Hydrological investigation at Howard East, N.T.

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Abstract

The pressure to develop groundwater resources in the wet/dry tropical woodlands of Northern Australia raises important engineering and ecological issues of sustainability. The key water-balance term associated with both aspects is the dry season groundwater throughflow. The small landscape (and hence groundwater) gradients, poorly defined zero flux groundwater boundaries and uncertainties in the connections between surface and ground waters make traditional hydrogeological approaches to these problems impractical. In this paper, throughflow estimates were based on measurements of tree water use and total evaporation at the beginning and end of the 1994 dry season. Total evaporation in the wet season approached equilibrium rates and in the dry season operated at 0.35 of equilibrium evaporation. These data, together with rainfall and runoff information, were used to test the Vardavas (1988) conceptual model in which dry season throughflow was assumed to be small; we conclude that this hypothesis cannot be rejected.

Introduction

The hydrology of the tropical ecosystems of Northern Australia is characterised by seasonal extremes in rainfall and streamflow. Wet season hydrology is dominated by heavy rains, with monthly runoff coefficients as high as 80%. During this period, surface aquifers are recharged generally to the level of the land surface. Streamflow declines rapidly following the cessation of rains, but over the long dry season groundwater levels recede by as much as 10m. The pathways and magnitudes of this dry season discharge are difficult to estimate due to a combination of low topographic relief, complex hydrogeology and potentially strong interaction with the atmosphere. The objective of this investigation was to estimate the diffuse (evaporative) discharge of groundwater, and by difference, the lateral dry season groundwater discharge from this system.

The importance of this work lies in the anticipated development of these groundwater resources as a water supply for Darwin and surrounds, supplementing existing surface water supplies. Local aquifers are currently exploited to an extent by urban and rural supply bores, but further substantial development is likely. It is anticipated that the current bore field on the western side of the Howard River, which has been operating since 1965, will be extended to include a bore network on the eastern side of the basin. This development is constrained by uncertainties regarding the sustainability of this supply, and the potential impact of development on the tropical woodland ecosystem. To date, groundwater extraction on the west side of the basin over the past 30 years has not lead to any discernible impact on tree health, but the effects of extraction on local water levels may not yet be realised. The depth of water table recession by the end of the dry season appears to be increasing; it is not yet possible to infer from monitoring of this bore field the long-term sustainability of similar developments.

From an engineering perspective, the minimum sustainable yield is considered equivalent to aquifer throughflow. On one hand, the volume of water associated with the dry season watertable recession has been used as an upper limit of throughflow and thus potential supply. Alternatively, the water balance model of Magela Creek (300 km east of Darwin) proposed by Vardavas (1988) implied that all of the dry season discharge is through local evapotranspiration, since in that model there was effectively no dry season baseflow associated with groundwater discharge. In these systems generally there can be some dry season streamflow, but the hydraulic connection with groundwater is uncertain; the drainage from perched surface waters may be chiefly responsible for sustaining dry season flow. Groundwater flow paths may not always be toward local stream networks nor defined by catchment topographic boundaries. For instance, Landsat TM imagery for the region during the dry season showed areas of persistent mesic vegetation in areas near the topographic divide between the Howard and Adelaide River catchments (Figure 1), well away from surface drainage networks (Held *et al.*, 1995). Thus, gauging dry season streamflow is not necessarily sufficient to assess dry season groundwater throughflow. Without such an assessment, there are risks of engineering a bore network which will not meet design yields, and of failing to allocate sufficient water to maintain the woodland system through the dry season,

The key to assessing sustainability is quantitative information about the volume of dry season groundwater discharge occurring by evapotranspiration as opposed to the lateral movement in the aquifer system, complemented by an understanding of how extraction might interact with the system’s recharge capacity and rainfall. In this paper, lateral dry season flux was determined by the difference between total volume loss and estimated evaporation. This approach places much emphasis on the reliability of the evaporation estimates.

Current understanding of evaporation from these tropical systems is limited. Vardavas (1987) proposed and tested radiation and evaporation models for water bodies in this region. In the Vardavas model, net radiation estimates were modelled as the difference between the downward solar flux and the net upward flux. The latter term was based on a Wein's Law expression involving surface temperature to the fourth power; surface water temperature (or air temperature) was used in this regard. Evaporation was modelled on the basis of the Penman (1948) equation, and was shown to agree with measured losses and previous estimates of evaporation from local water bodies (Hoy and Stephens, 1977; Garrett and Hoy, 1978). Vardavas (1988) modified this evaporation model to conform with the Priestley and Taylor (1972) expression, and argued that evaporation from the land surface should be at a rate of 90% of net radiation during the wet months. This same author reported annual evaporation rates averaging 935 mm from a system with a mean annual rainfall of 1437 mm. There are no previous reports of the direct measurement of evaporation from the tropical woodlands of northern Australia, although Pidsley (1990) scaled tree water use estimates by Greenwood *et al.* (1985) for eucalypts in southwestern Australia with the ratio of pan evaporation values for that site and a site in a tropical woodland similar to that in this study, and concluded that tree transpiration alone could account for 1.5 mm d^{-1} loss from the shallow aquifer during the dry season.

In this regard, a number of questions arise with respect to evaporation from these tropical woodland systems, and their susceptibility to groundwater pumping. Does wet season evaporation proceed at near equilibrium rates as proposed by Vardavas (1988)? What role does the tree canopy play in evaporation, and are trees ever (naturally) limited by the supply of water? Do some tree species use more water than others, or show more effects of water limitation toward the end of the dry season? In this paper we examine these aspects of evaporation and tree water use, and evaluate the sustainability of groundwater supplies and the potential impact on the tropical woodland within a simple water balance framework, and conclude that the bulk of the dry season watertable recession is evaporation, chiefly tree water use.

Climate and Surface Hydrology

The study area comprises the catchment of the Howard River (Lat. 12° 30' S Long. 131° 6' E), approximately 30 km southeast of Darwin, in the Northern Territory of Australia (Figure 1). The surface catchment area above the gauging station at Koolpinyah is 126 km^2, and is relatively flat with relief varying from 40m Australian Height Datum (AHD) at the southern limit to sea level at the mouth. The landform is characterised by poorly defined internal drainage systems and a number of seasonal lagoons. The region is subjected to monsoonal rainfall between November and March, followed by up to seven months of little or no rain. Annual rainfall averaged 1723 mm at the Darwin airport for the years 1963-1973, but ranges between 1100 to 2400 mm. Open ‘A’ class pan evaporation for the region is approximately 3000 mm yr^{-1}. Wet season runoff ranges between 33% of rainfall in average years to 48% in wet years based on gauging at Koolpinyah Station and rainfall at Howard Springs; this range is similar to that reported by Vardavas (1988) for the Magela Creek catchment.

