Models for Estimating Evapotranspiration of Irrigated Eucalypt Plantations

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Abstract

Evapotranspiration, a major component of water balance and net primary productivity in plant-based terrestrial production systems at local and regional scale, is difficult to measure. In order to better understand tree growth and water-use relationships, and to design plantations and optimize their irrigation schedules, it is important to estimate the climatically induced evapotranspiration demand of tree crops. This demand, considered as the maximum evapotranspiration (ETm), is regulated by the resistances imposed by canopy surfaces during the process of evapotranspiration. This chapter describes several simple methods that have been proposed previously to estimate ETm and compares various process-based estimates of ETm with water-use rates determined from a water balance study. The observations from the study conducted at Forest Hill near Wagga Wagga, NSW, Australia, show that ETm can be estimated from standard meteorological parameters as a one-step approach using the Penman-Monteith equation. In the absence of required climatic data, ETm can be estimated from the radiation using Priestley-Taylor technique. For irrigation scheduling, however, ETm may be estimated from pan evaporation data using an estimated pan factor. This factor is site specific and varies with the season and the age of the plantations. For purposes of design and scheduling of irrigation, monthly pan factors can also be determined from climatic data using the Penman-Monteith equation.

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Introduction

Annual average terrestrial rainfall in the world is estimated at 750 mm, and about two-thirds are being returned back to the atmosphere as evapotranspiration (ET), which makes ET the largest single component of the terrestrial hydrologic cycle. Vegetation ET and CO_2 exchange maintain a dynamic but continuous exchange between land surface, plantation, and atmosphere (Savabi and Stockle 2001). Greenhouse effect-induced warming under changing climate has further accelerated the need for understanding the disturbances in hydrologic cycle (Kaczmarek et al. 1996). As such, forest plantations have strong influence on the hydrologic and carbon cycles and salt balance of the site (Musselman and Fox 1991). Actual measurement of evapotranspiration on the trees is very difficult, but certain methods have been developed for regular measurement of humidity and wind velocities using the instrumentation mounted above the plantation and thus estimate (model) the water fluxes occurring out of the canopy at the plantation stand scale. Since the majority of the precipitation returns to the atmosphere as evapotranspiration, the most difficult process to physically measure in hydrologic cycle, an effective estimation of the evapotranspiration is important to understand the terrestrial ecosystem water balance.

In addition to a strong influence on site hydrologic and carbon cycles, plantations also have the potential that can be used for a variety of nontraditional roles such as recharge interception, maintaining favorable water, and salt balance in soil profile and for the productive and ecologically sound reuse of municipal sewage and industrial effluents or agricultural drainage water. An accurate estimate of the rate of water use of plantations is required for evaluating the effectiveness of plantations for achieving the same. The actual evapotranspiration (ETa) of a plantation is a complex interaction and aggregation of transpiration by individual tree in the overstory plantation, transpiration by the understory vegetation and evaporation from the soil surface. A number of methods exist for direct measurement of water use by individual components of the plantation (e.g., tree sap flow measurements for transpiration) or by integrated portions of the plantation (e.g., Bowen ratio energy balance, eddy correlation methods, ventilated chambers, and weighing lysimeters). Integrated plantation ETa is most commonly estimated by solving the water balance equation in which all input and output components are measured. However, all of these methods are cumbersome, labor intensive, and require complex set of instrumentations, which is expensive and not easily transportable and applicable at every site. Therefore, development and use of models in describing water fluxes out of the stand canopy is a necessary step in understanding the effect of plantations on sustainability and optimal utilization of available water resources (Kite 1998). For these reasons, many empirical and physical models have been developed to estimate evapotranspiration based on climatic data (Penman 1948; Monteith 1965; Priestley and Taylor 1972; Perry 1987). Vorösmarty et al. (1998) used water balance model and compared nine models on the watersheds of the continental USA. ETm models have also been compared on sparsely vegetated rangeland (Stannard 1993), wild land vegetation in semiarid rangeland (Dye 1993), partial canopy/residue-covered fields (Farahani and Ahuja 1996), maize with bare soil (Farahani and Bausch 1995), and barley (Tourula and Heikinheimo 1998). Federer et al. (1996) compared ETm models at seven locations, but did not compare the ETm estimates with actual measurements. These models estimate ET from calculated potential evaporation using a range of environmental, physical, and physiological factors, including temperature, humidity, radiation, wind speed, canopy height and configuration, and stomatal conductance. However, ET estimated using different models varies widely because of the differences in the parameters used for estimating the evapotranspiration among the models (VEMAP Members 1995; Ford et al. 2007). Only a few studies (Joshua et al. 2005; Domec et al. 2012) have analyzed evapotranspiration dynamics in forest ecosystems not only because of the general focus has been on agriculture, but also due to the difficulty of obtaining evapotranspiration measurements in forests. Therefore, to compare the plantations, ET estimated using different models with that of actual ETa, the non-limiting growth *Eucalyptus* (*Eucalyptus grandis*) and pine (*Pinus radiata*) plantations established at Wagga Wagga, Australia, and irrigated with effluents to maintain soil water at field capacity were monitored regularly at 15 days interval continuously for 4 years for their water balance. The observations were then used to model the pathways of water and nutrient use and develop the guidelines for optimizing their design and management (Myers et al. 1999). The evapotranspiration of a crop freely supplied with water is determined by the energy supply and resistances to vapor transport across the leaf and soil surfaces and out of the canopy (Monteith 1986). It was, therefore, assumed that ETa measured in this study was the maximum possible rate of evapotranspiration (ETm) by these plantations under the prevailing meteorological conditions.

Rationale to Develop and Use ET Models

Evapotranspiration has been the focus of quantitative agronomic studies because its quantitative link or relationship to growth has been well established by many research workers in the past (Passioura 1977; Doorenbos and Kassam 1979; Fischer 1979; Perry 1987; Wallace 1994; Myers et al. 1999). Since the capacity of plantations to use irrigation water may be limited by the evaporative demand of the environment or by nutrient availability, the maximum water use of plantation needs to be estimated to determine actual application rates. ET is the largest component of the water balance in the irrigated areas, but it is the most difficult process to estimate because it involves the integrated effects of soil, plant, and climate. The actual measurement of ETm is a site-specific, cumbersome, expensive, and time-consuming process because it requires a complex set of lysimetric and instrumentation installations with continuous precise monitoring of all input and output components of water balance like precipitation, irrigation, interception losses, changes in soil profile moisture, and deep drainage to arrive at actual water balance. For this reason, only limited published information is available on measurements of ETm of young irrigated plantations (Dunin and Mackay 1982; Myers et al. 1999). There are many empirical and physical models of measuring evapotranspiration based on climatic data, which are being used for designing and scheduling irrigation and for predicting crop growth. The water, carbon, and energy fluxes as well as meteorological variables above the forest ecosystem canopy are measured using FLUXNET network of towers across the world (Goldstein et al. 2000). Although the first modeling and analysis of forest evapotranspiration was done in the 1970s (Spittlehouse and Black 1979) as the novel way of acquisition of flux data from this tower, this facility, as part of AmeriFlux network, has been used by (Joshua et al. 2005) for comparing five potential evapotranspiration (PET) models on ponderosa pine forest ecosystem in Northern California at larger scale.

Prior to 1948, two theoretical approaches, viz., the aerodynamic ability of removal of moisture from any surface in relation to the turbulent transport of vapor by the process of eddy diffusion and the partition of incoming net radiation between sensible and latent heat transfer were used to estimate the crop evaporative demand. Penman combined these two approaches and termed the new term “the combination equation” to estimate open water evaporation (Penman 1948). Later, a seasonal factor “*f*” was introduced to derive evapotranspiration of the crops using the evaporation from an open water surface and coined the term potential evapotranspiration (PET). This was applied to areas of actively growing short green crops such as alfalfa or grass of uniform height of 15–30 cm, completely covering the soil surface, well supplied with water and about 100 m from the upwind edge of the crop (Penman 1948, 1956). Penman’s combined equation method has been widely used to determine the maximum water requirement of crops because growth of most crops is highest when the water supply is non-limiting.

Since Penman’s studies, several modifications have been incorporated in the combination equation in order to make it more applicable under variable conditions. A number of simple empirical forms of the aerodynamic wind speed functions have been derived by researchers for making it suitable under particular sets of conditions. In Australia, Dilley and Shepherd (1972) derived an empirical wind speed function for a potato crop at Aspendale, Victoria. Thom and Oliver (1977) incorporated a generalized ventilation term into the combination equation to estimate evapotranspiration of crops ranging from short grass to tall pine trees. Monteith (1965) revised the combination equation from first principles to include resistances to water transport from the soil to atmosphere. The evapotranspiration of a crop freely supplied with water (wet soil) is governed by the energy supply and the resistances to vapor transport across the leaf and soil surfaces (canopy resistance, or more precisely, surface resistance, e.g., Monteith 1986) and out of the canopy (aerodynamic resistance). This rate of water use, maximum evapotranspiration (ETm), postulates that the freely evaporating crop does not behave as the completely wet system to which crops were initially compared in Penman's definition of potential evapotranspiration (ETp). ETm is, however, the important upper boundary of actual evapotranspiration for any given crop (Monteith 1965; Tanner 1967; Ritchie and Burnett 1971; Jenson 1973; Connor 1975; Doorenbos and Pruitt 1977; Passioura 1977; Stewart et al. 1977a, b). These models estimate actual evapotranspiration from calculated potential evaporation using a range of factors or constants. In the present chapter, the accuracy and reliability of following six different models for predicting ETm of irrigated *Eucalyptus* plantations from time of planting to the stage of canopy closure have been compared by using data sets of Wagga Wagga experiments on sewage water use. These included (i) Penman universal combination equation (Penman 1948, 1956), (ii) A Penman-Monteith equation (Monteith 1965) using wind function of Thom and Oliver (1977), (iii) radiation equation (Priestley and Taylor 1972), (iv) two saturation deficit equations (Dilley and Shepherd 1972), and (v) class A pan evaporation measured on site. These models were chosen because they are commonly used in water balance studies (Arnell and Reynard 1996) and hydroinformatics (Naoum and Tsanis 2003).

