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Abstract

Paperbark (*Melaleuca viridifolia*) swamps form a relatively minor fraction of the natural landscape of the Howard East Basin of the Northern Territory, occupying small, low, run-on sites within the surrounding savanna woodland. There is concern that development of the regional aquifer system as part of Darwin's water supply may impact on the health of these swamps. The Howard East Basin is presently undeveloped, and therefore risk assessment must rely on indirect approaches based on observations of an unstressed system.

A combination of tree water use techniques, soil physics, isotopic techniques, groundwater hydrology and groundwater tracer approaches were applied to a paperbark swamp. These techniques established the water use needs of the trees, the nature of the local groundwater system, and the capacity of the soil to supply the trees with water under changing hydrological regimes.

It was determined that these swamps are driven by surface water and local rainfall, and are perched and drain slowly downward into the regional groundwater system. Further, the soil water holding capacity is high enough to satisfy the trees' water demands through the non-flooded (dry) period of the year (June – November). Even if water levels are affected by pumping, minimal adjustment in rooting depth by the trees should maintain their water supply and thus health.

Introduction

Paperbark (*Melaleuca viridifolia*) swamps form a relatively minor fraction of the natural landscape of the Howard East Basin of the Northern Territory, occupying small, low, run-on sites within the surrounding savanna woodland. This latter system has been the subject of extensive ecophysiological and hydrological investigation (Hatton et al., 1997; Cook et al., 1998a; Cook et al., 1998b), prompted by the anticipated development of groundwater resources in this region. At issue is the dependence, and hence vulnerability, of ecosystems to changes in groundwater levels resulting from pumping. While paperbark swamps are of only limited extent, the hydrological processes contrast dramatically with those of the woodland, and thus bear investigation with respect to groundwater dependency.

These swamps are characterised by a monospecific overstory of paperbark trees, with an understory of floating and emergent herbs that largely disappear during the dry season. The boundary between the swamps and woodland or grassland is generally quite marked and probably maintained by fire. During the wet season, standing water levels rise up to 1 m above the ground surface, and the swamps are generally inundated between December and June.

In the absence of observations on the health of paperbark swamps in the presence of groundwater pumping, indirect inferences based on their ecophysiology and local hydrology are the only alternative. In this report, we describe a set of such measurements on the trees, the soils and the groundwater aimed at characterising the likely dependence of these swamps on groundwater and their responses to changes in water levels.

In taking this indirect approach to assessing groundwater dependence, several key questions must be answered:

- How much water do the trees use (need), particularly in the dry season?
- What are the vertical hydraulic gradients in the groundwater?
- Are the trees in contact with a perched or regional aquifer system?
- If perched, what is the downward hydraulic conductivity?
- What is the soil water holding capacity above the current annual groundwater level minimum?
- If groundwater levels could be lowered by pumping at depth, would sufficient water remain in the profile to support the trees through the dry season?

Study Site

A paperbark swamp approximately three kilometres west of the woodland study site described in Hatton et al. (1997) was selected for study (Figure 1). This site (Lat 12° 30' S, Long 131° 5' E) is surrounded on three sides by eucalypt woodland, and on the upstream side by a natural grassland; during the wet season, surface runoff from this grassland moves into and through the paperbark swamp. The swamp is approximately 80 m wide and 250 m long. Climate data is monitored at the nearby woodland site.

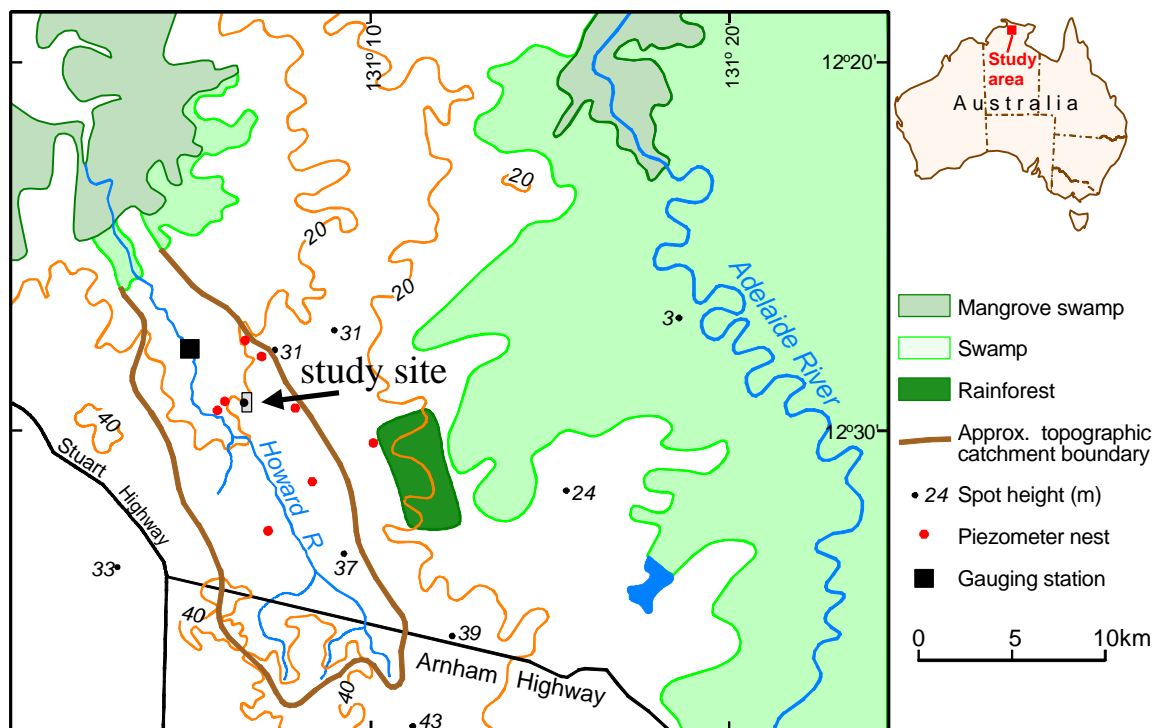


Figure 1. Location map, showing location of the paperbark swamp where measurements were taken.

METHODS

Tree Water Use

Transpiration from the overstory 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). 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).