Hydrogeology and Soils

The aquifer system is a combination of a shallow, unconfined, unconsolidated sediment overlying a more permeable, highly weathered fractured rock (Figure 2). The hydraulic behaviour of the shallow component ultimately controls the supply potential of the combined system, for it is the shallow layer which is first recharged by rainfall, and this layer supports evaporation and transpiration losses. On average, the water table is at 25m to 20m AHD (6 - 10 m below ground level) throughout the study area by the late dry season. Figure 3 illustrates a typical bore hydrograph for the upper sediments of the aquifer system. There is piezometric evidence that the seasonal lagoons and even portions of the Howard River itself may not be hydraulically connected to groundwater during the dry season.

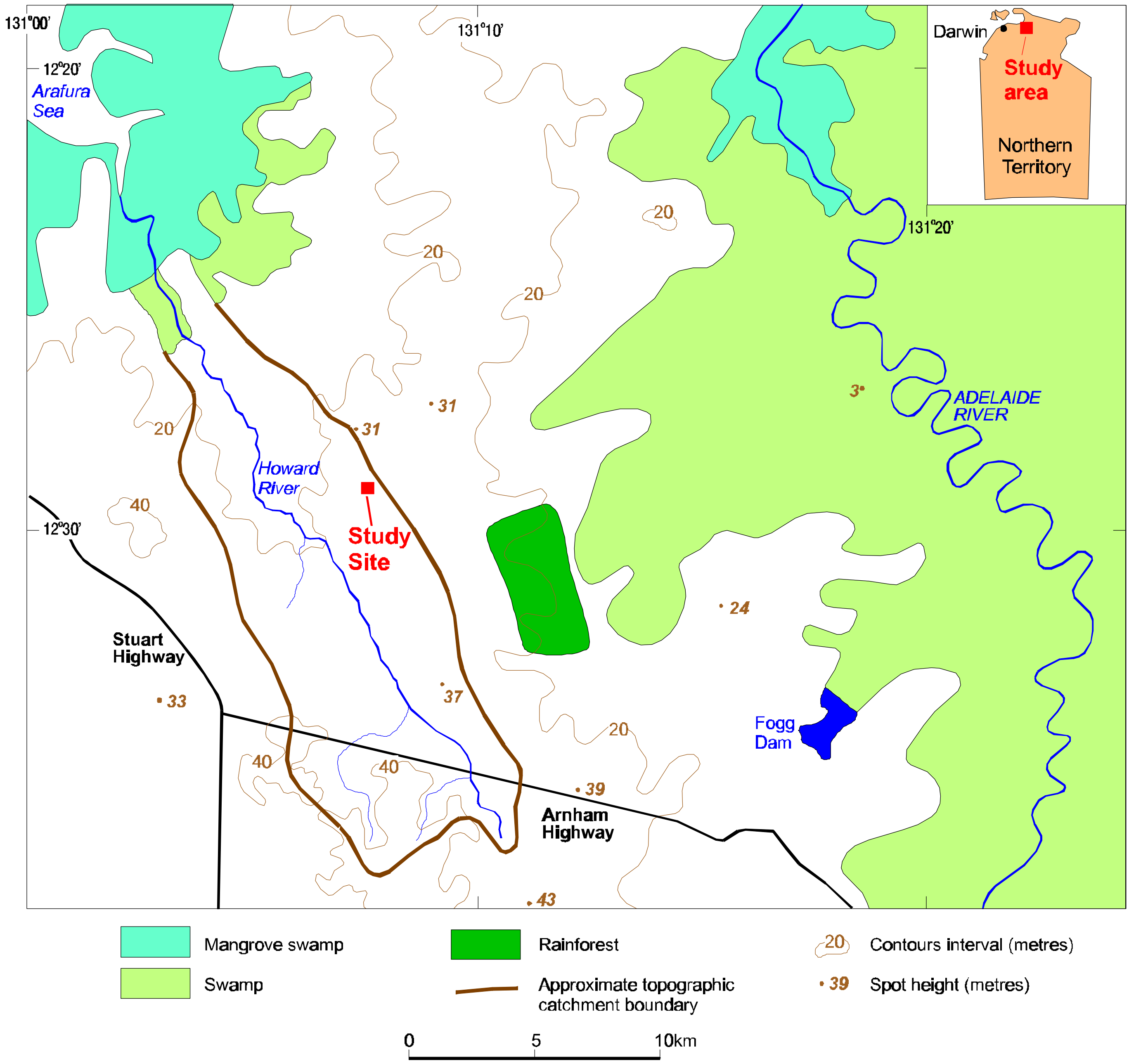
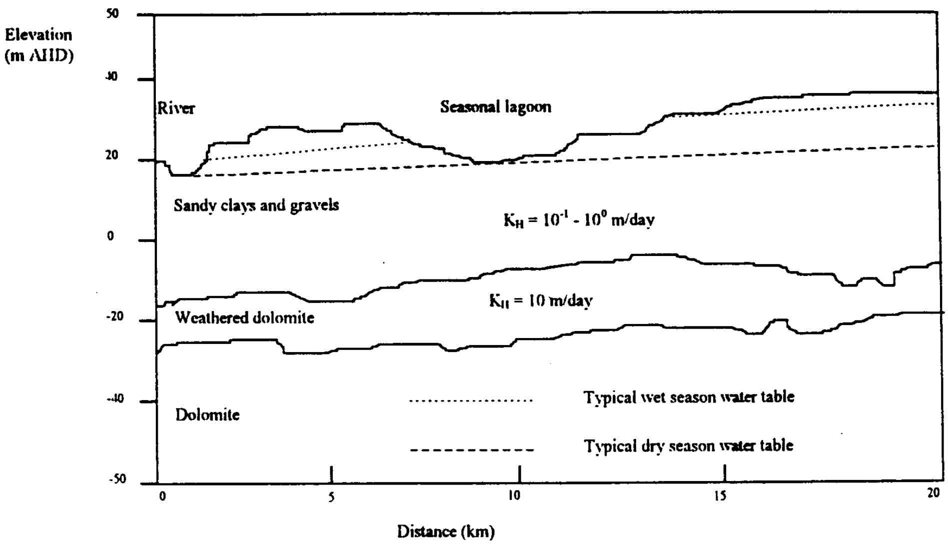


Figure 1. Study area location with representation of surface elevation of the Howard River Basin. Eddy correlation site and rainforest patch are indicated.

Figure 2. Typical cross-section of the Howard River basin, with seasonal water table levels in the undisturbed tropical woodland system.