Site Description

For comparing the ET of plantations estimated using different models with that of actual ETa, plantation was established adjacent to the sewage treatment works of Forest Hill town Wagga Wagga, NSW, Australia (35°10'S, 147°28'E). The site receives 570-mm mean annual rainfall with relatively more winter-dominant distribution. Annual pan evaporation is 1860 mm and strongly seasonal, varying from a monthly low of 35 mm in June and July to a peak of 320 mm in January. The mean minimum temperature of 3 °C is observed in the coldest month of June, while the mean maximum temperature of the hottest month of January is 31 °C. The site experiences on an average of about 13 frost days per year. Soils of the site are having a well-drained sandy loam or sandy clay loam A horizon (20–45-cm deep) overlaying a sandy-clay to medium-clay B horizon. These are classified as Red Chromosol and Red Kandosols and Red Podsolic and red earth, respectively, in the Great Soil Group Classification. The land was previously used for wheat cropping and sheep grazing. Meteorological data (rainfall, air temperature, humidity, solar radiation, pan evaporation, wind speed, wind run, and direction) were recorded at an hourly interval using an automatic weather station (Starlog, UNIDATA Australia, Perth, Western Australia) established at the site. While the supplementary data required for the analyses (e.g., 3-hourly wet and dry bulb temperatures and air pressure) were obtained from the Bureau of Meteorology weather station located 3 km from the site, daytime positive net radiation above the crop canopy (*Rn*) was estimated from daytime global radiation (*Rs*) using the following equations of models of Linacre (1968) and Leuning et al. (1991a):

$$Rn = Rs(1-\alpha) - Rl \tag{1}$$

$$Rl = \left[0.1 + (1-0.1)\left(\frac{n}{N}\right)\right] \cdot \left[(\varepsilon_a - \varepsilon_c) . \sigma . (T+273)^4\right] \tag{2}$$

where Rl is the net upward long wave radiant flux density, α is the canopy albedo (0.15 for eucalypts and 0.25 for grass), n is daily duration of clear sunshine (hrs), N is the time from sunrise to sunset in hours, ε_a is the clear sky emissivity, ε_c is the canopy emissivity (0.96 for eucalypts), σ is the Stefan-Boltzmann constant, and T is the near-ground air temperature (°C). Daily mean saturation deficit (es-ea) was calculated from 3-hourly observations of wet and dry bulb temperature taken between dawn and dusk (Lowe 1977).

Plantation Establishment and Management

Six-month-old *Eucalyptus grandis* seedlings were planted at 2 m×3 m spacing (1667 trees ha^{-1}). Irrigation treatments, applied in duplicate on 0.2 ha plots of 300 trees each, were based on the water-use rates of the plantations and varied seasonally in response to the climate and canopy development. Under-tree micro-sprinklers were used to apply secondary-treated municipal sewage effluent at a discharge rate of 4.6 mmh^{-1}. The medium (M) irrigation treatment consisted of application of effluents at the estimated water-use rate of the plantation less rainfall. The aim of applying irrigation at this rate in M treatment was to maintain the deep drainage near to naturally occurring rate, while other two irrigation treatment plots received nominally twice and half as much effluent, respectively. Two plots of only pasture without *Eucalyptus* plantation were also irrigated at their rate of water use and less rainfall. Complete details of the experimental design used and treatments applied are as per that of Myers et al. (1999). Irrigation scheduling was controlled, and the applied volumes were logged, by a PC-based irrigation program (IRRICOM, Peter Cornish & Associates Pty Ltd, Canberra, Australia). Irrigation was applied at night to minimize seasonal variation in irrigation interception loss. For the purpose of irrigation scheduling, plantation water use was estimated using the water balance equation over 2-weeks intervals. Inputs used were rainfall, canopy interception, irrigation volume, and changes in soil water storage. Soil water content of the plantation and the irrigated pasture was measured with a neutron probe (503 Hydroprobe, Campbell Pacific, Pacheco, CA, USA) every 2 weeks in three access tubes per plot at nine depths to 2 m. Plots were irrigated weekly during the first 3 years and twice weekly subsequently. The irrigation aimed to fill the top meter of soil to 90 % of the drained upper limit (DUL) of soil water holding capacity. DUL was taken as the wettest drained profile recorded, 2 days after substantial rain in spring. A refill level of 90 % was used to reduce the risk of drainage occurring if rain fell shortly after irrigation, and complete details of the irrigation strategy and scheduling were followed as suggested by Myers et al. (1999).

Weather During Study Period

Mean daily climatic data are presented for each month of the 4-year period in Table 1, and a comparison of seasonal daily variation of solar radiation (Rs), wind speed (U), average temperature (T ave), relative humidity (RH), and day length (DL) is shown in Fig. 2. These data illustrate that the trees were exposed to variation in the annual and seasonal climatic conditions. As the season progressed from July (midwinter) to January (midsummer), there was increase in radiation (195–488 W m^{-2}), temperature (8.1–22.9 °C), vapor pressure deficit (relative humidity decreased from 80 to 48 %), and hence evaporative demand (pan evaporation increased from 1.2 to 8.6 mm). During hot summer periods, higher radiation and higher vapor pressure deficit produced a greater evaporative demand (Epan of 7.7–8.6 mm d^{-1}). The wind speed was higher in December–January (2.3–2.4 m s^{-1}) which also contributed to increased evaporative demand.

Estimation and Measurements of Actual Evapotranspiration (ETa)

Surface runoff, subsurface lateral flow, deep drainage, ET (using crop factor of that stage), and interception losses are the components that need to be recorded for arriving at the periodic water balance at any given site. However, under our site (Wagga Wagga, NSW, Australia) conditions, neither surface runoff nor subsurface lateral flow (as monitored by logging piezometers) was observed during the experimental period. It implied that soil has

Table 1 Monthly climatic data compared with pan evaporation from class A pan for Wagga Wagga, NSW, during 1991–1995

	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Total rainfall (mm)	67	46	69	70	55	63	40	57	66	35	56	47
Average daily temp (°C)	8.1	8.4	10.6	14.9	17.5	21.5	22.9	22.8	19.0	15.2	11.5	8.6
Average daily relative humidity (%)	80	73	70	62	54	50	48	52	55	58	73	80
Average daily global radiation (W m^{-2})	198	269	331	422	463	435	488	437	411	341	271	195
Average daily wind speed (m s^{-1})	1.2	1.6	1.9	2.0	2.2	2.3	2.4	2.2	2.0	1.6	1.2	1.3
Average daily sunshine (h)	4.3	6.0	6.8	9.1	9.5	8.9	10.2	9.6	9.0	8.4	5.7	4.2
Average daily Epan (mm)	1.2	1.8	2.6	4.5	6.4	7.7	8.6	7.7	6.0	3.7	1.9	1.1

high hydraulic conductivity and the drainage was the main component of water loss other than evapotranspiration and interception. However, since the irrigations were designed to leave a soil water deficit of 25 mm or more in the top meter of soil, it was assumed that with < 25-mm rain in a cycle, drainage below 1 m would be negligible. The water balance equation could be solved for desired period of interval; in our case it was for every 2-week cycle. For the dry cycles, ETa was calculated as:

$$\Delta WU = \frac{WU}{(t2 - t1)} = SWt1 - SWt2 + \sum_{t2}^{t1} IRn + \sum_{t2}^{t1} Pn \qquad (3)$$

where ETa is the mean daily evapotranspiration between time t1 and t2, SWt1 and SWt2 are the soil water storage at time t1 and t2, and $\sum Pn$ and $\sum IRn$ are the cumulative net precipitation and net irrigation between time t1 and t2. A crop (plantation) factor was calculated for each of these dry 2-week cycles as the ratio between ETa and measured pan evaporation (Ep). When there was more than 25 mm of rainfall in a cycle, a crop factor for that wet cycle was calculated as the mean of the crop factors of the preceding and subsequent dry cycle. This was applied to the measured Ep to estimate the water use for the cycle. In this way, the water use of every 2-week cycle was either measured (dry cycles) or estimated (wet cycles). Only 31 % of all cycles were wet, and these were predominantly in winter when up to 50 % of cycles were wet. The proportion of wet cycles during the summer irrigation seasons was zero in the second year and 15 % in the third year. Net precipitation and irrigation (i.e., total minus interception loss) were measured during a number of rainfall and irrigation events using interception troughs and time domain reflectometry (TDR). Scaled from these measurements and those reported by Myers and Talsma (1992) and Myers et al. (1996), interception loss was calculated as a fixed rate per rain or irrigation event within an irrigation season. We calculated ETa from age 6 months to the time when the canopy was closed (age 2 years) with the foliage biomass of ~5 t ha^{-1} and the leaf area index (LAI) > 4.0. To partition the total plantation water use into tree and understory evapotranspiration prior to canopy closure, two pasture plots were also irrigated at their estimated water-use rates determined in the same manner as the *Eucalyptus* plots. Eighty-six fortnightly measurements of water-use data sets covering a range of LAI and atmospheric conditions were compared with the model predictions.

