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Water balance of tropical eucalypt plantations in south-eastern China

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Abstract

Monthly, seasonal and annual water balances of *Eucalyptus urophylla* plantations on the Leizhou Peninsula, southeastern China were estimated in 40 m × 40 m plots at two sites with contrasting soil types. The Jijia site is located on basalt-derived clay rich soils, while the Hetou site is characterised by coarse textured soils formed on Quaternary sediments. Observations of evaporative processes (overstorey canopy interception and transpiration, and soil evaporation), soil moisture dynamics, and climate variables were collected at both sites over 2 years. Canopy interception was measured by throughfall troughs and stemflow collectors, daily transpiration was measured by the heat pulse technique in year 1 and estimated from regressions with potential evapotranspiration and available soil water in year 2, soil evaporation was measured by periodic microlysimetry and used to derive a daily soil surface resistance—matric potential relationship for estimation of daily soil evaporation throughout the study period. Soil moisture storage was measured to 4 m depth and drainage estimated as the residual term in a water balance equation. Total annual evapotranspiration (E_t) was similar at 1118 and 1150 mm at Jijia and 969 and 1024 mm at Hetou for years 1 and 2, respectively, despite 20–30% higher rainfall in year 2. These values represent 71 and 66% of annual rainfall in year 1, and 54 and 50% in year 2. Transpiration did not exceed 600 mm in either year and annual soil evaporation was 15–26% of E_t, with the higher values from Jijia. The higher rainfall in year 2 was predicted to produce an increase in drainage and runoff rather than tree water use. Dry season water balances showed E_t exceeded or approached rainfall, indicating water use from deep soil or ground water storages following soil water depletion, particularly at Hetou. However, storages were replenished by high wet season recharge. The differences in soil properties between the sites resulted in a three-fold greater soil water store at Jijia that provided a supply for E_s, and the sandier Hetou soils with poor water holding capacity had greater wet season drainage and higher dry season abstraction from deep storages. The water use of the eucalypts does not appear to be seriously deleterious for water supply in this area.

Keywords: Eucalyptus urophylla; Evapotranspiration; Leizhou Peninsula; Drainage; Soil moisture storage

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1. Introduction

The widespread establishment of *Eucalyptus* plantations for commercial production of fibre and wood products throughout the world has been accompanied

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by concerns over possibly excessive water use in several countries. A number of robust scientific studies of eucalypt water use have been undertaken accordingly (see reviews by Calder, 1999, 1992), but the variety of species and environments studied do not allow generalised conclusions to be drawn. Studies in southern India have reported transpiration rates of 3–8 mm per day by eucalypts in tropical conditions (Kallarackal, 1992; Kallarackal and Somen, 1997a, b), while Roberts et al. (1992) observed up to 6 mm per day post-monsoon and less than 1 mm per day pre-monsoon in drier conditions in Karnataka. In summarising the findings of experiments in Karnataka, Calder et al. (1993) concluded that eucalypts could use 100% of rainfall, used more water than crops but less than indigenous forest, and at one site appeared to "mine" 400–450 mm of water annually from deep soil storages. For plantations in Brazil Soares et al. (1997) reported 8 mm per day transpiration when water was not limited and almost zero in dry periods. In Australia the impact of eucalypt plantations on catchment processes is the subject of considerable scientific and public debate, hindered by incomplete knowledge of the water use characteristics of the range of species planted in varying climates and physiographic settings. Research into the proclivity of eucalypts to transpire groundwater has produced variable results (e.g. Greenwood et al., 1982; George et al., 1999; Cramer et al., 1999; Morris and Collopy, 1999). Early reports of high groundwater uptake (Greenwood et al., 1985) have not been matched in subsequent studies, and clearly there is still much to be learned concerning physiological controls on eucalypt transpiration (Hatton et al., 1998). Australian studies into tropical eucalypt water use have been confined to natural savanna forests (Cook et al., 1998; O'Grady et al., 1999; Hutley et al., 2000) where low leaf areas mitigate against high transpiration.

A change in the water balance is expected to result from replacement of grassland with trees, principally through increased transpiration and interception (e.g. Van Lill et al., 1980; Scott and Smith, 1997; Fahey and Jackson, 1997; Samra et al., 2001). However, the impact of plantation establishment on the hydrology of multiple landuse catchments that include native trees or shrub species and tall crops such as sugar cane is, in many environments, still unknown. Zhang et al. (2001) proposed generalised curves for the relationship between mean annual evapotranspiration (E_t) and annual rainfall for grassland and forests. These curves show an average difference of 345 mm in E_t between grass and forest for a rainfall of 1500 mm, with E_t for crops falling between the two.

Over 200,000 ha of *Eucalyptus* plantations have been established on the Leizhou Peninsula in western Guangdong, a subset of more than one million ha of eucalypt plantations in southern China. Fast growing species and hybrids are favoured (e.g. *E. urophylla*, *E. tereticornis*, *E. grandis*) with *E. urophylla* the most widely planted species in tropical areas. In rural areas of the Leizhou Peninsula surface water resources may be insufficient to meet the requirements of rice, sugar cane, pineapples and other crops during the dry season, necessitating groundwater extraction from farm wells. The expansion of eucalypt plantations on land previously used for crops or occupied by shrubs and grass has been accompanied by an understandable fear among farmers that plantation water use may lower water tables and reduce the availability of water for irrigation. In order to better understand the hydrology of the plantations and make appropriate recommendations for management, an experimental program was carried out to quantify the water use and other components of the water balance in two plantations on the Leizhou Peninsula.

