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

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2002
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Acknowledgements

A number of people have provided valuable assistance throughout this project. For assistance in the field we would like to thank Krista Chin, Tara Kelly, Fransess Perrett and Phil Howie of Maneroo Station. Also we would like to thank the staff at the Douglas/Daly research farm for use of their facilities on the Douglas/Daly research farm. Staff from the Department of Infrastructure, Planning and Environment also provided valuable assistance especially Roger Farrow, Peter Jolly, David George and Errol Kerle.
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Executive Summary

The Daly River in the Northern Territory is one of the Northern Territories largest perennial rivers. Dry season baseflow is dominated by groundwater discharge from the underlying limestone aquifers. The catchment contains a diverse range of land use activities and is an important biological, economic and cultural resource. There is increasing development within the catchment. In particular, pastoralism and irrigated agriculture are expanding rapidly, increasing pressure on the natural resources of the catchment. This report outlines one of a series of projects commissioned by Environment Australia to examine groundwater dependence and environmental flow requirements of the Daly River. In particular, this report examines the spatial and temporal patterns of water use by riparian vegetation along the Daly River. While water use requirements and groundwater dependence have been examined in a number of ecosystems around Australia, we believe that this is the first attempt to quantify the sources and water use requirements of riparian vegetation in tropical Australia for consideration in assessing the environmental flow requirements of riparian vegetation.

Spatial and temporal patterns of water use were examined in *Eucalyptus bella* and *Melaleuca argentea* at three locations along the river; Dorisvale crossing, Oolloo 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 contrasting 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 seasonal differences in tree water use in either species along the river. Nor were there significant differences in water use along the length of the river. Tree water use was principally a function of tree size (e.g. DBH or sapwood area). In addition, there were also no seasonal differences in pre-dawn leaf water potential, or mid-day leaf water potential. This indicates that trees of both species had adequate access to available water throughout the course of the dry season. This pattern of aseasonal water use is a widespread feature in trees of the northern Australian wet-dry tropics. Tree water use in *M. argentea* trees was lower for any given tree size than water use by *E. bella*. Soil matric potential in the top metre was very low, suggesting that both *E. bella* and *M. argentea* are accessing deeper sources of water.

Sources of water used by riparian vegetation along the Daly River were assessed by examining the isotopic composition, in particular the concentration of deuterium, in river water, groundwater, soilwater and xylem water. 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.

Riparian vegetation along the Daly River contained high species diversity and exhibited considerable structural heterogeneity. However, over 80% of stand basal area was dominated by six evergreen species. In addition, there was considerable spatial heterogeneity in the sources of water and water availability. As a result, tree water use within riparian vegetation was highly variable. Tree size was an important determinate of tree water use. There was a strong correlation between stand water use (mm day\(^{-1}\)) and stand basal area (m\(^2\) ha\(^{-1}\)). Although water use by the dominant evergreen was predominately aseasonal, deciduous species were an important stand component of the monsoon forest at the confluence of the Douglas and Daly Rivers. As result, stand water use at this site was highly seasonal, increasing from 2.4 mm day\(^{-1}\) in August to over 4 mm day\(^{-1}\) in December. Overall stand water use by riparian vegetation along the Daly River was estimated to be in the order of 3.2 mm day\(^{-1}\).

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. Water use by *M. viridiflora* was also aseasonal. Further there were strong correlations with tree size, DBH, sapwood area or leaf area. 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. Stand water use by *M. viridiflora* forests was higher than water use by the surrounding *E. miniata/E. tetrodonta* forests, although this was principally a function of stand basal area. Stand water use in the monsoon forest within the Howard East catchment was, in contrast, highly seasonal varying from less than 1 mm day\(^{-1}\) during the dry season to more than 4 mm day\(^{-1}\) during the wet season. This was driven principally by leaf flushing in deciduous species.

There was strong evidence that riparian vegetation along the Daly River is groundwater-dependent. The full extent of this dependency is, at this stage, difficult to assess. This study was conducted during a period when the regional water table was high, a result of preceding above average wet seasons. In general, there was sufficient water stored within the soil profile to maintain transpiration throughout the dry season. During periods of below average rainfall, flooding and recharge of the soilwater stores would be reduced and vegetation may become increasingly dependent on groundwater resources.
Further work is required to fully assess the level of groundwater dependency and the environmental flow requirements of riparian vegetation. This study has not addressed the germination and establishment conditions of riparian species found along the Daly River. Seasonal flow variability and frequent flooding may be an important determinate of the distribution and composition of riparian forests in the wet dry tropics of northern Australia.
1.0 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, including the extension of the Ord River irrigation scheme into the Northern Territory. In the Daly River alone, almost 200,000 ha of land have been cleared of vegetation, with obvious implications for catchment hydrology (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 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. Unsustainable development of water resources in much of southern Australia has resulted in large-scale degradation of the environment, loss of important ecosystem services and declining productivity. In northern Australia, processes to manage groundwater resources to meet environmental values must identify groundwater dependent ecosystems and understand the nature of that dependency in its natural state. Accurately determining the environmental water requirements of groundwater dependent ecosystems relies on a sound conceptual framework and good information base (Clifton and Evans 2001).

In the Darwin region, examination of key components of savanna water regimes, in particular vegetation water use and evapotranspiration has contributed significantly to water resource planning. Cook et al. (1998), O'Grady et al. (1999) and Hutley et al. (2000) have examined in detail the water regime in *Eucalyptus miniata*/*E. tetrodonta* open-forests, one of the dominant vegetation types of the savannas of northern Australia. These studies examined the groundwater dependence of these forests at a range of temporal and spatial scales, providing a sound conceptual framework for water resource planners. Further, the techniques developed represent best available technology and are applicable to other ecosystems throughout Australia (URS 2001).

1.1 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 water moving
across the soil surface as runoff as well as sub-surface water moving through the soil to the river. Riparian vegetation is also important in regulating stream water quality though the regulation of water temperature (through shading), turbidity (by protecting against erosion and acting as traps for debris in surface flows) and maintaining bank stability (Askey-Dorin et al. 1999). 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 (Lynch and Catterall 1999).

Riparian communities are, however, prone to both natural and human-induced disturbance. These include: disturbances associated with flooding, water regulation, fire, vegetation clearance, the introduction of plant species and livestock, rising groundwater and salinity (Askey-Dorin et al. 1999). Indeed, the recent national audit of Australian rivers (NHT 2002) paints a bleak picture of the state of Australian waterways. In most states, river systems have been heavily modified and flow regimes extensively altered. In southern Australia, demand for water for irrigation has been shown to have a number of important effects on the health of riparian vegetation. Changes to the hydraulic characteristics of the Murray River have resulted in deterioration of the riparian vegetation, including reduced rates of tree growth, accelerated mortality and reduced recruitment (Bacon et al. 1993). Beavis and Lewis (2001) state that increased on-farm storage in small dams and impoundments is having a significant impact on the amount of surface flow reaching rivers thereby significantly reducing flow regimes. Similar impacts are also being reported in America (Horton et al. 2001a). In arid regions the problem is more difficult to assess as flow regimes are highly variable and recruitment by riparian trees is naturally low. Successful recruitment may rely on a specific set of rare climatic and hydrological variables that only occur infrequently over long time scales (Jones et al. 1994).

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 drives 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. Declines in the health of riparian vegetation may occur in the long-term, as there may be a significant lag period between the initiation of groundwater extraction and decreased groundwater discharge to streams and riparian zones (Sophocleous 2000). 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) provided by riparian vegetation may be impossible or extremely costly to replace.

1.2 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).

1.2.1 Leaf Water Relations

The leaf gas exchange characteristics of many riparian species are thought to be more sensitive to drought than other species, presumably due to their proximity to shallow groundwaters. (Horton et al. 2001a). However, this overarching assumption probably does not reflect the diversity of riparian ecosystems occurring in temperate, tropical, semi-arid and arid regions and will require further research. Leaf scale measurements of water relations of many species have provided valuable insights into a plant’s ability to respond to environmental stresses. Stomatal conductance and leaf water potential, key gas exchange parameters, have been shown to respond to a number of environmental variables including atmospheric vapour pressure and soilwater availability. Pre-dawn leaf water potential ($\Psi_{pd}$) provides information on the soilwater potential in the zone where roots are extracting water, while the gradient between pre-dawn leaf water potential and midday leaf water potential provides important insights to the diurnal water stress cycles of the plant at a range of temporal scales.

Mensforth et al. (1994) examined the leaf water relations of $E.\ camaldulensis$ growing over a range of water sources ranging from saline groundwater to riverside trees. They found that trees located away from the creek had the lowest pre-dawn leaf water potential and streamside trees had the highest pre-dawn leaf water potential. Pre-dawn leaf water potential at all sites matched the total soilwater potential of the soil at a depth of 1-1.5m, suggesting that trees may have been extracting water from this depth. Mid-day leaf water potential during summer did not vary between sites despite differences in pre-dawn water potential. Further, pre-dawn leaf water potential was significantly higher in winter than during summer. Mid-day leaf water potential did not vary between seasons. Mid-day stomatal conductance at all sites was significantly higher in winter than in summer, however there was no difference in ‘total’
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(presumably an integral of the diurnal conductance) daily conductance between seasons (Mensforth et al. 1994), possibly due to shorter day length during winter.

Horton et al. (2001a) concluded that stomatal conductance and net photosynthesis were higher in riparian cottonwood, saltcedar and willow at a site in the Sonoran Desert than previously reported due to increased water availability. However, higher net photosynthetic rates may have also reflected higher leaf nitrogen concentrations. Smith et al. (1991) examined the leaf water relations of trees in diverted and un-diverted reaches of the Sierra Nevada. They found that plants at low flow sites had reduced leaf size, reduced leaf area per unit branch length and increased leaf thickness. Plants at low flow sites also developed significantly lower mid-day water potentials than sites at high flow sites. The extent of midday depression was larger in juveniles although there was no effect of stream diversion on pre-dawn leaf water potential. An inverse linear relationship between leaf-air vapour pressure difference and maximum stomatal conductance was observed on diverted streams although this was not apparent at un-diverted sites (Smith et al. 1991), suggesting that these trees were not water limited. In streams in semi-arid Nevada, Horton et al. (2001b) found that rates of leaf gas exchange and leaf water potential were significantly related to depth to groundwater. Further, they showed that during dry years when river flows were reduced, riparian trees exhibited increased water stress and canopy die back. These results suggest that at least at the leaf level, gas exchange characteristics of many riparian species are sensitive to altered water regimes that result from large scale reductions in flow, loss of flow variability and increased depth to groundwater.

1.2.2 Tree Water Use

Whole tree water use by riparian species has rarely been examined. Jolly and Walker (1996) used heat pulse techniques to examine the seasonal rates of transpiration in *E. largiflorens* in the Chowilla Floodplain region of South Australia. They found that transpiration rates were low compared to potential evapotranspiration. Transpiration was highest mid-summer and lowest in winter. Further, there was no indication that transpiration was suppressed by flooding (Jolly and Walker 1996). Despite this, there was insufficient information to be able to make conclusions about the environmental flow requirements of *E. largiflorens* because of limited sample sizes and temporal scales. Akeroyd et al. (1998) used the heat pulse technique to examine the impact of flooding on the water use of *E. largiflorens* also in the Chowilla region. They found that the flood event itself had little immediate impact on tree water use, although at some sites water use increased after the flood, possibly due to leaching of salts in the soil profile. Marshall et al. (1997) examined water uptake by plantation *E. camaldulensis* in the west Australian wheatbelt. They found that water uptake closely matched rainfall during the wetter months but exceeded rainfall as the dry season progressed. Further, average annual tree water use exceeded annual rainfall by approximately 2.7 times, indicative of use of stored soilwater or groundwater. Water use was also affected by position in the landscape, soil type and genotype.
Strong relationships between tree water use and functional parameters relating to tree size such as DBH (diameter at 1.3 m), basal area and leaf area have been reported in a number of studies (for example Hatton et al. 1995, Vertessy et al. 1997, O'Grady et al. 1999). Such relationships provide a valuable scaling tool that allows for estimating of water use by stands of trees in areas where other methods such as eddy co-variance are inappropriate. Application of the heat pulse technique to assess water use by riparian communities has been limited. However, Thorburn (1992) demonstrated a good relationship between tree water use and sapwood area in *E. camaldulensis* and mean daily transpiration fluxes ranging from 0.1 mm day$^{-1}$ (*E. largiflorens*) to 1.9 mm day$^{-1}$ in *E. camaldulensis* forests (LAI 1.5). Morris and Callopy (1992) also reported a good relationship between tree water use and sapwood area, and demonstrated that significant day-to-day variation in water use was related to prevailing weather conditions.

### 1.2.3 Determining Water Sources Using Stable Isotopes

Increasingly, stable isotopes are providing new insights to plant and ecosystem functioning (Adams and Grierson 2001). Isotopes of oxygen and deuterium provide a valuable tool for examining the sources of water used by vegetation. This is because there is no fractionation of hydrogen/oxygen isotopes during water uptake by plant roots (Burgess et al. 2000). Therefore a comparison of the isotopic composition of groundwater, soilwater, river water and xylem water can be used to determine sources of water used by the plant. Using naturally occurring abundances of the stable isotopes oxygen and deuterium, Dawson and Ehleringer (1991) were able to demonstrate that riparian trees used a variety of water sources depending on life stage and proximity to the river. Mensforth et al. (1994) and Thorburn et al. (1994) used oxygen and deuterium isotopes to demonstrate that *E. camaldulensis* relied on saline groundwater and recent rainfall, as opposed to stream water. Stable isotopes may provide a valuable tool quantifying and determining sources of water used by riparian vegetation, providing a clear difference in the isotopic composition of the various water sources can be distinguished. Temporal and spatial information on the sources of water used by riparian vegetation can be used to assess the amount and duration of groundwater dependence.

### 1.3 Environmental Flow Requirements of Riparian Vegetation

Consideration of riparian vegetation is a recent addition to environmental flow assessment activities, and there are no prescriptive procedures for assessing the water regime requirements of riparian vegetation (McCosker 1998). Thus, assessing the environmental flow requirements of riparian vegetation can be a daunting task. There have been very few studies quantifying the seasonal and spatial patterns of riparian water use in Australia. Further, the knowledge base from which to evaluate the ecological impact of changes in flow regime is poor and there is no standard analytical procedure that can be adopted when investigating an environmental flow requirements problem (Stewardson 2001).
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).

McCosker (1998) has critically reviewed the existing methodology for assessing the environmental flow requirements of riparian vegetation and describes four methodologies that have been used in Australia to assess environmental flow regimes: expert panel assessment; habitat analysis method; holistic approach and the building block method. All of these methods rely to a greater or lesser extent on available information and consensus from either a panel or a workshop on what the environmental flow regimes should be. While the later two methods require considerably more information to be collected, in terms of floristic composition and structure of riparian vegetation, none of methods address the two fundamental questions of how much water is being used by the riparian vegetation and from where it is being sourced. This reflects the lack of a sound conceptual knowledge base upon which to compare and contrast methodologies and techniques for assessing environmental flow regimes (Stewardson 2001) and the multi-disciplinary nature of the problem (Thoms 2001).

The structural complexity of riparian vegetation presents a difficult suite of problems for defining the water requirements of the vegetation. 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.

1.4 Groundwater Dependence of Vegetation

Australia has a number of groundwater-dependent ecosystems, often containing a unique group of plants and animals that maintain ecosystem services and enhance biodiversity. 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 (SKM2000). 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.
The groundwater dependence of ecosystems is based on one or more of four basic groundwater attributes, which characterise a particular water regime:

- Flow - the rate and volume of discharge of groundwater to streams or other surface water bodies;
- Level - the depth below surface of the water table in unconfined or semi-confined aquifers;
- Pressure - the potentiometric head of a confined aquifer and its expression in groundwater discharge areas;
- Quality - the chemical composition of groundwater expressed in terms of pH, salinity, nutrients and contaminants (Clifton and Evans 2001).

A wide range of practices may affect groundwater discharge water level or pressure and groundwater quality. These include water resource development, agricultural land use, urban and commercial development mining and plantation forestry. Changes in groundwater level or pressure as the result of such activities pose the most common and perhaps greatest hazard to groundwater dependent ecosystems. It can result in:

- Reduced access to groundwater for terrestrial or riparian vegetation reliant on having access to groundwater within the root zone;
- Reduced baseflow in streams, which may reduce or eliminate habitat of aquatic biota in base flow dependent streams or reduce water availability to riparian vegetation (Clifton and Evans 2001).

The water regime required by groundwater dependent ecosystems is understood by considering the processes or uses for which water is required, the sources of the water exploited by the ecosystems and the patterns of groundwater requirements.

Requirements of ecosystems for groundwater can be grouped into three categories:

- Consumptive use - use by plants and animals to meets physiological demands;
- Habitat - whereby aquatic biota occupy discharged groundwater or aquifer ecosystems occupy groundwater in situ;
- Biophysical processes - where groundwater plays an important role in maintaining physical or biological processes such as recruitment, succession, salt and nutrient balance or the geomorphologic processes required for maintaining or forming habitat.

Hatton and Evans (1998) reviewed the distribution of groundwater dependent ecosystems within Australia. While acknowledging that these ecosystems occupied a small proportion of the Australian landmass, they concluded that protecting these ecosystems played a crucial role in maintaining Australia's biodiversity because of the role of these ecosystems throughout much of arid and semi-arid Australia.
1.5 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:

- 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 ($^{18}$O:$^{16}$O and $^2$H:$^1$H);
- To assess the groundwater dependence and environmental water requirement of riparian vegetation along the Daly River.

While the main body of this report details studies examining vegetation water use along the Daly River, water use patterns and groundwater dependency in Melaleuca forests and rainforest within the Howard East catchment near Darwin is also reviewed (Kelley 2002).

The hydrology, climate and vegetation of the Daly River are discussed in Chapter Two. Chapter Three deals with the water use of Eucalyptus bella and Melaleuca argentea, two species that occur along the river in contrasting microclimates. These two species were examined in detail in order to ascertain the relative importance of spatial and temporal sources of variability in tree water use. Thus tree water use was examined seasonally in these two species along the length of the river and with distance from the river. Chapter Four deals with the distribution of naturally occurring oxygen and hydrogen stable isotopes in order to determine spatial and temporal sources of water used by riparian vegetation. Chapter Five examines the stand scale water use by riparian and rainforest vegetation of the Daly River. Chapter Six reviews the work of Kelley (2002) who examined patterns and sources of water used by Melaleuca and rainforest communities within the Howard River region. A review of this nature is relevant in the context of this report as it allows a comparison of two potentially groundwater-dependent ecosystems within the same broad bio-geographical region, principally the wet-dry savannas of northern Australia. These communities are also represented within the Daly River Basin and are an important component of the hydrological cycle of the Daly River catchment. Finally, an assessment of the groundwater dependence and discussion of the possible impacts of future development on these communities is made in Chapter Seven. Figure 1.1 is a map showing the location of the field sites.
Figure 1.1 Location of the Daly River and sites within the Catchment in the Northern Territory
2.0 Site Description - The Daly River

2.1 General Overview

The Daly River, one of the Northern Territories largest perennial rivers, has a catchment area of approximately 52,577 km². The catchment of the Daly River consists of a number of important tributaries including; the Katherine, Flora, King, Fergusson, Edith and Douglas Rivers. The main valley of the Daly is a broad undulating area bounded by ranges to the south-west and north-east. The Daly River traverses coastal plains and is influenced tidally for a considerable distance inland. The township of Katherine is the largest town within the catchment although smaller towns and settlements occur in the catchment including Pine Creek, and the township of Daly River (Faulkes 1998). Faulkes (1998) has provided an excellent overview of the Daly River catchment as part of an assessment of catchment condition, however the major features of the catchment are summarised below.