The biweekly measurements of ETa made from 6 months of tree growth to the stage of canopy closure, i.e., 4 years are presented in Fig. 3 and

Table 2 Measurements[a] of monthly mean daily actual evapotranspiration (ETa, mm d^{-1}) of an irrigated eucalypt plantation for 4 years from planting

Season	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
1991–1992								3.8	3.0	2.1	1.1	0.8
1992–1993	0.9	1.5	1.8	2.8	3.3	4.4	6.1	6.0	4.7	4.3	2.5	1.7
1993–1994	1.6	1.9	2.3	3.5	5.9	6.3	7.3	6.2	4.6	3.3	2.3	1.1
1994–1995	1.1	1.1	2.5	3.6	5.3	6.5	6.1	6.8	6.1	3.5	1.9	1.5

[a] The measurements were taken at 14-day intervals

Table 2. Because these measurements were made under non-soil water-limited conditions, the magnitude of ETa and ETm in this study was found to be the same. These data were used in the comparisons presented in the following section. As the season progressed, ETa ranged from 1.1 to 7.3 mm d^{-1}. During the nonirrigation period of winter season, mean monthly ETa was around 1.1–2.3 mm d^{-1} increasing to 7.3 mm d^{-1} in the summer irrigation season. The results show that there was a sharp variability between the seasons reflecting a similar variation in the driving environmental variables of radiation, temperature, and wind. The seasonal variation in evapotranspiration was recorded to be most prominent after the canopy closure stage. Between the months of February and June, for example, ETa varied from 3.8 to 0.8 mm d^{-1} in 1992 compared with 6.2 to 1.1 mm d^{-1} in 1994. The results also show that evapotranspiration in the 1993–1994 season was higher than in 1994–1995 (e.g., in December, ETa of the eucalypt plantation was 7.3 mm d^{-1} in 1993 compared with only 6.1 mm d^{-1} in 1994) which again reflected the effect of environmental variation dominating the evaporative demand. The water balance measurements were made with every possible accuracy and care, and because ET was the only unmeasured component of the water balance during fortnights with low rainfall (dry cycles), the water use calculated by water balance was considered accurate enough to be used in comparing other indirect techniques (models) of estimating ET.

Models for Prediction of Maximum Evapotranspiration (ETm)

The six models of increasing complexity were assessed based on the precision and accuracy of their estimates of ETm compared to ETa for 86 2-week cycles using regression techniques. The coefficient of efficiency (E), coefficient of determination (R^2), the parameters to assess the closeness of fit of the regressions to the 1:1 line, and the precision of the estimates when forced through the origin, respectively, were determined statistically using the procedures of Aitken (1973) in following equation:

$$\mathrm{E} = \frac{\sum (Y_i - \bar{Y})^2 - \sum (Y_i - X_i)^2}{\sum (Y_i - \bar{Y})^2} \tag{4}$$

Prior to canopy closure, plantation water use can be estimated using the Penman-Monteith method by the sum of the tree water use and grass water use based on the proportion of the trees covering the ground within the plots. The ground cover estimates could be derived by fitting a logistic curve for the observed data taken from photographs (Fig. 1). In our studies, we assumed that evaporation from understory was negligible after the canopy closure stage, i.e., when the LAI>4.0. Details of functions and utility conditions of each model used are seen below.

(i) Penman Universal Combination Equation

This model assumes that for a crop/plantation freely supplied with water, potential evapotranspiration (ETp) can be calculated by combining the energy balance and aerodynamic equations developed using the meteorological data from nearby observatory. The combination equation used in this model involves the following functions:

$$\mathrm{ETp} = c\,(Er + Ea) \tag{5}$$

$$Er = \frac{\Delta R_n}{(\Delta + \gamma)} \tag{6}$$

$$Ea = \frac{gf(u)(e_s - e_a)}{(\Delta + g)} \tag{7}$$

$$f(u)=0.35(0.5+0.01*u) \tag{8}$$

Here, in equations from 5 to 8, the two terms *Er* and *Ea* are the energy and aerodynamic components, respectively, and *c* is the dimensionless correction factor which has been set equal to 1 in our study, Δ is the slope of the saturation vapor pressure versus temperature curve at mean air temperature, γ is the psychrometric constant, and *es* and *ea* are the saturated and actual vapor pressures, respectively. $f(u)$ is a wind speed function and u is wind speed measured in miles d^{-1}, and f is obtained from regression analysis of ETm and ETp. ETm was then estimated from ETp using the equation

$$\mathrm{ETm}=f\,\mathrm{ETp} \tag{9}$$

(ii) Penman-Monteith Combination Equation

The Penman combination equation was further generalized to a significant extent with incorporation of canopy responses to evaporative demand of the environment by Monteith (1965). In this one-step approach, the evapotranspiration (ETpm) can be calculated based on radiation and resistances to evaporation imposed by the atmosphere and the canopy. Under irrigated conditions, in soil moisture maintained at field capacity, evapotranspiration is assumed to be equal to maximum evapotranspiration (ETm). It involves the following function:

$$\mathrm{ETm}=\mathrm{ETpm}=N\left(\frac{1}{\lambda}\right)\left(\frac{\varepsilon(cRn)+\frac{\rho\lambda D}{ra}}{\varepsilon+1+\frac{rs}{ra}}\right) \tag{10}$$

where N stands for the period from sunrise to sunset in seconds, c is a dimensionless parameters assumed to be equal to 0.1 (Raupach 1995), ε is a dimensionless slope of the saturated specific humidity curve, respectively. λ is the latent heat of vaporization (J kg^{-1}), ρ is the density of air (kg m^{-3}), and D is the saturation deficit. *rs* and *ra* represent the canopy and aerodynamic resistances to water vapor transport from the soil and soil surface through the plant to the canopy surfaces and from there into the atmosphere.

Though the aerodynamic resistance, *ra,* has many formulations, some are based entirely on empirical evidence, and the others are related to the mixing length theory, but Thom and Oliver (1977) developed following general wind speed function by including crop geometry and height, which were used in present comparison of models.

$$r_a=\frac{(\ln\frac{Z-d}{Zo})(\ln\frac{Z-d}{ZoHE})}{k^2U} \tag{11}$$

Here, U stands for the average wind speed in m s-1 measured at Z m above the plantation canopy, d the zero plane displacement, k the von Karman constant, and Zo and Z_{oHE} are the roughness lengths (m) of the surface for momentum transfer and heat and water vapor transfer. These were calculated as explained in Raupach (1995).

Canopy resistance, the parallel sum of the stomatal resistances of the photosynthetically active leaves and dependent on LAI, varies significantly with the time of the day and therefore requires complex models to estimate (Dolman et al. 1991; Wallace 1994). In our studies at the Wagga Wagga, LAI was measured at 6-monthly intervals using both destructive and nondestructive techniques. These data were then used to derive a logistic function to obtain estimates of LAI (Fig. 1). Trees also control the environmental effect on evapotranspiration through opening and closing of stomata, and thus canopy resistance is an additional function of radiation, saturation deficit, and soil moisture stress as expressed in the following relationship of r_s to these important variables in an empirical equation (Leuning et al. 1991a; Raupach 1995; Shuttleworth 1989).

$$r_s=\frac{r_{s(\min)}}{f_R(Rs)\times f_D(D)\times f_W(W)\times f_L(L)} \tag{12}$$

In the above equation, $r_{s(\min)}$ represents the minimum value of the canopy resistance (27 s m^{-1} for *Eucalyptus* trees and 60 s m^{-1} for grass) under optimal growth conditions, and f_R, f_D, f_W, and f_L are dimensionless environmental functions, which range between 0 and 1. The evaporative stresses on the trees are caused by lower incoming solar radiation (Rs), higher saturation deficit (D), higher soil

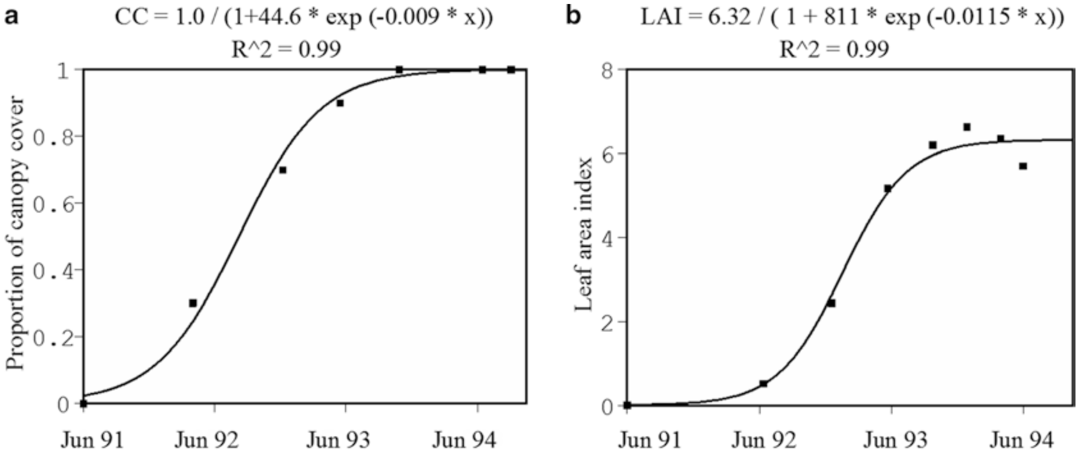

Fig. 1 Measurements showing (**a**) the proportion of tree canopy cover, CC, and (**b**) changes in the leaf area index, LAI, in relation to the age of the eucalypt plantation. The seedlings were planted in June 1991. The lines were fitted through the observed data using logistic functions

water deficit (*W*), and lower LAI. Threshold values for solar radiation (350 W m^{-2}; Leuning et al. 1991b), saturation deficit (35 g Kg^{-1}; Hookey et al. 1987), and LAI (3.0–3.5; Dunin and Aston 1984; Persson 1995) were used in this study. Since the irrigation strategy is based on bringing one-meter depth of soil twice every week to 90 % of the DUL of the soil moisture holding capacity, the average *fW* during the experimental period was assumed to be equal to 1.0. This model has also been used earlier to estimate ETm of Eucalyptus trees and grass by setting Zo to one tenth of plant height (Szeicz et al. 1969; Watts and Hancock 1984) (Fig. 2).