2. Methods

2.1. Study area

The plantations are located at two sites in the Nandu River catchment of the central Leizhou Peninsula (Fig. 1). The Jijia site (20°54′N, 109°52′E) is on a basalt-derived clay soil, while the Hetou site (21°05′N, 109°54′E) is approximately 40 km north on a sandy soil of sedimentary origin. Both sites are on flat to undulating terrain typical of the peninsular lowlands. The climate is tropical, with long term monthly mean temperatures of around 28 °C in July and 16 °C in January. Annual rainfall varies from 1300 mm in the south to 1800 mm in the north of the peninsula, with high annual variation. Over 80% of the rain falls between April and September, up to half of this in typhoons which average two to three times per year. Mean daily maximum temperatures in the vicinity of the study sites are 31 °C in July and 20 °C in January,

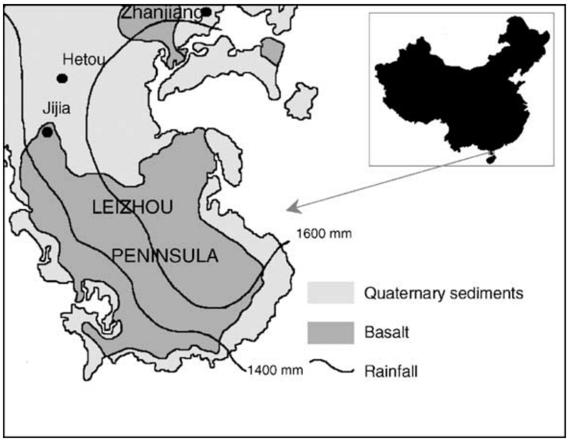

Fig. 1. Location map of the study sites.

with mean daily minima of 22 °C and 13 °C, respectively. The plantations at both sites were *Eucalyptus urophylla* planted in mid-1996 (3 m × 2.5 m spacing in Hetou, 3.3 m × 1.5 m spacing in Jijia) and monitored over a 2-year-period commencing in September 1999. The investigation of the plantations at this relatively young age is appropriate, as the usual rotation period for plantations in the area is 4–5 years. Plots of 40 m × 40 m were established within the plantations for measurement of the water balance components.

2.2. Climate variables

Meteorological observations were recorded at each site over a 2-year-period commencing in September 1999, by means of a Micropower data logger (Tain Instruments, Australia) and sensors mounted on a mast located in a cleared area within each plantation. Data were recorded at 30 min intervals, including solar radiation, wind speed, temperature and relative humidity at mid-canopy level. Half-hourly rainfall was measured by a tipping bucket rain gauge on each mast.

2.3. Stand characteristics

Stand growth and biomass characteristics were measured at approximately 6-monthly intervals in a representative 40 m × 40 m monitoring plot at each site. Measurements relevant to this paper were diameter over bark at breast height (DBH), overstorey leaf area index (LAI) measured using an Accupar ceptometer (Decagon Devices, Pulman, USA) and sapwood area derived from increment coring. Full details of these measurements and methods are given by Morris et al. (2004).

2.4. Soil properties and moisture content

Soil moisture content was monitored at 30 min intervals by MP-406 standing wave dielectric soil moisture probes (Agri-Tech Instruments, Beijing) buried at four depths (50, 150, 250 and 350 cm) in the soil profile in two locations at each site. Soil particle size distribution was measured from samples taken at 30 cm intervals to a depth of 3.9 m at the same locations, and fixed volume cores for bulk density determination were excavated from three locations at 20 cm intervals to a maximum depth of 80 cm. Gravimetric moisture content and matric potential obtained using the filter paper method of Greacen et al. (1989) on soil samples at 30 cm depth intervals to 3.9 m were used to derive a moisture release curve for each site. Falling head single-ring infiltrometer measurements were made at six positions in each plantation using 250 mm diameter rings with an initial head of water of 100 mm. The procedure was repeated immediately at each position to obtain a steady-state surface infiltration rate.

2.5. Evapotranspiration

2.5.1. Interception

Throughfall (TF) and stemflow (SF) were also measured at half-hourly intervals on 84 rain days at Jijia and 96 at Hetou representing a range of daily rainfall up to 60 and 86 mm per day, respectively. TF was measured using a series of four troughs with a total area of 1.06 m^2 placed beneath a representative section of canopy with an area of 10 m^2, and drained into a large tipping bucket recorder (1.0 mm per tip). The troughs were spaced to include two tree rows and two inter-row spaces. Stemflow was measured by means of PVC hosepipe cut in half laterally and fixed tightly around the trunks of four trees with diameter close to the stand mean, drained to a second tipping bucket recorder (0.5 mm per tip). Linear regressions relating rainfall to TF and SF were used to estimate TF and SF for each day (Table 1). Daily canopy interception was calculated as gross rainfall less throughfall and stemflow.

Table 1
Regression results for parameters used in E_t estimation.

Parameter	Equation	r^2	P-value	S.E.
TF vs. P Jijia	$y = 0.825x$	0.94	<0.0001	2.26
TF vs. P Hetou	$y = 0.776x$	0.91	<0.0001	3.50
SF vs. P Jijia	$y = 0.013x$	0.82	<0.0001	0.08
SF vs. P Hetou	$y = 0.025x$	0.77	<0.0001	0.25
T vs. Pet, ASW Jijia[a]	$\log y = 14.22 + 0.33 \log x1 + 0.626 \log x2$	0.81	<0.0001	0.22
T vs. Pet Hetou	$y = 0.431 + 0.125x - 0.0020x^2$	0.78	<0.0001	0.30
r_s vs. ψ_{50} Jijia, Hetou	$y = -0.602x + 106.9$	0.86	0.0009	99.24

[a] Where $x1$ is Pet and $x2$ is ASW.

2.5.2. Transpiration

Transpiration of the eucalypt overstorey during the first year of monitoring was measured by the heat pulse method using HeatPulser instruments (Edwards Industries, New Zealand). The methods of data collection and analysis have been reported separately by Morris et al. (2004). In brief, sapflow sensors were cycled through a representative sample of 18 trees at each site for 3–4 weeks per tree, and the resulting half-hourly estimates of sap flux density were scaled up to daily stand water use on a sapwood area basis following the approach of Khanzada et al. (1998). Understorey transpiration was not measured, although a discontinuous shrub understorey developed over time in the plantations, particularly at Jijia.