2.2 Climate

The climate of the Daly River region is dominated by a distinct monsoonal wet season occurring from October until April and a winter dry season. The summer monsoon is driven by low level westerly flows that switch to a low level easterly flow during winter resulting from the west to east passages of high pressure systems in southern Australia (Cook and Heerdegen 2001). The wet-dry classification of northern Australian climate is generally regarded as simplistic. McAlpine (1976), Nix (1983) and Taylor and Tulloch (1985) recognise four distinct seasons, a wet, a wet-dry transition, dry and a dry-wet transition, while others, for example Braithwaite and Estbergs (1988) describe six seasons recognised by Aboriginal communities throughout Northern Australia.

The transitional periods before and after the monsoons are an important feature of the Top End climate. Rainfall is driven by local convective thunderstorms that can contribute up to 30% of the annual rainfall (Cook and Heerdegen 2001). They are also characterised by changes in humidity and vapour pressure deficits (Duff et al. 1997). Large vapour pressure deficits occur during the dry season decline during the wet season, having important implications for the tree water use (O'Grady et al. 1999). Interestingly there is little seasonal variation in potential evaporation rates, potential evaporation being principally driven by high year-round temperature and insolation.

Rainfall is, on average, slightly lower throughout the Daly River region than recorded at Darwin. Mean annual rainfall for Katherine, Mango Farm and at the Douglas Daly Research farm is 1073 mm, 1343 mm and 1157 mm respectively. Mean annual rainfall at Darwin Airport is 1709 mm. The average number of rainfall days is also lower in the Daly region; 82 (Katherine), 98 (Mango Farm), 82 (Douglas Daly)
Daly River NT, Riparian Vegetation Water Use.

and 110 (Darwin). Average maximum daily temperatures are on the whole higher throughout the Daly region and the average daily minimum is lower than for Darwin. Table 2.1 shows the yearly daily maximum and minimum temperatures for Darwin, Katherine, Mango Farm and Wooliana. Temperatures are higher during the wet season and are lowest during the dry season. Further, the difference between the daily maximum and minimum is larger during the dry season (Fig 2.1). Average daily evaporation rates are lower in the Daly region than in the Darwin region. The mean daily evaporation rates are 5.6 mm, 6.3 mm, 6.1 mm and 7.2 mm for Katherine Wooliana, Mango Farm and Darwin respectively. Average monthly rainfall and evaporation rates for the Daly Region and Darwin are shown in Figure 2.2.

Table 2.1 Mean annual daily maximum and minimum temperatures for Darwin and the Daly River region.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Annual Daily Max (°C)</th>
<th>Annual Daily Min (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Katherine</td>
<td>43.1</td>
<td>20.4</td>
</tr>
<tr>
<td>Wooliana</td>
<td>41.1</td>
<td>19.6</td>
</tr>
<tr>
<td>Mango Farm</td>
<td>41.5</td>
<td>20.5</td>
</tr>
<tr>
<td>Darwin</td>
<td>38.9</td>
<td>23.2</td>
</tr>
</tbody>
</table>
Figure 2.1 Average daily maximum (♦) and minimum (□) temperatures for the Daly River Region and Darwin
Figure 2.2 Average monthly rainfall and evaporation at Darwin, Wooliana and Katherine
Plate 1 a) October storms over the Douglas/Daly research farm. b) Douglas/Daly Research farm during the dry season.
2.4 Geomorphology, Landform and Hydrology

The geology and landforms of the Daly river region have been mapped by several authors (Christian and Stewart 1952, Northcote 1968, Baker and Pickup 1987). Dominant features of the region include the Arnhem Land Plateau, comprising Kombolgie Sandstone, steep ridges and undulating plains, and extensive level floodplain systems extending up to five kilometres from the banks of the Daly River (Faulkes 1998).

A water balance for the Daly River catchment is included as Appendix 2 (P. Jolly). Nearly all of the water entering the Daly River catchment enters as rainfall, although almost half of the water entering the Flora River is sourced from aquifers outside of the Daly River catchment, principally the Sturt Plateau (P. Jolly unpub. data). Annual catchment discharge is highly variable, reflecting the highly variable annual rainfall in the region. During the dry season, base flow is fed by groundwater discharge from underlying limestone aquifers. Groundwater-fed base flow is an important source of dry season flow in the Daly and all of the major tributaries (Faulkes 1998).

Three major limestone formations form the aquifers that provide the source of the Daly Rivers’ strong permanent dry season flows. The oldest, the Tindal limestone formation, is 150-200 m thick and consists principally of limestone with thick interbeds of mudstone. This aquifer is generally high yielding and has high quality water. The Tindal aquifer is overlain by the Jinduckin formation consisting of mudstone beds up to 450 m thick interlaced with limestone. The yields from this formation are highly variable, as is water quality. The youngest, the Ooloo limestone, consists principally of dolomite formations up to 200 m thick. This aquifer is generally a high yielding aquifer with high quality water (Faulkes 1998).

There is strong connectivity between surface waters and groundwater. During the wet season aquifers are recharged by run off events. Groundwater levels decline during the dry season due principally to groundwater discharge into rivers and transpiration by trees. At the end of the dry season many smaller streams stop flowing and at this point base flow in the larger rivers is dominated by groundwater discharge (Faulkes 1998). Groundwater levels also vary considerably on an annual basis, reflecting the length, duration and pulse strength of the preceding wet seasons (P. Jolly unpub. data). This can have significant impacts on the flow regimes within the rivers of the catchment. Prior to this study the catchment had received five consecutive years of above average rainfall. Groundwater levels were rising and many normally annual streams were perennial throughout the course of the study (pers. obs.).
2.5 Vegetation

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 cunninghamamiana, 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 tectifica, Erythrophloem 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).

2.6 Land Uses

The majority of land in the Daly River region is held under pastoral lease, Aboriginal land trusts, freehold and crown land. Pastoralism is one of the major industries of the catchment and consists mainly of extensive cattle grazing. However, irrigated agriculture and dryland cropping are expanding within the Daly River Catchment. Other major contributors to the economy of the region come from a range of industries including tourism and mining. The Daly River itself is an important resource for recreational fishing and hosts a number of national fishing competitions each year. Katherine Gorge is a major national and international tourism destination. Aboriginal people have occupied the region for over 50,000 years and still maintain various levels of contact with the land. Sites of cultural significance occur throughout the region and many aboriginal people still rely on the rivers and surrounding habitats for food (Faulkes 1998).
Land clearing, pastoralism, irrigated agriculture, habitat and tourism in The Daly River catchment.
3.0 Water Use by Two Riparian Species, *Eucalyptus bella* and *Melaleuca argentea* Trees Along the Daly River

3.1 Introduction

Vegetation plays a critical role in the water cycle of most ecosystems and this aspect is increasingly being recognised as being poorly understood. In northern Australia, the role of vegetation in the water balance of tropical savannas has been extensively studied (Cook et al. 1998, O'Grady et al. 1999, Hutley et al. 2000, Eamus et al. 2001, Hutley et al. 2001). In these studies a range of techniques have been used to examine the movement of water through savannas. These techniques have included classical water balance techniques (Cook et al. 1998), stable isotopes (Cook et al. 1998), as well as whole tree techniques such as heat pulse, micrometeorological and open top chambers (O'Grady et al. 1999, Hutley et al. 2000, Eamus et al. 2001, Hutley et al. 2001). These have allowed partitioning of evapotranspiration into: understory/soil evapotranspiration (open top chambers); tree transpiration (heat pulse techniques) and ecosystem evapotranspiration (eddy covariance).

From an ecosystem perspective, eddy covariance techniques provide an integrated measure of evapotranspiration at large spatial scales (approx 1 km²), however they are limited by site heterogeneity, slope and fetch considerations. In contrast, heat pulse techniques are not limited by these constraints and can provide useful information on stand water use where eddy covariance cannot be easily applied. Heat pulse methods have distinct advantages over other measures of tree water use in that they are easily applied, can be operated at a range of spatial and temporal scales and easily automated (Smith and Allen 1996, Köstner et al. 1998, Wullschleger et al. 1998). Individual measures of tree water use can be scaled to stand water use using easily measured structural properties of the stand such as diameter at 1.3 m, basal area, sapwood area and/or leaf area. Strong relationships between tree water use and such structural parameters have been found in numerous studies (Calder et al. 1992, Dunn and Connor 1993, Vertessy et al. 1995, O’Grady et al. 1999).

Evapotranspiration in savannas of northern Australia is strongly influenced by prevailing soilwater availability and evaporative demand. However despite the seasonality in rainfall and vapour pressure deficits, O’Grady et al. (1999) and Eamus et al. (2001) showed that there was no significant seasonality in tree water use. Eamus et al. (2001) hypothesised that hydraulic limitations imposed on vascular architecture by the annual and predictable seasonal drought limits the potential water use during the wet season when water availability is high. In support of this Kelley (2002) showed that there was no seasonality in hydraulic conductance when expressed on a sapwood area basis. Further, O’Grady et al. (1999) proposed that the proportional decline in tree leaf area over the dry season was similar in magnitude to the proportional increase in vapour pressure deficit, an elegant method of controlling dry
season water use while at the same time maintaining assimilation. Interestingly, similar patterns of aseasonal water use have also been observed in Brazilian cerrado, a savanna system with very similar extremes of water availability and evaporative demand (Meinzer et al. 1999).

The aims of this study were to examine the seasonal and spatial patterns of water use in two riparian species: *Eucalyptus bella* and *Melaleuca argentea*. Both species are found along the Daly River although they occupy contrasting niches. *Eucalyptus bella* is found primarily along the top of the levee banks (generally 60 m from the river and 20 m above the river). *Melaleuca argentea* is most often found on the lowest terraces along the river. Further, *M. argentea* is believed to be sensitive to alterations or lowering of river flows as it is generally only associated with permanent water sources (Petheram and Kok 1983, Graham 2001). The principal aims of this study were to examine how tree water use varied with season, position along the river and with distance from the river. Further, we also examined seasonal and spatial patterns of water availability for these two species by examining patterns in leaf water potential and soilwater matric potential.

### 3.2 Methods

#### 3.2.1 Tree Water Use

Three sites along the river were selected. First, the Claravale/Dorisvale crossing, second a site downstream of Oolloo crossing (Oolloo) and third, the confluence of the Douglas and Daly Rivers (see Fig 2.1). These sites were selected principally because they were: (a) all underlain by the Oolloo 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 its remote location. The wet season further complicates the limited access that is available.

Tree water use was examined in five *E. bella* trees along the levee and five *M. argentea* trees along the river at each site. O’Grady (2000) demonstrated that at least five trees are required in scaling exercises in tropical savannas to obtain robust estimates of water use. Sampling was conducted during the dry season (July 2000), at the end of the dry season (September 2000) and before the onset of the build-up storms and at the end of the wet season (May 2001).

Tree water use was determined using the compensation heat pulse technique and using commercially available Greenspan Sapflow Loggers (Greenspan Technology Warwick QLD). This system is comprised of two probesets, with thermistor pairs located 5 mm upstream and 10 mm downstream of a central line heater. A 1.8 second heat pulse was fired at 15-minute intervals and the time, T2 (seconds), taken for the upstream and downstream thermistors to return to equilibrium was recorded by the data...
logger supplied with the probesets. The T2 time was converted to heat pulse velocity as described by Edwards and Warwick (1984). Swanson and Whitfield (1981) corrections for wounding were applied to the estimates of sap velocity using a wound diameter of 3.1 mm. Heat pulse velocity was then scaled to tree water use measurements using the weighted averages technique (Hatton et al. 1990). Tree water use was estimated at 15-minute intervals over four complete days at each site. For each tree, diameter at 1.3 m was recorded, bark thickness and depth of sapwood were also recorded. Sapwood area was determined from a core taken from each tree. The sapwood/heartwood interface was characterised by a distinct colour change.

3.2.2 Leaf Water Potential

Pre-dawn leaf water potential was measured as a surrogate of soilwater availability (Schulze and Hall 1982, Crombie et al. 1988). Leaf water potential was measured at each location along the river during each sampling period (ie July 2000, October 2000 and May 2001). Measurements of leaf water potential were made on three leaves from each tree for which tree water use was estimated. Leaves were cut and immediately placed in sealed humid bags and stored in a dark insulated container until measurement, typically within 30 minutes of sampling. Measurements were made using a Scholander type pressure bomb (Soil Moisture Corporation, USA). Further, hourly measurements of leaf water potential on each tree were made to assess the degree of diurnal water stress.

3.2.3 Soilwater Availability

Soilwater availability was measured by taking soil samples at each site. Three replicate soils samples were taken at 0.1, 0.5, and 1 m depth at the end of the dry season (September 2000) and at the end of the wet season (May 2001). During September 2000, further samples were collected at the Oolloo site at 0.5 m intervals to 7.0 m depth. During May (2001), soil samples were also collected from 3.0 m depth along the levee. Soil samples were stored in sealed soil tins and transported back to the laboratory in insulated containers. Soil matric potential was measured using the filter paper technique described by Greacen et al. (1989). Briefly, dried and weighed Whatman 42 filter papers were placed in between two more filter papers and then covered with the soil. The filter papers were then allowed to equilibrate with the soil matric potential for at least 7 days in a controlled temperature room. After this period the filter papers were removed, weighed then dried at 105 °C and then reweighed to obtain the relative water content of the filter paper. Soil matric potential was calculated from the relationship between RWC and matric potential for the filter paper, calculated as:

\[ \Psi_s (RWC: 0.278-0.453) = -\exp(12.27-17.93 \times \text{RWC}) \]
\[ \Psi_s (RWC: 0.453-1.784) = -\exp(5.55-3.11 \times \text{RWC}) \]
where $\Psi_s$ (kPa) is the matric potential and RWC (g/g) is the gravimetric water content of the filter paper.

### 3.3 Results

#### 3.3.1 Tree Water Use

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 3.1). Overall mean water use (± SE), normalised by sapwood area in *E. bella* was $2.7\pm0.2$ m$^3$ m$^{-2}$ day$^{-1}$ and in *M. argentea* $2.3\pm0.2$ m$^3$ 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 3.1 and Table 3.2 gives details of tree size for the trees presented in Figure 3.1.

<table>
<thead>
<tr>
<th>Season</th>
<th>Water Use (m$^3$ m$^{-2}$ day$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>E. bella</em></td>
</tr>
<tr>
<td>August 2001</td>
<td>$2.2\pm0.29$</td>
</tr>
<tr>
<td>September 2001</td>
<td>$3.0\pm0.43$</td>
</tr>
<tr>
<td>May 2002</td>
<td>$3.2\pm0.38$</td>
</tr>
</tbody>
</table>

Tree water use was strongly correlated with tree size parameters such as DBH and sapwood area. 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 3.2 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 were pooled in Figure 3.2 to demonstrate the overall relationship between tree size and water use and capture the variability.

Table 3.2 Tree size parameters for trees presented in figure 3.2

<table>
<thead>
<tr>
<th>Season</th>
<th>Site</th>
<th>Species</th>
<th>DBH (cm)</th>
<th>Sapwood area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 2000</td>
<td>Dorisvale</td>
<td><em>E. bella</em></td>
<td>28.5</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>M. argentea</em></td>
<td>30.9</td>
<td>0.018</td>
</tr>
<tr>
<td></td>
<td>Ooloo</td>
<td><em>E. bella</em></td>
<td>28.1</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>M. argentea</em></td>
<td>27.5</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td>Douglas/Daly</td>
<td><em>E. bella</em></td>
<td>14.5</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>M. argentea</em></td>
<td>16.5</td>
<td>0.021</td>
</tr>
<tr>
<td>October 2000</td>
<td>Dorisvale</td>
<td><em>E. bella</em></td>
<td>22.4</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>M. argentea</em></td>
<td>20.8</td>
<td>0.0098</td>
</tr>
<tr>
<td></td>
<td>Ooloo</td>
<td><em>E. bella</em></td>
<td>26.2</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>M. argentea</em></td>
<td>26.6</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td>Douglas/Daly</td>
<td><em>E. bella</em></td>
<td>29.7</td>
<td>0.018</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>M. argentea</em></td>
<td>32.1</td>
<td>0.017</td>
</tr>
<tr>
<td>May 2001</td>
<td>Dorisvale</td>
<td><em>E. bella</em></td>
<td>28.7</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>M. argentea</em></td>
<td>38.7</td>
<td>0.026</td>
</tr>
<tr>
<td></td>
<td>Ooloo</td>
<td><em>E. bella</em></td>
<td>22.5</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>M. argentea</em></td>
<td>24.7</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td>Douglas/Daly</td>
<td><em>E. bella</em></td>
<td>37.4</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>M. argentea</em></td>
<td>31.3</td>
<td>0.016</td>
</tr>
</tbody>
</table>
Figure 3.1 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 size parameters for each tree are given in Table 3.2.
Figure 3.2 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.

### 3.3.2 Leaf Water Potential

Seasonal patterns of pre-dawn leaf water potential and midday leaf water potential are shown in Figure 3.3. 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*. Typical patterns of decline in leaf water potential throughout the morning are shown in Figure 3.4.
Figure 3.3 Predawn and midday leaf water potential for July/August 2000 (top), October 2000 (middle) and May 2001 (bottom). Data represents the mean (± SE) leaf water potential of four trees at each site along the Daly River.
Figure 3.4 Patterns of decline in leaf water potential for *E. bella* (♦) and *M. argentea* (square) during the morning in July 2000 (left), October 2000 (middle) and May 2001 (right) along the Daly River.

### 3.3.3 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 were extremely dry during both seasons and soil matric potential decreased with depth. Soil matric potential for soils in the top metre were generally 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 3.3.
Table 3.3 Mean (± SE) soil matric potential along the Daly River

<table>
<thead>
<tr>
<th>Location</th>
<th>Habitat</th>
<th>Depth (m)</th>
<th>September (MPa)</th>
<th>May (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DV</td>
<td>Levee</td>
<td>0.1</td>
<td>-41.1±1.6</td>
<td>-55.2±21.5</td>
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<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>-10.4±4.5</td>
<td>-3.3±2.4</td>
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<tr>
<td></td>
<td></td>
<td>1</td>
<td>-3.3±2.6</td>
<td>0.5±0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>-0.6±0.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Riverbank</td>
<td>0.1</td>
<td>-89.2±7.6</td>
<td>-1.0±7.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>-7.4±6.3</td>
<td>-5.5±2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>-1.2±1.2</td>
<td>-0.4±1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.0±0.6</td>
<td>0.0±0.0</td>
</tr>
<tr>
<td>Oolloo</td>
<td>Levee</td>
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<td>-125.7±43.9</td>
<td>-65.9±5.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>-24.8±9.2</td>
<td>-10.4±2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
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<td>-4.3±1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>-0.5±0.22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Riverbank</td>
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<td>0.0±0.0</td>
<td>-19.8±0.0</td>
</tr>
<tr>
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<td>0.5</td>
<td>0.0±0.0</td>
<td>-8.5±0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>-0.6±0.6</td>
<td>-1.2±0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.0±0.0</td>
<td></td>
</tr>
<tr>
<td>DD</td>
<td>Levee</td>
<td>0.1</td>
<td>-48.8±1.6</td>
<td>-16.7±8.0</td>
</tr>
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<td>0.5</td>
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<td>1</td>
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<td>-6.4±1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.0±0.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Riverbank</td>
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<td>-42.2±0.0</td>
<td>-1.9±0.9</td>
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<tr>
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<tr>
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<td>1</td>
<td>3.3±0.6</td>
<td>-6.9±5.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.0±0.0</td>
<td></td>
</tr>
</tbody>
</table>

3.4 Discussion

Water use by riparian vegetation can be a significant component of a catchment water balance. In this study, patterns in the water use of *E. bella* and *M. argentea* have been examined in order to determine the amount and major sources of variability in water use. In addition seasonal patterns of leaf and soilwater potential were examined as a preliminary assessment of sources of water used by riparian vegetation along the Daly River.
Tree water use was lower in *M. argentea* trees along the riverbank than *E. bella* trees along the levee banks. This may reflect different micro-climatic conditions within the river channel itself. The Daly River is deeply incised with banks often being 20 metres or more above the level of river base flow. This large body of flowing water will reduce air temperature within the river channel resulting in lower evaporative demand within the river channel. Along the levee, air temperature, evaporative demand and wind speed tend to be larger and this will contribute to a larger rate of tree water use if water availability is not limiting. Soils along the riverbank also have a lower capacity to store water than the soils along the levee due to their sandy texture and *Melaleuca argentea* is highly susceptible to a loss of hydraulic conductivity due to embolism of fine roots (Graham 2001). This has the capacity to reduce water use by *M. argentea*, if *M. argentea* trees are unable to directly access river water.