Monitoring tree water use and other physiological responses was constrained by access during the wet season. In particular, the water depth toward the middle of the swamp limited many investigations to trees in shallower water. Ultimately, inferences must be made for the entire system, including the deepest parts; this deeper area is at the core of the swamp and includes the sites of the piezometers. To address this need, measurements at the leaf and whole tree scale were extrapolated based on allometric relationships to a 50 m by 50 m plot established in the core of the swamp. Estimates of tree water use were scaled into an estimate of transpiration for the core area by the method described in Hatton et al. (1995) on the basis of a linear relationship between tree basal area and water use. Individual tree leaf areas were estimated and related to basal area for scaling tree and leaf scale measurements to a land area basis as in Hatton et al. (1995).

Stand transpiration was estimated for the periods 16–24 April, 15–19 July and 15–25 September 1997, based on sapflow measurements on 8, 4, and 10 trees, respectively. Water levels around the sample trees during the April exercise varied between 30 and 75 cm above ground surface. The surface of the site was dry during the September exercise.

Soil and Groundwater Sampling and Analysis

A soil core to 8.2 m depth was obtained on 30.9.96 using a GEMCO 210B rig equipped with hollow-stemmed augers and wireline core recovery equipment. On 16.9.97 the surface soils were re-sampled to a depth of 2.0 m. Drilling was accomplished without the addition of drilling fluids, and soil samples were immediately stored in airtight glass jars to minimise evaporation. Gravimetric water contents were determined by oven-drying at 105°C for 24 hours, and matric suctions were estimated using the filter paper method (Greacen et al., 1989). Deuterium (^2H) and ^{18}O

concentrations were measured on soil water which had been extracted by azeotropic distillation. Analytical precision is approximately $\pm 1.0\%$ for ^2H , and $\pm 0.15\%$ for ^{18}O . Moisture characteristics were measured on selected soil samples by equilibrating on pressure plates held at 15, 300, and 1300 kPa. Soil texture was determined by mechanical analysis.

A piezometer nest was installed by drilling three separate bores, spaced approximately 5 m apart, shortly before the commencement of the study. A 50-mm diameter PVC casing was slotted over 0.3 or 0.5 m intervals, and installed in each bore. Wells 30982, 30983, and 30984 were completed with screens at 2.7–3.0, 5.0–5.5, and 7.0–7.3 m below ground level, respectively. Piezometers were sampled for deuterium ^2H , ^{18}O , and chlorofluorocarbons CFC-11 (CCl_3F) and CFC-12 (CCl_2F_2). Measurements of electrical conductivity, pH, Eh, and dissolved oxygen were also made. At least one well volume was pumped from each well prior to sampling. The hydraulic conductivity of the soils is very low, and wells take more than 24 hours to recover after purging, making additional purging difficult. The high pH's measured in well 30984 (Table 8) probably indicate remnant cement, suggesting that the well has not been sufficiently developed since installation.

Groundwater samples for isotopic analyses were obtained directly from the pump outlet. Samples for CFC analyses were collected from the screened interval using a sealed stainless steel bailer, in a manner similar to that described by Cook et al. (1995). CFC samples were collected on 10.9.97 and 13.1.98. ^2H and ^{18}O samples were collected on 12.9.97 and 13.1.98.

Concentrations of ^2H and ^{18}O were also measured on twig samples collected from paperbark trees on 1.09.97. Sap water was extracted from the twigs by azeotropic distillation, as described by Thorburn et al. (1993).

RESULTS

Scaling Relationships for Physiological Measurements

The 50 m by 50 m plot in the centre of the swamp contained 175 paperbark stems with a mean basal area at 1.3 m height above ground of 193.4 cm^2 (standard error 15.4 cm^2). Data appear in Appendix 1.

The relationship between tree basal area at 1.3 m above ground and tree leaf area appears in Figure 2. While basal area measurements were expected to be identical for trees sampled at both times, they were independently measured on each occasion; there was little change over the intervening time.

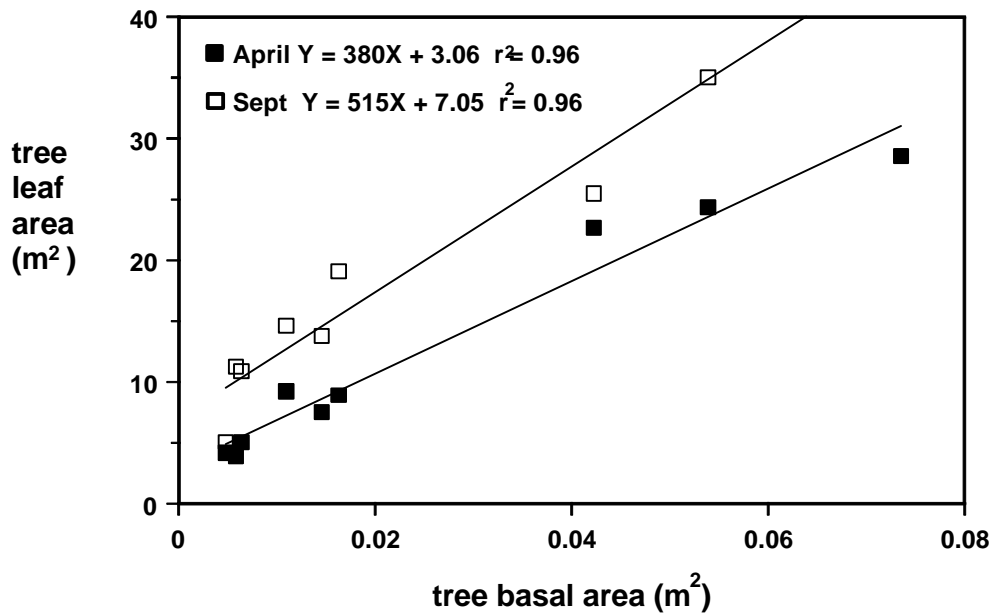


Figure 2. Tree basal area over bark at 1.3 m height against tree leaf area at a time when flooded (April) and toward the end of the dry season (September).

Application of these relationships to the basal area data from the 50 m by 50 m plot resulted in an estimated Leaf Area Index (LAI) for the entire site of 0.73 and 0.92 in April and September, respectively.

Tree Water Use

Water use by individual trees during April, July, and September appear in Tables 1–3, respectively. The key features of these data are that daily water use among the trees responds similarly to changes in daily weather conditions, and that there is a great deal of consistency in water use patterns among the sample trees in each season.

The values of tree water use in Tables 1–3 were scaled to transpiration from the core area of the swamp on the basis of basal area relationships with water use (Figure 3).