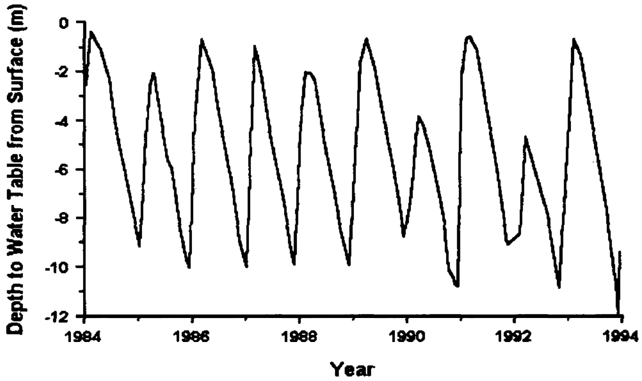


Figure 3. Water levels in the surface aquifer under an undisturbed tropical woodland system. Note that levels approach the land surface in most years. Data from PAWA piezometer no. 22069.

Vegetation

Vegetation composition and structure of the tropical woodland system are relatively homogeneous over the study area, apart from small and obvious waterlogged areas. The dominant canopy species *are Eucalyptus miniata* and *E. tetradonta,* which account for more than half of the canopy. Other significant elements of the canopy include *E. porecta, Erythrophleum chlorostachys* and *Terminalia ferdinandiana.* The overstorey canopy averages 13m in height, with a complex vertical structure. Understorey consists of speargrass, which senesces shortly after the end of the wet season. On average, any point on the landscape burns at least every two years, although usually these fire are relatively cool and do little damage to mature trees. Fire frequency is believed to be more frequent than in pre-European times. Leaf area index (A) of the tree canopy varies seasonally with a small deciduous component, but averages about 1.0 $m^2 m^{-2}$. Herbaceous and grassy understorey declines rapidly over the dry season from 0.4 to 0.2 $m^2 m^{-2}$.

Methods

Intensive field exercises to estimate evaporation coincided with two critical points in the annual cycle. The first of these is at the end of the wet season (April), when evaporation rates are at or near their peak (Vardavas 1988). The second period is near the end of the dry season (September), at a time when all herbaceous understorey has senesced, surface soil moisture is very low, and trees must apparently rely increasingly on groundwater for transpiration. The transition between these two phases is poorly understood.

Vegetation

A 2500 m^2 study plot was established near an existing set of piezometer wells (nest no. 4 in Cook *et al* 1997) and soil moisture monitoring tubes, following an assessment based on aerial photos and satellite data to ensure representativeness of the site to the rest of the woodland. Vegetation was sampled in early April and late August, 1994 by A. O'Grady, Derek Eamus, Gordon Duff and Tania Streeter of the Northern Territory University (Appendix 1). This sampling included the measurement of the bole diameters, basal areas and leaf areas of every individual tree and tree seedling within the plot (Appendix 1). Leaf areas were based on the ocular technique of Andrew *et al.* (1979) in which the number of standard modules in each tree was estimated by three independent observers. The leaf area of the module used for each tree species was later determined by electronic planimetry. The leaf area of the understorey was estimated by harvesting all of the green leaf material in ten 1 m^2 randomly located quadrats and measuring the leaf areas. To test the representativeness of the plot and to allow destructive estimates of biomass, five plots of 75 m^2 were established, and all plant material was harvested, weighed and measured for leaf areas.

Canopy Transpiration Measurement

Transpiration from the overstorey was estimated by scaling sap flow measurements of tree water use as described in Hatton *et al.* (1995). Sap flow was measured by means of the compensation (heat pulse) technique using Greenspan Technology Sapflow Sensors (Warwick, Queensland). This technique requires estimates of the volumetric wood and water contents, sapwood and heartwood radii, and the wound diameter associated with implanted probes. Wood and water contents were obtained gravimetrically on cores of known volume taken from each tree sampled. The dimensions of the conducting wood were determined in the field by (a) destructive sampling of similar trees subjected to dye tracing, and (b) incremental measurements of sap flow velocity in one tree of each species sampled as described in Hatton *et al.* (1995) (Figure 4). Wound diameters were estimated by examination of stained sections taken at the end of the measurement periods. Sap flow velocities were integrated into a flux for each tree as in Hatton *et al.* (1990). Estimates of tree water use were scaled into an estimate of transpiration by the method described in Hatton *et al.* (1995) on the basis of a linear relationship between tree basal area and water use.

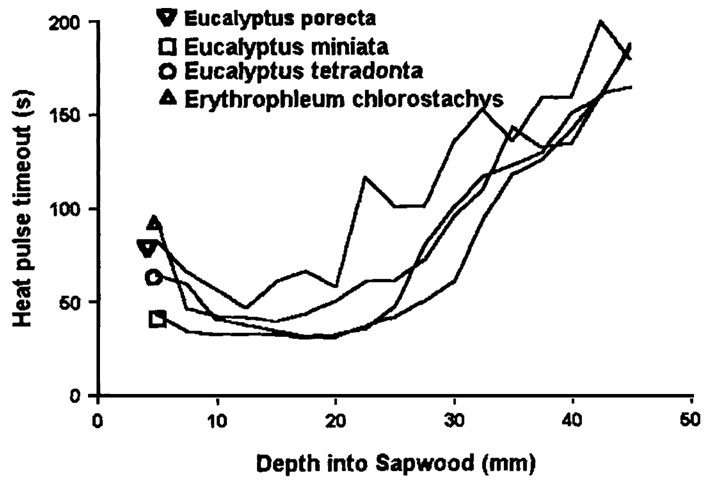


Figure 4. Heat pulse times (inversely proportional to sap flow velocity) taken incrementally with depth into the four dominant trees species at the site, as in Hatton et al (1995). Values in excess of 180 seconds are at the limit of low velocity detection with this equipment, and can be assumed as zero velocity. Note that all four species had approximately the same velocity profile and depth of sapwood.

Tree water use was electronically logged every twenty minutes during the periods 15-20 April and 3-9 September 1994. In the April experiment, 14 trees were monitored across 5 species (Table 1). In the September exercise, 13 trees were monitored across 4 species (the deciduous *Terminalia* were leafless at that time). Sampling is summarised in Tables 1 and 2. Further details of this aspect appear in Appendix 2.

Table 1. Tree species sampled with sap flow measurements, April 1994, with leaf areas (m^2) scaling factors to extrapolate to transpiration rate in 50 m^2 plot.

Species, # sampled	Total Leaf Area (La_t, m^2)	Measured LA (La_s, m^2)	Total Basal Area (B_t, cm^2)	Measured Basal Area (B_s, cm^2)	Conversion Factor (Bt/Bs)	Conversion Factor LAt/LAs)
Erythrophleum chlorostachys (2)	304	24	2333	164	14.20	12.67
Terminalia ferdinandiana (2)	236	20	1040	204	5.09	11.80
Eucalyptus miniata (5)	690	71	6159	734	8.39	9.72
E. tetradonta (4)	991	81	10759	763	14.10	12.23
E. porrecta (1)	109	8	1154	128	12.30	13.62
total	2330	204	21445	1993	10.76	11.42

Table 2. Tree species sampled with sap flow measurements, September 1994, with scaling factors to extrapolate to transpiration rate in 50 m^2 plot. Note that in a survey of understory vegetation at this site in October 1994, O'Grady (NTU) estimated an additional LAI of 0.23 associated with tree seedlings and other ground cover. Note also the larger discrepancy between the leaf area-based scalars and those based on basal area. The former were considered to be measured with less accuracy.