There were no significant differences in water use between any of the three locations. As a result we were able to pool tree water use data from these locations to generate curves relating tree water use and size (Fig 3.2). Strong relationships between tree size and water use have been observed in a number of studies (Hatton et al. 1995, Vertessy et al. 1997, Meinzer et al. 1999). Correlations in this study were lower than those generally reported. However, this study reports tree water use from a larger number of trees and from over a larger temporal and geographical range, thus increased variability was to be expected. Despite this, the relationships between tree water use and DBH reported here are significant. These relationships are important for scaling tree water use in riparian communities to community-averaged estimates of water use by riparian vegetation in northern Australia. However the strong gradient in tree water use from the riverbank to the levee banks needs to be taken into account.

The relationship between tree water use and basal area was more variable in *M. argentea* trees than in *E. bella* trees and this result is difficult to explain. It may be a function of the compressible, thick but variable and peeling nature of the bark of *Melaleuca* trees, which makes accurate determination of sapwood area difficult. High variability has been noted in a number of studies where the heat pulse technique has been applied to *Melaleuca* trees (Mensforth 1996, Kelley 2002), although Hatton et al (1998) demonstrated a strong relationship between basal area and mean daily water use in *M. viridiflora* within the Howard East Catchment near Darwin.

There was no distinct seasonal pattern to water use in either species, despite a prolonged dry season of over 6 months. Aseasonal patterns of water use have been observed in other tropical species in northern Australia (O'Grady et al. 1999, Eamus et al. 2000) and in savanna trees of Brazil (Meinzer et al. 1999). This aseasonality contrasts with observed water use patterns in other riparian species within Australia (Jolly and Walker 1996, Marshall et al. 1997) and appears to be a feature of tropical evergreen trees.

In the present study, trees did not develop significant water stress over the course of the dry season. There were no significant seasonal differences in pre-dawn leaf water potential in either *M. argentea*
along the riverbank and *E. bella* along the levee. Pre-dawn leaf water potential remained high year-round and the seasonal decline in mid-day leaf water potential at the end of the wet season was similar in magnitude to the midday decline at in leaf water potential at the end the dry season (Fig. 3.3). This suggests that trees of both species had access to adequate reserves of water year round. In contrast, Mensforth et al. (1994) demonstrated that trees on the Chowilla floodplain in South Australia, closer to the river, had higher predawn leaf water potential than trees up to 50 m away from the river, implying that water stress increased with distance from the river.

Soil matric potential in the top metre was generally low and lower than pre-dawn leaf water potential. This suggests that trees along the river and along the levees are accessing water at depths more than one metre. Soil matric potential was very variable in nature especially close to the river (Table 3.3). Soils along the river were often saturated at depths of more than one metre and it is likely that *M. argentea* trees are able to access this water year round. *Eucalyptus bella* trees on the other hand are able to exploit a larger volume of soil, as the unsaturated zone is much deeper (beyond 9 m). Soil matric potential decreased (became less negative) with depth in these soils and matric potential between 1-3 m was similar to pre-dawn leaf water potential. Further, the levee soils had higher clay content than river soils, and thus have a higher water storage capacity. Cook et al. (1998) and Kelley (2002) demonstrated that there was sufficient water stored in the top 4.5 m soil profile to maintain transpiration over the course of the dry season in *E. miniata/E. tetrodonta* savannas near Darwin. It is likely that there is also sufficient water stored in the soil profile of the levee to support transpirational demand in *E. bella* over the dry season.

The lack of seasonality in tree water use of *E. bella* and *M. argentea* suggest that trees are able to access either stored soilwater or groundwater water throughout the dry season. Pre-dawn and midday leaf water potential data suggest different sources of water used by *E. bella* and *M. argentea*. However, these data alone are of insufficient resolution and accuracy to definitively establish the source of water uptake by these species. Consequently we have investigated the distribution of stable isotopes of deuterium in river water, groundwater, soilwater and xylem water. These are discussed further in Chapter 4.
4.0 Sources of Water for Plant Transpiration

4.1 Introduction

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, over the last ten years, there has been an increase in the number of vegetation studies that have incorporated measurements of the stable isotope composition of soilwater, groundwater and xylem water in order 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).

Isotope methods for examining the sources of water used by plants have a number of advantages over more standard physical methods (Walker et al. 2001):

- Measurement of zones of root activity is most often destructive, intrusive and labour-intensive. Furthermore, the mere presence of roots is not of itself evidence of water uptake;
- Recent advances in soil moisture monitoring means that it is now possible to delineate changes in soil moisture on a fine temporal and spatial scale. However, this is problematic for determining plant water use in the presence of shallow water tables, streams or in areas of lateral water movement, and there are calibration problems when employing such techniques with some soils;
- Piezometric methods for determination of rates of groundwater use only work well if groundwater use exceeds aquifer transmissivity; and
- Lysimeters have been used for determining plant water use but they are difficult to use in natural field conditions, or in an attempt to replicate natural groundwater conditions.

Isotopic methods are not intended to replace, but rather to complement these approaches. Importantly, the isotopic techniques discussed in this report provide information that cannot be obtained by other means.

The isotope methods that have been developed have the particular advantage of being applicable to natural systems in remote locations. Although they may require frequent visits to the field to collect samples, they do not require sensitive equipment to be maintained in the field and in most cases involve little disturbance to the field site. Furthermore, isotope methods can be integrated easily into other water balance work; they cost a fraction of other water balance methods and require little in the way of specialist facilities (other than in already established analytical laboratories). On the negative side, the isotope methodology does not of itself guarantee unequivocal results with a high degree of resolution (Burgess et al. 2000). In every instance substantial supporting corroborative evidence is required before a clearly defined picture can be obtained.
Use of isotopic discrimination depends on different sources of water having different isotopic compositions. Such natural variations in isotopic composition arise because of isotopic fractionation, caused principally by transport processes (Gat, 1981) and phase transitions through the atmosphere, lithosphere and biosphere (Barnes and Allison, 1983). Since the relative proportion of the fractionating processes are likely to be different for groundwater, surface water and soilwater, different sources of water for plant use will often, but not always, have different isotope values and this is reflected in the isotopic composition of the xylem.

Previous studies that have used isotopes to determine sources of water used by plants have recently been reviewed by Walker et al. (2001). Isotopic methods have been successfully used to differentiate water sources for plants with access to both ocean and freshwater (Sternberg and Swart, 1987). Dawson (1993) used isotopes to demonstrate hydraulic lift by sugar maple during a drought period to corroborate fluctuations in soilwater potentials. Flanagan et al. (1992) combined measurements of $\delta^2$H with pre-dawn plant water potential to compare the relative uptake of summer precipitation by four co-occurring tree and shrub species in the semiarid region of the southwest United States. A study by Dawson and Ehleringer (1991) used isotopes to show that streamside trees were not using stream water, despite apparent availability. In contrast, Hatton et al. (1998) found little difference between isotopic signatures of soilwater and groundwater beneath Melaleuca viridiflora forests in the Howard River Basin, Northern Territory, making the isotope method difficult to apply in that system.

Isotopes have also been used to demonstrate temporal changes in water sources. White et al. (1985) showed that water extraction by white pine (Pinus strobus) in the eastern United States changed over time between surface soils and groundwater. Similarly, Ehleringer et al. (1991) investigated seasonal differences in water sources within a scrub community in southern Utah. They found that some species were completely dependent on summer rainfall, other species used summer and winter rains, while another species showed no response to summer rainfall, indicating that it used deeper water resources.

In this study, stable isotopes were used to investigate the source of water used by the riparian communities of the Daly River. First, we have examined the spatial variability in plant water use by examining the deuterium concentration in xylem water along transects spanning the riparian zone (with an emphasis on the end of the dry season). Secondly, the source of water used by plants in different sections of the riparian zone was further examined by comparing xylem deuterium concentrations with the one of soilwater, groundwater, and river water. Finally, an assessment of the temporal variability in deuterium concentration in E. bella, M. argentea, and river water was made by sampling trees and surface water at the same locations over a two-year period.
4.2 Methods

Samples of river water, xylem water, and soilwater were collected during sampling trips in September 2000 and August 2001 along transects at the Douglas/Daly and Oolloo sites (Fig 1.1). At the Douglas/Daly site, two transects were sampled in September 2000 and a third transect in August 2001. At the Oolloo site, one transect was sampled in both September 2000 and August 2001 and another transect in August 2001 only. Each transect extended across the riparian zone from the riverbank to the levee. The location of trees and the cross-sectional profile of each transect was measured using a laser theodolite in October 2001. Additional plant (*E. bella* and *M. argentea*) and river water samples were collected at the Dorisvale, Oolloo, and Douglas/Daly sites in August 2000, October 2000, and May 2001.

For sampling xylem water, three twig samples of 10–25 mm diameter were collected from the canopy using pruning shears. The twigs were stripped of bark, cut into 50-mm lengths, placed in McCartney bottles (i.e., robust glass vials with an air-sealed screwcaps), and covered with kerosene prior to sealing. Soil samples were collected by hand-augering to depths of up to 7 m, with samples taken at 0.1 m, 0.2 m, 0.5 m, and then at 0.5-m intervals. Soil samples were placed in glass jars sealed with electrical tape to minimise evaporation and stored in insulated containers for transport from the field to the laboratory. River samples were collected from close to the bank at approximately 0.5 m depth at each sampling site (Dorisvale crossing, Oolloo, and Douglas/Daly) using McCartney bottles. Groundwater samples were collected when water entered augured holes or directly from springs as they emerged from the ground along the terraces or the banks of the river.

Water was extracted from plant and soil samples using azeotropic distillation (Revesz and Wood 1990; Thorburn *et al.* 1993). This method is based on the principle that an azeotrope has a boiling point different from either of its constituents (Revesz and Woods 1990). The distillation of the sample with kerosene forms an azeotrope between the kerosene and water. The water is then condensed out of the azeotrope and can be retrieved, since it is immiscible with kerosene at ambient temperatures. Distillation took place in a Dean-Stark apparatus (Revesz and Woods 1990) and extracted water collected and stored in McCartney bottles. Wax was melted on the surface of the water to remove any residual kerosene. Water samples were analysed for $\delta^2$H through stable isotope mass spectrometry by reducing 25 µl of water to H$_2$ over uranium at 800 °C. Selected samples were also measured for $\delta^{18}$O but are not included here. Samples were analysed using a dual inlet gas ratio mass spectrometer (Europa Scientific Ltd.).

Isotopic concentrations were expressed as delta ($\delta$) values per mille (‰) relative to the standard SMOW (Standard Mean Ocean Water). The isotopic composition of SMOW is known, and the absolute isotopic composition of the sample was compared to this. Delta values were calculated using the formula:
where \( R_i \) is the ratio of the heavy to the light isotope in a sample and \( R_s \) the same ratio in a standard.

The error on plant and soilwater \( \delta^2\text{H} \) estimates obtained with the azeotropic distillation will be variable depending on field conditions but is usually less than ±5‰ (Walker et al. 2001).

For soil samples, the soilwater potential (expressed as matric potential) was measured using the filter paper method (Greacen et al., 1989). Further detail on the technique is given in Section 3.2.3.

### 4.3 Results

#### 4.3.1 Cross-Sectional Profiles

The riparian area of the Daly River typically consists of a steep riverbank, one to several benched areas (or terraces), and a levee (Figs 4.1 and 4.2). As described in earlier sections, many tree species have a clear distribution along the elevation gradient of the riparian zone. *Melaleuca argentea* is mostly restricted to riverbanks and lower terraces while *Eucalyptus bella* only occurs along levees. *Barangtonia acutangula* and *Cathormion umbellatum* are common on terraces. Some species (*Acacia auriculiformis* and *Casuarina cunninghamiana*) are also found at all elevations in the riparian zone.

In general, deuterium signatures in trees appeared primarily a function of landscape position. Trees along levees and upper terraces tended to have depleted deuterium signatures (−71 to −43‰) while trees along the riverbank and lower terraces were more enriched (−52 to −38‰). Groundwater entering the Daly River has a fairly constant deuterium signature (ca. −45‰). During the dry season, the Daly River also has a signature similar to groundwater (ca. −44‰) while the Douglas River is higher (ca. −40‰). Overall, riverside trees had deuterium signatures similar to groundwater or river water while trees higher in the landscape had signatures that often differed from river or groundwater.
Figure 4.1 Cross-section of the riparian zone for three transects sampled at the junction of the Douglas and the Daly rivers in 2000 - 2001. Distances and elevations all relative to river level at the time of sampling (baseflow conditions). Deuterium values (‰) for selected trees, river, and groundwater also shown. When present, the height of the water table in test holes is shown with an inverted triangle. Full name of tree species not mentioned in the text can be found in Appendix 1.
Figure 4.2 Cross-section of the riparian zone for three transects sampled at Ooloo in 2000 – 20001. All distances and elevations relative to river level at the time of sampling (baseflow conditions). Deuterium values (‰) for selected trees, river, and groundwater also shown.
The transects at the Oolloo site were steeper than at Douglas/Daly and the difference in deuterium signature between riverbank and levee trees was also greater (Fig. 4.2). Groundwater gradients were steep across the Oolloo riparian zone, with artesian flow conditions occasionally encountered during the drilling of holes along the riverbank and lower terraces. Clay lenses are common in the soil profile of the Oolloo riparian zone and may act as local semi-confining layers for groundwater flow. At Oolloo transect 1 in September 2000, both riverbank *M. argentea* (−48 to −43‰) and terrace *B. acutangula* (−46 to −40‰) had signatures similar to river/groundwater (Fig. 4.2a). In contrast, levee *E. bella* had a much more depleted signature (−71 to −59‰). A similar pattern occurred between *M. argentea* and *Pongamia pinnata*/*Poinciana* sp. at the same transect in August 2001 (Fig. 2b).

Comparison of deuterium in one tree species along the elevation gradient of the riparian zone revealed a similar pattern at the Douglas/Daly and the Oolloo sites. At Douglas/Daly Transect 3, *Acacia auriculiformis* tended to be more depleted in deuterium with increasing distance from the river (Fig. 4.1c). Similarly, *Casuarina cunninghamiana* deuterium signatures increased from −52 to −67‰ with elevation along Transect 3 at Oolloo (Fig. 4.2c). These results suggest that some riparian trees are opportunistic in their water use rather than restricted to a particular source of water.

The hydrogeological environments were different at the Oolloo and Douglas/Daly sites, with important implications for extrapolating our results to other areas of the Daly riparian zone. The Douglas/Daly transects are located on either sides of a triangular point forming the junction between the Douglas and the Daly rivers. At the Douglas/Daly transects, the surface topography was more subdued and the water table appeared reasonably flat. Distance from the surface to the water table was within the 5 to 10 m range throughout most of the riparian zone. However, the true distance to groundwater is probably one or two metres less than this because silty and clayey soils favour the development of extensive capillary fringes (see water potentials in soil profiles below). Steeper elevation and water table gradients were found at the Oolloo transects. At Oolloo, the water table was usually within 5 m of the surface along the riverbank and the terraces, and probably less than 10 m along the levee. Thus, despite a greater topography, distance to the water table was not necessarily greater at Oolloo than the Douglas/Daly. Overall, the Ooolloo transects may be more representative of the hydrogeological environment of the Daly River riparian zone because they are in a discharge area for regional groundwater. The Douglas/Daly transects are probably a part of a local groundwater system more dependent on river levels. The comparison of these two sites suggests that topography alone may not be a suitable indicator of distance to the water table in the Daly riparian zone.
Figure 4.3 Soilwater potential and deuterium concentration as a function of depth at the levee (a-b) and terrace (c-d) of the Douglas/Daly Transect 1, September 2000. The diagonally-shaded areas represent the part of the soil profile where trees probably cannot access water because of low soilwater potential (i.e., less than –3.5 MPa). Also indicated (by a dashed line) is the probable preferred range for soilwater use (i.e., soilwater potential between 0 and –1 MPa). Horizontally shaded boxes represent the range in xylem water deuterium for trees in the vicinity of the soil profiles. Closed circles represent soilwater deuterium.

4.3.2 Plant Water Availability Analysis

The use of soilwater potential in combination with the stable isotope signature of xylem water and potential sources of water can be used to further define from where plants obtain their water (Walker et al. 2001). In general, plants extract water from the soil at tensions down to –3.5 MPa but prefer to use
soilwater at tensions higher than −1 MPa. Thus, the part of the soil profile where water is at tensions less than −3.5 MPa would be considered unavailable to plants. These limits in soilwater potential have been used primarily in studies of water use by mallee trees (Walker et al. 2001). The preferred range in soilwater potential for the tree species found in the Daly riparian zone is not known. Water sources used by plants can be further constrained by comparing xylem deuterium to the one of the soil profile where the matric potential is above −3.5 MPa. Further evidence can also be obtained by comparing the pre-dawn leaf water potential with the soil matric potential at depth. Pre-dawn leaf water potential is representative of the soilwater potential in the zone of water uptake (Chapter 3).

At the Douglas/Daly Transect 1 in September 2000, levee *E. bella* did not have access to shallow soilwater because of low water potentials (Fig. 4.3a-b). *Eucalyptus bella* twig deuterium overlapped values of both deeper (>4 m) soilwater and groundwater. *Cathormion umbellatum* on the terraces were probably using soilwater near 4–5 m depth (Fig. 4.3c-d). However, because of the linear gradient in deuterium from shallow soilwater to groundwater, it is also possible that *C. umbellatum* was using a combination of shallow soilwater and groundwater. A similar pattern was observed at the nearby Douglas/Daly Transect 2, with *C. umbellatum* using soilwater at depths ranging from 2 to 4 m (Fig. 4.4). Thus, the increase in tree deuterium signature with elevation in the riparian zone is consistent with a greater reliance on soilwater. However, some groundwater may have been used by trees at all elevations.