2.5.3. Soil evaporation

Soil evaporation (E_s) was measured by microlysimetry on 13 rainless days distributed through the year in 6–10 locations at each site. The lysimeters were constructed from 75 mm diameter PVC pipe, with a length of 200 mm. Each lysimeter was filled by driving it into the soil, carefully removed, weighed and replaced so that the exposed soil surface was level with the surrounding soil. After 4–6 h the lysimeters were re-weighed, and the average rate of evaporation over the measurement period was calculated as the mean weight loss from all lysimeters divided by their surface area and the duration of exposure. An apparent soil surface resistance during each measurement period was determined by inverting the Penman–Monteith combination equation (Monteith, 1965), using the measured evaporation rate with net radiation and vapour pressure deficit data estimated from the half-hourly meteorological observations and assuming a boundary layer resistance of $5\,\mathrm{s\,m^{-1}}$. The calculated apparent surface resistances showed a strong linear relationship with soil matric potential at the depth of the shallowest moisture sensor (ψ_{50} kPa), with the exception of 1 day at the end of the dry season when the surface was moist from rain in the preceding 24 h but the soil at 50 cm remained dry. This is a rare circumstance in the conditions of the study area, and the remaining data from both sites were combined to derive a linear regression relating apparent surface resistance ($r_s\,\mathrm{s\,m^{-1}}$) with ψ_{50} ($r_s = -0.6019y_{50} + 106.9$, $R^2 = 0.86$). The combination equation was then applied to estimate E_s (mm) for each day from daily meteorological observations, with surface resistance estimated from the 50 cm soil moisture observations and the fitted moisture release curve for each site, and again adopting a boundary layer resistance of $5\,\mathrm{s\,m^{-1}}$:

$$E_s = \frac{\varepsilon R_n + \lambda \rho D_q / r_a}{\varepsilon + 1 + r_s / r_a} \tag{1}$$

where ε is the dimensionless rate of change of saturated specific humidity with temperature (estimated as 2.2), R_n is net radiation, D_q is specific saturation deficit (calculated as 0.00622 × vapour pressure deficit, VPD kPa), r_a is boundary layer resistance, l is the latent heat of evaporation of water and r is the density of air. Daily net radiation was estimated from solar radiation (R_s) as $R_n = 0.8R_s - 90\,\mathrm{W\,m^{-2}}$ (Landsberg, 1986). Mean daytime values of vapour pressure deficit were calculated by averaging half hourly data during the period of each day when solar radiation was greater than zero. Potential evaporation was also estimated by the combination equation with a surface resistance of zero and estimating r_a as $10/u$ where u is wind speed ($\mathrm{m\,s^{-1}}$).

2.6. Water balance

A monthly water balance for the first year of observations was estimated according to the equation:

$$P = E_\mathrm{t} + \mathrm{RO} + \Delta S + D \qquad (2)$$

where P is rainfall, E_t is total evapotranspiration, RO is surface runoff, ΔS is the change in soil water storage and D is drainage below the root zone, calculated as a residual after specifying the other terms in (1). E_t is composed of canopy interception (I), transpiration (T) and soil evaporation (E_s). The runoff term in (2) was included in the residual drainage term. At Jijia this component is believed to be negligible as there is no anecdotal or physical evidence of surface runoff or extensive ponding within the plantation outside of extreme rainfall events, and there were no observations of this process by the permanently resident site-watcher over the duration of the study. At Hetou surface runoff and evaporation of ponded surface water following rainfall may have been more significant, and the calculated drainage overestimates deep soil infiltration to this extent. Rainfall associated with typhoons can generate high intensity surface runoff in non-forested areas of the Leizhou Peninsula and surrounding regions. The low slopes, rough cultivated surface and relatively high soil infiltration rates of the monitored sites mitigate against both the ready generation of overland flow, and production of shallow lateral subsurface flow.

In order to estimate the monthly and seasonal water balance during the second year of data collection, daily transpiration was estimated for each day using regressions derived from the year 1 data. The best correlations were obtained from a multiple regression of daily transpiration on potential evaporation (Pet) and available soil water (ASW) for Jijia, and from transpiration on Pet for Hetou. The regression results are given in Table 1. As the Pet-transpiration relationship was best described by a second order polynomial equation, the data for Jijia were log transformed to linearise all variables and back transformed to calculate daily values. Inclusion of ASW as a second independent variable for the Hetou regression did not result in a statistically significant improvement. The calculated monthly transpiration values for each site were combined with observed rainfall, soil moisture and evaporation data to infer monthly water balances using Eq. (2).

3. Results

3.1. Environmental variables

Monthly rainfall, mean daily daytime radiation and VPD, mean daily Pet and mean daily maximum and minimum temperature for each month are shown in Fig. 2. Temperature, VDP and Pet were 13–17% greater at Hetou, although radiation was 6% lower than Jijia. In year 2 (October 2000–September 2001) rainfall was higher while radiation and VPD were less than in year 1. Mean values of daily Pet for the 2 years were 9.99 and 8.40 mm at Jijia, and 11.39 and 9.95 mm at Hetou, respectively. Mean daily VPD was 0.85 kPa in year 1 and 0.75 kPa in year 2 at Jijia, and 1.0 and 0.87 kPa at Hetou. The monthly distribution of both VPD and Pet were similar in both years with the exception of peak values recorded in June 2000 and September 2001.

3.2. Soil properties

Table 2 gives the average particle size distribution, and shows clearly the contrast in texture between the sites. The soils at Jijia are clays grading to silty clay and silty clay loam, whereas the Hetou soils are sandy loams grading to sandy clay loams. This contrast is reflected in the moisture content–matric suction relationship (Fig. 3). Although there is some scatter associated with texture variation down the profile, the data demonstrate the very different water holding and storage capacity of the soils. Saturation is at the volumetric moisture content of 0.38 $\mathrm{cm^3\,cm^{-3}}$ at

Table 2
Soil particle size

Site and depth	Sand (%)	Silt (%)	Clay (%)
Jija			
0–2 m	11	25	63
2–4 m	22	42	36
Hetou			
0–2 m	74	4	22
2–4 m	66	7	27