Table 1. April 1997 tree water use ($L d^{-1}$) based on sap flow measurements.

tree	1	2	3	4	5	6	7	8
date								
16/04/97	13.5	29.4	16.2	58.7	11.7	5.1	9.7	11.9
17/04/97	14.5	31.4	18.3	61.2	13.9	5.8	10.8	12.2
18/04/97	14.5	31.0	18.3	57.2	14.7	5.8	11.1	12.4
19/04/97	14.7	28.5	18.6	61.6	14.5	5.8	11.5	12.6
20/04/97	14.6	30.7	18.6	65.5	14.5	5.7	11.6	12.2
21/04/97	14.2	26.4	19.2	70.4	14.6	6.0	11.7	12.0
22/04/97	15.1	30.4	19.5	63.1	15.6	5.8	11.6	11.9
23/04/97	15.3	25.6	20.2	67.6	15.4	6.0	11.2	11.8
24/04/97	14.2	28.1	20.7	69.0	14.1	5.7	10.9	11.5
25/04/97	14.5	30.5	19.2	73.8	14.2	6.5	12.4	12.0
26/04/97	15.6	30.1	21.3	63.5	17.7	6.2	11.9	12.0
27/04/97	14.4	31.1	18.8	65.8	17.7	6.2	13.0	11.9
mean	15.1	29.4	19.1	64.8	14.9	5.9	11.4	12.0

Table 2. July 97 tree water use ($L d^{-1}$) based on sap flow measurements.

tree	2	3	4	5
date				
15/07/97	17.4	10.7	77.5	10.6
16/07/97	19.1	11.9	75.4	11.1
17/07/97	17.9	13.7	80.9	12.2
18/07/97	16.7	14.0	76.7	12.3
19/07/97	16.1	13.6	78.3	12.5
mean	17.4	12.8	77.8	11.8

Table 3. September 1997 tree water use ($L d^{-1}$) based on sap flow measurements.

tree	3	4	11	12	13	14	15	17	18	19
date										
15/09/97	14.6	49.1	20.3	16.7	15.9	4.0	71.9	23.1	18.3	13.0
16/09/97	17.1	49.7	19.6	16.5	15.6	3.9	73.4	22.0	18.3	12.2
17/09/97	16.7	48.5	18.2	15.8	14.6	3.9	70.9	22.7	17.7	11.9
18/09/97	16.0	44.9	17.8	15.6	14.8	3.7	67.9	23.2	17.0	11.8
19/09/97	15.4	45.3	18.0	15.7	14.6	3.6	69.5	24.6	16.5	12.3
20/09/97	14.7	47.5	17.4	15.4	14.1	3.6	68.5	22.6	15.8	12.5
21/09/97	15.1	46.0	16.9	15.4	14.3	3.7	62.4	23.6	14.6	11.8
22/09/97	16.8	49.3	17.6	16.6	15.6	3.9	70.2	22.8	16.5	12.9
23/09/97	15.7	46.5	17.3	16.8	15.6	3.9	70.4	23.3	15.3	13.1
24/09/97	15.6	45.5	17.0	16.1	16.2	3.6	69.3	22.9	15.2	13.2
25/09/97	15.4	44.6	16.8	15.9	15.5	3.9	68.4		14.2	12.6
mean	15.7	47.0	17.9	16.0	15.2	3.8	69.3	23.1	16.3	12.5

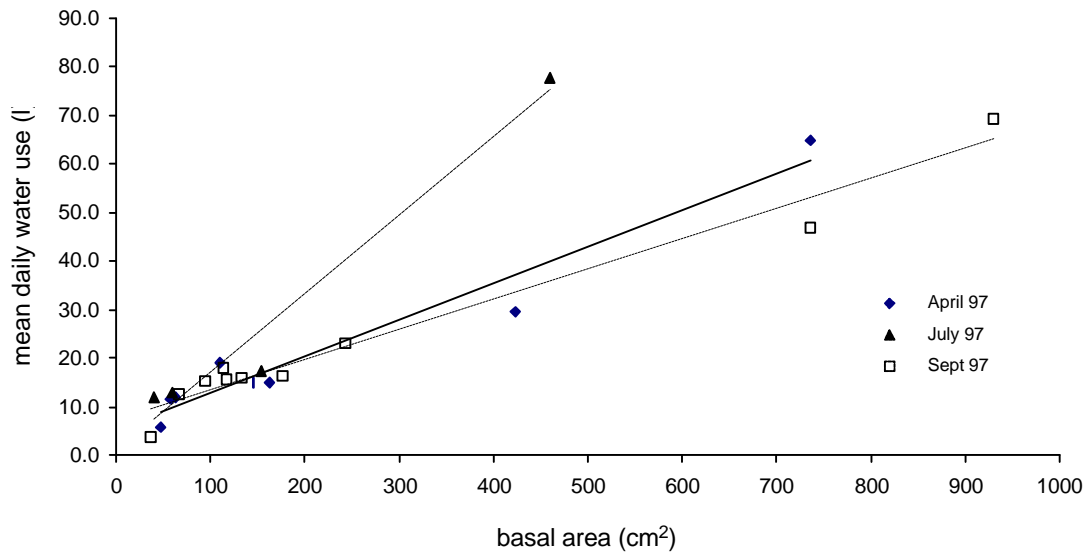


Figure 3. Linear regression relationships between tree basal area and mean daily water use for paperbarks. Note that the amount of water transpired per unit basal area is highest at that time (July) when water levels are below the ground surface, but then approach flooded (April) values toward the end of the dry season (September). The coefficients of determination (r^2) for these relationships were 0.95, 0.97, and 0.97 for April, July, and September, respectively.

The relationships shown in Figure 3 were applied to the basal area data from the core area plots to derive daily transpiration on an area basis. This resulted in estimates of daily transpiration from the core area of the swamp (Tables 4–6). Mean daily water use was 1.43, 2.05, and 1.36 mm day⁻¹ in April, July, and September, respectively.

Table 4. Daily tree water use scaled to an area of 2500 m² in the centre of a paperbark swamp during April, when flooded. Also shown are actual evaporation measurements made simultaneously over nearby woodland. In comparing these two values, it must be remembered that evaporation from free water at the surface under the paperbark trees is not accounted for.

