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A SEMI-EMPIRICAL MODEL FOR CALCULATING EVAPORATION AND TRANSPIRATION FROM WETLAND RICE

J.R. JENSEN

Division of Agricultural and Food Engineering, Asian Institute of Technology, P.O. Box 2754, Bangkok 10501 (Thailand)

Md.M. RAHMAN

Potato Seed Division, Krishi Bhaban, 49–51 Dilkusha C/A, Dhaka (Bangladesh)

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ABSTRACT

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A model for evapotranspiration (*ET*) from wetland rice fields was formulated, using the combination method and the wind functions of Penman (1956) and Stigter (1980) to calculate evaporation and transpiration, respectively. The partitioning of the total evaporation among the two surfaces, water and crop, was accomplished by assuming an exponential extinction of net radiation with leaf area index, and by introducing into the aerodynamic terms empirical aerodynamic efficiency functions, representing the ratio of the aerodynamic conductance in the presence of the other surface to the conductance when the surface is present alone. These two functions were calibrated and the model tested based on a dry season lysimeter field investigation on Bangkok Plain, including measurement of evaporation, transpiration and evapotranspiration. Although the model was not tested on a truly independent dataset, it was concluded that when accumulating daily estimates over 5-day periods, the model performed well with an *ET* estimation error of 2.3 mm per 5-days or 6%. There was a tendency for daily values to be underestimated on days of high *ET*, probably due to the prevailing intermediate advective condition ($\lambda ET/R_n = 1.31$). The aerodynamic efficiency functions remained constant in the period 25–84 days after transplanting, at values of 0.58 (water) and 0.75 (crop), and it was concluded that aerodynamically, the rice crop reached full cover at a leaf area index of ~1.5, but energetically at a leaf area index of 3. During the same period, evaporation was 1.4 mm day^{-1} and transpiration 6.1 mm day^{-1}, with a peak during flowering of 9.0 mm day^{-1}. For the entire crop season, it was estimated that evaporation contributed ~ 1/3 of *ET*. The importance of surface-water evaporation, when analysing water stress situations and for formulating a soil–plant–atmosphere concept applicable to wetland rice, is pointed out.

INTRODUCTION

Wetland rice is the main water user in many developing countries. Quantitative understanding of the water dynamics of the wetland rice system, in particular with respect to evaporation and transpiration, usually the main components of the rice field water balance, is therefore a prerequisite for

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efficient use of water resources in these countries. With the future introduction of microcomputer-based near real-time water requirement estimation and allocation systems, an evapotranspiration model will be needed for calculating water use and requirement at time intervals of a few days, from early land preparation to harvest.

Tomar and O'Toole (1980) gave an extensive discussion on empirical models relating ET_{rice} to E_{pan}. In view of the well-known problems of interpreting pan observations for water requirement estimation, such models are not likely to provide an accurate enough estimation unless calibrated on site. A general calibration was attempted by Doorenbos and Pruitt (1977) for various evapotranspiration models, crops and environments. However, the underlying database for wetland rice seems rather weak, and extensive local calibrations may be needed. Batchelor and Roberts (1983) used the Penman–Monteith model to calculate transpiration from paddy rice. Although theoretically attractive, this model still requires non-standard crop observations. Also, the Penman–Monteith equation is not really applicable to estimating total evaporation from wetland rice, since water vapor originating at the ground contributes significantly to ET_{rice}.

It is the purpose of this study to develop a relatively simple semi-empirical evapotranspiration model for wetland rice, calculating ground evaporation and canopy transpiration separately, applicable to small time intervals of the entire crop season, and only requiring standard crop and weather variables.

THEORETICAL

The model proposed has some resemblances to the model developed by Ritchie (1972) for estimating evapotranspiration (ET) from a row crop well supplied with water, separating ET into ground evaporation (E) and crop transpiration (T) and partitioning the available radiational energy between E and T, assuming an exponential extinction of net radiation within the canopy. However, three fundamental changes are proposed. Firstly, there is no unique evaporative demand determined by the atmospheric condition alone. Consequently, E and T must be modelled separately rather than being constrained by the other through a potential evaporation concept. Secondly, meteorological variables used to model any process must be averaged over the same time interval as that over which the process is active. Thirdly, for a constantly wet surface such as that of a wetland rice field, the aerodynamic term cannot be neglected in the ground evaporation model.