Species, # sampled	Total Leaf Area (La_t, m^2)	Measured LA (La_s, m^2)	Total Basal Area (B_t, cm^2)	Measured Basal Area (B_s, cm^2)	Conversion Factor (LAt/LAs)	Conversion Factor (Bt/Bs)
Erythrophleum chlorostachys (2)	222	54	1154	164	4.11	14.2
Eucalyptus miniata (5)	1164	145	6160	708	8.03	8.70
E. tetradonta (4)	1338	157	10759	763	8.52	14.1
E. porrecta (2)	218	34	1154	344	6.41	3.35
total	2942	390	19227	1979	7.54	9.71

Evaporation from the plot was estimated by eddy correlation techniques for the same periods as tree water use measurements. Micrometeorological sensors were deployed on a platform at least 4m above the canopy, and included a Fritchsen-type net radiometer, a one-dimensional sonic anemometer combined with a fast response thermocouple (CA 27, Campbell Scientific, Logan, Utah), and a open-path ultraviolet absorption hygrometer (KH20, Campbell Scientific). In addition, four soil heat flux plates (Radiation Energy Balance Systems, Seattle, Washington) were deployed at a depth of 5mm into the soil around the base of the platform. Climate information was electronically logged at a frequency of 10Hz, and integrated into fluxes every 20 minutes. Evaporation was calculated as the difference between net radiation, soil heat flux and sensible heat flux. The canopy heat storage was not accounted for but was assumed to be a small component of the energy balance in these systems and effectively zero over a diurnal cycle. To compare fluxes with atmospheric demand, equilibrium evaporation (E_{eq}) was calculated as

$$E_{eq} = \frac{\Delta}{\Delta + \gamma}\left(R_n - G\right)$$

where

A = slope of the saturation vapour pressure curve

γ = psychometric constant

R_n = net radiation

G = soil heat flux

In October 1996, the dry season transpiration and micrometeorological estimation of evaporation was repeated at this site by the Northern Territory University. Reference is made to their preliminary results in this paper.

Hydrological Data

Streamflow data were available for the Howard River for the period 1963-1973 as gauged near Koolpinyah Station. Rainfall records were available from gauges within the catchment as well as nearby at the Darwin Airport. Groundwater levels were monitored monthly for the period 1983-94 at a number of sites within the catchment.

We approached the annual water balance calculations using two sets of information which shared in common our evaporation estimates. First, we compare mean annual rainfall, mean annual streamflow and estimated annual evaporation to calculate the magnitude of annual groundwater discharge (throughflow) not appearing in the Howard River. Alternatively, we estimated the site water balance for the period of water table recession on the basis of the above terms for the period March-October together with the estimated change in storage at the end of that period.

Results

Tree Water Use and Total Evapotranspiration

Dye tracing and incremental measurements of sap flow velocity with depth gave comparable indications of the boundaries of the sapwood conducting area in all species. There was a remarkable similarity in sapwood thicknesses across the species in the plot. Wound diameters developed to a width of about 2.8mm during both field exercises; these values are comparable to those reported by Barrett (1992) for eucalypt and rainforest species in New South Wales and by Hatton *et al.* (1995) for *Eucalyptus populnea* in Queensland. Linear regressions between basal area and tree water use (all species together) resulted in coefficients of determination of 0.91 in both April and September, confirming the utility of leaf area as a scalar of flux (Figures 5a,b).

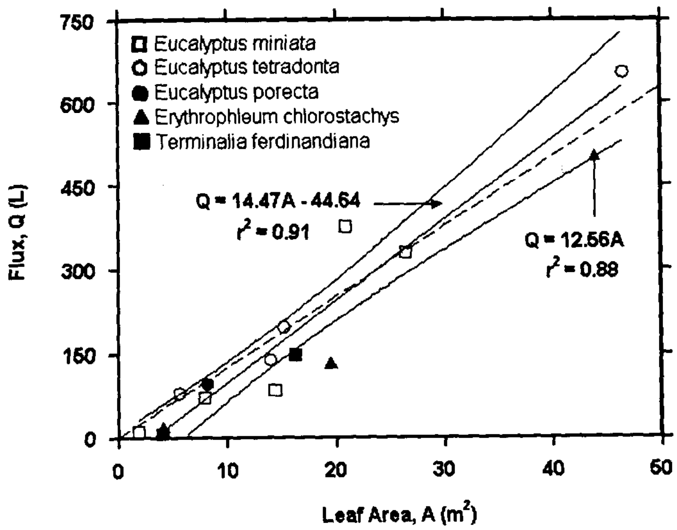


Figure 5a. Leaf area - flux relationship for monitored trees, 15-20 April 1994, for all tree species. The dashed line is a linear model fitted through the origin. Also shown is a solid line indicating a first-order linear regression and associated 95% confidence intervals.

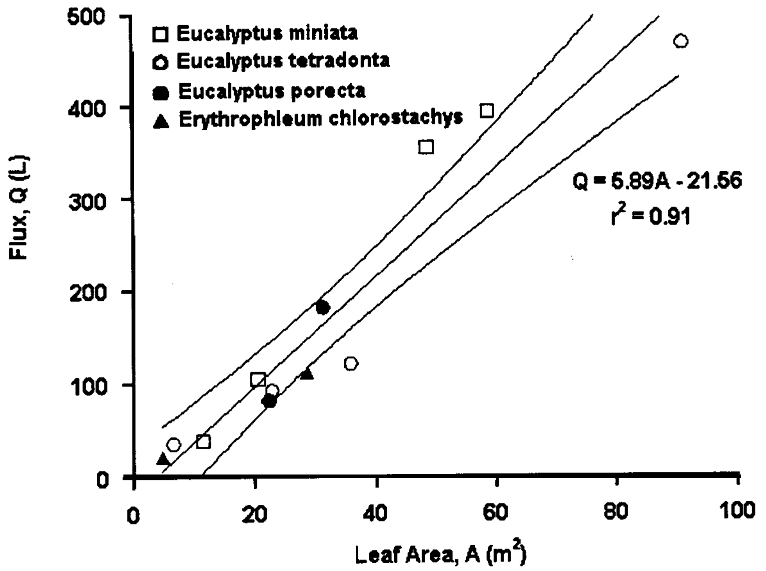


Figure 5b. Leaf area - flux relationship for monitored trees, 3-9 September 1994, for all tree species. Also shown are the first-order linear regression with 95% confidence intervals.