Date	transpiration (mm)	woodland evaporation (mm)
16/04/97	1.29	
17/04/97	1.40	
18/04/97	1.38	
19/04/97	1.39	2.38
20/04/97	1.43	3.31
21/04/97	1.41	3.09
22/04/97	1.44	2.76
23/04/97	1.40	2.46
24/04/97	1.54	
25/04/97	1.48	3.46
26/04/97	1.48	
27/04/97	1.48	
mean	1.43	

Table 5. Daily tree water use scaled to an area of 2500 m² in the centre of a paperbark swamp during July, when water levels had declined to below ground level.

Date	transpiration (mm)
15/07/97	2.01
16/07/97	2.06
17/07/97	2.13
18/07/97	2.03
19/07/97	2.02
mean	2.05

Table 6. Daily tree water use scaled to an area of 2500 m² in the centre of a paperbark swamp during September, toward the end of the dry season. Also shown are actual evaporation measurements made simultaneously over nearby woodland.

Date	transpiration (mm)	woodland evaporation (mm)
15/09/97	1.39	1.27
16/09/97	1.40	1.17
17/09/97	1.36	1.18
18/09/97	1.32	1.11
19/09/97	1.33	1.11
20/09/97	1.30	1.13
21/09/97	1.27	1.09
22/09/97	1.36	
23/09/97	1.34	
24/09/97	1.32	
25/09/97	1.30	
mean	1.33	

Soil and Groundwater Investigations

Water Content and Matric Suction

Piezometric heads are above land surface between approximately January and June, during which time the area is also inundated. The water level in all three piezometers, and the surface water level (when the area is inundated) appear to track each other relatively closely (Figure 4). This may suggest hydraulic connection between the different piezometers, or alternatively, water level variations in the deeper piezometer could be the result of hydrostatic loading (van der Kamp and Moathius, 1991). The position of the water table fell to approximately 1.8 m below ground level in September 1997.

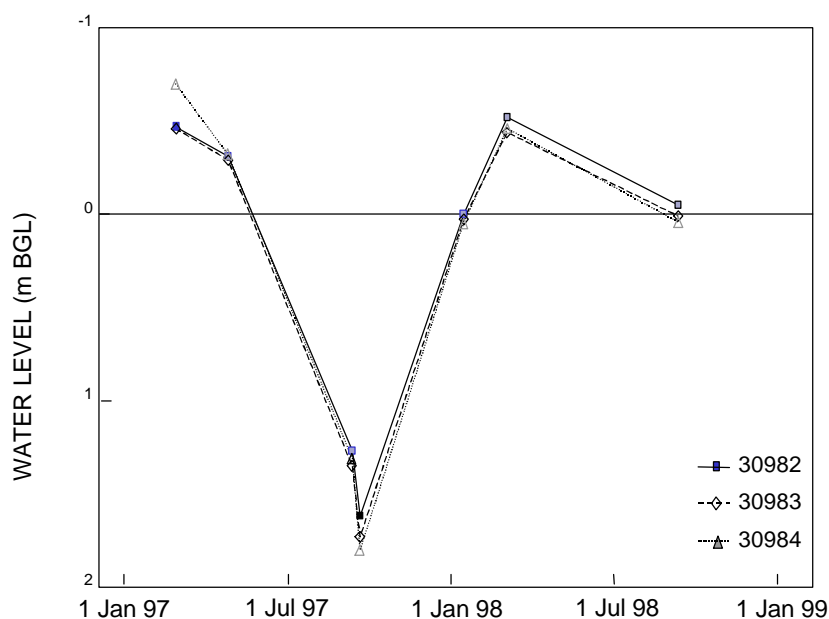


Figure 4. Piezometric levels under the paperbark swamp. Piezometer 30982 is the most shallow of the nest; 30984 is the deepest.

Beneath the adjacent eucalypt woodland, water tables usually fall to between 7 and 11 m BGL by November to early December, and rise to within 1 and 3 m of land surface by March to April. The paperbark swamp occupies a topographic depression, some 2–3 m below the level of the eucalypt woodland. Thus the water level in the paperbark swamp appears to be above that of the eucalypt savanna at the end of the dry season. At the end of the wet season, the water tables may be at a similar level. The position of the water table in the swamp at the end of the wet season, is likely controlled by shallow throughflow from the eucalypt woodland. During the dry season, the water table beneath the woodland recedes to a depth below that of the swamp. The low conductivity of the soils beneath the swamp appear to maintain the elevated water table relative to the woodland.

Soil-water contents and matric potentials beneath the paperbark are given in Table 7. A heavy clay layer occurs between 2.3 and 5.5 m, and relatively high matric suctions were measured in this interval. It appears likely that the high clay contents (up to 65% clay) between 2.3 and 3.0 metres depth form a low permeability unit, and that a perched water table often forms on top of this unit. During the period of observation (February 1997 to June 1998), the perched aquifer (sampled in piezometer 30982) was always present. However, matric suction data obtained prior to the installation of the piezometers, suggest that the soil is unsaturated between 2.5 and 5.0 m depth, and it is possible that during extended dry periods the perched layer is absent. During such dry periods, the vegetation may extract water from the deeper soil layers, near the permanent, regional water table.

Table 7. Soil core data.

Date Drilled	Depth (cm)	Water Content (g g ⁻¹)	Matric Suction (kPa)	² H (%)	¹⁸ O (%)	Soil Texture (%)				
						Clay	Silt	F. Sand	C. Sand	Gravel
30.9.96	0–30					16	12	50	23	
	40–60					26	2	39	33	1.0
	60	0.097	27							
	60–70	0.132	12	-32.9	-4.71					
	80–100					22	2	43	33	1.0
	120–130	0.230	12	-33.7	-4.72					
	130–150					40	3	30	27	
	160–170	0.191	50	-32.4	-4.45					
	180–200					41	2	30	27	0.7
	200	0.168	23							
	230–250					65	2	17	11	
	240–250	0.233	133	-26.4	-3.86					
	270–300					61	3	21	15	
	330	0.192	433							
	330–350					52	3	26	20	
	400–420	0.226	196	-30.0	-4.19	52	1	23	23	
	480	0.143	172	-30.3	-4.35					
	480–500					48	3	24	26	
	530–550					48	6	21	25	
	550	0.187	10	-25.0	-3.00					
620	0.161	63	-28.0	-3.69						
620–650					43	3	23	32		
690	0.159	65	-28.3	-3.95						
700–720					38	6	25	32		
760	0.140	73	-31.7	-4.43						
760–780					40	5	22	33	1.0	
800–820					36	6	27	32		
820	0.139	345	-30.2	-4.20						
16.9.97	0–10	0.263	807	-29.8	-2.91					
	10–50	0.171	190	-35.8	-4.52					
	50–100	0.151	21	-31.0	-4.25					
	100–150	0.159	25	-25.4	-3.54					
	150–200	0.245	144	-20.5	-2.79					

Deuterium and Oxygen-18

^2H and ^{18}O concentrations in soil water are given in Table 7. Concentrations measured in groundwater samples obtained from piezometers, in surface water, and on sap extracted from twig samples are given in Table 8.