The range in *Acacia auriculiformis* deuterium signatures across the Douglas/Daly riparian zone in August 2001 also suggests that they used different sources of water at different landscape positions (Fig. 4.5). On the levee, *A. auriculiformis* did not have access to soilwater in the top 4 m of the profile because of low water potentials. This was consistent with the deuterium profile, which indicated a use of deeper soilwater (Fig. 4.5a-b). On the terrace, *A. auriculiformis* deuterium was intermediate between soilwater and groundwater, suggesting that both sources were used (Fig. 4.5c-d). In contrast, riverside *Acacia* could have been using either river water or groundwater but probably not soilwater (Fig. 4.5e-f). At Oolloo Transect 1 in September 2000, levee *E. bella* were using soilwater while terrace *B. acutangula* and riverbank *M. argentea* were using river or groundwater (Fig. 4.6). At the same transect in August 2001, *Pongamia pinnata* and *Poinciana* sp. on the levee and the upper terrace were using soilwater or a combination of soil and groundwater (Fig. 4.7). Overall, while it was not always possible to unambiguously determine the source of water used, trees on riverbanks and terraces almost always had at least some groundwater use. Trees on levees relied more heavily on soilwater but could have used groundwater occasionally as well.
Figure 4.4 Soil matric potential and deuterium concentration as a function of depth for the levee (a-b) and terrace (c-d) of the Douglas/Daly Transect 2, September 2000. Shaded areas represent unavailable soilwater (i.e., soilwater potentials below −3.5 MPa).
Figure 4.5 Soil matric potential and deuterium concentration as a function of depth along the levee (a-b), terrace (c-d), and riverbank (e-f) of Douglas/Daly Transect 3, August 2001. Shaded areas represent unavailable soilwater (i.e., soilwater potentials lower than –3.5 MPa).
Figure 4.6 Soil matric potential and deuterium concentration as a function of depth along the levee (a-b), terrace (c-d), and riverbank (e-f) of Oolloo Transect 1, September 2000. Shaded areas represent unavailable soilwater (i.e., soilwater potentials below –3.5 MPa).
Figure 4.7 Soil matric potential and deuterium concentration as a function of depth for the levee (a-b), terrace (a-b), and riverbank (e-f) of Ooloo Transect 1, August 2001. Shaded areas represent unavailable soilwater (i.e., soilwater at potentials below \(-3.5\) MPa).
4.3.3 Temporal Variability in Tree Deuterium

There was a consistent pattern in the deuterium signature of *E. bella* and *M. argentea* sampled at the same location over a two-year period. Deuterium concentrations in the xylem of *M. argentea* remained constant and similar to river/groundwater over the course of the dry season. However, deuterium concentrations in the xylem sap of *E. bella* tended to be more enriched as the dry season progressed (Table 4.1). This is consistent with *M. argentea* primarily using river water or groundwater throughout the dry season. The decline in *E. bella* deuterium is more difficult to interpret. On the one hand, the change in signature towards more depleted values may indicate an increased reliance on deeper soilwater or groundwater as the season progresses. On the other hand, the deuterium signature of the soilwater profile may change during the dry season, resulting in a corresponding shift in signature without trees necessarily accessing a different source of water. Occasional rainfall and evaporation may be responsible for a shift in the soilwater deuterium profile during the dry season. More frequent sampling of tree and soilwater deuterium will be required to identify the possible shifts in *E. bella* water use during the dry season.

Table 4.1 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).

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th><em>M. argentea</em> (‰)</th>
<th><em>E. bella</em> (‰)</th>
<th>Daly River (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dorisvale</td>
<td>May 2000</td>
<td>−55.9 ± 3.8</td>
<td>−100.1 ± 4.2</td>
<td>−52.5 ± 0.2 (2)</td>
</tr>
<tr>
<td></td>
<td>Sep 2000</td>
<td>−56.4 ± 2.6</td>
<td>−85.3 ± 5.0</td>
<td>−45.4</td>
</tr>
<tr>
<td>Oolloo</td>
<td>May 2000</td>
<td>−45.2 ± 1.4</td>
<td>−70.0 ± 8.6</td>
<td>−46.4 ± 2.6 (6)</td>
</tr>
<tr>
<td></td>
<td>Sep 2000</td>
<td>−45.6 ± 2.4</td>
<td>−63.3 ± 6.6</td>
<td>−44.2 ± 0.8 (5)</td>
</tr>
<tr>
<td></td>
<td>Aug 2001</td>
<td>−47.5 ± 1.1 (2)</td>
<td>−</td>
<td>−45.9 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>Oct 2001</td>
<td>−45.1 ± 5.0</td>
<td>−58.3 ± 2.4</td>
<td>−</td>
</tr>
</tbody>
</table>

4.4 Discussion

Unlike in the *M. viridiflora* forest studied by Hatton et al. (1998) near Darwin, different sources of water were distinguishable on the basis of variation in the stable isotope composition of water in the riparian zone of the Daly River. It was possible to distinguish between soilwater and groundwater, but not between groundwater and river water, as these had similar isotopic signatures. The range of signatures encountered in soilwater suggests a large event-to-event variability in the isotopic signature of precipitation in the area. Regional groundwater tends to have constant stable isotopic signature
because it integrates the long-term average precipitation for a given region. In contrast, in a given year, the soil moisture pool could be recharged by a series of large individual rain events with an isotopic signature significantly different from the long-term average in precipitation. Large event-to-event variability in the isotopic signature of precipitation can occur because of the “rain-out” effect. As atmospheric water gradually moves inland, it becomes “depleted” in the heavier isotopes of the water molecule because these tend to condense more readily than the lighter isotopes. Thus, storms having travelled inland for different distances may impart different isotopic signature to soilwater relative to the long-term average. Another mechanism to impart a different signature to soilwater in the riparian zone is bank recharge during floods. Floodwater would be expected to originate from rainfall higher in the catchment. It is likely that this rainfall would have a different isotopic composition to rainfall lower in the catchment. Both rainout and orographic effects (i.e., increased depletion of heavier isotopes with land elevation) may result in precipitation in the upper part of a catchment to be more depleted than in the lower sections. The depleted signature of shallow soilwater relative to groundwater in the Daly riparian zone indicates that replenishment of the riparian soil moisture pool by bank recharge during floods is possible.

The similarity in stable isotope signatures between the Daly River and the riparian groundwater highlights that groundwater is the main component of baseflow to the Daly during the dry season. The apparent lack of evaporative enrichment of surface water indicates that the volume of groundwater input is large and that the water residence time is too short to enable significant evaporative enrichment of surface water. In addition, high relative humidity can diminish the potential for isotope fractionation during the evaporation process (Clark and Fritz 1997). At Dorisvale in 2000, river water appears slightly more depleted than groundwater early during the dry season (Table 4.1). This suggests that bank discharge of floodwater accumulated during the wet season may also contribute to baseflow early during the dry season.

As rainfall is rare during the dry season, it was expected that trees would increasingly rely on groundwater as the dry season progressed. It is apparent from the concentration of xylem deuterium that *Eucalyptus bella* along the levees at Ooloo and Dorisvale relied principally on soilwater throughout the dry season and that the riverbank *M. argentea* relied principally on river or groundwater (Table 4.1). However, while deuterium signatures remained unchanged in *M. argentea* during the dry season, deuterium in *E. bella* tended to decline. This suggests either a shift in soilwater deuterium during the dry season or an increase reliance on deeper soilwater or groundwater by *E. bella*.

Due to the restricted distribution of many tree species along the riparian elevation gradient, it was not clear whether the differences in deuterium signature observed were a function of landscape position or tree species *per se*. It is plausible that different species have different rooting distributions, thus water resources are partitioned on the basis that different species are better able to exploit different water resources (Jackson et al. 1999). Alternatively, trees may be opportunistic in water use and utilise
whatever resource is available. Two additional transects where the same tree species occurred along
the whole elevation gradient were sampled in August 2001 to further test these hypotheses. These
transects indicated that some trees are flexible in the source of water used. Both *Acacia auriculiformis*
and *Casuarina cunninghamiana* gradually shifted to greater soilwater use with increased elevation in
the riparian zone. In addition, while *E. bella* mostly relied on soilwater at Dorisvale and Ooloo during
the dry season, they appeared to be using groundwater at Douglas/Daly. Other species (*M. argentea*
and possibly *B. acutangula*) where always relying on shallow groundwater. Thus, it is likely that two
strategies exist for water use in the Daly riparian zone: One opportunistic and the other specialized on a
particular source.

The main conclusion from the comparison of deuterium in trees, soilwater and groundwater is that trees
along riverbanks and terraces of the Daly River riparian zone heavily rely on groundwater. Trees along
levees may also use groundwater at some locations or during some parts of the year. It is important to
note that the hydrogeological environment of the Daly riparian zone is complex and can vary
significantly from site to site. In other words, the relationships between water use and elevation
established here must be applied with caution to the rest of the Daly River. Water use in trees at higher
elevations (such as *E. bella*) needs to be further examined. More frequent sampling of tree and
soilwater during the dry season is required to determine if and when a shift in water use occurs in levee
trees. In addition, it may be necessary to contrast water use between wet and dry years. As observed
elsewhere, some trees may only rely on groundwater during drought periods, when all other sources are
unavailable. While groundwater may be a small percentage of water use in opportunistic trees, it may
still be essential for their long-term survival.
Daly River NT, Riparian Vegetation Water Use.

5.0 Stand Water use by Riparian Vegetation Along the Daly River

5.1 Introduction

Improvements in technology and instrumentation now allow for the routine measurement of water use by vegetation communities. However, these techniques have rarely been employed for the measurement of water use by riparian communities. Further, the water use requirements of riparian vegetation have rarely been considered in environmental flow studies. Micro-meteorological techniques provide measures of whole ecosystem fluxes of water and carbon but are constrained by site heterogeneity and fetch requirements. Whole tree techniques, in contrast, allow measurement of tree water use in a range of species and a range of site conditions, are easily automated and allow measurements at a number of spatial and temporal scales.

Riparian communities present unique challenges in scaling of tree water use, as there are steep gradients in water availability and water use (Chapter Three, Chapter Four). Further, riparian communities often have higher species diversity than upslope communities. In the present study, water use by *Melaleuca* trees along the river was lower than eucalypt trees along the levee. In addition, trees located at different distances from the river used different sources of water. Thus, *Melaleuca* trees along the riverbank access groundwater or riverwater while eucalypt trees along the levees were using soilwater from the unsaturated zone (Chapter Four). Vegetation along the Daly River also exhibits distinct zonation; *Melaleuca* communities line the riverbanks, monsoon forests occupy the terraces and savanna type forests occur on the levee banks (Faulkes 1998). Although tree water use for eucalypt and *Melaleuca* trees was aseasonal, many of the rainforest species that occupy the terraces exhibit a range of leaf phenologies. This suggests that water use by the riparian community may be seasonal.

There have been very few studies that have examined water use by rainforest communities in Northern Australia. Kelley (2002) demonstrated strong seasonality in stand water use in a monsoon forest in the Darwin region. Water use varied from less than 1 mm day\(^{-1}\) during the dry season to over 2.5 mm day\(^{-1}\) in the late dry to wet season. Much of this seasonal increase in stand water use could be attributed to increased leaf area associated with leaf flush by deciduous and semi-deciduous species and a higher sapwood area for any given DBH than in the surrounding savannas. The principal aim of this chapter was to examine seasonal patterns of stand water use in riparian vegetation along the Daly River. Further we examined the relationship between stand water use and basal area along the Daly River in order to develop a functional basis for scaling water use in the riparian communities of northern Australia.
Daly River NT, Riparian Vegetation Water Use.

The number of species and the range of phenologies present in riparian communities along the Daly River represent difficult challenges to determining community averaged water use. Temporal and spatial scaling of tree water use in any vegetation community represents a significant challenge. In this study vegetation communities along the Daly were surveyed for species composition, position from river and diameter at 1.3 m height (DBH). Information on the structural composition of these forests was vital to assess the adequacy of sampling techniques, to provide information on the spatial variability of forest structure and to allow tree-based estimates of water use to be scaled to stand-based estimates.

5.2 Methods

5.2.1 Vegetation Surveys

Vegetation was surveyed along five transects at Dorisvale Crossing, Oolloo and Douglas/Daly (Fig 2.1). At Dorisvale Crossing and Oolloo, transects were 150 m long and two metres wide. At the Douglas/Daly site, transects were 90 m long as the composition and structure of the community varied little from the river to the levee. Further, savanna-type communities were absent and the site is dominated by closed monsoon rainforest. Within each transect the following data were recorded; species, DBH, distance from the river and habitat (riverbank, terrace, levee or savanna). Three transects were established at each of two extra locations, Oolloo Crossing and Black Bull Yards (Fig 2.1). These were sampled to provide a comprehensive description of the riparian vegetation along the Daly River. Access to these sites was restricted to the mid-late dry season; hence they could not be included in the studies of water use.

5.2.2 Tree Water Use

Tree water use was measured using the heat pulse technique as described in Chapter Three. Reference trees were established at each site to examine day-to-day variation in tree water use. Four trees were instrumented with heat pulse loggers, two (M. argentea and E. bella) at the Oolloo site and two (E. bella and Terminalia microcarpa) at the Douglas/Daly site. Trees were instrumented in August 2001 and logging continued at half-hour intervals until December 2001.

Three permanent water use-monitoring sites were established: two transects at the Oolloo site and one plot at the Douglas/Daly site. Transects at the Oolloo sites were 2 m wide and equivalent in length to the width of the riparian strip. Thus, Transect 1 was 2 m wide, 60 m long and contained 8 trees (species n=5). Transect two was 2 m wide, 80 m long and contained twelve trees (species n=9). Cross sectional profiles of transect one and two at the Oolloo site are shown in Figure 4.1. At the Douglas/Daly site, which was characterised by a large stand of monsoon forest, a 20 m x 5 m plot was
established (21 trees, 5 species). Tree water use was measured in all trees in each plot or transect. A system of roving loggers was employed to measure all trees within a plot or transect. During each measurement period, one tree within each transect or plot was maintained as a reference tree, so that the tree water use of other trees within the plot/transect could be compared to that reference tree. For all other trees water use was measured for two complete days after initial instrumentation with a heat pulse logger. Although a longer period of logging on each tree would have been preferable, time and equipment constraints prohibited this.

5.3 Results

5.3.1 Vegetation Surveys

Forty-four tree species were recorded during the vegetation surveys. A list of species is included in Appendix One. Of these, three were unidentified, as they had no leaf during the surveys and three were introduced species (Poinciana, Mahogany, and Kalope). Mean (± SE) basal area for the riparian vegetation was 71±13.1 m² ha⁻¹ but ranged from 9 m² ha⁻¹ to 286 m² ha⁻¹. Mean tree density (± 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*). The basal area and stocking rate for each transect are shown in Table 5.1.
Table 5.1. GPS co-ordinates, width and basal area of vegetation survey transects along the Daly River.

<table>
<thead>
<tr>
<th>Site</th>
<th>Transect</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Width of Riparian Strip (m)</th>
<th>Basal area of Riparian Strip (m² ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mango camp</td>
<td>1</td>
<td>s 14 00 15</td>
<td>e 131 14 19</td>
<td>70.5</td>
<td>152.7</td>
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<td>e 131 14 12</td>
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<td>e 131 08 45</td>
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<tr>
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<td>e 131 08 36</td>
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Table 5.2 Structural characteristics of riparian vegetation along the Daly River

<table>
<thead>
<tr>
<th>Site</th>
<th>Transect</th>
<th>Basal Area (m² ha⁻¹)</th>
<th>Stems ha⁻¹</th>
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5.3.2 Tree water Use

There was a good correlation between water use in the two reference trees at Ooloo (Fig 5.1). However, correlations between tree water use of the reference trees at the Douglas Daly site were poor. Variability in daily tree water use, during the sampling periods, increased from August to December. Daily tree water use during each sampling period for the reference trees at Ooloo is shown in Fig 5.2. Long-term daily tree water use in all reference trees was variable but there was no seasonal pattern in
Daly River NT, Riparian Vegetation Water Use.

water use in any tree except *Terminalia microcarpa* at the Douglas/Daly site (Fig 5.3b). *Terminalia microcarpa* is a deciduous tree of monsoon rainforest and an increase in water use was observed as this tree flushed. Although no seasonality was observed in evergreen trees, daily variability in water use increased with the onset of the build-up and wet season, associated with an increasing number of cloudy days and scattered and intermittent rainfall.

![Graph showing the relationship between daily tree water use in the two long-term reference trees at Ooloo (E. bella and M. argentea)](image)

Figure 5.1 The relationship between daily tree water use in the two long-term reference trees at Ooloo (*E. bella* and *M. argentea*)
Figure 5.2 Daily tree water use in reference trees at Ooloo during August (top), October (middle) and December (bottom). (OLEB, Ooloo *E. bella*. OL Mel, Ooloo *M. argentea*. T1 Cas, Transect 1 *Casuarina cunninghamiana*. T2 Ficus spp, Transect 2, *Ficus racemosa*)
There was considerable variability in the relationships between tree water use and tree size at each site. These relationships varied between sites and sampling times, reflecting varying contributions of deciduous trees to forest water use and possible differences among sites (Fig 5.4). At the Douglas/Daly site a large component of standing basal area was contributed by the deciduous tree *Strichnos lucida*. Generally, however, a power relationship with a $r^2$ of more than 0.6 was obtained.
Figure 5.4 Water use/tree size relationships within the three permanent water use monitoring sites. Transect 1 (top), transect 2 (middle) and Douglas Daly (bottom). Data represent mean daily water use ± standard error of each tree measured during each measurement period. Thus data represents a range of species.

Water use was scaled to plot water use on the assumption that daily water use varied little over the measurement period. Thus, mean water use for each tree, measured over a two-day period was summed to calculate a census of water use for each plot. In general, daily water use in each of the reference trees showed very little variability over each of the measurements periods (Fig 5.2). December tree water use was the exception, however. Correlations between tree water use for reference trees at the Oolooloo sites were also variable. During the dry season reference trees along the terraces exhibited good correlation with the Melaleuca tree along the riverbank and poor correlation with the eucalypt tree on the terrace. During the wet season, water use in the Casuarina tree was correlated with water use by
both the *Eucalyptus* and *Melaleuca* trees. There was no correlation between the *Ficus* tree and water use of either the *Eucalyptus* or *Melaleuca* tree (Fig.5.5)

Figure 5.5 Relationships between reference trees at Oolloo site during the dry season and during the wet season. See Figure 5.3 for descriptions of x-axis.
Mean daily 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 4.8 mm day$^{-1}$ (Transect 1, October) and mean water use increased slightly from August (2.87 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 5.2. Throughout the dry season there was a strong relationship between stand water use and stand basal area. However, this relationship varied seasonally as deciduous trees contributed to stand water use in the wet season at the Douglas/Daly site (Fig 5.6). 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.

### Table 5.3 Stand water use (mm day$^{-1}$) by riparian vegetation at three sites along the Daly River

<table>
<thead>
<tr>
<th>Plot</th>
<th>Basal area (m$^2$ ha$^{-1}$)</th>
<th>August 2001</th>
<th>October 2001</th>
<th>December 2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 (Oolloo)</td>
<td>98.17</td>
<td>4.22</td>
<td>4.89</td>
<td>4.28</td>
</tr>
<tr>
<td>T2 (Oolloo)</td>
<td>25.76</td>
<td>1.98</td>
<td>1.88</td>
<td>1.46</td>
</tr>
<tr>
<td>Douglas/Daly</td>
<td>52.88</td>
<td>2.32</td>
<td>2.54</td>
<td>4.32</td>
</tr>
</tbody>
</table>

Figure 5.6 The relationship between stand water use (mm day$^{-1}$) and stand basal area (m$^2$ ha$^{-1}$) at three sites along the Daly River
5.4 Discussion

Riparian vegetation along the Daly River exhibited considerable structural complexity. Over forty species were recorded at 5 sites along the river. Although large evergreen trees dominated basal area, deciduous and semi-deciduous species are an important component of the stand. 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. The factors controlling the development of riparian vegetation are complex and include, frequency and intensity of flood events, geomorphology, and bank stability among others. The complexity in vegetation structure and floristics probably reflects the interactions between these controlling processes and suggests that the vegetation communities that make up the riparian zone are dynamic.

Tree water use by riparian vegetation varied principally with tree size, however, distance from the river was also important (Chapter 3). Trees at different elevations in the landscape had access to different sources of water, depending principally on distance from and height above the river (Chapter 4). *Melaleuca* trees growing along the rivers edge used less water and sourced water directly from the river or groundwater whereas *Eucalyptus* trees along the levee banks had a higher water use for any given DBH and were principally using soilwater. Despite this complexity in patterns of tree water use, and the floristic and structural diversity, there were reasonable correlations between tree size and water use along transects that spanned the width of the riparian strip (Fig 5.4). However, the slope of the relationship varied with both season and site (Fig 5.4) making generalisations about stand water use difficult.