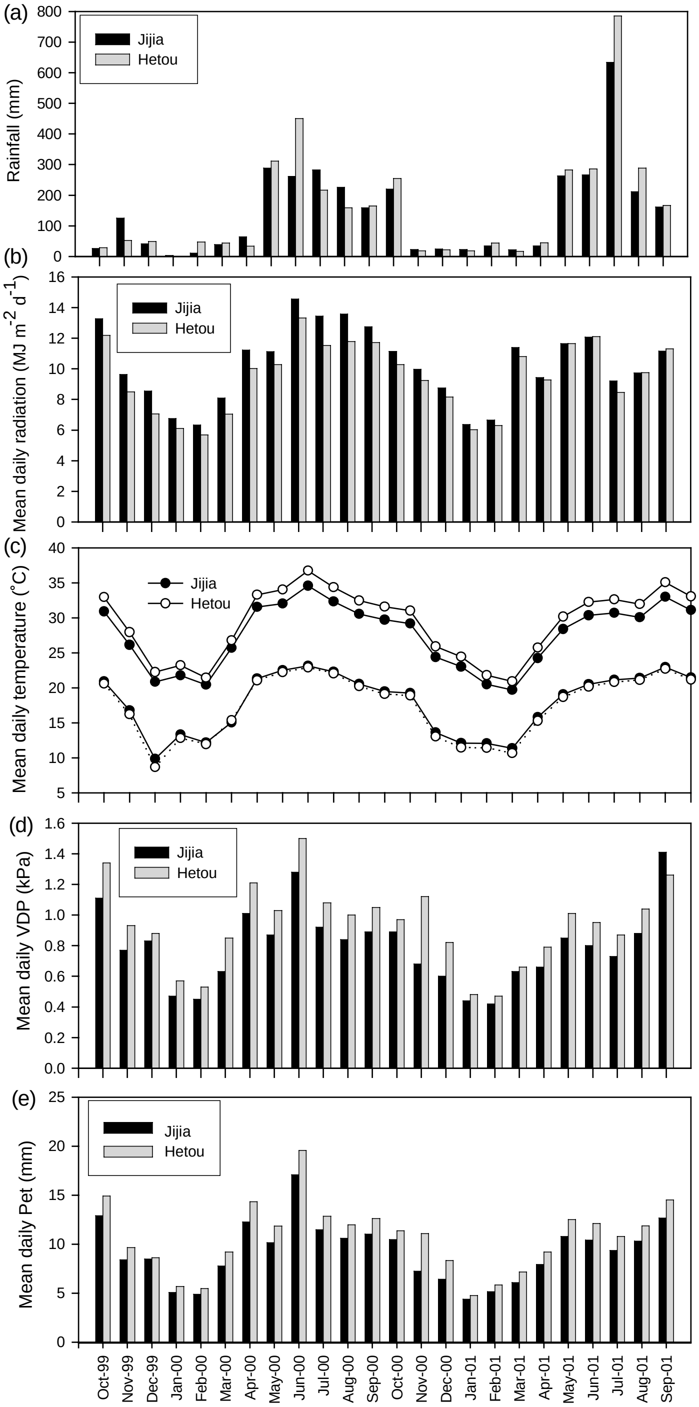

Fig. 2. (a) Monthly total rainfall, (b) mean daily radiation, (c) mean daily maximum and minimum temperature, (d) mean daily VPD, and (e) mean daily Pet, for each month.

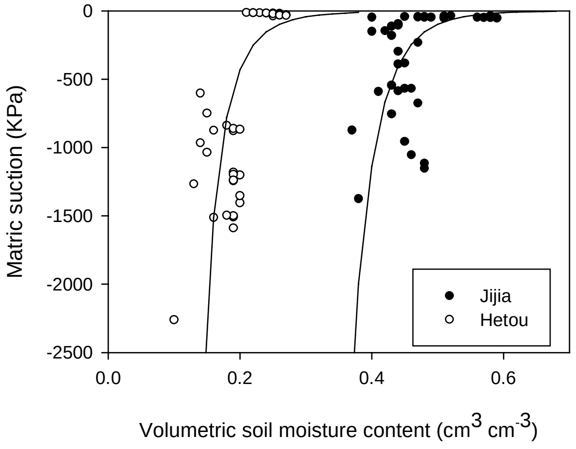

Fig. 3. Volumetric soil moisture content vs. matric suction for soil depths 0.5–4 m at Jijia and Hetou.

Hetou and 0.58 cm^3 cm^{-3} at Jijia. Mean bulk densities ranged from 1.5 to 1.7 g cm^{-3} at Hetou and 1.0 to 1.2 g cm^{-3} at Jijia. Mean surface infiltration rates were 473 mm h^{-1} at Hetou and 710 mm h^{-1} at Jijia.

3.3. *Stand characteristics*

The basal area of the 40 m × 40 m plots was 12.9 m^2 ha^{-1} in September 1999 at Jijia and 9.0 m^2 ha^{-1} at Hetou. Basal area increased by 2–2.7 m^2 ha^{-1} at both sites over the first year of observations and was 16.0 m^2 ha^{-1} at Jijia by May 2002. Conversely, the basal area at Hetou decreased in year 2 to 9.9 m^2 ha^{-1} by September 2001, as a result of typhoon damage in July 2001. Morris et al. (2004) report higher stand sapwood areas at Jijia (7.65–8.77 m^2 ha^{-1}), with values at Hetou ranging from 4.74 to 6.03 m^2 ha^{-1} over year 1. Stocking densities declined over time at both sites, from 1994 to 1612 stems ha^{-1} at Jijia, and 1356 to 1125 stems ha^{-1} at Hetou, with most of the decline in year 2. Leaf area index (LAI) was relatively low at both sites, with a mean of 1.5 at Jijia and 1.0 at Hetou. LAI peaked at both sites during the year 1 wet season.

3.4. *Water balances*

Monthly water balance values during the first year (October 1999–September 2000), derived from direct measurements of stand transpiration together with soil and climate observations, are depicted in Fig. 4a and b. Annual and wet/dry season values of the water balance components are tabulated in Table 3. Monthly water balance values for year 2 (October 2000–September 2001) are shown in Fig. 8a and b, based on transpiration estimates derived from the regressions in Table 1.

3.4.1. *Soil water storage*

Fig. 5 shows the total available soil water to 4 m at both sites for the duration of the study. There is a very large difference between the sites, both in terms of depth of available water stored and the amplitude of responses to rainfall. The water holding capacities of the soils are substantially different as evidenced by Fig. 3. The seasonal changes can be best seen at Jijia where deficits of up to 200 mm are recorded during the dry seasons. Daily losses at Jijia during the wetter months can be 10–20 mm, with generally <3 mm evaporated or transpired. At Hetou, the small changes in daily storage suggest either very rapid drainage of infiltrated water or significant losses by surface runoff or evaporation of ponded water. There were no observations of the latter during visits by field staff, but the very high rainfalls in July 2001 may well have generated overland flow. The measured infiltration rates indicate most rainfall intensities could be accommodated. Fig. 5 indicates the incidence of peak soil water availability to be very transient, suggesting persistence of at least small moisture deficits throughout the study period.