Table 8. Groundwater, surface water, and twig water chemistry. Negative values of SWL indicate a water level above the ground surface.

Location	Date	SWL m BGL	EC $\mu\text{S cm}^{-1}$	pH	Eh mV	DO mg l^{-1}	^2He ‰	^{18}O ‰	CFC-11 pg kg^{-1}	CFC-12 pg kg^{-1}
30982 (2.7–3.0m)	25.02.97	-0.47								
	24.04.97	-0.31								
	9–12.09.97	1.27	61	6.0	+43		-32.9	-4.9	57	49
	19.09.97	1.62								
	13.01.98	0	71	6.0			-3.15	-5.26	148	105
	3.03.98	-0.52								
	11.06.98	-0.05				0.1			18	23
30983 (5.0–5.5m)	25.02.97	-0.46								
	24.04.97	-0.29								
	9–12.9.97	1.35	86	7.5	-14		-25.1	-4.36	79	68
	19.09.97	1.73								
	13.01.98	0.03	49	5.9			-26.2	-4.43	37	62
	3.03.98	-0.44								
	11.06.98	0.01							50	57
30984 (7.0–7.3m)	25.02.97	-0.7								
	24.04.97	-0.32								
	9–12.09.97	1.31	1556	11.3	-98		-31.4	-4.63	0	108
	19.09.97	1.8								
	13.01.98	0.05	1055	11.2			-30.7	-4.71	0	37
	3.03.98	-0.46								
	11.06.98	0.04				4.8			0	12
Surface Water	26.3.98						-38.3	-6.31		
	11.06.97		17			5.2			228	130
Twig	1.09.97						-31.8	-4.26		
	1.09.97						-30.3			
	1.09.97						-29.2	-4.13		

Figure 5 depicts ^2H and ^{18}O concentrations measured in soil and groundwater samples. Also shown on this figure are concentrations measured on groundwater samples obtained beneath Eucalypt savanna woodland (Cook et al., 1998b), the long-term weighted mean concentration for Darwin rainfall, and the global meteoric water line. Stable isotope concentrations obtained from both soil and groundwater samples beneath the paperbark swamp are generally distinct from those obtained beneath eucalypt woodland. The data from the paperbark site soil cores fall on a line of low slope, displaced to the right of the meteoric water line. The surface water sample collected in June 1998 also falls close to this line. This suggests significant evaporation during recharge, and that the original soil water would have had a composition close to that measured for surface water at this time. The only soil samples that do not fall close to this line are those from the upper 50 cm of the soil profile. Isotopic concentrations in the upper 50 cm of the soil profile would be expected to change throughout the year, in response to variations in rainfall and evaporation. In contrast, samples obtained beneath eucalypt woodland fall close to the meteoric water line, and show little evidence of isotopic enrichment from evaporation.

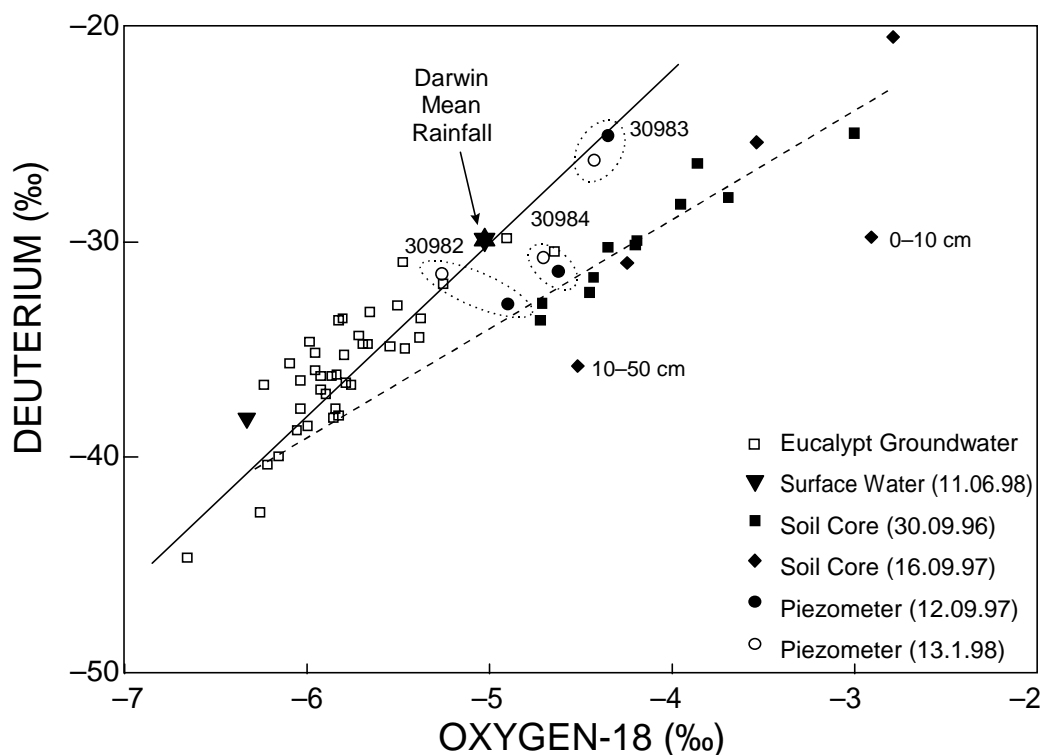


Figure 5. Deuterium and oxygen-18 concentrations measured on soil water and groundwater beneath paperbark, compared with concentrations measured on groundwater beneath Eucalypt savanna. The solid line depicts the global meteoric water line, and the broken line is an approximate evaporation line defined by the paperbark soil isotopes (fitted by eye).