Water use by trees, within a site, are usually strongly correlated with each other (Vertessy et al, 1997, Hunt and Beadle 1998). Further, studies on the water use by several tree species in northern Australian savanna found that there were no significant differences between species in the relationship between water use and tree size (Hatton et al 1998b, O’Grady et al. 1999, O’Grady 2000). This does not appear to be the case in riparian vegetation. Tree water use by *Melaleuca* trees along the river is 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. There were poor correlations between the water use of most reference trees with the riparian strip (Fig 5.5) and this may be related to the large spatial heterogeneity of the physical environment with the riparian zone. This may be the result of steep gradients in microclimate, soil texture and water availability and the interaction of these factors.

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 (m\(^2\) ha\(^{-1}\)) (Fig. 5.6). 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. 5.7). The largest seasonal change in stand water use occurred at the Douglas/Daly site, reflecting the seasonal
contribution of deciduous *S. lucida* to stand water use. 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 5.2).

![Dry Season Water Use](image)

**Figure 5.7** Stand water use during the dry season in relation to stand basal area 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 m\(^2\) ha\(^{-1}\) and 90 m\(^2\) ha\(^{-1}\) respectively). This suggests that stand water use during the wet season was at a maximum at a basal area of about 50 m\(^2\) ha\(^{-1}\). Potential evaporation rates for the area are approximately 6 mm day\(^{-1}\) (Fig 2.2). 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, understory evapotranspiration can contribute up to 30% of site Et, suggesting that the total vegetation water use along the Daly is running at close to potential Et during the wet season (overstorey and estimated understory).
Daly River NT, Riparian Vegetation Water Use.

The structural complexity of the vegetation and the lack of a single clear scaling relationship between tree water use and tree size reduces the capacity for predicting of stand water use in riparian vegetation. Work from around Australia has demonstrated that there are usually clear relationships between tree size parameters and tree water use (Hatton et al 1995, Vertessy et al. 1997, Hatton et al 1998b, O’Grady et al. 1999). These relationships have often formed the basis for scaling individual measures of tree water use to estimates of stand water use. In riparian vegetation along the Daly River these relationships were not as consistent and varied spatially and temporally. In addition, the relationship between sapwood area and tree size varies between *Melaleuca*, savanna and monsoon rainforest species (Kelley 2002) further complicating this approach to scaling. In this study we have taken a census approach to plot water use. Tree water use in the majority of trees was measured over a two-day period, assuming that day-to-day variability in tree water use would be small over the measurement period. Day-to-day variability in water use was tracked with a series of reference trees and increased from the dry to the wet season. These factors suggest that the census of plot water use approach used here was the most practical approach to solving the problem of stand water use in this environment. However, uncertainty in the estimates is introduced by the limited number of sampling days for most trees (ie two days). Further, increased variability in day-to-day water use with the onset of the wet season increases uncertainty in these estimates. Ideally water use should have been measured in all trees over the same time frame. The approach used here represents of trade off between available resources and attempting to sample over a range of sites and basal area. Mean basal area for riparian vegetation along the Daly was 71 m$^2$ ha$^{-1}$, thus, the range of basal areas covered in this study provides a useful insight into water use along the Daly River.

In conclusion, tree water use in riparian vegetation was principally a function of tree size. This relationship was reflected strongly in the good relationship between stand water use and stand basal area (Fig 5.6). Although, the predictive capacity of this relationship is undermined somewhat by the high variability in individual tree water use, Figure 5.7 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 understory and soil evaporation. 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 Douglas Daly).
Daly River NT, Riparian Vegetation Water Use.

Plate 4  Seasonal changes in leaf area at the Douglas/Daly site
6.0 Water Use by *Melaleuca* Forest and Rainforest Communities within the Howard East Catchment Area-A Review of Kelley 2002

6.1 Introduction

Savanna communities, defined as having a discontinuous tree canopy over a highly seasonal grass community, dominate Northern Australia. Eucalypts dominate much of these savannas and a considerable amount of work has been done over the last ten years in northern Australia into the ecophysiology of these savannas (see for example Fordyce et al. 1997, Myers et al. 1997, Duff et al. 1997, Williams et al. 1997, Cook et al. 1998, O’Grady et al. 1999, Hutley et al. 2000 or Eamus and Prior 2001). The savanna community however, is a matrix within which other communities such as, *Melaleuca* forests and monsoon rainforests occur. While being only a small component the northern Australian landscape spatially, these communities are a valuable resource, economically, culturally and biologically.

There have been many studies of tree water use in northern Australian savannas that have established the spatial and seasonal patterns of water use (Myers et al. 1997, O’Grady et al 1999, Eamus et al. 2000). However, relatively little is known of the water use requirements of either *Melaleuca* forests or monsoon rainforests although there has been some work on temperate *Melaleuca* forests (Mensforth 1996) and sub-tropical rainforests (see for example Barrett et al. 1996). Information on the distribution of water use in relation to habitat and season is vital for understanding the water balance of the region as a whole.

In the Northern Territory, Hatton et al. (1998) studied the hydrology of *Melaleuca* swamps within the Howard East Catchment using a combination of tree water use techniques, soil physics, isotopic techniques and groundwater hydrology. They found that there was little evidence to support that these systems were groundwater dependent and that they were principally dependent on local rainfall and runoff. There was enough water stored in the shallow soil profile to support transpiration over the dry season. However, they were also unable to definitively determine the sources of water being used by *Melaleuca* trees as they were unable to differentiate between soilwater and groundwater based on the isotopic composition.

This study compares the sources and rates of water use by *Melaleuca* and monsoon rainforest communities in the Howard East Catchment. The catchment is being developed as a water management zone that includes significant borefield development. While the sources and amount of water required by the dominant savanna communities have been well quantified (Hatton et al. 1997, Cook et al 1998), it is thought that the position of the *Melaleuca* forests and monsoon rainforest communities in the
Daly River NT, Riparian Vegetation Water Use.

landscape may make them more vulnerable to groundwater extraction. In particular this study aimed to assess: a) daily and seasonal patterns of water use in these communities; b) quantify the sources of water used by these communities and c) make an assessment of the environmental water use requirements of these communities.

6.2 Methods

The Howard East catchment area has been described in detail by a number of authors (Hatton et al 1997, Cook et al 1998, O’Grady 2000). Briefly, the area 35 km south east of Darwin is dominated by E. miniata/E. tetrodonta open-forests. Melaleuca forests, dominated by M. viridiflora, occur at low points in the landscape that are the result of dissolution of the protozoic dolomites 20 to 50 m below the ground surface. This dissolution process resulted in voids into which cretaceous sediments above have subsided (McFarlane et al. 1995). These areas within the catchment are generally interconnected to form a poorly defined drainage network (O’Grady 2000). Monsoon forests in the catchment are found along the banks of the Howard River, along the edges of the Adelaide River Floodplain or associated with permanent springs arising from the dolomite aquifer (P. Jolly pers. comm.). The Black jungle site, used in this study is one such forest. Four species; Terminalia microcarpa, Syzygium nervosum, Nauclea orientalis and Ficus racemosa contribute more than 80% of stand basal area.

6.2.1 Tree and Stand Water Use

Rates of tree water use were estimated using the heat pulse velocity method (chapter three). Water use was estimated in 8-10 trees over a two-week period at three times during the year; late wet (March), dry season (May) and Late Dry (September). In the Melaleuca forest, daily rates of tree water use (Q) were regressed against DBH for all sampled trees on each day. DBH of all trees in a 50 x 50 m plot were estimated and the power relationship applied to estimate water use of trees in the plot. A pilot study in the monsoon forest found no clear relationship between tree size and water use. Hence stand water use was estimated using a census approach. The water use of all trees within three plots were summed and expressed on an area basis. The species measured and the area of each plot is shown in Table 6.1.

Soilwater availability was investigated in each community. Predawn leaf water potentials were measured as a surrogate of soilwater availability during each sampling period in the Melaleuca forest. Four leaves from each of 8-10 trees were measured using a Scholander-type pressure chamber. In the monsoon rainforest, the height of the canopy precluded leaf sampling for water potentials. Instead, soilwater content was measured gravimetrically to 0.5 m depth.
6.2.2 Isotope Sampling

Seasonal sources of water were assessed only in the Melaleuca forests because of the inaccessibility of monsoon forests for much of the year. Branch, soil and groundwater samples were collected over an 18-month (July 1998-October 1999) period corresponding to the dry season, late dry season and late wet season. During May 1999, surface water samples were also collected. Groundwater samples were taken from three piezometers, installed by the Power and Water Authority (NT). These were pumped to remove standing water and allowed to refill for several hours. Soil samples were taken using a hand augor to 1.5 m (intervals 0 - 0.5, 0.5 - 1.0 and 1.0 - 1.5 m).

Table 6.1 Plot size and species measured at the monsoon rainforest site.

<table>
<thead>
<tr>
<th>Plot number and size (m²)</th>
<th>Tree ID</th>
<th>Species</th>
<th>DBH (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plot 1</td>
<td>T1.1</td>
<td><em>N. orientalis</em></td>
<td>34.7</td>
</tr>
<tr>
<td></td>
<td>T1.2</td>
<td><em>T. microcarpa</em></td>
<td>32.5</td>
</tr>
<tr>
<td></td>
<td>T1.3</td>
<td><em>S. nervosum</em></td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>T1.4</td>
<td><em>S. nervosum</em></td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>T1.5</td>
<td><em>S. nervosum</em></td>
<td>30.5</td>
</tr>
<tr>
<td>Plot 2</td>
<td>T2.1</td>
<td><em>T. microcarpa</em></td>
<td>48.5</td>
</tr>
<tr>
<td></td>
<td>T2.2</td>
<td><em>T. microcarpa</em></td>
<td>30.3</td>
</tr>
<tr>
<td></td>
<td>T2.3</td>
<td><em>S. nervosum</em></td>
<td>23.3</td>
</tr>
<tr>
<td></td>
<td>T2.4</td>
<td><em>N. orientalis</em></td>
<td>25.9</td>
</tr>
<tr>
<td></td>
<td>T2.5</td>
<td><em>S. nervosum</em></td>
<td>15.0</td>
</tr>
<tr>
<td>Plot 3</td>
<td>T3.1</td>
<td><em>N. orientalis</em></td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td>T3.2</td>
<td><em>T. microcarpa</em></td>
<td>31.5</td>
</tr>
<tr>
<td></td>
<td>T3.3</td>
<td><em>T. microcarpa</em></td>
<td>29.5</td>
</tr>
<tr>
<td></td>
<td>T3.4</td>
<td><em>S. nervosum</em></td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td>T3.5</td>
<td><em>T. microcarpa</em></td>
<td>37.5</td>
</tr>
</tbody>
</table>

In November 1998 and October 1999 soil was sampled for matric potential and soilwater isotopic composition to 2.3 m and 2.0 m depth respectively. Samples were collected at: 0 - 0.1, 0.1 - 0.3, 0.3 - 0.5, 0.5 - 0.75 and 0.75 - 1.0 m intervals (both sample times); 1.3 - 1.6, 1.6 - 2.0, 2.0 - 2.3 and 2.3 - 2.6 m (1998) and 1.3 - 1.5, 1.5 - 1.7, 1.7 - 1.9 and 1.9 - 2.0 m (1999). In August 1999 samples were taken to the groundwater (0 - 0.1, 0.1 - 0.3, 0.3 - 0.5 and 0.5 - 0.75 m). Although the site was inundated in May 1999, a metal frame was used to create an area where the surface water could be pumped out and two soil samples (0 - 0.2 m and 0.2 - 0.4 m) were taken.
Plant material was taken from three individual mature *M. viridiflora* trees at each sampling time. A number of branches of at least 1 cm diameter and from the secondary and tertiary branches were cut from several areas of the canopy, in order to estimate variability and provide a sample representative of the whole canopy. Samples were cut to 5 cm lengths, placed in screw lid jars full of kerosene and sealed with plastic film.

Plant material and soils were azeotropically distilled in kerosene, following the methodology of Revesz and Wood (1990) and Thorburn *et al.* (1993). This method is based on the principle that an azeotrope has a boiling point different from either of its constituents (Revesz and Woods 1990). The distillation of the sample with kerosene forms an azeotrope between the kerosene and water in the sample. The water then condenses out of the azeotrope and can be retrieved, since it is immiscible with kerosene at ambient temperature. Distillation took place in a Dean-Stark apparatus (Revesz and Woods 1990) and retrieved water was collected and stored in glass jars with screw lids. Wax was melted on the surface of the water to remove any residual kerosene.

Surface and groundwater, and water extracted from soil and branches, was analysed for $\delta^2$H through stable isotope mass spectrometry for $\delta^2$H by reducing 25 µl of water to H$_2$ over uranium at 800 °C. For the measurement of $\delta^{18}$O, one ml of water was equilibrated with CO$_2$ in a small, pre-evacuated rubber-top vial. Samples were analysed using a dual inlet gas ratio mass spectrometer (Europa Scientific Ltd.).

Isotopic concentrations were expressed as delta ($\delta$) values per mille (‰) relative to the standard SMOW (Standard Mean Ocean Water). The isotopic composition of SMOW is known, and the absolute isotopic composition of the sample was compared to this. Delta values were calculated using the formula:

$$\delta(‰) = \left( \frac{R_i}{R_s} - 1 \right) 1000$$

(6.1)

where $R$ is the ratio of heavy:light isotope, $i$ is the isotope sample, $s$ is the standard, $\delta^2$H refers to $^2$H and $\delta^{18}$O to $^{18}$O. Sampling and analysis precision was approximately ±1.3 ‰ for $\delta^2$H and ±0.3 ‰ for $\delta^{18}$O values for soils (Revesz and Woods 1990) and plant material (*E. camaldulensis*, Thorburn *et al.* 1993).
Daly River NT, Riparian Vegetation Water Use.

Plate 5 Monsoon rainforest in the Howard East Catchment
6.3 Results

6.3.1 Tree Water Use

In 1998, in the *Melaleuca* site, mean $\psi_{pd}$ was highest (least negative) during the wet season (-0.036 MPa), but during 1999 was least negative during the dry season (-0.034 MPa; Figure 6.1). Soilwater content in the upper 0.3 m of soil of the wet monsoon forest site was highest during the wet season and lowest during the late dry season. At 0.4 m and 0.5 m depth, water content was more than 0.3 g g$^{-1}$ throughout the year (Figure 6.2).

Both wet monsoon forest and *Melaleuca* forest sites were typically inundated between December and May. Groundwater depth decreased in the *Melaleuca* forest to a depth below the soil surface of 3.1 m at the end of dry season 1998, and 1.8 m at the end of the 1999 dry season. Estimated depth to groundwater in the wet monsoon forest site was 0.7 m at the end of the dry season 1999 (data not shown).

![Figure 6.1 Pre-dawn leaf water potentials for the *Melaleuca* forest (MSF; open columns) for each season during 1998 and 1999. Also included are predawn water potential values form the surrounding eucalypt open forest for comparison. Error bars indicate standard error of the mean in this and following figures.](image-url)
Water use in the *Melaleuca* forest, expressed on a sapwood area basis ($Q_s$), was not significantly different between years or seasons. Estimates of $Q_s$ ranged from 1.63 m$^3$ m$^{-2}$ d$^{-1}$ (wet season 1999) to 3.43 m$^3$ m$^{-2}$ d$^{-1}$ (dry season 1999). In wet monsoon forest, *T. microcarpa* was leafless during the dry season and so analyses of seasonal effects on water use were undertaken only for *N. orientalis* and *S. nervosum*. Data for *T. microcarpa* from the wet season and late dry season are included in figure 6.3 for comparison, but were not part of the statistical analyses. Estimates of $Q_s$ ranged from 1.09 m$^3$ m$^{-2}$ d$^{-1}$ to 2.88 m$^3$ m$^{-2}$ d$^{-1}$. There were no differences in water use, expressed on a sapwood area basis ($Q_s$; m$^3$ m$^{-2}$ d$^{-1}$) between *N. orientalis* and *S. nervosum* at any time during the year. $Q_s$ did not vary significantly between seasons for any individual species or if all species were pooled within a season. Seasonal water use for both ecosystems is shown figure 6.3.
Figure 6.3 Seasonal water use ($Q_s$) in *Melaleuca* forests and Monsoon forests of the Howard East Catchment.
Daly River NT, Riparian Vegetation Water Use.

Plate 6 *Melaleuca viridiflora* swamps within the Howard East Catchment
6.3.2 Stand Water Use

In the *Melaleuca* forests, the correlation coefficient for $Q$ against DBH at each sampling time was generally greater than 0.60. There was no significant variation in $Q$ with season at any time during the study period. However, there was no clear relationship between $Q$ and DBH during the 1999 late dry season. Thus, a generalised relationship was developed between $Q$ and DBH for all sample times and this relationship was used to scale individual tree water use to $E_t$ for the late dry season 1999. For all other sample times, however, scaling relationships were developed based on that season’s data only.

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 6.4). 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 0.384 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 6.4](image-url) 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)
6.3.3 Distribution of Stable Isotopes Within the *Melaleuca* Forest

Standing water levels in the *Melaleuca* forest ranged from −3.5 m at the end of the dry season to +0.15 m during the wet season. This meant that the shallowest bore, which was screened at 2.5 – 3.0 m, was dry and could not be sampled at the end of the dry season in 1998. The $\delta^2$H composition of groundwater sampled from the three piezometers remained relatively constant between sampling periods. Mean isotopic composition throughout the study was $-30.9 \pm 1.7$, $-26.2 \pm 0.7$ and $-29.4 \pm 1.1$ for the shallowest to deepest bores respectively (Fig. 6.5). Due to inaccessibility of the site during the 1998-99 wet season, the bores were not sampled mid-wet (January).

Surface water was present during the end of the 1999 wet season sampling at an average depth of 0.50 m, and a mean ($n = 3$) $\delta^2$H value of $-38.8 \pm 1.36$ (Fig. 6.6f). This value agrees with that recorded by Hatton *et al.* (1998) from surface water sampled in March 1998.
In contrast to groundwater, the isotopic composition of soilwater showed considerable variation between seasons, with \( \delta^2H \) values ranging from \(-0.25\%_e\) to \(-44\%_e\) (Fig. 6.5a). The largest variation in signature occurred at 0 - 0.1 m depth, where \( \delta^2H \) values ranged from \(-0.25\%_e\) to \(-39.98\%_e\) (Fig. 6.5). Soilwater at this depth was most depleted at the end of the wet season 1999. The \( \delta^2H \) value decreased during the wet season, then became more enriched (i.e. less negative in value) during the dry season due to evaporation from the soil surface (Fig. 6.5). Soil from 0 - 0.1 m was highly enriched in November.
Daly River NT, Riparian Vegetation Water Use.

1998 (Fig. 6.6d) as a result of rainfall during the 30 days preceding sampling. Rain during November was usually highly enriched (data not shown).

The $\delta^2$H values of soilwater from 0.1 to 0.75 m showed less variation with time (e.g. 5.0 $\%e$ at 0.5 - 0.75 m) compared with 0 - 0.1 m and were also more negative (Fig. 6.5). When soil was sampled deeper than 0.75 m (late dry season 1998 and 1999), $\delta^2$H values were similar to the upper soil (0.1 - 0.5 m), with the exception of the enriched surface soil (0 - 0.1 m; Fig. 6.6a and i). Soil at depth (1.5 – 2.0 m) was also more enriched at the end of the dry season in 1998 than 1999 (Fig. 6.6d and i).
Figure 6.6 Branch, soil, groundwater and surface water $\delta^{2}H$ (‰) values for a) late dry season 1997, c) dry season 1998, d) late dry season 1998. Mean values of branch samples are shown by a vertical solid bar, with standard errors. Groundwater samples are from bores 30982 (Δ), 30983 (Ο) and 30984 (□). For c), error bars on soil data show range of three values. Error bars on soil values (♦) indicate technique error of $\pm 1.3$ ‰; on twig values, error bars represent the standard error of the mean. Soil matric potential (-MPa) for b) late dry season 1997 and e) late dry season 1998. Data for late dry season 1997 taken from Hatton et al. (1998). (Figure continued next page)
Figure 6.6 cont’d: Branch, soil, groundwater and surface water δ2H (‰) values for f) wet season 1999, g) dry season 1999 and i) late dry season 1999. Mean values of branch samples are shown by a vertical solid bar, with standard errors. Groundwater samples are from bores 30982 (∆), 30983 (○) and 30984 (□). Surface water (x) was present in May 1999 only. Error bars on soil values (♦) indicate technique error of ±1.3 ‰; on twig values, error bars represent the standard error of the mean. Soil matric potential (-MPa) for h) dry season 1999 and j) late dry season 1999. Note different scale on h).
Daly River NT, Riparian Vegetation Water Use.