There are strong statistical as well as theoretical reasons as to why leaf area is generally the most appropriate scalar, and indeed, the relationships between flux and leaf area were strong and linear, with nonsignificant (from 0.0) intercepts ($p > 0.05$). However, to apply these relationships to the rest of the trees in the plot meant that similarly accurate estimates of leaf areas of these trees had to be available. While such accurate estimates were available for April, they were not available for the September analyses.

Therefore, scaling was done by means of basal area (under bark), which had a similar strength of relationship and nonsignificant zero intercept as was the case with leaf area, but could be surveyed with greater accuracy across the plot for both seasons. These relationships are shown in Figure 6:

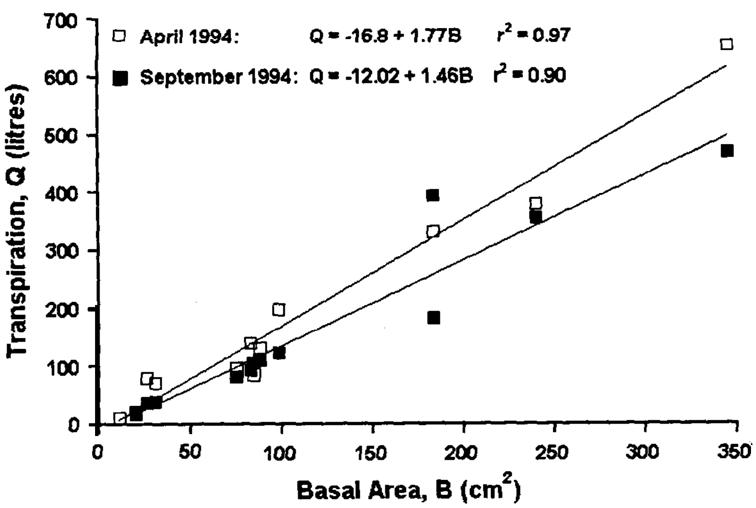


Figure 6. Basal area (under bark) vs. transpiration flux for 15-20 April and 3-9 September 1994. The strong linear relationship and insignificant intercept justified scaling sap flow measurements on this basis.

Daily times series of scaled sap flow estimates of tree water use, eddy correlation measurements of total evaporation and equilibrium evaporation for days with complete records in April and September appear in Figures 7a-e. The daily totals for these quantities appear in Table 3 for those days with complete diurnal records. In general, the tree canopy transpired at a constant rate relative to radiation throughout the dry season, but early in the dry season there were substantial contributions from other sources of evaporation (e.g., from understorey and soil evaporation). Dry season evaporation began at a rate near equilibrium, but declined to only about two-thirds that rate by September.

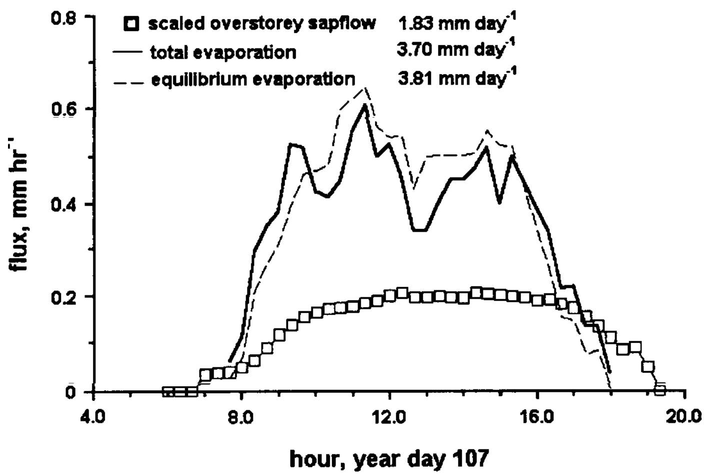


Figure 7a. Scaled overstorey transpiration based on sap flow measurements, total evaporation as measured by eddy correlation, and calculated equilibrium evaporation for 17 April 1994.

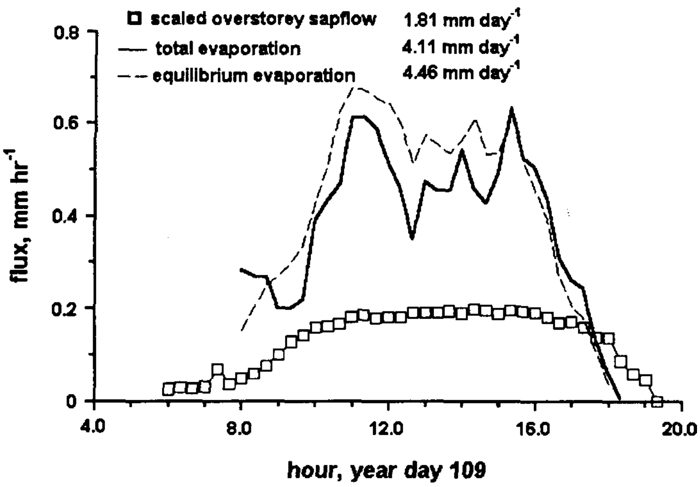


Figure 7b. Scaled overstorey transpiration based on sap flow measurements, total evaporation as measured by eddy correlation, and calculated equilibrium evaporation for 19 April 1994.

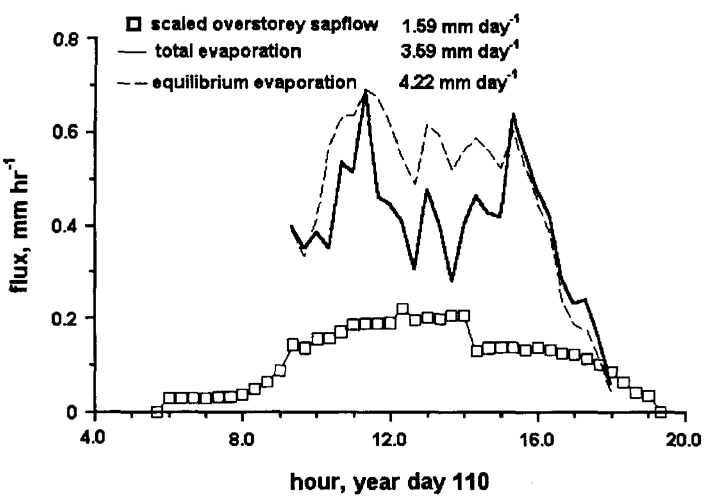


Figure 7c. Scaled overstorey transpiration based on sap flow measurements, total evaporation as measured by eddy correlation, and calculated equilibrium evaporation for 20 April 1994.