All of the soil samples were collected at the end of the dry season. Groundwater samples collected from the deepest piezometer (30984), and from the shallow piezometer (30982) during September 1997, also fall close to this evaporation line. In contrast, groundwater from the shallow piezometer showed no evidence of evaporation when sampled during the wet season (January, 1998). Thus, it is likely that the distinct signature of the paperbark soil and groundwater samples arises through soil evaporation of surface water that infiltrates the soil during the wet season. Given the similar isotopic signatures between the groundwater under the eucalypt woodland and the surface water in the swamp, it is also possible that there are contributions to the inflow to the swamp from shallow subsurface flow derived from the woodland.

The groundwater from the middle piezometer (30983) falls close to the meteoric water line, but is more enriched than mean annual rainfall, and more enriched also than the groundwater samples obtained beneath eucalypt woodland. The reason for this is not known.

Figure 6 shows deuterium profiles measured on soil and groundwater samples at the paperbark site, and also concentrations measured on twig samples. There is very good

agreement between concentrations measured on soil samples, and those obtained on groundwater samples from piezometers installed at 5.0–5.5 m and 7.0–7.3 m depth. Isotopic concentrations in groundwater from the shallowest piezometer (30982, 2.7–3.0 m) would be expected to change significantly throughout the year, and hence the difference is not surprising considering the different sampling times. Deuterium concentrations measured on twig samples on 1.9.97 varied between –29.2 and –31.8‰, similar to concentrations measured on soil samples at 0–10 and 50–100 cm at this time. Oxygen-18 concentrations indicate that the twig water is most similar to soil water at 50–100 cm depth. Matric suction data (Table 7) shows highest water availability at this depth at this time, which would also indicate water extraction from this depth. (Twig water isotope concentrations are also similar to soil concentrations at certain depths below 2 m as measured in September 1996, and it is not possible to rule out water extraction from these greater depths based on the isotope data alone. However, it is most likely that the paperbark would preferentially extract water from the shallower depths, where very low matric suctions were also recorded.)

Moisture Characteristic and Water Storage Capacity

Water contents at 15 kPa, 300 kPa, and 1300 kPa were measured on soil samples obtained in September 1996 (Table 9). While water contents at saturation were not measured, the deeper soils (below 1 m depth) appear similar to those beneath the adjacent eucalypt woodland, with saturated water contents mostly between 0.3 and 0.5 g g⁻¹. Thus, most of the soil water (0.2–0.25 g g⁻¹) is released between saturation (0 kPa) and field capacity (15 kPa). A further 0.04–0.05 g g⁻¹ (on average) is released between 15 kPa and 300 kPa. Little additional water is released as the soil suction is increased to 1300 kPa.

Table 9. Pressure plate measurements of gravimetric water content (g g⁻¹).

Depth (m)	Matric Potential		
	15 kPa	300 kPa	1300 kPa
1.2–1.3	0.210	0.156	0.144
3.3	0.201	0.161	0.162
5.5	0.166	0.154	0.144
7.6	0.240	0.180	0.178

We use the measured water retention relationship in combination with the theoretical model of the water contents in swelling clay soils under overburden pressure to determine the amount of water that is available to the vegetation. In the following, we have used the same moisture characteristic as used by Cook et al. (1998b) for the Eucalypt savanna site (Figure 7). We have also assumed soil wet bulk density and compressibility factors of $\rho_{wb} = 1.4 \text{ g cm}^{-3}$ and $\beta = 0.5$ respectively. By the end of the dry season, the water table falls to approximately 2.5 m depth. If we assume that the soil was saturated to the soil surface at the end of the wet season, that the water table is at 2.5 m by the end of the dry season and the unsaturated zone is at wilting point, then the change in water storage between the wet and dry seasons is estimated to be 340 mm. The difference between field capacity and wilting point over the same depth interval is 210 mm.