6.3.4 Soil Matric Potential

Soil matric potential varied with depth and season, ranging from close to zero during the dry season to more than -2.0 MPa during the late dry season 1998 (Fig. 6.6). It was higher than -1.0 MPa during all sampling times (Fig. 6.6b, h and j), except for late dry season 1998, when $\psi_{\text{soil}}$ was less than -1.2 MPa between 0.7 and 2.5 m (Fig. 6.6e). During late dry season 1997 and 1999, $\psi_{\text{soil}}$ was lower in the upper soil (0 - 0.3 m) than at depth (0.5 - 2.0 m), where it was close to zero (Fig. 6.6a and j). A region of lower $\psi_{\text{soil}}$, about -0.8 MPa, was found at 1.7 m depth during the late dry season 1999 (Fig. 6.6j). Soil was considerably wetter during the dry season 1999, with $\psi_{\text{soil}}$ higher (closer to zero) than -0.01 MPa between the surface and 0.75 m depth (Fig. 6.6g).

6.3.5 Deuterium Composition of Plant Water

Branch $\delta^2$H values represent the mean of material from three trees, with the three samples generally within several ‰ of each other at any given time. Values follow a broadly similar seasonal pattern to that of the upper soil (Fig. 6.5), being most depleted at the end of the wet season (-43.1 ‰), becoming more enriched throughout the dry season to reach -2.63 ‰ (late dry season 1998). Although $\delta^2$H values at the end of the dry season 1998 were much more enriched than the similar period during 1999 (-2.63‰ compared with -36.7‰), branches sampled during the late dry season 1999 were still more enriched than during the wet season of the same year (-43.1 ‰). The $\delta^2$H values of branches typically lay between the values for soil and groundwater, except during the wet season, when values were much more negative than groundwater (Fig. 6.6f) and the late dry season 1998 when branch $\delta^2$H values were very similar to those of upper soil (Fig. 6.6d).

6.3.6 $\delta^2$H - $\delta^{18}$O Comparison

Not all samples were analysed for $\delta^{18}$O, due to the cost of the analysis and access to the mass spectrometer. Groundwater samples from the 1998 dry season and 1999 late dry season were analysed in order to clarify sources of tree water. $\delta^2$H - $\delta^{18}$O plots show that signatures from Melaleuca swamp forest groundwater were more enriched in both isotopes than samples taken from groundwater under the nearby eucalypt open-forest during wet and late dry seasons of 1995 (see Cook et al. 1998; also Fig. 6.4). The signatures of Melaleuca swamp forest groundwater were quite similar to the Darwin mean rainfall signature (Fig. 6.7).

$\delta^2$H - $\delta^{18}$O signatures of soil samples were usually more depleted compared with groundwater signatures during the dry season (1998) or late dry season (1999; Fig. 6.7b and e). However, data from Hatton et al. (1998) taken during the late dry season 1997 show that soil isotope signatures were more similar to groundwater signatures at this time (Fig 6.4a).
Figure 6.7 $\delta^3$H - $\delta^{18}$O plots for soilwater, plant water and groundwater during a) late dry season 1997 and b) dry season 1998. Also included are data for groundwater samples from under eucalypt open-forest during 1995 (from Cook et al. 1998) and mean isotopic signature of Darwin rainfall. (continued next page)
Figure 6.7 cont’d: $\delta^{2}H - \delta^{18}O$ plots for soilwater, plant water and groundwater during c) dry season 1999 and d) late dry season 1999. Note that groundwater samples are not included for c). Also included are e) data for groundwater samples from under eucalypt open-forest during wet and late dry seasons 1995 (from Cook et al. 1998) and mean isotopic signature of Darwin rainfall.
6.4 Discussion

6.4.1 Tree, Stand and Community Water Use

There were similarities in the patterns of tree water use observed in the Howard East catchment to those observed along the Daly River. Individual tree water use in the *Melaleuca* forest was aseasonal. This pattern of aseasonal water use has been observed in a number of evergreen species in wet-dry savanna ecosystems in both Australia (O’Grady et al. 1999, Eamus et al. 2000, this report Chapter 3) and in Brazil (Meinzer et al. 1999). Despite this, stand water use in the *Melaleuca* forest was higher in the wet season than during the dry season. This result is difficult to reconcile, although it may be an artefact of sampling. This result may be skewed by the very high stand water use recorded during the 1999 wet season (approx 2.5 mm day$^{-1}$ compared to approx. 1.5 mm day$^{-1}$ 1998). There was no clear relationship between Q and water use in the 1999 wet season sampling. Hence a generalised relationship between Q and DBH based on the preceding sampling periods was used. This is likely to have introduced errors into the estimation of stand water use. Further, water use during 1998 was scaled in one 50 x 50 m plot but in three 30 x 30 m plots during 1999. Slight differences in tree basal area could account for significant changes in stand water use.

Patterns of water use in the monsoon rainforest were more difficult to interpret due to increased structural and floristic composition of these forests. Four species dominated the basal area of these forests and the seasonal patterns of tree water use within species varied. Two species, *T. microcarpa* and *F. racemosa* are dry season deciduous, *N. orientalis* is semi-deciduous and *S. nervosum* was evergreen. These varying leaf phenologies had significant consequences on tree water use. Patterns of water use for three of the four species exhibited distinct seasonal cycles. Water use in the evergreen tree *S. nervosum* peaked in the dry season, probably in response to higher VPD and the presence of significant soil moisture throughout the dry season. There were no differences in water use between the wet season and the late dry season in this species. Water use in *N. orientalis* and *T. microcarpa* were lowest in the dry season as a result of leaf loss. The late dry season is an interesting period for patterns of tree water use. Most forest trees commence leaf flush during the late dry season at a time when water availability would be at a minimum (Williams et al. 1997) but presumably still high enough to support leaf flush and expansion and concomitant water use. Differences in tree water use between species probably reflect differences in the phenological cycle between species.

Stand water use in the monsoon forest closely reflect the seasonal patterns of LAI. Stand water use was highest during the late dry season/wet season and lowest during the dry season. Leaf area index in August was 1998 was 4.3 (Kelley 2002). Problems with access during the wet season inhibited further sampling. However, Bach (1998) demonstrated that canopy cover declined by about 10% during the dry season in wet monsoon forests around Darwin region. The decline in canopy cover though would
be highly influenced by the leaf phonologies of trees within the forest and would be highly variable between forests.

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 6.2 gives a comparison of community water use for each ecosystem.

Table 6.2 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

<table>
<thead>
<tr>
<th>Eucalypt open-forest</th>
<th>Melaleuca swamp forest</th>
<th>Wet monsoon forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seasonal water use</td>
<td>LAI</td>
<td>Seasonal water use</td>
</tr>
<tr>
<td>Wet season</td>
<td>124</td>
<td>1</td>
</tr>
<tr>
<td>Dry season</td>
<td>94</td>
<td>0.8</td>
</tr>
<tr>
<td>Late dry season</td>
<td>96</td>
<td>0.7</td>
</tr>
<tr>
<td>Total Annual water use (mm y$^{-1}$)</td>
<td>315</td>
<td>508</td>
</tr>
</tbody>
</table>

6.4.2 Sources of Water Used by *Melaleuca* Forests

Sources of water used by *M. viridiflora* were determined, in the first instance, by a comparison of the $\delta^{2}$H values of xylem water with $\delta^{2}$H values of soil and groundwater samples. If there was not a unique solution (ie. tree water $\delta^{2}$H composition suggested a number of possible sources), then information about soilwater potential ($\psi_{soil}$) was used to eliminate possible sources where $\psi_{soil}$ was too low and so relatively unavailable for extraction by plant roots. Finally, if any further evidence was required, $\delta^{18}$O data were combined with $\delta^{2}$H data in a 2-dimensional plot to determine the most likely source of plant water (Fig. 6.7).
Data for late dry season (September) 1997 are from Hatton et al. (1998) and were included here for comparison. During the dry season the distribution of δ²H data were ambiguous. Soil matric potential was higher than -1.0 MPa throughout the profile, however, in the upper 0.5 m, ψₘ₉₉ was lower than at depth. A plot of δ²H - δ¹⁸O signatures indicated tree water was likely to be sourced from soilwater at 0.5 – 1.0 m depth (Fig. 6.7a). No significant rain had fallen since April 1997, and so it is reasonable to expect that fine roots would be growing in the lower profile as the water table receded (Mensforth and Walker 1996) and matric potential decreased in the upper soil. Trees were therefore more likely to use soilwater at depth (0.5 - 1.0 m) where ψₘ₉₉ was more favourable.

During the dry season (July) 1998, trees were sourcing water from soil at 0 – 0.5 m depth, as indicated by the δ²H - δ¹⁸O plot (Fig. 6.7b). Soilwater availability data were not available for this time, and the large sample intervals do not allow enough resolution to determine if soilwater at the surface or at 0.5 m was being used. There is one sample of tree water that is quite different from the others and lies closer to the groundwater signatures than any soilwater signatures. There are two possible explanations for this anomalous sample. The most likely is that the sample jar may have been improperly sealed and allowed some enrichment of the sample due to evaporation. Alternatively, that particular tree may have accessed groundwater while other, smaller, individuals were using soilwater. Standing water level at this time was 1.2 m below the surface, and so it is possible that the ‘outlier’ tree had a deeper root system than the other trees and could access groundwater.

Samples taken during the late dry season of 1998 indicate trees were sourcing water from soil at both 0 - 0.1 and 0.1 - 0.3 m (Fig. 6.6d). This interpretation of the δ²H data is supported by the high ψₘ₉₉ (-0.05 to -0.35 MPa) in the top 0.5 m of soil. Local rainfall records show 232 mm of rain fell in the 30 days preceding the sample collection date, which would significantly increase water content in the top 0.5 m of soil. Soil samples at depths below 0.5 m had matric potentials of approximately -1.5 MPa (Fig. 6.6e) indicating a low availability of water. Following a large rainfall event, drainage would reduce ψₘ₉₉ to field capacity (-0.03 MPa). Prior to the rain that increased water availability in the upper soil, trees were probably extracting water from soil at 0.5 to 2.0 m depth, resulting in decreased ψₘ₉₉ to approximately -1.5 MPa (Fig. 6.6e). However, once the upper soil had become wet, extraction shifted to these upper layers, as indicated by close matching of δ²H signatures of upper soil (0 - 0.3 m) and branches (Fig. 6.6d).

δ²H data from the end of the wet season 1999 indicate that trees were not using groundwater (Fig 6.3f). Signatures of soil and plant water do not completely match, with plant water error bars only just overlapping with soilwater at 0.4 m. This suggests that soilwater from deeper than 0.4 m may have been used. However, from these data it is difficult to exclude the possibility that trees are using either surface water or soilwater from 0 - 0.4 m depth.
Groundwater had declined to 0.8 m below the soil surface by end of the dry season 1999. Again, the source of plant water use was not clear as the $\delta^2$H signature for plant water fell between the signature for surface soil (0 - 0.1 m) and those for samples to 0.8 m (Fig. 6.6g). Soil matric potential was higher than -0.004 MPa throughout the profile to the water table (Fig. 6.6h) indicating that there was water available for plant extraction. Further evidence ($\delta^{18}$O data combined with $\delta^2$H data) indicates that trees were most likely sourcing soilwater from 0.3 – 0.75 m depth (Fig. 6.7c).

Groundwater recession during 1999 was less than during 1998, and there had not been any rain prior to sampling, in contrast to 1998. Soil below 0.5 m was wetter during the late dry season of 1999 than during the same period in 1998 (Fig. 6.6e and j). Regions of lower $\psi_{soil}$ in the surface soil to 0.5 m and at 1.5 -1.7 m may indicate areas where root water extraction had reduced $\psi_{soil}$ (Fig. 6.6j), although for surface soil this was likely to be due to evaporation. A $\delta^2$H - $\delta^{18}$O plot for this sampling period indicates that tree water samples fell between the signature for soilwater from 0 - 0.1 m depth and groundwater from the shallowest bore (Fig. 6.7d). The signature that appears in the plant material is the result of a proportional combination of the signatures from the possible sources. Evidence from $\delta^2$H - $\delta^{18}$O plot, in addition to $\psi_{soil}$ data, suggest that there were two regions of water uptake: soil at 0 – 0.1 m depth and the capillary fringe of the water table.

Table 6.3 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.

<table>
<thead>
<tr>
<th>Sample time</th>
<th>Mean SWL (m)</th>
<th>Likely water source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Dry 1997</td>
<td>1.3</td>
<td>soilwater 0.5 - 1.0 m</td>
</tr>
<tr>
<td>Dry 1998</td>
<td>1.2</td>
<td>soilwater 0 - 0.5 m; groundwater?</td>
</tr>
<tr>
<td>Late Dry 1998</td>
<td>3.2</td>
<td>soilwater 0 - 0.1 m</td>
</tr>
<tr>
<td>Wet 1999</td>
<td>-0.15</td>
<td>soilwater &gt; 0.4 m</td>
</tr>
<tr>
<td>Dry 1999</td>
<td>0.8</td>
<td>soilwater 0.3 - 0.75 m</td>
</tr>
<tr>
<td>Late Dry 1999</td>
<td>1.7</td>
<td>soilwater 0 - 0.1 m and groundwater</td>
</tr>
</tbody>
</table>
7.0 General Discussion

7.1 Water Use by Riparian Vegetation

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 in water use patterns between the *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. A number of explanations for this trend were discussed including, differing micro-climatic conditions by the river, varying access to different sources of water and possibly differences in the soil-root hydraulic conductivity as a result of changes 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. 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. 5.6) and indeed the Northern Territory (Fig 5.7). Stand structure along the Daly River was highly variable. Mean basal area was 72 m$^2$ ha$^{-1}$, but ranged from less than 10 m$^2$ ha$^{-1}$ to more than 200m$^2$ ha$^{-1}$. Based on figure 5.6, 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 m\(^2\) ha\(^{-1}\). Wet season water use at both the Douglas/Daly confluence and at Ooloo reached maximum stand water use at about 4 mm day\(^{-1}\). Although understory/soil evapotranspiration was not accounted for due to the difficulties of making these measurements in the riparian strip, understory \(E_t\) would probably represent a significant fraction of \(E_t\) during the wet season (Hutley et al. 2000). It is likely that total ecosystem wet season \(E_t\) was close to potential for the riparian strip.

7.1.1 How Much Groundwater is Used by Riparian Vegetation?

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 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 m\(^2\) ha\(^{-1}\). Applying Figure 5.6 to each of the surveyed vegetation transects (Table 5.1), mean (± SD) daily water use by the riparian vegetation was 3.2 ± 1.9 mm day\(^{-1}\) (0.62 ML km\(^{-1}\) 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 ML (groundwater) km\(^{-1}\) day\(^{-1}\)). Under scenario b), i.e. trees within 40 m of the river that source 100% of the their water use requirements from groundwater, groundwater use by riparian vegetation along the Daly River was 2.4 mm day\(^{-1}\) (0.24 ML (groundwater) km\(^{-1}\) 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 underestimate fluxes by up to 40 %. The problems associated with obtaining fluxes in this study have been discussed in detail in chapters Three and Five 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. Thus, this data may provide a useful guide when allocating environmental water provisions during extended dry periods when regional water tables are likely to decline. Thus during extended dry periods the allocation of groundwater to riparian vegetation should not be decreased.
7.2 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 (Chapter 4). Some tree species (Acacia auriculiformis and Casuarina cunninghamiana) appeared opportunistic in their use of water rather than specifically targeting a given source (Fig. 4.1, Fig 4.2). 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 (Mensforth and Walker 1996), 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 (Thorburn and Walker 1993). 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) (Jones and Mulholland 2000) 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 Gnangara 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.
7.3 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 1998, Clifton and Evans 2001). These steps tend to have an increasing level of complexity. 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 (Hatton and Evans 1998). 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, but Hatton and Evans (1998) and Clifton and Evans (2001) outline methods to approximate them.

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 later 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. For a given rate of groundwater extraction, the new equilibrium on the long-term will be the same. However, how a given amount of groundwater is extracted may affect the transition period. In other words, while groundwater extraction inevitably impacts the environment, there may be ways to extract this groundwater that will be least damaging.

7.4 Assessment of the Environmental Flow Requirements of Riparian Vegetation Along the Daly River

McCosker (1998) described 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. However, this information on its own is insufficient to make definitive EFR recommendations. This will need to be the focus of workshops that draw together the conclusions of a number of concurrently occurring EFR projects that were being conducted along the Daly River.

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 2001b).

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 throughout 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 the *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.

**7.5 Further work**

Large variability in water use is a feature of the riparian vegetation along the Daly River. This report has quantified the water use of a number of species that are commonly found along the river and developed guides to estimating water use in this community. However due to the large variability there
is uncertainty about the absolute water requirements of many of the species found along the Daly. Further targeted research may be required to assess the water use of key species, i.e. species that may be strongly reliant on river water or shallow groundwater (for example *M. leucadendra*) or making recommendations on the groundwater dependency and EFR on a case-by-case basis.

This study has been conducted when groundwater levels are above the long-term average. Long-term monitoring of the tree water use, groundwater levels and river flow may be required to assess the groundwater dependence (if any) of many of the species that occur along the river. Many of the species studied in this report used stored soilwater throughout the course of the dry season. Groundwater dependence of these species may only become apparent during times when river-flows and water tables are reduced.

Further targeted research using both isotopic discrimination and tree water use studies is required to clearly define the nature of position in the landscape and sources of transpired water. In this study, this was limited to three transects thus the spatial and temporal resolution of his interaction is very coarse. This is essential information for assessing the seasonal and spatial groundwater requirements. This studied has identified some of the major sources of variation in water use requirements of riparian vegetation along the Daly River. Further research or regular monitoring has the potential to vastly improve this resolution.

The dependence of many of the species on river flows for dispersal and establishment is unknown. Such dependence needs to be assessed to make comprehensive EFR recommendations. These studies were, however, outside the scope of this project.

Vegetation clearing for improved pasture and irrigated agriculture is likely to have significant impacts on recharge to groundwater aquifers. Along large stretches of the Daly River, discharge of groundwater is a significant fraction of dry season baseflow. An assessment of the potential scale of land clearing in the catchment is required. This will allow focused research directed towards modelling and predicting the impact of these large scale land use changes on groundwater recharge and the subsequent impact on river flows. This is a rare opportunity to conduct such risk analysis *a priori*. 
Plate 7 Crystal Falls on the Douglas River
8.0 References


Daly River NT, Riparian Vegetation Water Use.


Daly River NT, Riparian Vegetation Water Use.


Petheram R.J. and Kok B. (1983). Plant of the Kimberley Region of Western Australia. University of Western Australia Press, Perth WA.