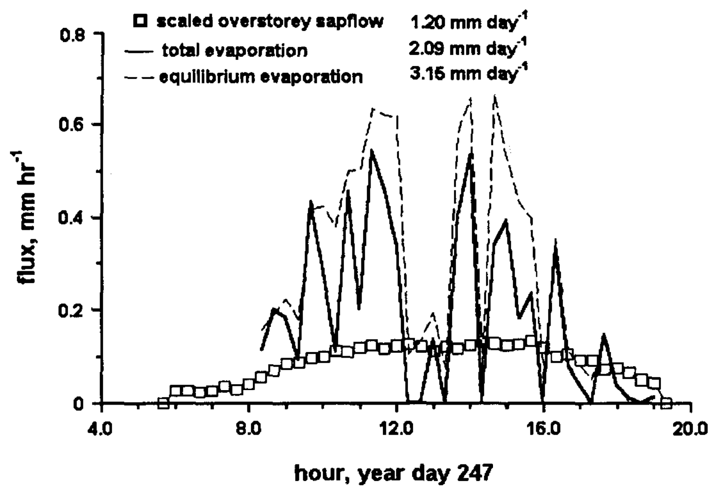


Figure 7d. Scaled overstorey transpiration based on sap flow measurements, total evaporation as measured by eddy correlation, and calculated equilibrium evaporation for 4 September 1994.

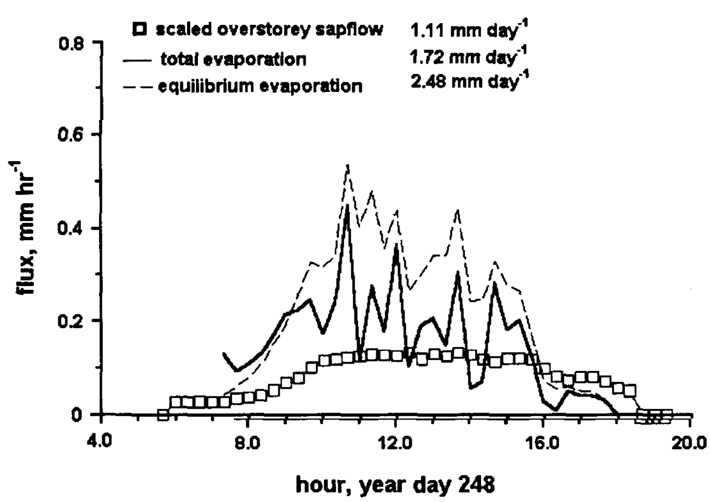


Figure 7e. Scaled overstorey transpiration based on sap flow measurements, total evaporation as measured by eddy correlation, and calculated equilibrium evaporation for 5 September 1994.

Table 3 Canopy transpiration via sap flow, total evaporation via eddy correlation, and equilibrium evaporation rates, in mm day^{-1}. Values reported in parentheses for transpiration in April are based on scaling by leaf area.

Date	Yearday	Canopy Transpiration T	Total Evaporation λE	Equilibrium Evaporation λE_{eq}	T / λE	λE / λE_{eq}
15 April	105	1.68 (1.78)	-	-	-	-
16 April	106	1.86 (1.97)	-	-	-	-
17 April	107	1.83 (1.94)	3.70	3.81	0.49	0.96
18 April	108	1.81 (1.92)	-	-	-	-
19 April	109	1.81 (1.92)	4.11	4.46	0.44	0.92
20 April	110	1.59 (1.69)	3.59	4.22	0.44	0.86
$\bar{x}$, s		1.76, 0.11 (1.87)	3.80, 0.27	4.16, 0.32	0.46, 0.03	0.91, 0.05
3 Sept	246	1.25	-	-	-	-
4 Sept	247	1.20	2.09	3.15	0.57	0.66
5 Sept	248	1.11	1.72	2.48	0.64	0.68
6 Sept	249	1.20	2.11	3.10	0.57	0.68
7 Sept	250	1.23	2.08	3.10	0.59	0.67
8 Sept	251	1.22	2.02	2.92	0.60	0.69
9 Sept	252	1.28	-	-	-	-
$\bar{x}$, s		1.21, 0.05	2.00, 0.16	2.95, 0.27	0.59, 0.03	0.68, 0.01

In a similar exercise to the September 1994 experiment described above researchers at the Northern territory University (L. Hutley, Derek Eamus, Tony O'Grady) repeated the dry season sap flow and eddy correlation measurements in October 1996. Over four days in October (10-13), mean actual evaporation, equilibrium evaporation, and mean transpiration from the overstorey were 1.55, 5.01, and 0.84, respectively. Note that evaporation is significantly lower than that measured by the CSIRO in September 1994 (1.55 vs 2.00), resulting in a fraction of 0.35 equilibrium evaporation. Of this, 0.54 was overstorey transpiration, as compared with 0.59 in the 1994 exercise.

The fact that overstorey transpiration was a very similar fraction of actual evaporation is encouraging. It is something of a mystery, however, as to the source of the remaining evaporation in the dry season. Understory LAI is approximately 1/3 of the overstorey value, and thus may contribute proportionally to total evaporation. This, together with soil evaporation, may account for the missing 0.41 of the total rate, although the soil was quite dry at this time.

The discrepancy between the 1994 CSIRO estimate of dry season actual evaporation from the woodland (2.00) and the 1996 NTU estimate (1.55) is not easily resolved. The Vardavas (1988) water balance model for Magela Creek prescribes a dry season soil water-holding capacity (in that model, treated synonymously with the combined soil water/groundwater store) of 200 mm. With a dry season extending over 6 months (with an average of 131 mm of rainfall over May - October for the years 1963-1973 as measured at Darwin Airport), this is equivalent to a daily dry season evaporation rate of about 1.50 mm day^{-1}, which is more consistent with the NTU estimates. Pidsley (1990) estimated dry season tree transpiration at 1.50 mm d^{-1} for a woodland site in this region based on tree water use estimates by Greenwood et al. (1985) scaled by potential evaporation.

Scaling to Yearly Evaporation Estimates

Inferring annual evaporation from the two measurement periods is difficult and uncertain. If we accept Vardavas' (1987, 1988) evidence that wet season evaporation in this region scales with radiation, and use monthly global irradiation values reported Frick *et al.*

using a eucalypt woodland albedo of 0.2 (Vertessy et al 1996) and scaled by the fraction of the equilibrium rate reported for April in Table 3, we obtain a wet season (November to April) evaporative loss of 810 mm. Evidence from monitored soil moisture profiles showed substantial drying to greater than 1 m depth by the end of May, with senescence of the herbaceous understorey complete well before this time. We thus infer evaporation after this date to be almost completely tree water use (including woody understorey), at rates similar to those measured in late in the dry season. If we fit a simple two-stage model of actual evaporation such that dry season (May - October, inclusive) rates run at 0.35 of equilibrium potential, then we can derive the following table based on Vardavas' potential estimates by month (Table 4).

Table 4. Mean daily evaporation rates (mm d^{-1}) for Darwin region. Potential estimates based on Vardavas (1987) corrected for woodland albedo as described therein. Actual evaporation rates for wet season assumed to run at 90% of this rate; dry season evaporation assumed to run at 0.35 of these potential rates. Transpiration by overstorey trees taken as 0.46 of actual in wet season, and 0.59 of actual in dry season, as reported above.