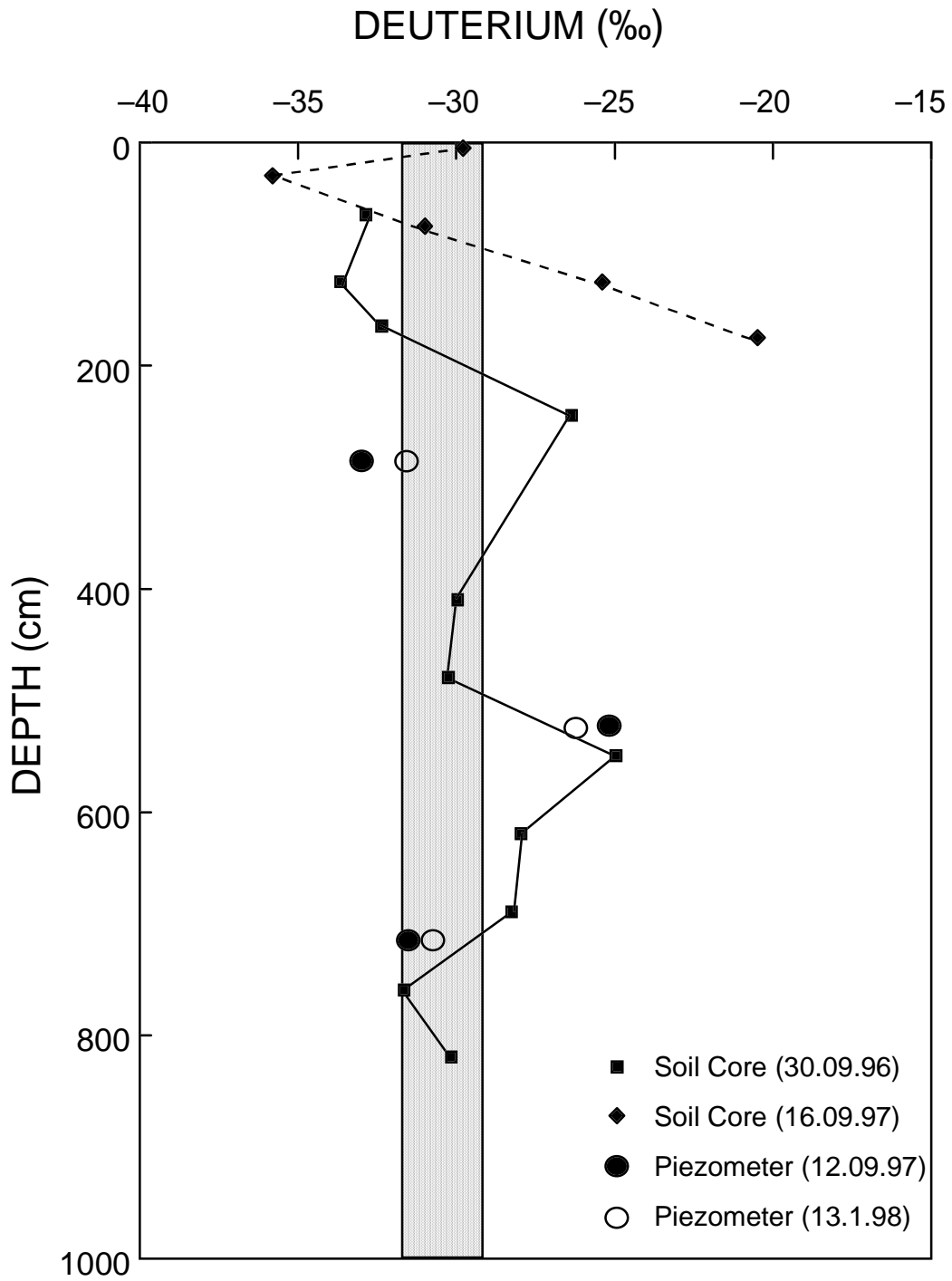


Figure 6. Deuterium concentrations measured in soil water and groundwater. The range of deuterium concentrations measured in twig sap on 1.9.97 is indicated by the shaded area.

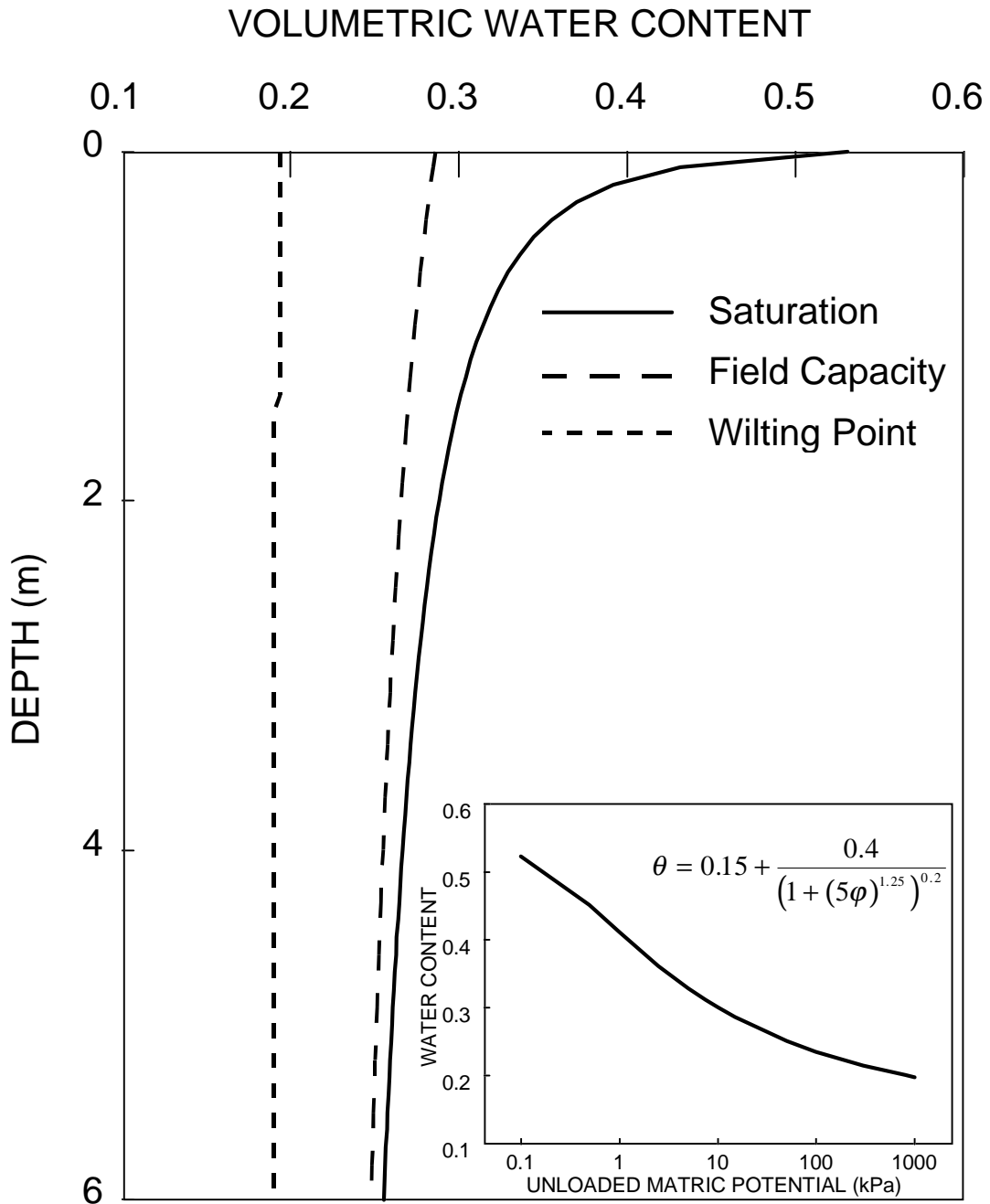


Figure 7. *In situ* moisture profiles for a uniform, swelling clay ($\rho_{wb} = 1.4 \text{ g cm}^{-3}$, $\beta = 0.5$), with moisture characteristic given in the inset.

Chlorofluorocarbons and Groundwater Chemistry

A surface water sample collected in June 1998 had CFC-11 and CFC-12 concentrations of 228 and 130 pg kg^{-1} respectively. This is lower than expected based on atmospheric equilibrium with modern air at a recharge temperature of 28°C, and may also indicate some microbial degradation of these compounds in the surface water. (The CFC-12 concentration is equivalent to an apparent age of 10 years.)

Chlorofluorocarbon CFC-12 concentrations measured on the deepest piezometer (30984) decreased from 108 pg kg^{-1} in September 1997 to close to background (12 pg kg^{-1}) in June 1998. Electrical conductivities decreased from more than 1500 $\mu\text{S cm}^{-1}$ in September 1997 to 1050 $\mu\text{S cm}^{-1}$ in January 1998. pH was more than 11 at both times in which it was measured. The data appears consistent with contamination of the aquifer during well construction, and the decreasing electrical conductivity and CFC-12 concentrations are consistent with the contamination being slowly removed over time.