The widely accepted combination method of Penman forms the basis for calculating E and T, introducing empirical aerodynamic efficiency functions, α_w and α_c, to be discussed below:

$$E = (W/\lambda)_w R_{n,w} + (1 - W)_w \alpha_w f_w(u) \Delta e_w \tag{1a}$$

$$T = (W/\lambda)_c R_{n,c} + (1 - W)_c \alpha_c f_c(u) \Delta e_c \tag{1b}$$

where the subscripts w and c refer to water and crop, respectively. In selecting eq. 1b, it is assumed that the canopy resistance to water vapor transfer is small compared to the boundary layer resistance, as suggested by Tomar and O'Toole (1980) for wetland rice.

The total energy available for latent and sensible heat flux is assumed to equal the net flux of radiation (R_n) above the crop, assuming the ground heat flux (G) and the rate of change of heat stored in the surface (J) to be negligible over a 24-h period. Although generally applicable to very shallow bodies of water (Tanner and Pelton, 1960), the validity of this assumption in wetland rice depends, among others, on the degree of crop cover, since when the leaf area index increases, the storage ratio, defined as $(G + J)/R_{n,w}$, may increase (Uchijima, 1976). However, $R_{n,w}$ decreases simultaneously, so the resulting error in ET by neglecting $G + J$ is probably small, although the relative error in E may be large. Also, from observations by Hussain (1983) and the discussion of Uchijima (1976) on soil and water temperature regime in wetland rice, it seems likely that the ground system is heating in the early crop development stage and cooling in later stages, when the crop is shading the ground. When neglecting $G + J$ in this situation, the sum of latent and sensible heat will be overestimated during early growth stages and underestimated later in the season. Another complication arises due to the influence of the irrigation water temperature and management on the $G + J$ term. However, Evans (1971) found $G + J$ to be very small compared with R_n in the whole crop season except for a few days.

The net radiation absorbed by the ground is assumed to decrease exponentially with leaf area index (L):

$$R_{n,w} = R_n \exp(-k_n L) \tag{2a}$$

The extinction coefficient (k_n) of net radiation in rice fields has been reported in the range 0.45–0.65 (Uchijima, 1976). A k_n in the lower end of this range is likely to apply to modern high-yielding rice varieties with an erectophile canopy. Changes in leaf orientation during the season, from erectophile to plagiophile-like structure, as reported by Uchijima (1976), probably result in changes in k_n during the season.

The net radiation absorbed by the crop canopy is calculated as:

$$R_{n,c} = R_n - R_{n,w} \tag{2b}$$

The net radiation (R_n) above the crop is estimated from the energy balance equation:

$$R_n = (1 - \rho)S_t - L_n \tag{3}$$

where S_t is incident shortwave radiation and L_n is the outgoing net longwave radiation flux in units of $\mathrm{MJ\,m^{-2}\,day^{-1}}$.

The shortwave reflection coefficient (ρ) is calculated as suggested by Uchijima (1976):

$$\rho = \rho_c - (\rho_c - \rho_w) \exp(-k_\rho L) \tag{4}$$

increasing exponentially with leaf area index, from the reflection coefficient of shallow water (ρ_w) to that of a fully developed rice canopy (ρ_c). Uchijima suggested $\rho_w = 0.08$ and $\rho_c = 0.22$. These values are expected to vary somewhat with location and season, since reflectivity depends strongly on solar angle, resulting in lower values at lower latitudes (Monteith, 1973). Also, ρ may be significantly influenced by the rice variety through the effect of canopy structure on reflectivity, including seasonal changes as discussed above for k_n.

The outgoing net longwave radiation flux (L_n) is, in the absence of locally calibrated coefficients for the humidity term of the atmospheric radiation component, calculated using coefficients proposed by Goss and Brooks (1956) as adopted by Doorenbos and Pruitt (1977):

$$L_n = \sigma T_a^4(0.34 - 0.044e_a^{1/2})(0.1 + 0.9n/N) \quad (5)$$

where σ is the Stefan–Boltzmann constant ($4.9 \times 10^{-9}\,\mathrm{MJ\,m^{-2}\,day^{-1}\,K^{-4}}$), T_a is mean air temperature (K) and e_a is actual vapor pressure of the air (mbar), both at screen height, and n/N is the ratio of actual to potential hours of sunshine.