## Appendix 1 Tree Species Recorded During Transect Surveys Along the Daly River
### September 2001

<table>
<thead>
<tr>
<th>Family</th>
<th>Species</th>
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<td>Apocynaceae</td>
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<tr>
<td></td>
<td>Wrightia saligna</td>
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<tr>
<td>Bombacaceae</td>
<td>Bombax ceiba</td>
</tr>
<tr>
<td>Burseraceae</td>
<td>Canarium australianum</td>
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<tr>
<td>Caesalpiniaeae</td>
<td>Erythrophloeum chlorostachys</td>
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<tr>
<td>Casuarinaceae</td>
<td>Casuarina cunninghamiana</td>
</tr>
<tr>
<td>Combretaceae</td>
<td>Terminalia ferdinandiana</td>
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<tr>
<td></td>
<td>Terminalia microcarpa</td>
</tr>
<tr>
<td></td>
<td>Terminalia spp</td>
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<tr>
<td>Euphorbiaceae</td>
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<td></td>
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<tr>
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</tr>
<tr>
<td>Fabaceae</td>
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<td>Lauraceae</td>
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<td>Lecythidaceae</td>
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<td>Loranthaceae</td>
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<tr>
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<td>Lysiphyllum cunninghamii</td>
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<td>Acacia holosericea</td>
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<td>Cathormion umbellatum</td>
</tr>
<tr>
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<td>Ficus racemosa</td>
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<td>Ficus scobina</td>
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<td>Myrtaceae</td>
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<td>Eucalyptus latifolius</td>
</tr>
<tr>
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<td>Eucalyptus spp</td>
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<tr>
<td></td>
<td>Eucalyptus tectifica</td>
</tr>
<tr>
<td></td>
<td>Melaleuca argentea</td>
</tr>
<tr>
<td></td>
<td>Melaleuca leucadendra</td>
</tr>
<tr>
<td>Rubiaceae</td>
<td>Nauclea orientalis</td>
</tr>
<tr>
<td>Sapindaceae</td>
<td>Atalaya varifolia</td>
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<tr>
<td>Sterculiaceae</td>
<td>Brachychiton diversifolius</td>
</tr>
<tr>
<td>Introduced Sp</td>
<td>Kalope</td>
</tr>
<tr>
<td></td>
<td>Mahogany</td>
</tr>
<tr>
<td></td>
<td>Poinciana</td>
</tr>
</tbody>
</table>
Appendix 2 Water Balance for the Daly River Catchment

Daly River Catchment

Water Balance

REPORT 10/2002

Peter Jolly
Natural Resources Division
DLPE

June 2001
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1. **Introduction**

The aims of this document are:

To provide an overview of the current state of knowledge of the water balance for the Daly River Catchment; and

To document work that is required to improve our understanding of the components of the water balance, both areally and with time.

The Daly River catchment covers an area of approximately 52,600 square kilometres. Its extent is shown on Figure 1. Data has been collected on various aspects of the surface water and groundwater hydrology of the Catchment for at least the last 50 years.

2. **What is a Water Balance?**

A water balance is a summary of the current state of knowledge of the inflows and outflows of water within a catchment. The water balance takes into account any temporary storage of water within the catchment.

The various components of the water balance, as they apply to the Daly River catchment, are summarised in the following Table.

<table>
<thead>
<tr>
<th>Inflow</th>
<th>Outflow</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>Runoff</td>
<td>Reservoir storage</td>
</tr>
<tr>
<td>Inflows from adjacent</td>
<td>Evaporation and Transpiration</td>
<td>Water stored above and below the water table</td>
</tr>
<tr>
<td>groundwater resources</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumping</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The following sections provide an overview of the current state of knowledge of these various components.
Figure 1: Daly River Catchment
3. **Rain**

Nearly all of the water entering the Daly River Catchment does so as rainfall. The whole of the catchment comes under the impacts of the monsoon, as well as intense rain depressions resulting from decaying tropical cyclones. This results in a rainfall that is highly variable. Katherine’s daily rainfall record since 1940 has been plotted on Figure 2 to illustrate this variability in intensity throughout the year and from year to year. Katherine’s daily rainfall record is continuous since 1884. Annual (October to September) rainfall totals vary from a low of 364 mm (1951/52) to a high of 1990 mm (1897/98). Annual rainfall totals for the full period of record are plotted on Figure 3.

The impact of the monsoon results in over 90% of Katherine’s mean annual rainfall of 980 mm occurring between the months of November and March. The mean annual rainfall increases slightly to the north to approximately 1100 mm near the Douglas Daly Research Station and decreases slightly to the south west of Katherine to about 900 mm in the Dry River area. The seasonal variability across the catchment will be similar to that shown in Table 2 for Katherine with monthly values being up to 10% higher or lower.

**Table 2 Mean Monthly Rainfall – Katherine PO DR014902**

<table>
<thead>
<tr>
<th>Month</th>
<th>Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October</td>
<td>30</td>
</tr>
<tr>
<td>November</td>
<td>90</td>
</tr>
<tr>
<td>December</td>
<td>195</td>
</tr>
<tr>
<td>January</td>
<td>243</td>
</tr>
<tr>
<td>February</td>
<td>210</td>
</tr>
<tr>
<td>March</td>
<td>165</td>
</tr>
<tr>
<td>April</td>
<td>30</td>
</tr>
<tr>
<td>May</td>
<td>5</td>
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<td>June</td>
<td>2</td>
</tr>
<tr>
<td>July</td>
<td>2</td>
</tr>
<tr>
<td>August</td>
<td>1</td>
</tr>
<tr>
<td>September</td>
<td>7</td>
</tr>
</tbody>
</table>
Figure 2. Daily Rainfall Data for Katherine PO DR014902 for Period 1940 to 2000
Figure 3. Annual (Oct – Sep) Rainfall Data for Katherine PO DR014902 for Period 1884/85 to 1999/2000
Daly River NT, Riparian Vegetation Water Use.

4. **Inflows from Adjacent Groundwater Resources**

   Over most of the Daly River catchment small quantities of groundwater flow either into or out of the catchment within aquifers that occur adjacent to the catchment boundary. It would be expected that over most of the catchment the inflows will balance the outflows and the nett impact will not be significant.

   The only exception to this is the aquifer system that provides the source of dry season flow in the Flora River. It would be expected that approximately 50% of the groundwater fed flow in the Flora River is sourced from recharge that occurs outside of the Daly River catchment. This recharge occurs across the Sturt Plateau to the south east of the Dry River.

5. **Runoff**

   Runoff has been measured at a number of locations throughout the catchment. This overview presents data from those stations with more than 25 years of data that have significant dry season river flows; and two other representative stations that have more than 25 years of data and have flow records that are typical of larger river systems that stop flowing during each dry season. The following table indicates the period of record and number of gaugings that have been recorded at each site. A qualitative statement has also been made regarding the quality of data relating to groundwater-fed dry season flows at each site. The location of each site is also shown on Figure 1.

   **Table 3. Gauging Station Details**

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of GS</th>
<th>Period flows gauged</th>
<th>Number of Gaugings</th>
<th>Quality of low flow records</th>
</tr>
</thead>
<tbody>
<tr>
<td>Katherine River-Low Level</td>
<td>G8140001</td>
<td>1952 – 1999</td>
<td>290</td>
<td>Good</td>
</tr>
<tr>
<td>Ferguson River</td>
<td>G8140008</td>
<td>1953 – 1996</td>
<td>135</td>
<td>No dry season flow</td>
</tr>
<tr>
<td>Dry River</td>
<td>G8140011</td>
<td>1971 – 1995</td>
<td>55</td>
<td>No dry season flow</td>
</tr>
<tr>
<td>Daly River - Mount Nancar</td>
<td>G8140040</td>
<td>1966 – 1999</td>
<td>287</td>
<td>Good</td>
</tr>
<tr>
<td>Flora River</td>
<td>G8140044</td>
<td>1966 – 1999</td>
<td>27</td>
<td>Poor</td>
</tr>
<tr>
<td>Douglas River</td>
<td>G8140063</td>
<td>1957 – 1997</td>
<td>280</td>
<td>Moderate</td>
</tr>
<tr>
<td>Daly River upstream of Dorisvale Crossing</td>
<td>G8140067</td>
<td>1957 – 1998</td>
<td>240</td>
<td>Good</td>
</tr>
<tr>
<td>Seventeen Mile Creek</td>
<td>G8140159</td>
<td>1961 – 2000</td>
<td>252</td>
<td>Moderate</td>
</tr>
<tr>
<td>Katherine River at Galloping Jacks</td>
<td>G8140301</td>
<td>1974 – 1998</td>
<td>67</td>
<td>Good</td>
</tr>
</tbody>
</table>

   Runoff can be divided into three components:

   a.) Overland flow and interflow - Due to the highly permeable nature of the soil profile over most of the catchment, true overland flow rarely occurs, except following very intense rainfall events. Most water
Daly River NT, Riparian Vegetation Water Use.

spends some part of its flow path from where it has fallen to the nearest small creek beneath the ground. Almost all of the flow above 10 cumecs in the following hydrograph (Figure 4) for the Katherine River is overland flow and interflow.

![Figure 4. Discharge Hydrograph for the Katherine River at G8140001](image_url)

b.) Groundwater discharge from offstream bank and aquifer storage – When the level of the water in a river exceeds the water level in the aquifer beneath and adjacent to the river, water discharges from the river to the aquifer. The higher the level in the river, and the higher the permeability of the river sediments and strata comprising the aquifer, the greater the amount of water that moves into the aquifer during a river flow event. This water then discharges into the river during the dry season. This process is illustrated by the data contained in Figure 5. Monitoring bore RN 22397 is located on the top of the levee bank adjacent to the Katherine River. Monitoring bore RN22001 is located 22 kilometres from the River. Both bores monitor water levels in the aquifer developed in the Tindall Limestone.

c.) Groundwater discharge from regional aquifer systems - This is the discharge process by which diffuse recharge to the regional aquifer system discharges to adjacent creeks and rivers. This diffuse recharge mechanism also includes recharge via sinkholes and via the bed of creeks and rivers where the water levels in the aquifer underlying the creek or river are below the bed of the creek or river (eg Dry River). This recharge mechanism is illustrated by the water level data for monitoring bore 20851 (refer Figure 6). This is a monitoring bore for the aquifer in the Tindall Limestone in the Douglas River area.
Figure 5. Katherine River – Tindall Limestone Aquifer Interaction

Figure 6. Water Level data for Bore RN 20851 in the Tindall Limestone
5.1 Annual Runoff from the Daly Basin

In this overview the first two runoff components - overland flow and interflow, and groundwater discharge from offstream bank and aquifer storage – will be considered as surface water runoff. The third component - groundwater discharge from regional aquifer systems – will be considered separately as regional groundwater discharge.

The total annual runoff that represents the outflow from the Daly River Catchment is that recorded at the river gauging station G8140040 near Mount Nancar. This station is located on the Daly River just above the upper tidal limit on the Daly River (refer Figure 1). The values for total annual runoff given in Table 4 have been derived from hydrographs, rating curves and flow gaugings. The values for regional groundwater discharge are based on the mean annual instantaneous flow rate being 20% more than the minimum annual flow rate. The values for surface water runoff have been derived by subtracting regional groundwater discharges from the total annual runoff.

Table 4. Components of Runoff at G8140040 on the Daly River

<table>
<thead>
<tr>
<th>Year (October to September)</th>
<th>Total Annual Runoff (x 10^5 ML)</th>
<th>Surface Water Runoff (x 10^5 ML)</th>
<th>Regional Groundwater Discharge (x 10^5 ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1969/70</td>
<td>10</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>1970/71</td>
<td>32</td>
<td>29</td>
<td>3</td>
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<tr>
<td>1971/72</td>
<td>58</td>
<td>55</td>
<td>3</td>
</tr>
<tr>
<td>1972/73</td>
<td>NA</td>
<td>NA</td>
<td>3</td>
</tr>
<tr>
<td>1973/74</td>
<td>147</td>
<td>136</td>
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<td>75</td>
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<td>1975/76</td>
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<td>1981/82</td>
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<td>1982/83</td>
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<td>1984/85</td>
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<td>NA</td>
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<tr>
<td>1985/86</td>
<td>13</td>
<td>8</td>
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<td>1988/89</td>
<td>62</td>
<td>56</td>
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<td>1989/90</td>
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<td>1990/91</td>
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<td>95</td>
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</tbody>
</table>
Daly River NT, Riparian Vegetation Water Use.

<table>
<thead>
<tr>
<th>Year</th>
<th>Annual Discharge (x 10^5 ML)</th>
<th>Min</th>
<th>Maximum</th>
<th>Mean</th>
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<td>1991/92</td>
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<td>17</td>
<td>5</td>
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<td>1992/93</td>
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<td>1995/96</td>
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<td></td>
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<tr>
<td>1996/97</td>
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<td>157</td>
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<tr>
<td>1997/98</td>
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<td>102</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>1998/99</td>
<td>94</td>
<td>86</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>1999/2000</td>
<td>120</td>
<td>111</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

Note: NA indicates that the quality of the data was not good enough to calculate the annual flow.

The mean total annual runoff of 69 x 10^5 megalitres equates to a runoff of 148 mm.
The mean surface water runoff of 63 x 10^5 megalitres equates to a runoff of 135 mm.
The mean regional groundwater discharge of 6 x 10^5 megalitres equates to catchment wide effective recharge rate (ie in excess of evapotranspiration) of 13 mm.

5.2 Discussion on surface water runoff across catchment

Data has been extracted on total annual runoff and discharges from representative gauging stations across the Daly River Catchment to provide a basis for comment on surface water runoff. The data is presented in Tables 5 and 6.

Table 5. Annual Discharge Data

<table>
<thead>
<tr>
<th>Gauging Station (G)</th>
<th>Start of record</th>
<th>Catchment Area (km²)</th>
<th>Annual Discharge (x 10^5 ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8140001 Katherine R</td>
<td>1957</td>
<td>8640</td>
<td>3.8</td>
</tr>
<tr>
<td>8140008 Ferguson R</td>
<td>1957</td>
<td>1490</td>
<td>0.7</td>
</tr>
<tr>
<td>8140011 Dry River</td>
<td>1970</td>
<td>6290</td>
<td>0.05</td>
</tr>
<tr>
<td>8140040 Daly R at Nancar</td>
<td>1969</td>
<td>46600</td>
<td>10</td>
</tr>
<tr>
<td>8140044 Flora River</td>
<td>1967</td>
<td>5900</td>
<td>1.8</td>
</tr>
<tr>
<td>8140063 Douglas River</td>
<td>1957</td>
<td>842</td>
<td>0.2</td>
</tr>
<tr>
<td>8140067 Daly R at Dorisvale</td>
<td>1961</td>
<td>35800</td>
<td>7.2</td>
</tr>
<tr>
<td>8140159 Seventeen Mile Creek</td>
<td>1963</td>
<td>619</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Table 6. Annual Runoff Data

<table>
<thead>
<tr>
<th>Gauging Station</th>
<th>Start of record</th>
<th>Catchment Area (km²)</th>
<th>Annual Runoff (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G81400001 Katherine R</td>
<td>1957</td>
<td>8640</td>
<td>Min: 44 Maximum: 589 Mean: 223</td>
</tr>
<tr>
<td>G8140008 Ferguson R</td>
<td>1957</td>
<td>1490</td>
<td>Min: 47 Maximum: 784 Mean: 294</td>
</tr>
<tr>
<td>G8140011 Dry River</td>
<td>1970</td>
<td>6290</td>
<td>Min: 1 Maximum: 177 Mean: 23</td>
</tr>
<tr>
<td>G8140040 Daly R at Nancar</td>
<td>1969</td>
<td>46600</td>
<td>Min: 21 Maximum: 362 Mean: 148</td>
</tr>
<tr>
<td>G8140044 Flora River</td>
<td>1967</td>
<td>5900</td>
<td>Min: 31 Maximum: 470 Mean: 146</td>
</tr>
<tr>
<td>G8140063 Douglas River</td>
<td>1957</td>
<td>842</td>
<td>Min: 24 Maximum: 826 Mean: 185</td>
</tr>
<tr>
<td>G8140067 Daly R at Dorisvale</td>
<td>1961</td>
<td>35800</td>
<td>Min: 20 Maximum: 388 Mean: 119</td>
</tr>
<tr>
<td>G8140159 Seventeen Mile Creek</td>
<td>1963</td>
<td>619</td>
<td>Min: 27 Maximum: 517 Mean: 153</td>
</tr>
</tbody>
</table>

The Ferguson River runoff data is typical of rivers that obtain all their runoff from the sediments that flank the carbonate sediments of the Daly Basin (geological unit shown in various shades of green on Figure 1). These sediments have a low permeability and produce the highest surface water runoff of any of the sediments in the Daly River Catchment. A number of small to medium sized dam sites have been identified within this terrain. Sustainable yields of between 500 and 5000 ML/year are typical for these type of dams. A number of potential larger dam sites have also been identified – Kekwick, Douglas, Nancar – with yields in excess of 5000 ML/year. Detailed studies have not been undertaken at any site.

The Dry River runoff data is typical of rivers that get the majority of their runoff from the carbonate sediments of the Daly Basin. Runoff is usually low unless the groundwater level rises to near to, or above, the surface. This only occurs in some areas close to the Katherine, Daly or Douglas Rivers in years of very heavy rainfall.

Hydrological studies have indicated that small dams may be constructed with yields of up to 1000 ML/year over the carbonate sediments. No detailed studies have yet been undertaken.

The Seventeen Mile Creek data is typical of creeks that get the majority of their runoff from the Cretaceous sediments (shown in blue on the accompanying map).

The data for the other rivers reflect runoff that originates from either two or all of the above types of sediments.

All rivers exhibit great variability in their maximum instantaneous flow rates, total annual runoff and
Daly River NT, Riparian Vegetation Water Use.

variation in river water levels between the “wet” and “dry”. Data for G8140001 on the Katherine River and G8140040 and G8140067 is given in Figures 8, 9, and 10.

The maximum instantaneous flow rate at G8140001 in 1997/98 (refer Figure 7) has been determined to equate to an event with a 1 in 150 year return period flood event. It is more than double the next highest flow rate.

Data from Table 4 and Figure 8 indicate that the minimum annual surface water discharge from the Daly River Catchment, as measured at G8140040 for the period 1969/70 to 1999/2000, was $7 \times 10^5$ cubic metres (15 mm runoff) in 1969/70 and 1989/90. The discharge of $8 \times 10^5$ cubic metres in 1985/86 was the next lowest.

The maximum annual surface water discharge from the Daly River Catchment, as measured at G8140040 for the period 1969/70 to 1999/2000, was $165 \times 10^5$ cubic metres (360 mm runoff) in 1975/76.

The variation between highest and lowest river water level each year ranges from less than 15 metres to more than 20 metres at G8140001 on the Katherine River and G81400040 and G8140067 on the Daly River. Data given in Figure 9 for G8140001 indicates that rise in river water level of more than 12 metres is required before significant quantities of water discharge from the Katherine River to the aquifer developed in the Tindall Limestone. In the 41-year period shown on Figure 5, this occurred during approximately 50% of the years. At the higher levels the Daly River forms a flood plain that in places is many kilometres wide.

Little data exists on the hydrology of the lower coastal floodplains of the Daly River (area shown in pink on the accompanying map).
Figure 7. Maximum Instantaneous Flow Rate data for G8140001, G8140067 and G8140040

Note: Where no data is shown for a station for a year, it indicates that inadequate data exists to define data point.
Figure 8. Annual Discharge data for G8140001, G8140067 and G8140040

Note: Where no data is shown for a station for a year, it indicates that inadequate data exists to define data point.
Figure 9. Variation between Annual Highest and Lowest River Water Level for G8140001, G8140067 and G8140040

Note: Where no data is shown for a station for a year, it indicates that inadequate data exists to define data point.
5.3 Discussion on Regional Groundwater Discharge

The majority of this discussion will focus on the regional groundwater discharges from aquifers developed in the carbonate strata of the Daly Basin (shown in green on the accompanying map) and Cretaceous sandstones (shown in blue on Figure 1).

Smaller springs occur throughout the region. Some have a small flow (<10 litres per second) throughout the year. Most cease to flow early in the dry season. These springs drain a very small area (less than 1 square kilometres) and, while they may be ecologically significant, are outside the scope of this discussion.