Piezometer 30983 had CFC-12 concentrations between 57 and 68 pg kg^{-1} on each sampling occasion, consistent with a groundwater age of 20–25 years (assuming a recharge temperature of 28°C). The CFC-11 concentration is lower and more variable, and consistent with microbial degradation of this compound. Assuming a mean age of 22 years at a depth of 5.25 m would give a vertical water velocity of 0.24 m yr^{-1} . At a volumetric water content of 0.25 $\text{cm}^3 \text{cm}^{-3}$, this would indicate a mean recharge rate of 60 mm yr^{-1} . However, the surface water concentrations are lower than atmospheric equilibrium, and probably vary throughout the year. In the absence of time series data for the surface water, the measured an apparent age of 10 years in June 1998 gives a travel time to 5.25 m of 12 years. This would indicate a recharge rate of 110 mm yr^{-1} .

A large variation in CFC-12 concentration occurs in the shallowest piezometer (30982). During the wet season, concentrations of 148 and 105 pg kg^{-1} were measured for CFC-11 and CFC-12 respectively. While the measured CFC-12 concentration is consistent with a groundwater age of approximately 15 years, it is very close to that measured in the surface water in June 1998, and probably indicates relatively rapid infiltration to this depth. Large decreases in both CFC-11 and CFC-12 concentration between January and June 1998 may indicate microbial degradation of both compounds within the aquifer.

Groundwater Dependence

The time between the disappearance of surface water (approximately mid-June) and the return of significant rains (1 November) is the period of concern with respect to the trees having sufficient water. If we apply the mean tree water use for July and September measured in this study to the first and second halves of this period, respectively, we obtain a tree water use of approximately 240 mm. We presume that

if this amount of water remains available to the trees, then no decline in health will develop.

The fact that the shallow groundwater under the paperbark swamp is isotopically enriched relative to the regional groundwater under the surrounding woodland supports the view that ponded water slowly infiltrates downward at this site (slow enough for significant evaporative enrichment), restricted at depth by a layer of low permeability. CFC concentrations in the groundwater also suggests a relatively low recharge rate.

Isotopic techniques established the likelihood that the trees do rely on water from the developing unsaturated zone to a large extent during the dry season. Calculating the total available soil water holding capacity down to the depth of the annual groundwater level minimum (2.5 m) yields a value of 340 mm. If groundwater pumping would not increase the rate of drainage in the perched system, there is clearly enough soil water over this interval to carry the trees through the dry season, even allowing for additional losses through soil evaporation. If groundwater pumping could eliminate the water held above field capacity, then the available water over this depth would be reduced to 210 mm, indicating a potential vulnerability of the trees. However, this would be true only if the trees could not adjust their rooting depth by an additional metre, and if the saturated conductivity of the perching layer was sufficient to drain perched water to the deeper regional system at a greatly accelerated rate. It is unlikely that either of these conditions would operate.

Discussion

Limited hydrological and ecophysiological measurement suggest that this paperbark swamp is driven by surface run-on and local rains, which ponds and infiltrates slowly through the wet season and extending approximately two months into the dry season. The shallow groundwater system which develops is perched on a layer of low permeability, resulting in limited recharge to the more regional aquifer flowing from under the surrounding savanna woodland. The conditions under which this system might be vulnerable to groundwater pumping from the regional aquifer system are:

- the permeability at depth is sufficient to drain away the perched system and sufficiently extend the period of unsaturated conditions beyond the capability of the current rooting zone to supply sufficient water to the trees.
- the rooting zone of the trees cannot increase the depth over which they extract water by an additional metre given the above decrease in water levels.

As in Cook et al. (1998b), we conclude that the water holding capacity between field capacity and the permanent wilting point, which would be unaffected by groundwater pumping, is relatively large compared to the needs of the trees during the dry season. This provides a potential buffer to development impacts. This is similarly coupled with the observation that the system fills from the top down, and that this process would also be unaffected by pumping.

There are real ecophysiological and hydrological differences in water use patterns between the savanna and the paperbark trees. Transpiration from the paperbarks in the wet season (April) is lower than that for the woodland at that time (1.48 mm d^{-1} vs 1.87 mm d^{-1}). Conversely, transpiration rates may be slightly higher in the paperbarks than the woodland toward the end of the dry season (1.33 mm d^{-1} vs 1.21 mm d^{-1}). Both systems appear to have characteristics that would buffer them from the impacts of groundwater development. In the case of the woodland, the large unsaturated zone that develops as the dry season progresses contains a large reserve of soil water. In the case of the paperbark swamps, the relatively short non-flooded period, the perched nature of the groundwater system, and the potential to exploit a thicker unsaturated zone should one develop as a result of lowered watertables combine to minimise the risk to these systems associated with groundwater resources development.

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Appendix 1. Basal area (cm², over bark) at 1.3 m above ground for paperbark trees in a 50 m by 50 m plot.

103.1	38.5	92.0	140.4	66.9	215.2	0.1	258.5	183.3	315.8	412.5
198.9	92.0	127.3	161.1	215.2	207.0	0.1	1303.8	168.4	602.3	267.7
315.8	223.5	76.5	103.1	28.7	121.0	0.3	0.1	522.1	378.9	97.5
81.5	25.8	296.1	378.9	223.5	108.9	81.5	0.3	389.9	435.8	13.4
175.8	53.8	215.2	76.5	928.2	127.3	161.1	0.3	81.5	240.7	81.5
0.3	103.1	945.5	25.8	147.1	267.7	249.6	108.9	588.6	114.9	240.7
0.3	28.7	49.7	35.1	31.8	114.9	183.3	86.7	71.6	659.0	315.8
0.1	81.5	207.0	325.9	53.8	2.9	168.4	49.7	357.2	183.3	1.3
0.7	58.0	71.6	58.0	121.0	315.8	103.1	522.1	223.5	412.5	0.1
49.7	191.1	114.9	97.5	97.5	267.7	154.1	35.1	616.2	267.7	0.1
17.9	357.2	305.9	38.5	49.7	296.1	198.9	28.7	357.2	401.1	161.1
81.5	258.5	81.5	35.1	28.7	71.6	215.2	2.0	401.1	277.0	
35.1	378.9	71.6	53.8	38.5	215.2	183.3	401.1	215.2	277.0	
103.1	108.9	121.0	42.1	673.5	86.7	207.0	215.2	175.8	175.8	
66.9	267.7	121.0	175.8	779.9	31.8	147.1	31.8	223.5	296.1	