(iii) Radiation Equation (Priestley-Taylor Model)

Radiation methods assume that the ultimate source of energy required for evaporation is the sun. Priestley and Taylor (1972) used the radiation term of Penman's combination equation (Er) for estimate ETm as under and established values of α, the adjustment factor or widely known as Priestley-Taylor parameter, from comparisons with lysimetric data (e.g., McNaughton and Black 1973).

$$\mathrm{ETm} = \alpha Er = \alpha \frac{\Delta \mathrm{Rn}}{\Delta + \mathrm{g}} \qquad (13)$$

Using selected days of measurements, they found α to vary between 1.08 and 1.34 with an overall mean of 1.26. They derived from the Penman combination equation the limits of variation of α under potential conditions to be $1 < \alpha < (\Delta + \gamma)/\Delta$). However, Pereira and Villa-Nova (1992) suggested that the fluctuations for α are governed primarily by the sensible heat flux and Stannard (1993) using multiple linear regression analysis established the dependence of α on LAI and the time of rainfall under sparse vegetation in San Luis Valley in southern Colorado. For a Douglas fir forest, McNaughton and Black (1973) found $\alpha = 1.05$. Davies and Allen (1973) reported α values between 1.01 and 1.34. Pereira and Villa-Nova (1992) showed that the fluctuations of α, either on an hourly or on a daily basis, are governed primarily by the sensible heat flux variations. Viswanadham et al. (1991) obtained a mean value of 1.16 for the Amazon forest. Shuttleworth and Calder (1979) showed that the Priestley-Taylor model is of limited use for tall vegetation, where there are large atmospheric exchange coefficients. However, Viswanadham et al. (1991) found good agreement between the model and independent measurements made with an eddy correlation technique. In our studies, we estimated ETm using the Priestley-Taylor model by obtaining a value for α through -regression analysis of the measured data at the site.

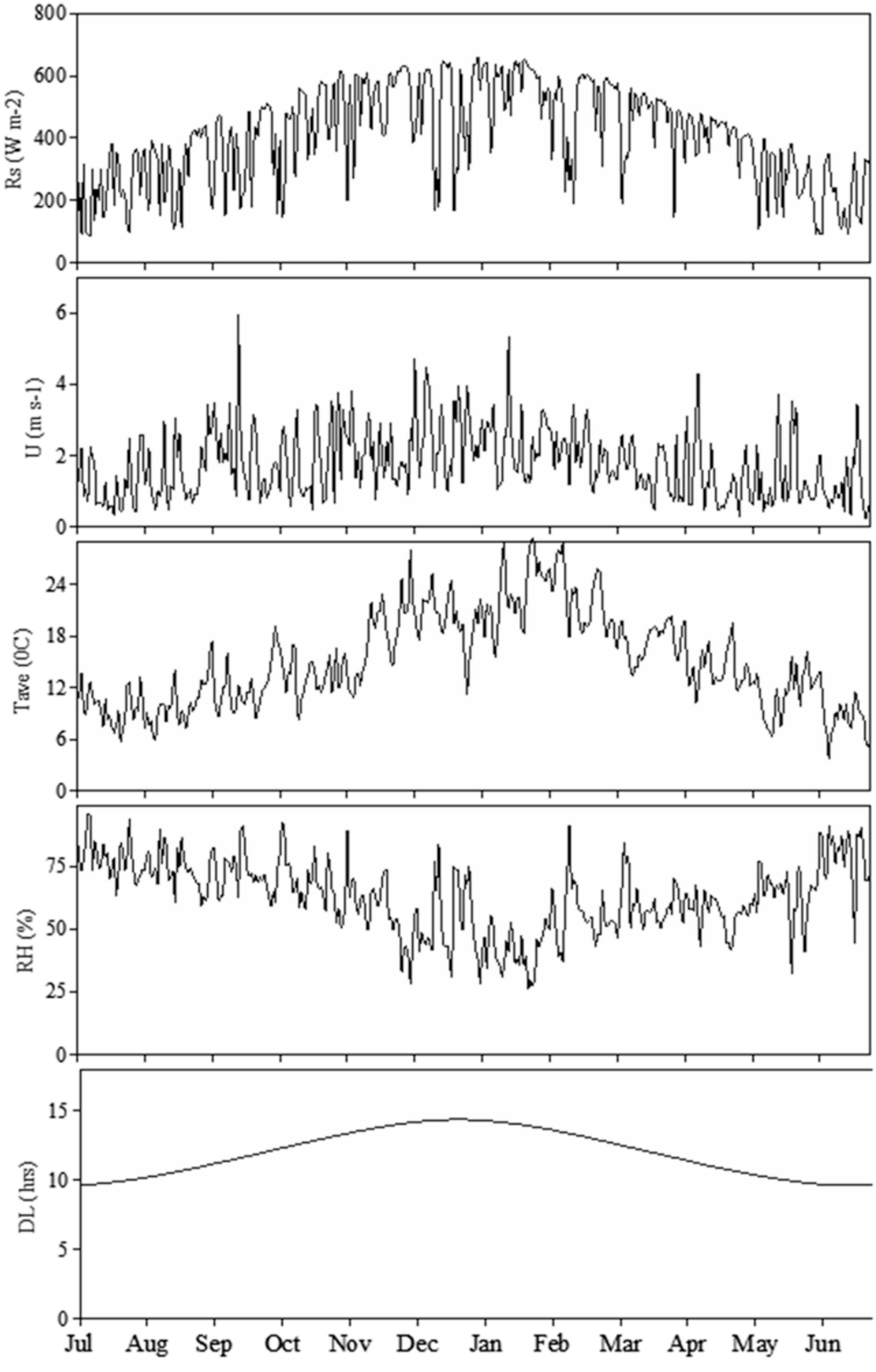

Fig. 2 Variation in daily values of daytime solar radiation (Rs), wind speed (U), average temperature (Tave), relative humidity (RH), and daylength (DL) for Wagga Wagga, New South Wales, during a year (1993–1994) of the experimental period

(iv) Two Saturation Deficit Equations

Correlation between ETp and saturation deficit was first pioneered by Dalton (1802) and later on used to estimate ETm of various crops (Tanner and Sinclair 1983) and also for trees (Perry 1987). Responses of trees to atmospheric humidity tend to limit water use during high atmospheric demand. However, Australian studies of water use indicate that although *Eucalyptus* species tend to have effective stomatal response mechanism to soil moisture deficits, but certain species may not have a well-developed response to atmospheric humidity (Carbon et al. 1981; Colquhoun et al. 1984; Greenwood et al. 1985). However, Dye (1993) observed that the stomatal response to atmospheric humidity in *Eucalyptus grandis* varied seasonally and at high saturation deficit, the response was less. This model assumes that the evaporative demand of the atmosphere, ETm, can be adequately represented by the vapor pressure gradient above the tree canopy. Two forms of this model were used in our study. The first and complex form (VPD1 method, Eq. 13) included both the canopy and aerodynamic resistances to estimate ETm and referred as Esd1 as under.

$$\mathrm{ETm} = \beta\mathrm{Esd1} = \frac{\rho \times Cp}{\gamma}\frac{(e_s - e_a)}{(r_s + r_a)} \qquad (14)$$

In this, β is a constant of proportionality, ρ is density of air (kg m^{-3}), Cp is specific heat of air (J kg^{-1} $°C^{-1}$), and γ is the psychrometric constant (mb $°C^{-1}$). The second form (VPD2 method, Eq. 14) used a simpler relationship between ETm, and vapor pressure deficit referred as Esd2 as depicted below.

$$\mathrm{ETm} = \beta 1\mathrm{Esd2} = \frac{\gamma}{\Delta + \gamma}(e_s - e_a) \qquad (15)$$

Here, $\beta 1$ stands for a constant of proportionality (mm mb^{-1}), and Δ is slope of the vapor pressure curve at the daily average air temperature point (mb $°C^{-1}$).