Data on instantaneous flow rates for various locations in the Daly River Catchment at the end of the “dry season” are given in Table 7. This data represents flows at these locations after a series of below average, average and above average wet seasons. These flows are sustained by significant regional groundwater discharges.


<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Seventeen Mile Creek G8140159</td>
<td>0.2</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Katherine River - Low Level Crossing G8140001</td>
<td>0.9</td>
<td>1.9</td>
<td>2.9</td>
</tr>
<tr>
<td>Katherine River - Galloping Jacks G8140301</td>
<td>1.0*</td>
<td>2.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Flora River G8140044</td>
<td>3.4*</td>
<td>3.4*</td>
<td>3.7</td>
</tr>
<tr>
<td>Daly River - Dorisvale Crossing G8140067</td>
<td>2.8</td>
<td>5.1</td>
<td>8.5</td>
</tr>
<tr>
<td>Daly River near Stray Creek</td>
<td>5.2</td>
<td>9.9</td>
<td>15.2</td>
</tr>
<tr>
<td>Daly R downstream of junction with Jinduckin Creek</td>
<td></td>
<td></td>
<td>20.8</td>
</tr>
<tr>
<td>Daly River - Oolloo Crossing</td>
<td>5.9</td>
<td>13</td>
<td>20.8</td>
</tr>
<tr>
<td>Douglas River G8140063</td>
<td>0.3</td>
<td>0.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Douglas River above junction with Daly R</td>
<td></td>
<td></td>
<td>3.3</td>
</tr>
<tr>
<td>Daly above junction with Douglas R</td>
<td></td>
<td></td>
<td>21*</td>
</tr>
<tr>
<td>Daly River - Nancar G8140040</td>
<td>8.5</td>
<td>19.4</td>
<td>24*</td>
</tr>
</tbody>
</table>

Note: * indicates estimated value
Daly River NT, Riparian Vegetation Water Use.

The data contained in the above table has been used on the map accompanying this report to identify those stretches of the rivers and creeks of the Daly River catchment that have strong regional groundwater discharges into them.

More detailed discussion on regional groundwater discharges from aquifers developed in the Cretaceous sandstones and carbonate strata of the Daly Basin follows.

5.3.1 Cretaceous Sandstones

Regional groundwater discharges from these sandstones provide the dry season flow for Seventeen Mile Creek. This Creek maintains the water level in the first pool in Katherine Gorge and provides the source of most of Katherine’s water supply via Donkey Camp pool. The minimum instantaneous flow rates have varied between 0.15 and 1 cumec since 1960 (refer Figure 10).

These changes in minimum flow rates occur in response to changes in the amount of rainfall that recharges the aquifer each year. The changing recharge rate is reflected in the variation in water level measured in a monitoring bore intersecting the aquifer. Figure 11 is a plot of data for bore RN22747 which is located near Maranboy. The data indicates that annual recharge rates vary from 0 to about 150 mm. The mean for the period would be about 40 to 60 mm. Low water levels correspond to the period when flows were at their lowest at G8140159, higher water levels to higher flows.

![Minimum Instantaneous Flows in Seventeen Mile Creek at G8140159](image)

Figure 10. Minimum Instantaneous Flows at Seventeen Mile Creek G8140159
5.3.2 Carbonate Sediments of the Daly Basin

Regional aquifers developed in the Tindall Limestone are the source of large dry season inflows into the Katherine, Flora and Douglas Rivers (near G8140063). It is also probable that the Tindall Limestone provides significant input into the Daly River upstream of its intersection with Bamboo Creek. However, no reliable data for dry season flows exists for this stretch of the Daly River.

Regional aquifers developed in the Oolloo Limestone are the source of large dry season inflows into the Daly and Douglas Rivers. The general locations of the most significant inflows are given in Fig 1. The best data on regional groundwater discharges from the carbonate sediments exists for G8140001 on the Katherine River, and G8140040 and G8140067 on the Daly River. The dry season flow data for G8140044 and G8140063 is not as good. Analysis will therefore be confined in this overview to data from G8140001, G8140040 and G8140067.

Regional groundwater discharges are maintained by recharge into the regional aquifer systems that has occurred over the preceding wet season or wet seasons. This recharge results in water levels rising in the aquifers. The magnitude of the water level rise can be used to estimate the quantity of recharge.

Data is given in Figures 12 and 13 for two bores in the Douglas – Claravale area that monitor water levels in the Oolloo Limestone. At the site given in Figure 12 the Oolloo Limestone outcrops. At the site given in Figure 13 the Oolloo Limestone is overlain by Cretaceous Sandstone. Where the Oolloo Limestone outcrops annual rises of up to 8 metres occur with water levels falling about 2 metres a year.
Where it is covered by Cretaceous Sandstone annual rises of up to 2 metres occur, with levels falling about 0.5 metres per year. This indicates that about four times as much water is recharging and discharging from the aquifer where the Ooloo Limestone outcrops. The extent of the Cretaceous cover has not yet been areally determined. The mean annual recharge rate for the period shown has been determined to be approximately 150 mm where the Ooloo Limestone outcrops and about 40 mm where it is covered by Cretaceous Sandstone. The mean areal recharge rate for the Ooloo Limestone between Claravale and the Douglas River has been estimated by Jolly (1983) to be 100 mm. This would indicate that Cretaceous Sandstone covers about 50% of the Ooloo Limestone in this area.

Data is given in Figures 14 and 15 for two bores in the Katherine area. At the site given in Figure 14 the Tindall Limestone outcrops. At the site given in Figure 15 the Tindall Limestone is overlain by Cretaceous Sandstone. Where the Tindall Limestone outcrops annual rises of up to 7 metres occur with water levels falling about 5 metres a year after above average wet seasons, and about 0.7 metres after below average wet seasons. Where it is covered by Cretaceous Sandstone annual rises of up to 3 metres occur, with levels falling about 0.7 metres per year. This indicates that about twice as much water is recharging and discharging from the aquifer where the Tindall Limestone outcrops. The extent of the Cretaceous cover has not yet been areally determined. The mean annual recharge rate for the period shown has been estimated to be about 50 mm where the Tindall Limestone is covered by Cretaceous Sandstone and approximately 100 mm where the Tindall Limestone outcrops. The mean areal recharge rate for the Tindall Limestone in the Douglas River area has been estimated by Jolly (1983) to be about 100 mm. In the Douglas River area there is no Cretaceous Sandstone covering the Tindall Limestone.
Daly River NT, Riparian Vegetation Water Use.

Figure 12. Water Level for Aquifer in Oolloo Limestone (Limestone outcrops)

Figure 13. Water Level for Aquifer in Oolloo Limestone (Cretaceous cover)
Daly River NT, Riparian Vegetation Water Use.

Figure 14. Water Level for Aquifer in Tindall Limestone (Limestone outcrops)

Figure 15. Water Level for Aquifer in Tindall Limestone (Cretaceous cover)
The amount of recharge to an aquifer system can also be determined from data on dry season flows. Minimum instantaneous flow data for each year for which adequate records exist have been plotted on Figure 16 for the three stations G8140001, G8140040 and G8140067. Detailed analysis has only been attempted for G8140001. This work was reported on by Jolly (2000). That work also identified that a linear relationship existed between regional groundwater discharges at G8140001 and those at G8140301. Discharges as measured at G8140301 are 17% greater than at G8140001. Discharges measured at G8140301 represent the total outflow from the aquifer in the Tindall Limestone in the Katherine area into the Katherine River. This data was then used to predict regional groundwater discharges at G8140301 for the full period of Katherine’s rainfall record (Jolly 2000). The predicted discharges are plotted on Figure 16 along with actual discharges (either gauged or predicted from the flow record at G8140001). The underestimation of the higher flow values has probably occurred because in those years river flow at the end of the dry was likely still being influenced by groundwater discharge from offstream bank and aquifer storage.

Based on the predicted minimum flows for G8140301 for the period 1884/85 to 1999/2000, and assuming that the mean annual regional groundwater discharge rate is 10% greater than the minimum yearly value, the mean annual regional groundwater discharge rate for the period 1884/85 to 1999/2000 is approximately 1.6 cubic metres per second. This equates to a mean annual recharge rate of 90 mm for the period.
Figure 16. Minimum Yearly Flow Rates for Katherine River at G8140001 and Daly River at G8140067 and G8140040

Note: Where no data is shown for a station for a year, it indicates that inadequate data exists to define data point.
Comparison of Predicted and Gauged Minimum Instantaneous Flow Rates for Each Year at G8140301 (Galloping Jacks) on the Katherine River

Figure 17. Predicted Minimum Annual Flows at G8140301 derived from gauged data at G8140301 and G8140001
6. Evapotranspiration

Evapotranspiration occurs from the trees, understorey and the ground surface. Data acquired by Hutley et al (2001) suggests total evapotranspiration during the wet season for the Katherine area is 3.1 mm per day. Annual tree water use was estimated to be approximately 150 mm. Wet season pan evaporation rates averaged about 5.5 mm per day.

Jolly (2000) trialed a range of values for evapotranspiration for the recharge area for the Tindall Limestone aquifer in developing a model to predict historical groundwater fed flows in the Katherine River. A value of 150 mm was used for the maximum soil moisture deficit (difference between saturated and free draining moisture content of the profile above the water table) during development of the model. A range of values was trialed for wet season daily losses (primarily due to evapotranspiration). A value of 5 mm per day was chosen in the model as it yielded the best correlation between gauged and predicted groundwater fed river flows. Use of these values yielded a predicted mean annual potential recharge rate of 225 mm. This is considerably higher than the 90 mm estimated from the flow record. This difference is due to runoff being included in the figure derived for the potential recharge rate. No data exists for mean annual surface water runoff from the ground overlying the Tindall Limestone in the Katherine area. However, the mean annual surface water runoff from the Daly River Catchment is approximately 135 mm. If this figure was subtracted from the predicted mean annual potential recharge rate, the value for the mean annual recharge would be 90 mm. More work, however, is required to refine the baseflow synthesis developed for G8140001 and G8140301 in Report 36/2000D, with that work initially focusing on quantifying the runoff component of the potential annual recharge.

Zaar (in Stewart and Zaar 1990, Zaar 1991, Sanders and Zaar 1991) reported late dry season losses in flow rate in the Katherine and South Alligator Rivers ranging between 2.9 and 5 litres per second per kilometre length of river. The higher (5 litres per second per km) calculations were made over stretches of the Katherine and South Alligator Rivers where groundwater inflow from and outflow to the river was deemed to be negligible due to the rivers incising very low permeability strata. The lower value (2.9 litre per second per km) was calculated over a stretch of the Katherine River where the river was likely to be gaining a small amount of inflow from the limestone strata the river was incised into. These losses in flow rate were attributed to evaporation losses from the rivers and transpiration from their riparian zones.

In Table 8 an attempt has been made to evaluate the amount of water that is evapotranspired from creeks / rivers / wetlands and their riparian zones. An allowance has to be made for additions to, or losses from groundwater storage. However, the data contained in the table indicates the variability in the amount available each year.
Daly River NT, Riparian Vegetation Water Use.

Table 8 Evapotranspiration from creeks, rivers and wetlands of the Daly River Catchment

<table>
<thead>
<tr>
<th>Components of Groundwater Balance</th>
<th>Annual Amounts for Catchment (mm)</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall (DR014902, 1957 – 2000)</td>
<td></td>
<td>500</td>
<td>1620</td>
<td>970</td>
</tr>
<tr>
<td>Recharge (1957 – 2000)</td>
<td></td>
<td>0</td>
<td>300</td>
<td>90</td>
</tr>
<tr>
<td>Inflow from adjacent aquifers</td>
<td></td>
<td>0.8</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Groundwater outflow as measured at G8140040 on the Daly River</td>
<td></td>
<td>6</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>ET from creeks / rivers / wetlands and their riparian zones and water added / taken from storage</td>
<td></td>
<td>?</td>
<td>276.5</td>
<td>78</td>
</tr>
</tbody>
</table>

7. Groundwater and surface water extraction

The National Land and Water Audit Theme 1 study has estimated usage figures for the Katherine Water District. This area covers parts of the Ooloo Limestone, as well as the Tindall Limestone. Their estimate of usage is approximately 16000 ML/year (ie 44 ML/d). The predicted use in 2020 and 2050 is 80000 ML/year (220ML/d) and 120000 ML/year (330ML/d), respectively.

No figures exist for the amount of water currently being used in the Katherine / King River area which is sourced from the aquifer in the Tindall Limestone. However, based on water usage of 10 ML/ha/year for irrigation, and using existing satellite images, and the author’s estimates for private and public water supply use, the current usage of groundwater sourced from the Tindall Limestone (either from bores or river baseflow) is approximately 9000 ML/year (or 25 ML/d). This figure is consistent with the figure being used in the NLWA Theme 1 study. It is probable that peak daily usage currently would approach 50 ML/d in the August – September period.

The following data exists for licensed surface water allocations in the Daly River catchment:
For Katherine, the annual allocation is 7569 megalitres. Of this amount, 4500 megalitres is allocated to PAWA for use in Katherine’s water supply system.
For the rest of the Daly River catchment annual allocations total 1180 megalitres.

Unlicensed water usage (riparian and groundwater) for the rest of the Daly River catchment would be about 1000 megalitres per year.

There are only two small weirs used for water supply purposes in the Daly River catchment. Both storages are very small. The weir at Donkey Camp on the Katherine River (Katherine water supply source) provides an additional storage of about 1500 megalitres when full. The small weir on a tributary of Copperfield Creek (Pine Creek water supply source) has a storage capacity of less than 100 megalitres.
8. Water stored above and below water table

No detailed work has been undertaken to quantify either of these parameters. Therefore the following estimate has been based on the author’s extensive knowledge of the study area.

The amount of water stored above the water table varies according to the type of strata and the season. All strata in the catchment have negligible primary porosity except where they have been extremely weathered. Based on data from boreholes drilled in the catchment it is probable that the average depth of this extremely weathered zone averages about 20 metres. In most aquifers in the study area seasonal water table fluctuations occur in this zone. However the change from unsaturated to saturated conditions usually results from the addition of only a small amount of water (up to 5% by volume) due to the clayey nature of most of the extremely weathered strata. The average water content of this 20-metre zone would be expected to be about 25% by volume.

The porosity, and hence water content, of the strata below 20 metres is dependent on the amount of weathered fractures or voids. The occurrence of these weathered fractures or voids is dependent on the composition of the strata they occur in. The consistent factor for each type of strata is that the number of weathered fractures or voids decreases with depth. Averaged over the catchment, weathered fractures or voids would occupy about 2% by volume of the strata above 100 metres depth and negligible amounts below 100 metres.

Based on the above assumptions, the following estimates have been derived for the amounts of water stored in the various parts of the profile over the 52,600 square kilometres of the Daly River catchment:

Volume of water stored above and below the water table - 350 x 10^6 megalitres.
Volume of free draining water stored in the extremely weathered zone - 50 x 10^6 megalitres.
Volume of adsorbed water stored in the extremely weathered zone - 220 x 10^6 megalitres.
Volume of free draining water stored in the weathered zone - 80 x 10^6 megalitres.
Average volume of water added as recharge each year - 5 x 10^6 megalitres.
Daly River NT, Riparian Vegetation Water Use.

9. Water Balance Summary

The following table provides an overview of the water balance for Daly River Catchment (based on Katherine rainfall and runoff data) for the major components of the water balance in the Daly River catchment.

Table 9 Water Balance Summary

<table>
<thead>
<tr>
<th>Components of Water Balance</th>
<th>Annual Amounts for Catchment (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>Rainfall (DR014902, period 1957 – 2000)</td>
<td>50</td>
</tr>
<tr>
<td>Runoff (G8140001, period 1957 – 2000)</td>
<td>50</td>
</tr>
<tr>
<td>Recharge (period 1957 – 2000)</td>
<td>0</td>
</tr>
<tr>
<td>Transpiration by large trees</td>
<td>150</td>
</tr>
<tr>
<td>Understorey Evapotranspiration</td>
<td>300</td>
</tr>
<tr>
<td>Inflow from adjacent aquifers</td>
<td></td>
</tr>
<tr>
<td>Water stored above and below water table</td>
<td>6500</td>
</tr>
<tr>
<td>Pumping for water supply purposes</td>
<td></td>
</tr>
</tbody>
</table>

The main hydrologic characteristic of this catchment is the great variability in rainfall from year to year, within a single year and over periods of years. This variability results in a similar great variability in both surface water runoff and groundwater recharge.

The period of record for most gauging stations and groundwater monitoring points within the catchment is biased towards a period of above average rainfall (based on the existing rainfall data). This needs to be taken into consideration when analysing flow and recharge data. This is the primary reason for the work undertaken to synthesise the historical regional groundwater discharge record for discharge from the aquifer in the Tindall Limestone into the Katherine River (refer Figure 16).

The catchment is still largely undeveloped. Prior to further significant development of the water resources occurring a sounder understanding is required of the interaction between the regional aquifers and those sections of rivers identified on the accompanying map as being sections into which a significant amount of groundwater discharges.

There is also a need to undertake a preliminary analysis of the hydrological data that exists for the various parts of the catchment. This analysis is required to identify the type of hydrological data that the Government needs to collect to underpin the sustainable development of the Daly River catchment.
10. **Recommended Work**

- Determine the reason for the apparent increase in dry season flow at GS8140044 on the Flora River and re-evaluate existing flow data.
- Undertake groundwater resource investigation of the Ooloo Limestone to better define recharge / discharge characteristics.
- Develop regional groundwater flow models for aquifers developed in the Tindall Limestone and Ooloo Limestone in the Daly Basin.
- Refine the baseflow synthesis developed for G8140001 and G8140301 in Report 36/2000D. This refinement should initially focus on quantifying runoff for the various times of the wet season.
- Undertaking similar exercises for groundwater fed flows at gauging stations GS8140044, GS8140063, GS8140067 and GS8140040.
- Further develop the relationship between near river recharge to aquifers during the wet season, and subsequent discharge to the Katherine River and Daly Rivers.
- More precisely identify major groundwater inputs into the Daly River.
- Develop runoff and small dam design criteria for small catchments in close proximity to soils suitable for irrigated agriculture.
- Undertake an overview study of the Daly River coastal floodplain to identify work required to better understand hydrological processes and management responses required.
- Undertake a preliminary assessment of significant issues and work required to assess the feasibility of large dams in the Daly River catchment.
- Evaluate the impact of clearing trees on the water balance in the Douglas River – Stray Creek area.
11. References (Chronological order)


Unnamed, (1976). Daly Region stage 1, resource inventory, Department of Northern Territory, Forward Planning and Major projects Co-ordination Branch.


Daly River NT, Riparian Vegetation Water Use.


Daly River NT, Riparian Vegetation Water Use.

References with an existing Natural Resources Division Reference Number (most available in digital form)

Hydrology report on low flows of Katherine River at Nixon crossing. WRD63032

Geomorphology of the Tipperary Region. WRD64022

Field Trip Report -DR Morrison - Katherine River. WRD65022

Surface Water investigation - Douglas River Catchment as part of Daly River Investigations. WRD65023

A report on the quality of Katherine water supply February 1967 to July 1968. WRD68035

Preliminary appraisal of the geology and Hydrogeology of the Daly basin. WRD68036

Katherine Town - Investigation of Flooding from Katherine River. WRD70022

Daly-Katherine river basin - Water resources review 1975. WRD75024

Katherine water supply proposals 1976. WRD76022

Pine Creek Water Supply: Hydrology of Chinamans Camp Dam. WRD77023

Katherine River Development, Project 24. WRD80004

Lower Daly River Basin Investigation of Flood Protection and Flood Forecasting - Projects 42 & 77. WRD80017

Katherine Hydrological Investigation. WRD81007

Pine Creek Water Supply. WRD81021

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