The wind function of the aerodynamic term for evaporation is the revised function of Penman (1956):

$$f_w(u) = 0.26(0.5 + 0.0062u_2) \quad (6a)$$

with the coefficients adjusted to the units of km and mbar used in this study.

The wind function adopted for the aerodynamic exchange involved in transpiration is the wind function of Stigter (1980):

$$f_c(u) = 8(1 + 0.1u_i)[\ln((z_i - d)/z_0)]^{-2} \quad (6b)$$

This function combines the generalized transfer coefficient for water vapor, derived by van Bavel (1966), following the analysis of Thornthwaite and Holzman (1939) and Businger (1956) for adiabatic conditions, with the empirical wind function of the FAO-modified Penman equation (Doorenbos and Pruitt, 1977). The wind speed (u_i) used here is the diurnal 12-h wind run measured at instrument height z_i.

The zero plane displacement height (d) and the roughness length (z_0) are estimated from the crop height (h) as suggested by Uchijima (1976):

$$d = 1.04h^{0.88} \quad (7)$$

$$z_0 = 0.062h \quad (8)$$

The complex effect of wind speed on d and z_0, discussed by Monteith (1973) and found by Evans (1971) to be partly responsible for failure of the combination approach in predicting total evaporation from a rice field, is not quantified here.

The vapor pressure deficits of eqs. 1a and b, Δe_w and Δe_c, are calculated from the mean relative humidity and mean temperature for the appropriate averaging period, i.e. 24-h daily and 12-h diurnal, respectively. Similarly, the weighting factor (W) and the latent heat of vaporization (λ) are calculated from standard relationships as presented by Burman et al. (1983).

The wind functions of eqs. 6a and b apply to unrestricted aerodynamic transfer during adiabatic conditions, through the boundary layers above an open water surface and that within heights $d + z_0$ and z_i above an extensive, saturated, fully covering and relatively smooth surface, respectively. However, the presence of the crop canopy increases the aerodynamic resistance to movement of water vapor, originating at the ground, through the canopy layer (Katerji and Perrier, 1985). Also, the crop does not cover the ground fully during a significant part of the season. Consequently, the empirical aerodynamic efficiency functions (or relative conductances), α_w and α_c, are introduced in eqs. 1a and b. These dimensionless functions express the efficiency of aerodynamic exchange relative to the exchange when the respective surface is present alone. Since both surfaces contribute water vapor to the atmosphere in response to the vapor pressure deficit, resulting from the complex interaction between the two surfaces and the mesoclimate, the α functions can approximately be seen as factors partitioning the contribution of the aerodynamic terms to total evaporation among the two surfaces, water and crop.

The bulk canopy drag coefficient is expected to increase in direct proportional to the leaf area index (L) at small foliage densities (Thom, 1975). Therefore, since the wind function is proportional to that coefficient, α_c is expected to increase with L, from a hypothetical value of zero before transplanting to a near constant value during full cover period. Since it is approximately complementary to α_c, α_w is, therefore, expected to decrease with L, from a value of ~ 1 prior to transplanting to a near constant value < 1 during full cover. Since wetland rice is expected to evapotranspire in excess of potential evaporation, the sum $\alpha_w + \alpha_c$ is likely to be > 1, at least during the period of peak crop water use.

EXPERIMENTAL

The field experiment was conducted in the dry season during January–May, 1986, at the Agrometeorological Research Station for Wetland Rice, located on the campus of the Asian Institute of Technology (14°04′N, 100°37′E; 2 m above msl) on the Southern Central Plain $\sim$40 km north of Bangkok, Thailand. The climate is of the maritime monsoon type, with moderate rainfall and 6–8 humid months (van den Eelaart, 1973). The soil was a hydromorphic alluvial soil (acid sulphate soil) on recent brackish-water sediment (Moorman and Rojanasoonthon, 1972), also classified as a Sulphic Tropaquept of the Rangsit Series (Ariyabandu, 1986). The experimental plot was 45 × 30 m, surrounded by wetland fields for $\sim$100 m in the prevailing upwind direction.