Month	Potential Evaporation (Vardavas 1987)	Actual Evapotranspiration	Overstorey Transpiration
January	5.0	4.5	2.1
February	4.4	4.0	1.8
March	4.7	4.2	1.9
April	4.6	4.1	1.9
May	4.3	1.5	0.9
June	4.3	1.5	0.9
July	4.1	1.4	0.8
August	4.6	1.6	0.9
September	5.3	1.9	1.1
October	5.7	2.0	1.2
November	5.4	5.0	2.3
December	5.2	4.9	2.3

These rates translate to 810 mm of evaporation in the wet season (373 mm by overstorey trees) and 300 mm of evaporation in the dry season (175 mm by overstorey trees). This gives an annual evaporation rate of 1110 mm.

Discussion

The above observations are qualitatively consistent with the Vardavas (1988) conceptual model for Magela Creek, in that dry season groundwater throughflow is small, that the wet season response operates largely as a simple bucket which must first be filled before significant runoff occurs, and that wet season evaporation approaches equilibrium rates. In the above analyses, it is important to note the expected uncertainty in the water balance calculations arising from the use of monthly average rainfall, runoff and water levels, as well as evaporation estimates made at only one site in the dominant vegetation. For instance, Hatton *et al* (1995) estimated potential errors in scaling tree water use measurements to the stand level at 44%, although in practice the realised error can be much less (e.g., Hatton and Vertessy, 1990). Errors in eddy correlation measurements of vapour flux can be of the order of 14 to 20% (Baldocchi and Meyers, 1991). We arrived at a small value for groundwater throughflow in the dry season, but it is quite possible that this figure may be out by 100 mm or more. However, the lack of any identifiable groundwater discharge into the Howard or any other nearby system during this period, in combination with observations at Magela Creek, suggests that in fact throughflow is minimal in undisturbed tropical woodland systems, at least in systems with likely backwater effects due to proximity to the coast. Most importantly, a figure of 1 -2 percent of annual rainfall would be sufficient to support the current extraction rates over a similar area as the development on the west side of the river.

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Appendix 1.

Overstorey Tree Survey, Howard East Woodland Site, 1994. Survey undertaken by Tony O'Grady, Gordon Duff, Tania Streeter and Derek Eamus of the Biology Department, Northern territory University as part of the Howard East Basin Study. Trees located in a 50m by 50m plot at site of 1994 sapflow and eddy correlation study. Leaf areas (LA, m') as estimated from modules (as in Hatton et al 1995, *Tree Physiology* 15:219-227); values reported are products of number of modules and module size as used for each species. Diameter at 1.3m over bark (DB, cm) is also reported below. Under-story leaf areas and biomass data held by Tony O'Grady at the NTU. Genus denoted as "Er." is *Erythrophleum*, and genus "T." is *Terminalia*. Note that O'Grady tested the module method against the known leaf areas of 32 trees in this woodland, and found a strong least-squares linear relationship ($Y = 0.736 + 0.936X$, $r^2 = 0.869$) with a slope very close to 1.00 and an intercept not significantly different from 0.

E. miniata		E. tetradonta		E. porecta		Er. chlorostachys		T. ferdinandiana	
DB	LA	DB	LA	DB	LA	DB	LA	DB	LA
15.2	32.0	6.4	6.52	7.1	4.47	4.3	2.39	1.10	0.518
10.9	11.52	9.2	6.52	7.4	4.47	4.2	1.195	2.00	1.036
12.0	15.36	8.5	8.15	6.7	6.705	8.0	4.78	3.00	2.072
18.4	28.16	9.2	9.78	5.0	3.725	5.4	4.78	1.10	0.863
19.5	48.64	5.3	1.63	7.2	10.43	12.1	15.535	1.5	1.21
7.1	7.68	8.6	11.41	18.5	20.86	3.1	2.39	2.3	0.518
17.3	58.88	16.1	26.08	7.9	5.96	8.4	2.39	1.00	0.518
6.3	1.28	2.3	1.63	5.1	0.745	9.80	13.145	1.00	1.036
10.9	7.68	8.0	9.78	5.2	2.235	5.0	2.39	1.00	1.036
15.9	19.2	7.2	6.52	10.1	10.43	4.0	0.5975	1.00	1.036
12.0	8.96	10.1	13.04	8.4	5.96	6.5	0.5975	1.00	1.036
17.5	43.52	6.9	1.63	12.2	17.88	4.1	1.195	1.00	1.036
17.9	32.0	12.5	17.93	5.6	3.725	5.1	9.56	1.00	1.036
8.4	6.4	10.9	16.3	5.2	2.235	2.8	3.585	1.00	1.036
23.2	33.28	5.7	3.26	9.4	9.685	5.3	0.5975	1.00	1.036
7.5	7.68	2.7	1.63	10.1	10.43	11.3	2.39	1.00	1.036
14.9	21.76	3.5	1.63	8.30	0.745	13.1	2.39	1.00	1.036
18.4	16.64	4.7	1.63	5.7	5.215	7.1	11.95	1.00	1.036
12.7	15.36	3.9	1.63	12.8	22.35	5.2	1.195	1.00	1.036
6.7	6.4	3.4	1.63	18.3	31.29	5.0	1.195	1.00	1.036
20.4	33.28	1.5	0.815	10.4	16.39	13.9	2.39	1.00	1.036
7.1	3.84	5.0	3.26	6.3	4.47	2.1	1.195	9./80	14.5
21.1	40.96	2.6	1.63	7.3	4.47	13.7	7.17	5.6	3.97
14.7	20.48	5.7	3.26	6.7	3.725	12.7	15.535	2.6	1.036
14.2	17.92	4.9	3.26	8.7	2.98	7.2	1.195	1.00	1.036
16.4	30.72	4.3	1.63	4.6	2.235	10.1	1.195	3.30	2.24
18.7	23.04	3.4	1.63	5.7	4.47	5.1	1.195	5.8	7.60
14.7	35.84	8.5	4.89	6.4	0.3725	12.0	3.585	3.7	1.90
12.9	23.04	10.2	14.67	6.0	3.725	7.6	1.195	5.3	3.80
5.9	3.84	2.1	1.63			10.9	13.145	5.6	3.45
8.3	11.52	11.6	21.19			3.0	1.195	1.80	1.036
12.4	20.48	4.4	3.26			9.6	1.195	1.90	1.036
8.5	8.96	2.1	1.63			6.4	7.17	2.00	1.036
5.3	2.56	8.2	8.15			17.0	3.585	2.30	1.036
4.9	1.28	6.9	4.89			14.3	4.78	4.10	1.21
5.88	3.84	10.5	9.78			7.3	4.78	5.50	2.76
19.7	66.56	7.1	3.26			15.7	3.585	3.30	2.072
10.4	7.68	13.6	26.08			7.1	4.78	3.1	1.554
5.6	2.56	9.5	11.41			12.6	28.68	4.7	4.14
5.8	5.12	5.0	3.26			2.4	1.195	2.6	1.036