3.4.2. *Evapotranspiration, year 1*

Total E_t comprised 70% of rainfall in year 1 at Jijia and 66% at Hetou. Dry season E_t exceeded rainfall at both sites, 144% of P at Jijia and 153% at Hetou, while wet season E_t was 55 and 52% of P for Jijia and Hetou, respectively. Transpiration is the largest constituent of E_t for most months, but is very close to, or slightly exceeded by, the sum of I and E_s during the wet season at Jijia (Fig. 6a and b). At Hetou T is exceeded by $I + E_s$ during the year 1 wet season. T rarely rose above 2.5 mm per day, with a mean daily value of 1.49 mm at Jijia and 1.53 mm at Hetou for the period of direct measurements (year 1). Daily values of T are plotted against Pet in Fig. 7a and b. A second order polynomial equation gave a slightly better fit to the data than a linear equation ($r^2 = 0.76$ cf. 0.70 for Jijia, and 0.78 cf. 0.70 at Hetou), suggesting transpiration

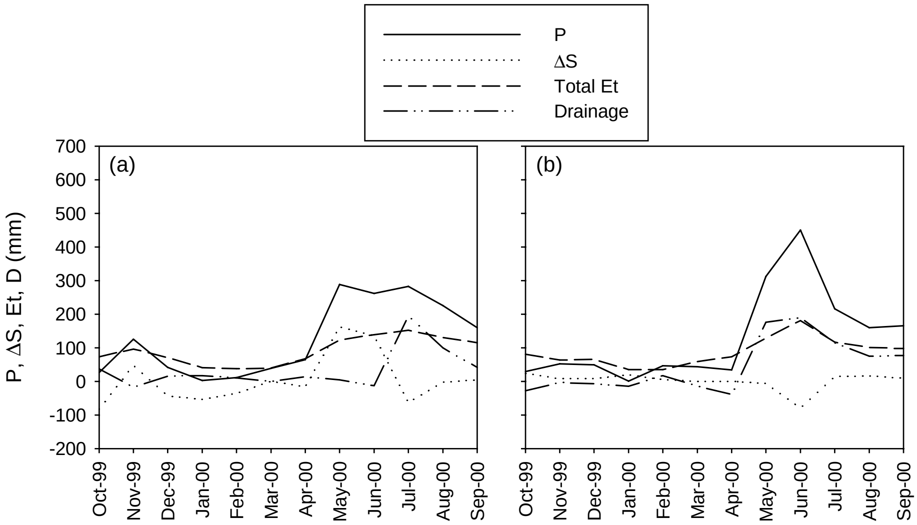

Fig. 4. Monthly water balance for (a) Jijia and (b) Hetou for year 1 (October 1999–September 2000).

may be approaching an asymptote at higher values. The values from Hetou clustered around 10–15 mm Pet and 0.5–1.0 mm *T* are from February 2000 when soil water availability was at a minimum.

The proportion of rainfall intercepted by the canopy was constant for both sites over the range of observed daily rainfall, averaging 16.2% of rainfall at Jijia and 19.9% at Hetou. TF and SF were 82.5 and 1.3%, and 77.6 and 2.5% at Jijia and Hetou, respectively. The relationship between daily rainfall and TF was strongly linear, and a linear fit was also satisfactory for SF (Table 1).

Soil evaporation was clearly an important component of total E_t, particularly at Jijia where it reached 49 mm per month in July 2000, and was 19 and 11% of annual rainfall, and 26 and 16% of ET in 1999–2000, for Jijia and Hetou, respectively. Thirty percent of the year 1 wet season E_t was from E_s at Jijia. The maximum daily rate was 2.77 mm at Jijia and 1.37 mm at Hetou. The difference in year 1 E_t between the sites

Table 3
Annual and wet/dry season water balance

Period	P	I	E_s	T	ΔS	R
Jijia						
October 1999–September 2000	1525	247	285	548	50	396
October 1999–March 2000 (dry)	243	39	72	243	−170	59
April 2000–September 2000 (wet)	1282	208	212	305	220	337
October 2000–September 2001	1918	311	208	519	−126	1007
October 2000–March 2001 (dry)	346	56	75	227	−265	253
April 2001–September 2001 (wet)	1571	255	133	292	139	753
Hetou						
October 1999–September 2000	1555	310	177	546	−15	538
October 1999–March 2000 (dry)	221	44	66	226	−63	−53
April–September 2000 (wet)	1282	266	111	320	48	591
October 2000–September 2001	2226	437	169	498	32	1090
October 2000–March 2001 (dry)	373	74	62	214	−21	44
April 2001–September 2001 (wet)	1853	363	108	283	53	1046

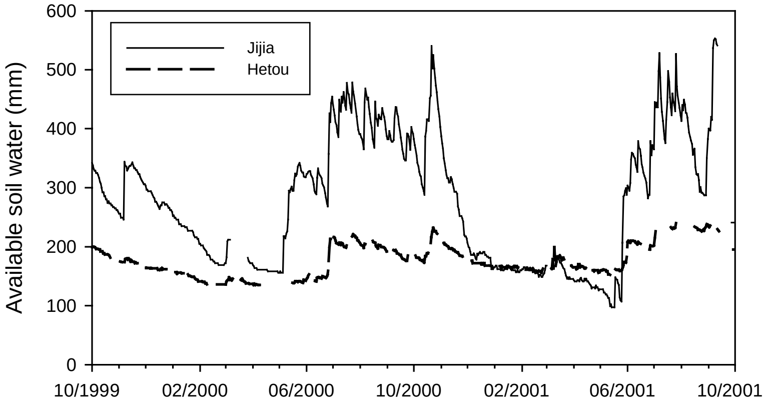

Fig. 5. Daily available soil water for October 1999–September 2001.

is explained by E_s. Mean soil surface resistance was higher at Hetou, averaging 696 versus 499 s m^{-1} over year 1. E_s for both years was highly linearly correlated with Pet for both wet and dry seasons at Hetou ($r^2 = 0.98$ and 0.96, respectively, $P < 0.0001$). The correlation with Pet was similarly strong at Jijia for the dry seasons ($r^2 = 0.94$, $P < 0.0001$), but E_s exhibited far greater variance during the wet season ($r^2 = 0.46$, $P < 0.0001$) where the variance increased with the value of Pet. The addition of available soil water, which fluctuates considerably at Jijia during the wet season (Fig. 5), to a multiple regression explained 71% of the variance.