(v) Class A Pan Evaporation (Epan)

This model, a simple method of estimating ET, requires only evaporation data from an open container such as an evaporation pan, which are easily available from Class A pans. Many researchers have used this method to estimate daily ETm of various crops including trees. Many irrigation models use pan evaporation data for estimating ET and to schedule irrigation (Jones and Bauder 1987; Smittle and Dickens 1992; Smittle et al. 1992; Theiveyanathan et al. 2004). It is always easier to collect data from an evaporation pan than from vegetation (Doorenbos and Pruitt 1977; Myers and Talsma 1992). The pan evaporation method is a two-step process involving conversion of pan evaporation to ETp using pan coefficient followed by calculation of ETa by using crop coefficient (Pereira et al. 1995). In the present study, both these coefficients have been combined as a single pan factor (Kp) and used to estimate ETm from the pan evaporation data as seen below.

$$\mathrm{ETm} = \mathrm{Kp}\,\mathrm{Epan} \qquad (16)$$

In the past, pan factors have been derived and used for monthly intervals (Doorenbos and Pruitt 1977), for daily intervals (Smittle and Dickens 1992), and for 5-day intervals (Chiew et al. 1995). In this study, 2 years of weekly totals of pan evaporation and ETa data were used to derive monthly pan factors for the irrigated *Eucalyptus* plantations. ETa is obtained from the Penman-Monteith ET estimation. The weekly totals were used because in many cases the daily pan evaporation data suffer from measurement errors especially when evaporation was low during winter months. The weekly total pan evaporation helped to mitigate the errors of daily measurements.

Comparison of Model Estimates and Actual Evapotranspiration

The 2-weekly actual evapotranspiration and the calculated estimates from the two forms of the combination equation (i.e., ETp and ETpm), from radiation (Er), from two forms of saturation deficit (Esd1 and Esd2), and from pan evaporation (Epan) were plotted against time for the plantation growth period of 6 months to canopy closure stage of 4 years (Fig. 3). The monthly mean values of the estimates of Er, Esd1, Esd2, ETp, ETpm, and Epan for

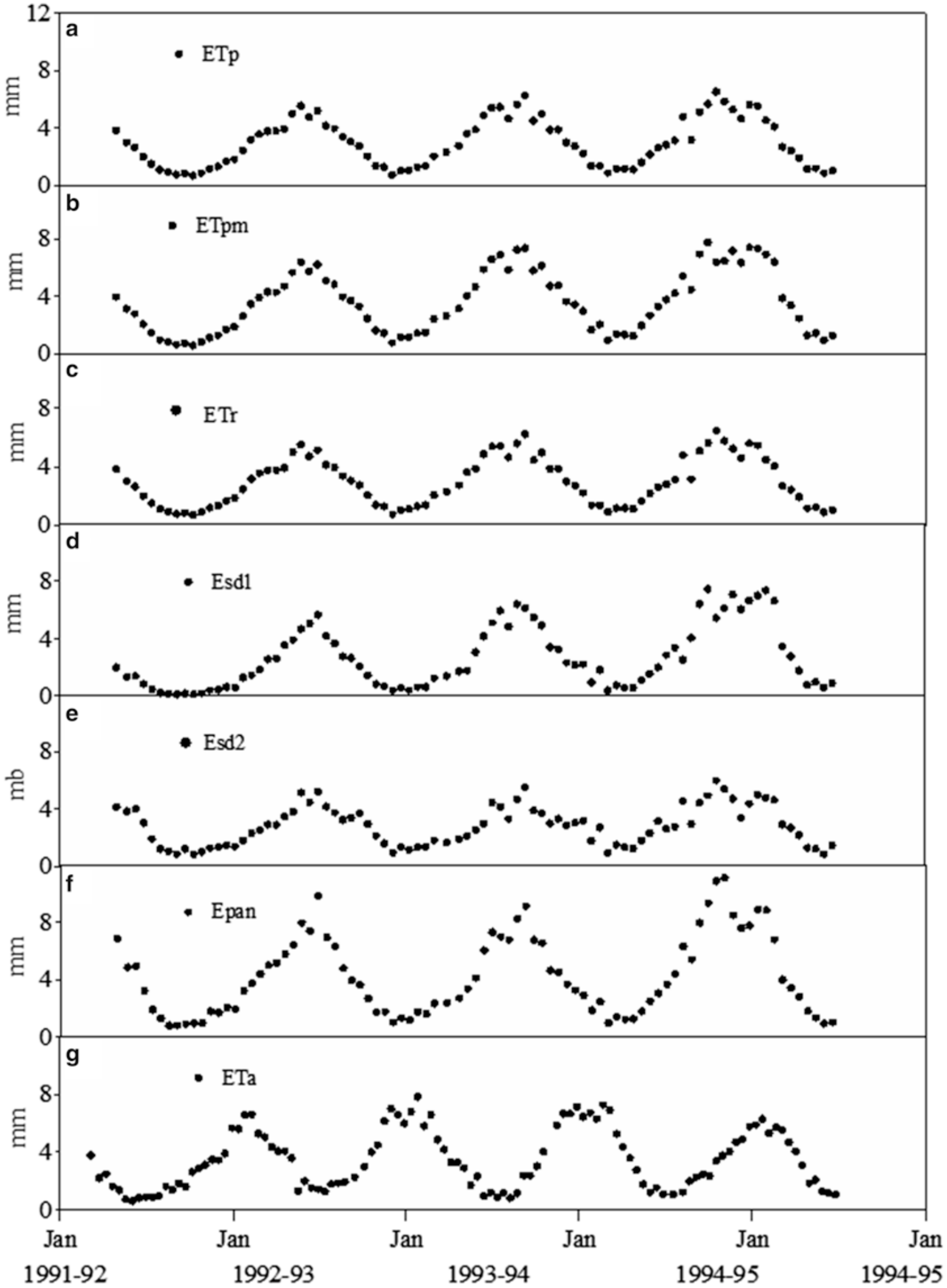

Fig. 3 Fourteen-day mean daily estimates of maximum evapotranspiration (ETm) using the following methods: (**a**) Penman combination (ETp), (**b**) Penman-Monteith (ETpm), (**c**) Priestley and Taylor (Er), (**d**) and (**e**) saturation deficit method 1 and 2 (Esd1 and Esd2), (**f**) pan evaporation (Epan), and (**g**) mean daily measurements of actual evapotranspiration (ETa)

the study period years (1991–1995) are also shown in Table 3.

During the 4-year period, all the estimates of ETm showed marked variation between seasons, fluctuating from a minimum value in June–July to a maximum value in December–January (Table 3). Pan evaporation was consistently higher than the other estimates throughout the period especially during summer months when it was the highest. Joshua et al. (2005) observed that, for all potential evapotranspiration models, simulated ETm compared reasonably well with measured evapotranspiration at the beginning of the summer season (April–May). However, as the soil moisture decreased through the summer, all models tended to overpredict evapotranspiration because these were designed for well-watered soil conditions rather than natural summertime Mediterranean drought conditions.

In our studies, various estimates of ETm were also plotted against measured ETa (Fig. 4), and a statistical analysis of these relationships was also carried out. The coefficient of efficiencies for all the data sets was estimated from the regression analysis. With the exception of the Esd1 estimate, all relationships were forced through the origin to result in zero measured water use implying zero estimate of ETm and valid comparisons of the relationships made in terms of their slope and coefficient of determination. Further, a power relationship was used to relate the response of Esd1 estimate to Eta. During hot summer months of December and January when the vapor pressure deficit was high, the ETpm method consistently overestimated the actual water use by 0.5–1 mm. By varying the threshold vapor pressure deficit in the Penman-Monteith combination equation from 0.010 to 0.045 kg kg^{-1}, a better prediction of actual water-use rate was obtained for *Eucalyptus* trees at this site compared to use of a constant threshold vapor pressure deficit of 0.023 kg kg^{-1} (Fig. 4).

Comparisons Across Seasons

Eighty-six measurements of fortnightly mean daily water use recorded from 6 months of tree growth to the stage of canopy closure were compared against the estimates of ETm to produce the relationships between the estimated and measured data (Figs. 4 and 6). The models, which were used to describe the regression analysis of the two forms of the vapor pressure deficit methods, ES1 and Es2, were different: Esd1 was fitted with a power function and Esd2 was fitted with a linear function. The most important parameter observed in these analyses was the coefficient of determination, which varied from 0.72 for Esd2 to 0.92 for ETpm as shown in Table 4. This parameter was used to define the consistency of the relationship and hence models' predictive capacity over the range of measured values.

When we compared these models for their consistency, the order of decreasing consistency was ETpm > Er > ETp > Epan > Esd1 > Esd2. The most noteworthy features of the comparison are the poor performance of Esd2 and the ability of Er to match the high performance of ETpm. The second important parameter is the coefficient of efficiency (E), which varied from 0.65 for Esd2 to 0.90 for ETpm (Table 4). This parameter determined the closeness of agreement of the relationships between the observed and the estimated values. High E values in the Penman and radiation methods indicated the high quality of estimation by these models. However, it should be noted that ETm is the only one-step approach of calculating ETa rather than estimating it (i.e., coefficient of efficiency is 0.90 and the slope of the regression analysis was almost equal to 1). In the case of Er, the slope of the relationship with ETa, i.e., the value of α was 1.17, which was consistent with that of 1.1–1.3 depending upon the surface conditions as observed by Priestley and Taylor (1972). With the exception of the Esd1 estimate, all other estimates showed a linear response to ETa (Fig. 4). Esd1 showed a power relationship with the ETa, indicating that at higher vapor pressure deficits, the response to evapotranspiration rate was lower.

