the maximum depth at which groundwater can be extracted will be important. For other ecosystems (for example, baseflow streams), the volume, quality and timing of availability of groundwater may be more important. The EWR for most groundwater-dependent ecosystems in Australia are not well known.

The last stage in the management of groundwater-dependent ecosystems is the establishment of Environmental Water Provisions. An Environmental Water Provision (EWP) is the groundwater regime that will be established under a given scenario of groundwater extraction. EWP assessments require a good knowledge of the regional hydrogeology and a careful assessment (usually through modelling) of the expected changes in the water balance over time following the initiation of extraction. The latter point is important because the impacts of groundwater extraction may take a long time before they are felt by groundwater-dependent ecosystems (Sophocleous 2000). This occurs because hydrogeological systems tend to change slowly following a perturbation, resulting in a transition period between the “old” and “new” groundwater systems.

Assessment of the environmental flow requirements of riparian vegetation along the Daly River

There are four methodologies that have been used within Australia to assess environmental flow regimes; expert panel assessment, habitat analysis, holistic approaches and a building block method. In the past all of these approaches have involved, to a larger or lesser extent, reliance on available knowledge and expert opinion. The lack of targeted research into water use by riparian vegetation within Australia has meant that it is very unlikely that such panels would have had even basic information on the amount and sources of water used by riparian vegetation. This report has addressed these two fundamental questions.

Distinct zonation with the riparian vegetation and gradients in water use that are related to soilwater availability and sources of available water are probably strongly related to the highly variable annual and inter-annual flow regimes of the Daly River. This highly variable flow regime has resulted in a structurally complex riparian ecosystem.

Reductions in flow and flow variability are likely to have significant impacts on the structure and physiology of the riparian vegetation (Smith et al. 1991, Bacon *et al.* 1993, Horton et al 2001).

Changes to flow regimes may reduce flooding events. Flooding events are important in recharging soilwater stores. Many of the species in this study exhibited a strong dependence on stored soilwater at some time through out the year. Thus reductions in recharge of the stored soilwater will impact on the ecophysiology and structural diversity of these forests and may result in a loss of habitat heterogeneity. Further, species within the riparian zone may be reliant on seasonal floods and replenishment of soilwater for dispersal and establishment. Woolfrey and Ladd (2001) showed that the distribution of *Casuarina cunninghamiana* along the Murrumbidgee River in south-eastern Australia was within the 'envelope' of maximum floods and that episodic flooding increased establishment. *Casuarina cunninghamiana* is widely distributed throughout the Daly River, and the annual flow variability may be an important determinate of its distribution within the catchment. On the whole, however, very little is known about the conditions required for the establishment and dispersal of many of the species found throughout northern Australia. Many of the species found along the Daly River also occur in monsoon forests, thus dispersal by water *per se* may not be crucial, but the distribution of this forest type is strongly correlated with permanent water sources (be that groundwater or surface water).

Reductions in groundwater recharge will reduce base flow during the dry season within the Daly River. It appears that *M. argentea* may be particularly sensitive to reduced water tables or river base flow. *Melaleuca argentea* has been declining in parts of the Pilbara where flow regimes have been altered due to extraction of water from rivers for mining activities (Graham 2001). Although not specifically studied in this report, *M. leucadendra* is also restricted to the riverbanks along the major rivers in the Daly Catchment. It is highly likely that this species is also dependent on access to shallow water tables or river water.

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