3.4.3. Evapotranspiration, year 2

The total estimated E_t was very similar to that of year 1 at both sites despite a 20–30% increase in rainfall (Fig. 8a and b). For prediction of T from ASW and Pet (Jijia) or Pet alone (Hetou) we have assumed that the environmental conditions and physiological factors driving transpiration have not altered markedly from year 1. The plots of Pet and VDP in Fig. 2 demon-

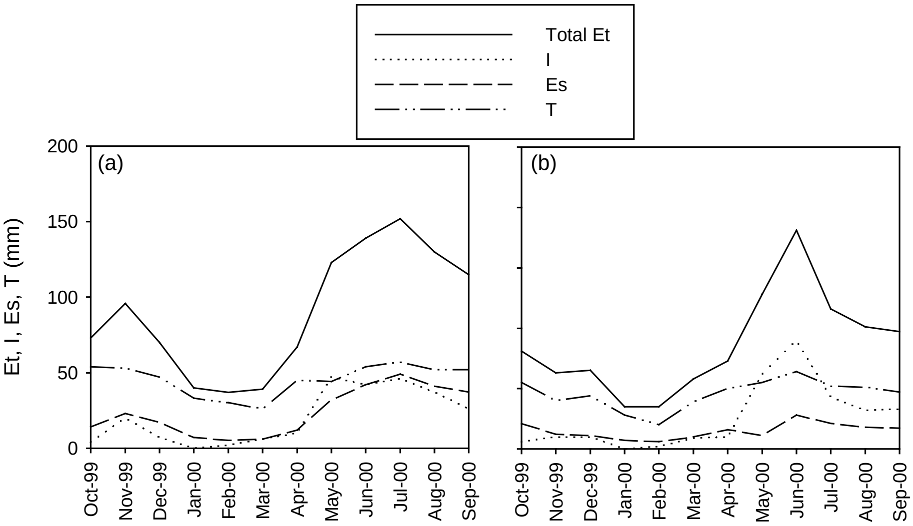

Fig. 6. Monthly values of E_t components, E_s, T, and I for (a) Jijia, and (b) Hetou, for year 1 (October 1999–September 2000).

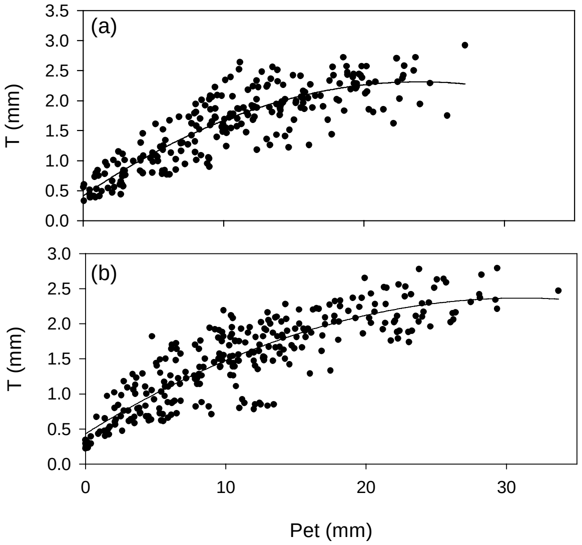

Fig. 7. Daily potential evaporation vs. transpiration for (a) Jijia and (b) Hetou for year 1 (October 1999–September 2000).

strate that atmospheric demand did not exceed the values recorded in year 1. Although there was an overall decline in basal area and LAI at Hetou by August 2001, for most of the year values of both variables would have been similar to those in the early part of year 1. Conversely, there was higher water availability at Hetou in year 2 (Fig. 5). Basal area increased at Jijia in year 2, but there was slightly less available water.

The total measured and estimated E_t for year 2 was 54% of P at Jijia and 50% at Hetou. These values were 42 mm less than in year 1 at Jijia and 71 mm greater at Hetou. Again dry season values exceeded rainfall at both sites, while wet season E_t decreased to 43% of rainfall at Jijia, and 41% at Hetou. The estimated T at Hetou was exceeded by interception alone in the year 2 wet season (Table 3, Fig. 9b). As interception was estimated as a linear function of daily rainfall it must increase in year 2, but on three wet days during year 2 rainfall exceeded the range of data used to derive the I versus P relations by 20–120 mm, and overprediction of I on these days is a possibility. Soil evaporation was less in year 2, both in depth of water and as a percentage of rainfall, particularly at Jijia (Fig. 9a). This may have been partly in response to the slightly lower Pet, and to lesser ASW in the early wet season.

3.5. Drainage

Drainage at Jijia was 23% of rainfall for year 1, and 47% in year 2, with corresponding values of 39 and 53% at Hetou. There are a number of months in the wet seasons in which drainage becomes the major loss term in the water balance at both sites (Figs. 4 and 8). Importantly, there is a significant proportional

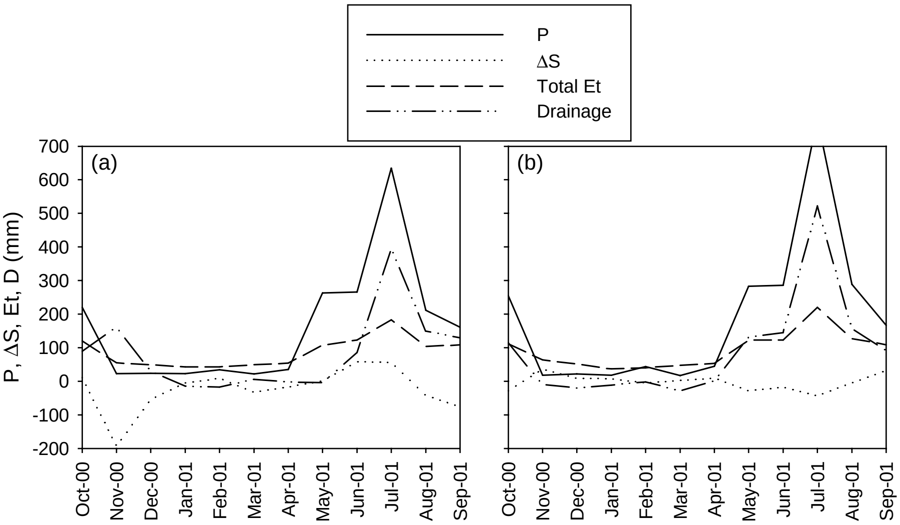

Fig. 8. Monthly water balance for (a) Jijia and (b) Hetou for year 2 (October 2000–September 2001).