E. miniata		E. tetradonta		E. porecta		Er. chlorostachys		T. ferdinandiana	
DB	LA	DB	LA	DB	LA	DB	LA	DB	LA
4.7	1.28	2.5	1.63			10.3	1.195	5.7	4.83
5.1	3.84	3.5	1.63			8.1	1.195	3.4	1.036
5.5	5.12	5.6	3.26			7.0	5.975	3.0	1.036
5.3	3.84	9.5	8.15			13.9	1.195	4.9	5.35
5.3	2.56	6.7	3.26			5.8	2.39	1.4	0.518
4.4	1.28	15.1	35.86			3.5	1.195	5.6	6.39
7.9	6.4	8.3	13.04			4.3	2.39	3.4	1.21
7.5	3.84	5.5	3.26			4.8	3.585	3.6	2.42
15.6	25.6	5.3	4.89			9.8	4.78	1.1	0.518
17.4	46.08	6.2	4.89			17.5	4.78	1.1	0.518
13.5	20.48	6.2	1.63			17.7	2.39	1.1	0.518
17.8	35.84	13.1	14.67			3.2	1.195	3.5	1.55
19.5	71.68	8.4	9.78			7.4	3.585	2.1	1.036
10.2	10.24	8.9	9.78					3.6	1.90
12.6	25.6	13.8	27.71					4.8	3.11
8.5	6.4	0.5	0.815					4.7	6.91
6.8	1.28	13.5	30.97					3.2	1.38
12.1	20.48	7.1	9.78					2.5	1.036
13.2	28.16	8.3	9.78					0.90	0.512
13.9	17.92	6.9	9.78					5.9	5.67
3.9	1.28	11.9	22.82					2.2	1.21
4.1	1.28	2.1	0.815					4.5	3.28
8.3	7.68	5.2	0.815					6.8	14.5
4.0	1.28	5.3	6.52					5.5	6.56
6.6	5.12	4.0	3.26					2.8	2.24
17.0	12.8	8.2	13.04					4.1	3.97
9.8	8.96	8.7	9.78					4.4	2.07
6.2	0.5	7.5	9.78					12.9	3.97
		5.5	6.52					10.1	16.2
		9.9	14.67					8.0	9.30
		9.0	13.04					2.5	0.69
		7.1	8.15					4.3	6.91
		7.6	11.41					2.1	2.07
		9.0	9.78					5.1	7.60
		10.5	17.93					1.7	0.518
		10.2	19.56					1.6	1.036
		11.4	14.67					13.0	26.9
		12.0	26.08					2.9	1.55
		3.6	1.63						
		7.1	3.26						
		2.2	1.63						
		4.2	1.63						
		3.7	1.63						
		10.8	16.3						
		3.2	3.26						
		6.0	6.52						
		10.7	16.3						
		1.0	0.815						
		1.9	1.63						
		2.6	3.26						
		1.7	0.815						
		7.8	16.3						
		1.7	0.815						

E. miniata		E. tetradonta		E. porecta		Er. chlorostachys		T. ferdinandiana	
DB	LA	DB	LA	DB	LA	DB	LA	DB	LA
		2.4	1.63						
		7.8	11.41						
		5.8	4.89						
		3.5	1.63						
		4.4	4.89						
		7.8	11.41						
		17.1	26.08						
		17.3	14.67						
		17.6	13.04						
		1.5	3.26						
		3.4	3.26						
		5.3	3.26						
		5.2	3.26						
		5.3	4.89						
		3.1	3.26						
		1.4	1.63						
		8.8	4.89						
		2.5	3.26						
		5.4	3.26						
		4.2	3.26						
		6.2	3.26						
		4.1	3.26						
		7.5	11.41						
		8.3	6.52						
		88.5	9.78						
		2.2	0.815						
		1.8	0.815						
		4.2	1.63						
		9.4	8.15						
		8.0	19.56						
		11.0	16.3						
		1.3	1.63						
		1.8	1.63						
		2.9	1.63						
		6.8	4.89						
		8.7	8.15						
		13.7	35.86						
		15.9	35.86						
		14.1	19.56						
		7.3	8.15						
		8.2	14.67						
		11.9	26.08						
		12.3	21.19						
		5.9	4.89						
		13.1	21.19						
		4.6	4.89						
		4.7	4.89						
		12.8	22.82						
		6.3	8.15						
		23.5	91.28						
		7.5	9.78						
		9.5	16.3						
		7.4	4.89						
		3.6	0.815						

Summary statistics for vegetation survey, woodland site, April 1994. Survey undertaken by Tony O'Grady and Derek Eamus of the Biology Department, Northern territory University as part of the Howard East Basin Study

Area: 2500 m^2

Overstorey LAI: 0.94
Understory LAI: 0.37

Species	# modules	leaf area/module	leaf area, m^2
Erythrophleum chlorostachys	389.4	0.781	304.1
Terminalia ferdinandiana	227.7	1.036	235.9
Eucalyptus miniata	743.8	0.928	690.3
E. tetradonta	979.3	1.012	991.0
E. porrecta	201.0	0.544	109.4
SEEDLINGS			
E. miniata	78	0.250	19.5
E. tetradonta	115	0.257	29.6
E. porrecta	38.5	0.110	4.24

Appendix 2.

Heat Pulse Data

In the April 1994 exercise, fourteen trees were selected from within the plot for sapflow measurement, as follows:

5 x Eucalyptus miniata (wooly butt)………………. Ml to M5
4 x Eucalyptus tetradonta (stringy bark).. ………… Tl to T4
2 x Terminalia ferdinandiana ……………………… Dl, D2
2 x Erythrophleum chlorostachys (ironbark). ……… I1, I2
1 x Eucalyptus porrecta …………………………… El

Heat pulse data was recorded for each of these trees, with data for full days for the period 15-20 April. This data was analysed by means of the SAPCAL (Greenspan Technology) software using solutions based on equal weighting of sensors and a wound diameter of 3.0 mm. Daily water use was summed between the hours of 0730 and 1800 each day; night time water use was negligible.

In the September 1994 exercise, twelve trees were monitored as follows:

4 x Eucalyptus miniata (wooly butt). ……………… M 1 to M4
4 x Eucalyptus tetradonta (stringy bark). ………… Tl to T4
2 x Erythrophleum chlorostachys (ironbark). ……… I1, I2
2 x Eucalyptus porrecta …………………………… El, E2

Note that *Terminalia* is dry season deciduous and thus were bare during the September exercise.

Data was recorded for full days between 3-9 September, inclusive. Analyses were repeated as described above.