Comparisons Between Seasons

As the season progressed to summer, the evaporative demand increased (Fig. 3), and, importantly, the relative contribution of radiant and aerodynamic energy to total evaporation changed. During winter when the evaporative demand was less,

Table 3 Monthly mean daily estimates of evapotranspiration (mm d^{-1}) using six methods[a] for the years 1991–1995

Methods	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
1991–1992												
Penman (ETp)	0.8	1.3	2.1	3.5	4.4	4.2	5.0	3.9	3.4	2.2	1.3	0.8
P-M (ETpm)	0.7	1.2	2.0	3.7	4.7	4.5	5.1	4.0	3.5	2.3	1.2	0.7
P & T (Er)	0.8	1.2	2.1	3.5	4.4	4.2	5.0	3.8	3.4	2.2	1.2	0.8
VPD1 (Esd1)	0.2	0.4	0.6	1.3	2.5	2.6	2.8	2.1	1.6	1.1	0.3	0.2
VPD2 (Esd2)	0.9	1.4	1.8	3.4	5.0	5.1	5.3	4.4	3.9	3.3	1.5	1.0
Pan eva (Epan)	1.0	1.7	2.7	5.3	7.9	8.1	9.4	7.3	5.7	3.9	1.5	0.8
1992–1993												
Penman (ETp)	0.8	1.2	1.8	3.0	3.8	4.1	5.2	4.8	3.7	2.9	1.6	1.0
P-M (ETpm)	0.7	1.2	1.8	3.3	4.3	4.8	6.1	5.8	4.4	3.5	1.8	1.1
P & T (Er)	0.8	1.2	1.8	3.0	3.8	4.1	5.2	4.7	3.6	2.8	1.6	1.0
VPD1 (Esd1)	0.2	0.4	0.7	1.5	2.4	3.3	4.8	5.0	3.2	2.4	1.0	0.5
VPD2 (Esd2)	1.0	1.3	1.5	2.2	2.9	3.3	4.8	4.8	3.5	3.6	2.3	1.2
Pan eva (Epan)	1.0	1.6	2.1	3.7	4.9	5.6	7.7	8.6	5.4	3.8	2.0	1.2
1993–1994												
Penman (ETp)	1.1	1.7	2.4	3.4	4.8	4.9	6	4.8	3.9	2.8	1.6	1.0
P-M (ETpm)	1.2	2.0	2.8	3.9	5.7	6.1	7.4	6.0	4.7	3.5	2.2	1.2
P & T (Er)	1.1	1.7	2.4	3.4	4.8	4.9	5.9	4.7	3.8	2.7	1.6	1.0
VPD1 (Esd1)	0.5	1.0	1.5	2.0	3.9	5.3	6.4	5.2	3.3	2.3	1.6	0.7
VPD2 (Esd2)	1.2	1.6	1.8	2.1	3.2	3.7	5.1	3.8	3.2	3.1	2.4	1.4
Pan eva (Epan)	1.5	2.0	2.4	3.4	5.8	6.7	8.8	6.7	4.5	3.5	2.4	1.3
1994–1995												
Penman (ETp)	1.2	1.9	2.7	4.2	4.5	6.2	5.1	5.5	4.3	2.5	1.3	1.0
P-M (ETpm)	1.4	2.3	3.5	5.2	6.2	6.6	7.0	7.2	6.6	3.4	1.4	1.2
P & T (Er)	1.2	1.9	2.7	4.2	4.5	6.1	5.1	5.4	4.2	2.5	1.3	1.0
VPD1 (Esd1)	0.6	1.3	2.5	3.4	5.9	6.0	6.7	6.7	6.9	2.9	0.8	0.8
VPD2 (Esd2)	1.4	2.1	2.8	3.9	4.1	5.6	4.2	4.7	4.6	2.8	1.3	1.2
Pan eva (Epan)	1.3	2.1	3.3	5.9	7.5	10.5	8.4	8.2	7.6	3.5	1.9	1.1

[a] The six methods are *Penman* = Penman combination equation, ETp; *P-M* = Penman-Monteith combination equation, ETpm; *P & T* = Priestley and Taylor method, Er; *VPD1* = vapor pressure deficit method 1, Esd1; *VPD2* = vapor pressure deficit method 2, Esd2; and *pan eva* = pan evaporation method, Epan

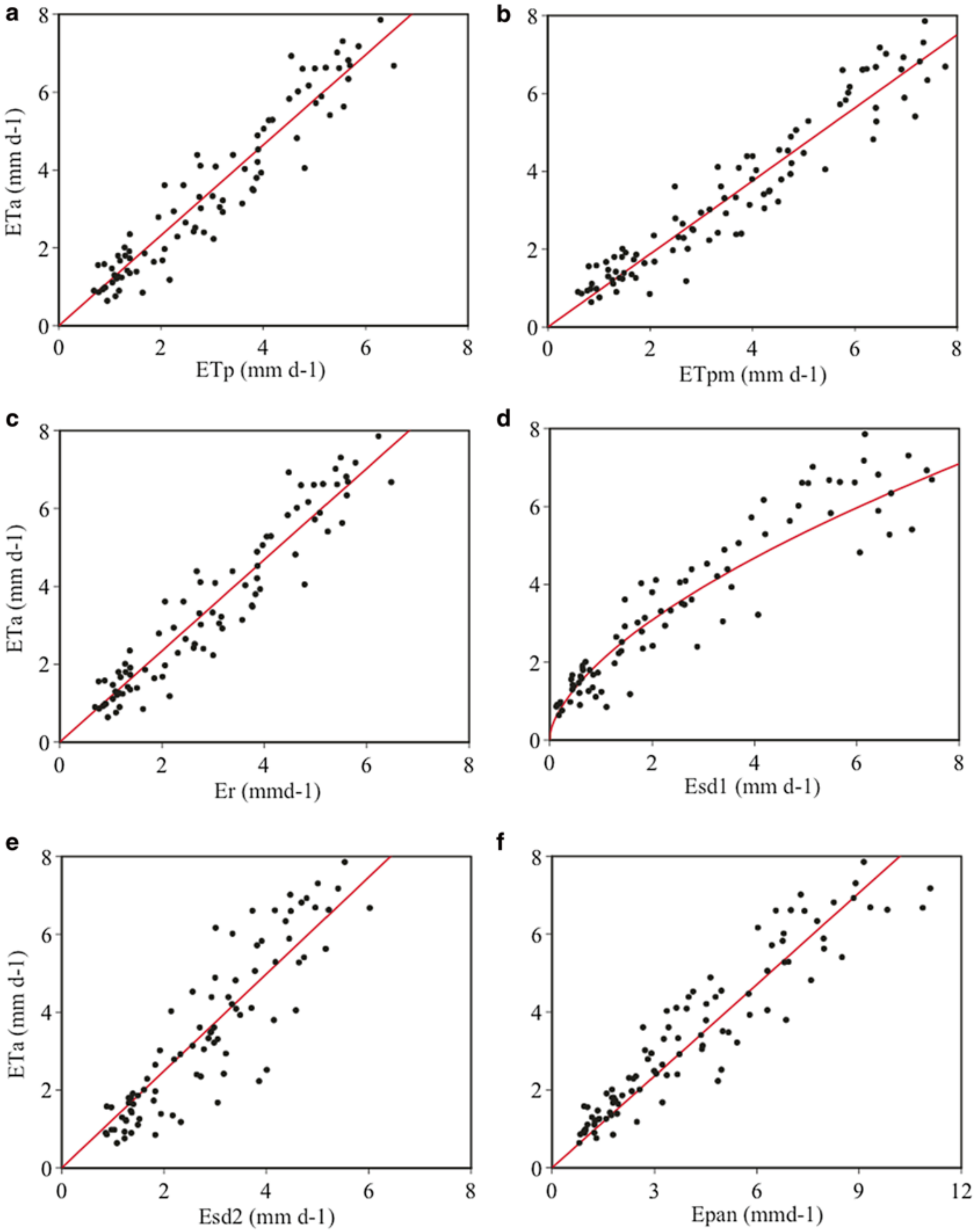

Fig. 4 The correlation between 14-day mean daily measurements of actual evapotranspiration (ETa) and the estimates of maximum evapotranspiration (ETm) during the years 1991–1995 using the following methods: (**a**) Penman combination (ETp), (**b**) Penman-Monteith (ETpm), (**c**) Priestley and Taylor (Er), (**d**) vapor pressure deficit 1 (Esd1), (**e**) vapor pressure deficit 2 (Esd2), and (**f**) pan evaporation (Epan)

Table 4 Overall regression analysis of the estimated and measured ET data for the irrigated eucalypt plantations during the 4 years of 1991–1995

Estimating method	Coefficient of efficiency (E)	Regression equation	1991–1995	
			Parameter values	CD (R^2)
Penman (ETp)	0.84	$y=a * x$	$a=1.16$	0.88
P-M (ETpm)	0.90	$y=a * x$	$a=0.95$	0.92
P & T (Er)	0.83	$y=a * x$	$a=1.17$	0.91
VPD1 (Esd1)	0.71	$y=a * x^b$	$a=2.07$, $b=0.63$	0.81
VPD2 (Esd2)	0.65	$y=a * x$	$a=1.25$	0.72
Pan eva (Epan)	0.57	$y=a * x$	$a=0.78$	0.82