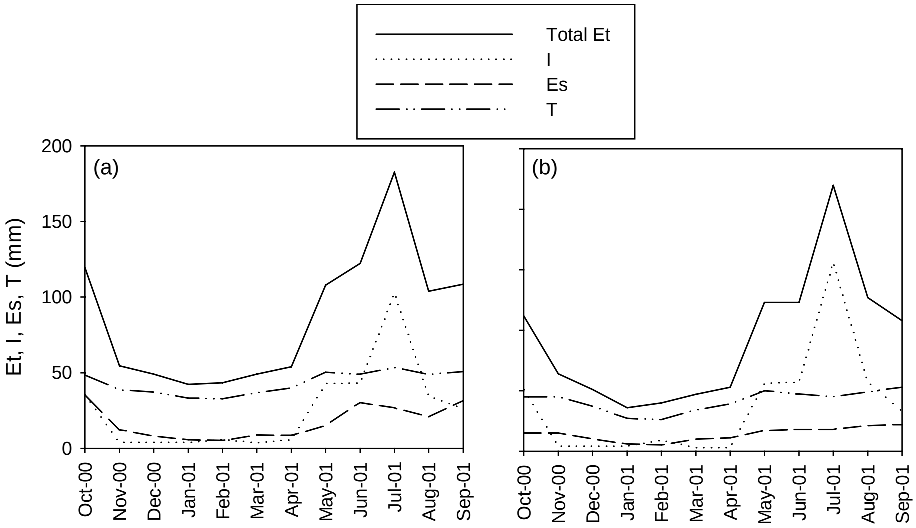

Fig. 9. Monthly values of E_t components, E_s, T, and I for (a) Jijia and (b) Hetou, for year 2 (October 2000–September 2001).

increase in drainage at both sites with higher rainfall in year 2. During July 2001 at Hetou some surface runoff is likely to have occurred during the typhoon rainfall, and is included in the drainage term. Table 3 and Figs. 4 and 8 show the majority of drainage occurred in the wet seasons when rainfall easily exceeded soil storage capacity and evapotranspiration. Negative drainage values during the dry months in Figs. 4 and 8 denote water accessed by trees from storages beneath the soil moisture sensors. This condition prevailed for 5 months in both dry seasons at Hetou, with totals of 110 and 71 mm in years 1 and 2, respectively, and 32 and 39 mm at Jijia. These values account for 31 and 33% of dry season transpiration at Hetou and 13 and 17% at Jijia. The relatively high drainage estimated at Jijia for the year 2 dry season is a product of high rainfall in late October 2001, filling soil water storages which then drained over the subsequent month. An illustration of the ready drainage of water during the wet season is given in Fig. 10 where drainage at Jijia for 1 week at the end of the wet season (October 2000) is compared with a week at the height of the previous dry season (December 1999).

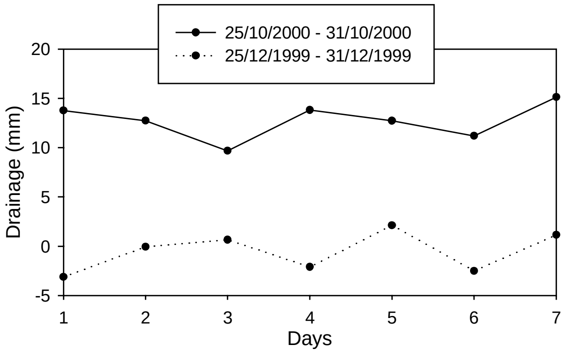

Fig. 10. Drainage at Jijia for the weeks 25–31 December 1999 and 25–31 October 2000.

4. Discussion

The measured and estimated water balances for the 2 years suggest the E_t rates are relatively constant despite the increased rainfall in year 2. This finding is conditioned by the estimation of year 2 transpiration from regressions on Pet for Hetou and on Pet and ASW for Jijia. As the driving variables do not exceed those in year 1 (Fig. 2), we believe the year 2 transpiration rates are defendable. Morris et al. (2004) found that although low VPD contributed to capping transpiration at around 2.5 mm per day, analysis of stomatal conductance–soil moisture–VPD relationships showed available soil water depletion suppressed transpiration to 61% of maximum potential water use at Jijia, and 67% at Hetou. ASW did not increase markedly in year 2, probably due to the strongly seasonal rainfall distribution and rapid drainage at both sites. Soil evaporation was somewhat decreased in year 2, reflected in the lower Pet, while the interception term increased proportionally with rainfall. On the available evidence, it is plausible to expect E_t to remain at similar values to those reported here for annual rainfall of 1500 mm or greater, given a reasonably similar distribution of rainfall and other climatic factors. Excess rainfall appears likely to recharge deep soil water or groundwater stores. The rates of non-transpired ΔS at Jijia during the wet seasons demonstrate that large volumes of water can drain through these soils even with the relatively high clay content. At a rate of 15 mm per day, monthly drainage could reach 450 mm if the supply existed. The negative monthly drainage estimates suggest prolonged dry seasons would see mining of deeper soil or ground water stores, particularly at Hetou where this process provided a third of the dry season transpired water. The extent to which this could cause a lasting depletion of stored water would clearly depend on the wet season recharge. The reason for the differences in deep extraction between the sites probably lies in the contrasting soil texture. Although we have no observations of rooting depth, it is likely roots could more easily penetrate the sandier Hetou soil, and the lower ASW in the upper profile would tend to promote deeper rooting. The capacity to access water stored at depth may also explain the non-significance of including the ASW term in regressions of T on Pet at Hetou. Deeper rooting would help to both compensate for the lower ASW of the upper profile and act to smooth seasonal fluctuations in soil moisture. On the experimental evidence, abstraction from deep water storages at Hetou does not appear to be on the scale of that observed by Calder et al. (1997), and the low rates indicate an unsaturated soil moisture store is being accessed rather than an aquifer. However, stocking density and sapwood area are significantly lower at Hetou (Morris et al., 2004), and higher VPD and the ability to extract water from deep stores probably account for the similarity of transpiration rates at both sites. Increased stocking would potentially increase water use, but additional trees would compete for the limited available soil water.