CD=coefficient of determination. The six methods are *Penman*=Penman combination equation, *P-M*=Penman-Monteith combination equation, *P & T*=Priestley and Taylor method, *VPD1*=vapor pressure deficit method 1, *VPD2*=vapor pressure deficit method 2, and *pan eva*=pan evaporation method

Table 5 Regression analysis between the estimated and measured ET data for irrigated (November–April) and nonirrigated (May–October) seasons during the 4 years of 1991–1995

Estimating method	Regression equation	Irrigated season		Nonirrigated season	
		Parameter values	CD (R^2)	Parameter values	CD (R^2)
Penman (ETp)	$y=a * x$	$a=1.18$	0.83	$a=1.07$	0.69
P-M (ETpm)	$y=a * x$	$a=0.96$	0.87	$a=0.91$	0.79
P & T (Er)	$y=a * x$	$a=1.19$	0.83	$a=1.08$	0.69
VPD1 (Esd1)	$y=a * x^b$	$a=2.07$	0.75	$a=1.85$	0.69
		$b=0.63$		$b=0.45$	
VPD2 (Esd2)	$y=a * x$	$a=1.30$	0.50	$a=1.04$	0.52
Pan eva (Epan)	$y=a * x$	$a=0.78$	0.62	$a=0.90$	0.70

CD=coefficient of determination. The six methods are *Penman*=Penman combination equation, *P-M*=Penman-Monteith combination equation, *P & T*=Priestley and Taylor method, *VPD1*=vapor pressure deficit method 1, *VPD2*=vapor pressure deficit method 2, and *pan eva*=pan evaporation method

wind speed was the predominant factor contributing toward evaporation (Table 1), but during summer, solar radiation was noticed as the major determinant of evaporation. Fortnightly, mean daily water-use data of 40 biweekly measurements of the nonirrigation season during winter and 46 measurements of the irrigation season during summer were compared against the estimates of ETm to produce relationships between the estimated and measured data for these two seasons, and the results of the analyses are given in Table 5.

The ETpm method showed consistently higher R^2 than the other methods for the irrigated and nonirrigated seasons, 0.87 and 0.79, respectively (Table 5). The other important features of the comparison are the overall poor performance of Esd1 and Esd2 and the ability of Epan to predict better during the summer months ($R^2=0.70$) than in winter months ($R^2=0.62$). The ETpm method also gave a slope of the relationship with ETa of 0.96 and 0.91 for both seasons indicating that the method clearly takes care of the effect of environment on evaporation of trees (Fig. 5a).

Er, although overall slightly inferior to ETpm, gave the next best analysis of evaporation during the summer period ($R^2=0.83$). The slope of the relationship with ETa also varied from 1.19 to 1.08 between the two seasons which was within the limits of Priestley and Tailor's estimates. Joshua et al. (2005) observed that modified Priestley-Taylor model was found to perform well given its relative simplicity; however, they suggested that a soil moisture function should be integrated in all the ET models for improving their accuracy in simulations of actual evapotranspiration under variable soil moisture conditions.

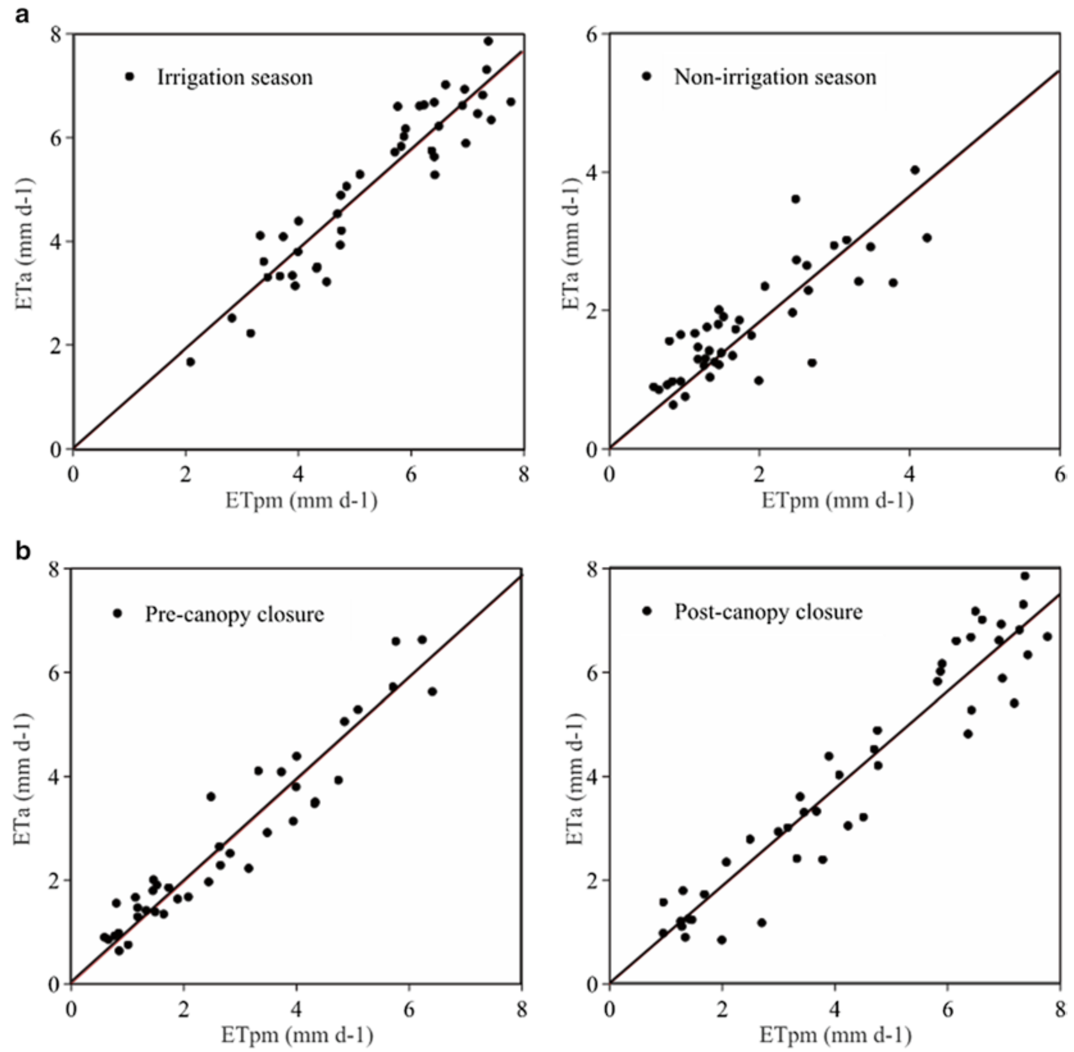

Fig. 5 The correlation between fortnightly measurements of mean daily evapotranspiration (ETa) and the Penman-Monteith estimates evapotranspiration (ETpm) during (**a**) irrigation and nonirrigation seasons and (**b**) pre-canopy closure (1991–1993) and post-canopy closure (1994–1995) periods

Similarly, Ge Sun et al. (2010) also observed that the growing season ET from wet forests was generally higher while those from woodlands in the arid and semiarid regions were lower than ETo. Esd methods did not show any difference between periods of lower and higher evaporative demand (i.e., during winter and summer), whereas ETp gave its best estimates during summer period ($R^2=0.83$), but Epan showed poor correlation during summer ($R^2=0.62$).

Comparisons during Pre- and Post-Canopy Closure

To investigate the predictive ability of the functions through this changing pattern of tree structure and environment, an analysis of the relationships between the five methods and ETa was made for the periods before and after canopy closure (Table 6). The ETpm model gave good estimates throughout the period of growth (R^2 of

Table 6 Regression analysis between the estimated and measured ET data for the pre- and the post-canopy closed eucalypt plantations from 1991 to 1995

Estimating method	Regression equation	Pre-canopy closure		Post-canopy closure	
		Parameter values	CD (R^2)	Parameter values	CD (R^2)
Penman (ETp)	$y = a * x$	$a = 1.12$	0.87	$a = 1.19$	0.93
P-M (ETpm)	$y = a * x$	$a = 0.98$	0.91	$a = 0.94$	0.94
P & T (Er)	$y = a * x$	$a = 1.13$	0.87	$a = 1.20$	0.93
VPD1 (Esd1)	$y = a * x^b$	$a = 2.24$	0.92	$a = 1.64$	0.87
		$b = 0.58$		$b = 0.72$	
VPD2 (Esd2)	$y = a * x$	$a = 1.12$	0.79	$a = 1.33$	0.81
Pan eva (Epan)	$y = a * x$	$a = 0.75$	0.85	$a = 0.80$	0.82

CD = coefficient of determination. The six methods are *Penman* = Penman combination equation, *P-M* = Penman-Monteith combination equation, *P & T* = Priestley and Taylor method, *VPD1* = vapor pressure deficit method 1, *VPD2* = vapor pressure deficit method 2, and *pan eva* = pan evaporation method

0.91 and 0.94 for pre-canopy closed and post-canopy closed conditions, respectively). This model also gave a slope of 0.98 and 0.94 for the two periods indicating its reliability of application at all stages of development of the plantation (Fig. 5b). Er recorded the best analysis of evaporation after canopy closure ($R^2 = 0.93$). The Esd methods gave better estimates when the data was analyzed separately for pre- and post-canopy closed conditions. The Esd1 method showed consistently higher reliability of prediction of ETa during pre-canopy closure stage of the plantation but the ETp produced best estimates after the canopy was closed. Epan showed similar correlation with ETa during pre- and post-canopy closed conditions.

Table 7 Estimated monthly pan factors (Kp) and coefficient of determination (CD) obtained using a regression analysis between the weekly totals of measured Epan and estimated ETpm for the irrigated eucalypt plantation at Wagga Wagga

Months	Pan factor (Kp)	CD (R^2)
January	0.70	0.75
February	0.70	0.67
March	0.77	0.76
April	0.81	0.42
May	0.80	0.67
June	0.85	0.49
July	0.84	0.51
August	0.89	0.79
September	0.94	0.70
October	0.84	0.76
November	0.76	0.68
December	0.65	0.75

Monthly Pan Factors

Since pan data is being used to estimate evapotranspiration and to schedule irrigation in many irrigated plantations, monthly pan factors were determined using analyses between weekly totals of pan evaporation and ETpm for mature plantations after canopy closure (Table 7). ETpm is used here as a surrogate for ETa because it has been conclusively identified from the above analyses that ETpm is an accurate one-step approach for estimating ETa. The measured daily pan evaporation and the estimated daily ETpm for the *Eucalyptus* plantation were used to obtain weekly mean Epan and ETpm for the study period. A statistical analysis of the relationships between estimated ETpm and Epan for each month was carried out. The slope of the regression line gives an estimate of the pan coefficient for that month. These relationships have also been forced through the origin and assessed in terms of slope and the coefficient of determination (Table 7).

Poor relationships were obtained during the winter months of April ($R^2 = 0.42$) and June ($R^2 = 0.49$). On average, there was greater consistency in the predictive ability of Epan during summer months than in winter months. Pan factors ranged from 0.65 in December when the evaporative demand is high to 0.94 in September when the demand is low. Lower pan factors during summer months from November to March (0.76–0.77) and higher pan factors from April to October (0.81–0.84) indicate that pan evaporation is effected by different processes to plantation evapotranspiration.

Conclusions

Reliable estimates of plantation ET are fundamental to improve the understanding of the relationships between soil moisture content and water fluxes from the soil and the vegetation and ultimately the ecosystem hydrology and environmental management. Direct measurements are usually too expensive, laborious, and time-consuming in most cases. Our study evaluated five methods commonly used to estimate ETm of tree plantations, by comparison with measurements made by the water balance technique.

The two methods, ETp and ETpm, based on the combination equation are technically the most satisfying because they represent the processes of evaporation from tree canopies more completely. At the Wagga Wagga site, these two methods consistently performed better than the other methods used to estimate ETm (particularly the ETpm method as shown in Fig. 5). The disadvantage of these methods, however, is that they require comprehensive measurements of climatic conditions and crop structure.

Methods based upon component processes, e.g., radiation (Er) and saturation deficit (Esd), require less input data, and for this reason have been widely used. For success, these techniques rely upon the existence of strong correlations between the individual processes of evaporation. In these data, Esd1 gave a hyperbolic response indicating that at higher deficits, the rate of evapotranspiration begins to decline. This observation highlights the importance of selecting the right species when designing irrigated tree plantations for climates where the vapor pressure deficits may rise above the threshold level of some species. The poor performance of the Esd2 method is of interest in the light of much recent work on crop water-use efficiency where saturation deficit has been used to standardize the performance of crops in different seasons and in different locations. The two humidity methods (Esd1 and Esd2) assume that the process of evapotranspiration affects the changes in the vapor pressure levels above the tree canopy, and hence if such changes could be monitored it would be possible to estimate ETm using an empirical relationship with saturation deficit. Although theoretically this procedure appears to be reasonably good, accurate measurements of the vapor pressure deficit above the tree canopy are often very difficult to obtain.

Er performed well with comparable consistency of prediction to ETp in all years. However, the value of α needs to be estimated for a particular location because it is sensitive to the fluctuations in sensible heat flux and advection. Epan was poorly related to ETa. Pan evaporation involves the same basic processes as evapotranspiration, and therefore it is possible to calculate an estimate of evapotranspiration from measured pan data. However, it is very difficult to make a general and a practical use of pan data except in special situations. The pan evaporation method also assumes that the pan behaves in the same way as a crop with zero resistance. Pans unlike crops are small in area and therefore experience advection differently. Measurements of pan evaporation are also well known to suffer from inappropriate siting and often from inadequate maintenance of the pans. The present data did not suffer in this way as these were collected in similar way as the other climatic data at the site and compared against the data collected by the Bureau of Meteorology, 2 km from the experimental site. The pan evaporation data collected from these two sites gave a 1:1 relationship, indicating the high level of accuracy of measurements collected at the site.

Pan evaporation has been found more sensitive to surrounding conditions than the tree vegetation. The albedo of trees is about 0.25 whereas the surface albedo of water varies from 0.02 to 1. Heat storage within the pan is large compared to that of soil, and the roughness to air movement also differs between vegetation and pan. Heat transfer through the sides of the pan and the turbulence, temperature, and humidity of the air immediately above its surface compared with that above plantation canopy changes the relationship between the measured Epan and ETm. Also, there may be more evaporation from the pan at night compared to plantation ET. It is reasonable therefore to assume that as a standard meteorological measurement, pan evaporation does not define ETa of plantations without calibration. Further, the low correlation ($R^2 < 0.4$) during winter months casts doubt on the general utility of pan evaporation measurements during these periods even with calibration. It seems that there is a good argument to replace such measurements with others that could be used to calculate ETa of tree crops. In general, this would require substantial extension of the radiation network.

Irrigation scheduling programs require input data which could be either measured or estimated by the users. Daily evapotranspiration is one of them. The accuracy of its measurement depends on the accuracy of the estimation of other inputs and also on the accuracy of forecasting the weather. Under these circumstances, a simple method to estimate evapotranspiration is sufficient in designing and scheduling irrigated plantations. The pan evaporation method, though not very accurate, showed greater reliability and predictability when used on annual or seasonal basis than on a monthly, weekly, or a daily basis. Regression on a monthly basis was, however, better than on a weekly or daily basis, which could be employed in irrigation scheduling programs in plantation crops. For a site under an irrigated *Eucalyptus* plantation, monthly pan factors could be better derived from many years of historical climatic data using the Penman-Monteith combination equation (Fig. 6). These pan factors may then be used in designing and scheduling irrigation for areas of similar climatic zones. The pan factors derived for *Eucalyptus* plantation under irrigated conditions at the Wagga Wagga site can be compared with pan factors derived by other workers in similar climatic regions and under similar set of conditions.

The analyses presented here show that it is possible to estimate ETa of *Eucalyptus* plantation from standard meteorological data. The best technique, based upon the Penman-Monteith combination equation, requires a complete climatic

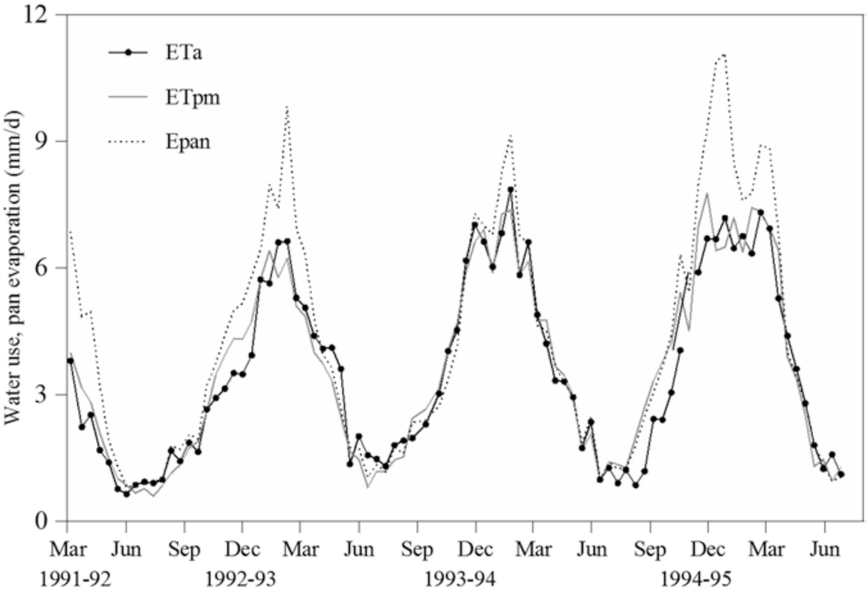

Fig. 6 Comparison of 14-day mean daily measurements of actual evapotranspiration (ETa) and pan evaporation (Epan) and the estimates of maximum evapotranspiration using Penman-Monteith equation (ETpm) of the eucalypt plantation from planting to 4 years. The comparison shows that ETpm was an accurate estimate of ETa during 4 years of growth

data set and additional information on tree height and cover. Almost comparable values can be calculated from radiation data alone (the Priestley-Taylor technique) which has the advantage of requiring considerably less input data. Estimates based on saturation deficit (Esd), although widely used in analyses of water-use efficiency, did not show strong linear correlation with ETa. Pan evaporation was shown to be poorly correlated with ETa if used for time steps less than the seasonal or monthly periods, adding weight to the growing concern about the utility of this measurement for daily predictions and the transportability of this relationship to different sites.

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