E_s/E_t ratios are relatively high at Jijia, at 0.26 and 0.2 for years 1 and 2, respectively, peaking at 0.3 in the year 1 dry season. These values underline the importance of incorporating E_s into studies of forest water use. This is particularly pertinent for plantations where tree spacing and suppression of weeds, shrubs and understorey may leave substantial areas of bare soil. Soil properties appear to control the differences in E_s and in drainage between the two sites. The greater water holding capacity at Jijia provides a near surface store for soil evaporation which was almost 3 times higher than at Hetou and is associated with notably higher soil surface conductance. The difference in E_s between years largely accounts for the higher total E_t rates in year 1. The importance of ASW on Jjiia E_s is confirmed by the improved regression relationship for T when ASW is added to Pet as an independent variable. Estimated drainage through the sandier Hetou soils was higher during the wet seasons, when water could not be stored as at Jijia although as noted, some surface runoff or evaporation of ponded water may have contributed to the calculated drainage during periods of very high rainfall. There was a 300 mm difference between the sites in the maximum change in storage from wet to dry season, although the unaccounted deep abstraction of water by trees at Hetou compensates for this difference to some extent.

Some discussion of the methods used in this study is warranted. In spite of the increased uncertainty arising from assumptions used in estimating year 2 transpiration, the extension of water balance calculations to a second year has helped to further our insights into the likely hydrologic impact of plantations in this area. There is no experimental evidence to indicate that errors would be so great as to invalidate our general conclusions. Multiple regressions of year 1 T on monthly Pet and ASW yielded higher r^2 values than those for the daily regressions. However, the daily analyses based on a larger number of observations are considered to be more robust and less prone to the influence of outliers. Estimates of transpiration from the monthly predictions were within 5 mm per month of the summed daily predictions. Ideally, estimation of E_s would include observation of the energy balance at ground level. However the correlation of actual E_s from lysimetry with the estimated E_s via the apparent soil conductance–Ψ_{50} relationship produces a practical solution that directly relates continuously measured variables with evaporative processes. Finally, the residual term in the water balance equation collects the errors. Any unobserved surface runoff or understorey

E_t will be represented as drainage. Given the high rates of daily ΔS observed during the wet season, the monthly drainage totals appear well within reasonable limits. A further point is the age of the plantations, 3–5 years. Research on eucalypt plantations in temperate climates (particularly South Africa) has shown peak E_t generally occurs at 8–12 years (Scott and Lesch, 1997; Scott and Smith, 1997), although Dye (1996) demonstrated an earlier peak response. This time frame is substantially longer in natural eucalypt forests (e.g. Langford, 1976; Cornish and Vertessy, 2001; Vertessy et al., 2001). Potentially, it might be suggested that estimation of the water balance at 3–5 years could underestimate plantation water use in this environment should rotations be lengthened. However, permanent plot measurements, biomass sampling and leaf area observations at the Leizhou sites found growth to be declining by age 5 or less (Baker et al., 2003), strongly indicating that the timing of this study was appropriate for investigating the hydrologic impact of eucalypt plantations in the study area.

What are the implications of these results for assessing the impact of eucalypt plantations on water resources? It is difficult to answer this question without knowledge of the water use of other vegetation or alternative land use in the area. There are no comparable studies in the Leizhou area. The E_t rates are at the lower end of the spectrum tabulated by Bruijnzeel (1990) for tropical lowland forests and transpiration rates are similar to those measured by Giambelluca et al. (2003) for rainforest species in nearby Vietnam. The results may also be compared with the relationship between mean annual rainfall and E_t for forests estimated by Zhang et al. (2001) from 250 catchments worldwide. These data indicate that E_t at Hetou is significantly lower that that expected for the recorded rainfall, and for year 1 Jijia conforms to the Zhang et al. (2001) model but is on the lower bounds of the model for year 2. The implication is that the eucalypts do not use more water than other forest species, and that E_t rates at both sites are lower than may be expected, at least during wetter years. Estimates of sugar cane water use have been made in several countries, all with differing environmental conditions and experimental or analytical methods. Published E_t rates for non-water limited conditions are equal to or greater than those found in this study (Jalota and Arora, 2002; Yang et al., 1997; Wallace et al., 1991; Inman-Bamber and de Jager, 1988; Thompson, 1976), but may not be in an environment with comparable atmospheric demand. Certainly leaf areas quoted are higher than the Leizhou eucalypt plantations, but rooting depths are likely to be far shallower. The much shorter and more variable crop rotations within a mixed agricultural system would also heavily influence water balances. Experimental data for a range of crops have shown E_s/E_t for the same LAI to be around twice that estimated here for Jijia (Villalobos and Fereres, 1990; Wallace et al., 1991; Leuning et al., 1994) which could compensate for reduced extraction of water at depth. The interplay of these factors make generalised predictions of crop water balances difficult. The experimental evidence indicates that eucalypt plantation water use in Leizhou is limited by environmental factors, but they can contribute to dry season soil moisture deficits. Irrigation is frequently required for crops in the area at the end of the dry season. The evaporative demand far outweighs the dry season rainfalls recorded during this project, suggesting a net deficit would occur under most vegetation. Relatively small abstraction of water from deep storages by the plantations could be viewed as self-irrigation.

5. Conclusions

Estimation of a monthly water balance of two *E.urophylla* plantations in tropical southeastern China found evapotranspiration rates were relatively stable at each site over a 2-year-period despite a 20–30% increase in rainfall in year 2. These rates ranged from 969–1150 mm. Transpiration was measured during year 1 and estimated during year 2 to be <600 mm per year. The difference in total E_t between the sites was partly attributable to higher soil evaporation at Jijia, where fine textured soils exhibited far greater water holding capacity and hence evaporative availability than the coarser textured soils at Hetou. Drainage rates were 26 and 35% of annual rainfall at Jijia and Hetou, respectively, in year 1, and increased to 52 and 49%, respectively, in response to higher rainfall in year 2. Although E_t exceeded P during the dry season, indicating the plantations abstracted water from soil profile storages, it would seem the plantations do not pose a threat to water resources in this region.

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