Transpiration, evaporation and evapotranspiration were measured independently using two volumetric lysimeters, each consisting of a soil tank (1 m × 1 m × 0.75 m) located at the center of the field and a constant head supply reservoir placed at the field bund. The tanks were installed to a depth of 65 cm 2 weeks before transplanting, the excavated soil being backfilled layerwise. This depth was considered sufficient as we have not observed rice roots deeper than 40 cm in this soil. The water level in the tanks was maintained nearly constant, at water depths of 3 and 5 cm in the transpiration and the evapotranspiration tank, respectively. To observe transpiration, one tank was covered 3 weeks after transplanting with a 5-cm deep, transparent PVC tray, allowing the 16 rice hills in the tank to develop through tubes of 10 cm diameter and 5 cm height. Any remaining gap between hills and tubes were closed using thin polyethylene bags. The water level in the tray, maintained at ~ 2 cm depth of water, was monitored for estimating evaporation, using four replicate readings of a hook gauge with a vernier scale allowing an accuracy of ~ 0.1 mm. Water level in the *ET* tank was monitored similarly from DAT 23 (23rd day after transplanting), while the level in the reservoirs was read directly from transparent pipes connected to the reservoirs with an accuracy of ~ 0.5 mm, corresponding to 0.025 mm of water loss from the lysimeter. All water level readings were taken at 6:30, 12:30, and 18:30 h.

Cultivation practices were according to normal recommendations. The rice variety was the locally popular RD23, a high-yielding variety not sensitive to the daylength. On February 12, 26-day-old seedlings were transplanted at a spacing of 25 × 25 cm using three seedlings per hill. During final land preparation prior to transplanting, $(NH_4)_3PO_4$ was applied at the rate of 0.04 kg m^{-2}. Later, at the end of the active tillering period, two topdressings of urea were given at a rate of 5.50 g m^{-2}, the total field application being 115 kg N ha^{-1} and 80 kg P ha^{-1}. The field was frequently irrigated to maintain a water depth of ~ 5 cm. Final drainage was initiated on May 7, one week before harvesting. Other details of the experimental procedure can be found in Rahman (1986).

Crop observations were performed in the lysimeters and surrounding field, in order to evaluate the lysimeter performance in addition to providing model input. At 1-week intervals, six hills were randomly sampled in the field, to determine: crop height, defined as the average of the heights from the ground to the top of the raised leaves of each hill; tiller number, including the three main culms; leaf area index of green and partly yellow leaves, using an optical area measurement system (Delta-T Devices, U.K.). Similarly, crop height and tiller number were determined non-destructively in each lysimeter. At harvest, top and root biomass and yield components were determined according to Yoshida et al. (1976) and Yoshida (1981). During the crop season, major phenological events, including panicle differentiation and heading as defined in De Datta (1981), were observed.

Meteorological variables were monitored 30 m upwind from the lysimeters, on a weather station located on a raised bed with a grassed surface surrounded by wetland fields. Global radiation was continuously recorded using a star-shaped pyranometer (Thies Clima, F.R.G.) connected to a datalogger (CR21, Campbell Scientific Inc., U.S.A.), averaging 5 instantaneous readings taken at 1-min intervals. During a few days of system failure, global radiation was estimated from a bimetallic actinograph (Casella, U.K.) calibrated to the pyranometer. Manual observations were taken at 6:30, 9:00, 14:00 and 18:30 h. Observations in a thermometer screen, 2.3 m above field ground, included: wet and dry bulb temperature using an aspiration psychrometer of the Assman type

(Yoshino Keiki Co., Japan); air temperature and relative humidity with a hygrothermograph (Wonder Instrument, Republic of China); and maximum and minimum temperature with a max/min thermometer (ELE International Ltd., U.K.). Wind run was observed at the same height using a cup counter anemometer (Casella, U.K.). Shortwave reflection was measured from DAT 21 in the field 2 m above ground with an inverted star-shaped pyranometer. An attempt to measure net radiation did not succeed due to frequent malfunctioning of the net radiometer. The water temperature in the lysimeter tanks and the field was monitored for 3 weeks using thermistors (model 102, Campbell Scientific Inc., U.S.A.).

The dry bulb temperature was used as the reference for other sensors. Daily 24-h average temperature was calculated as the average of the maximum and minimum temperature according to the max/min thermometer. Other averages of temperature and humidity were based on readings of the hygrothermograph chart at hourly intervals, calibrating to the Assman psychrometer as discussed by Doorenbos (1976). u_2 was estimated from u_i according to Burman et al. (1983). The ratio n/N was calculated from the Ångström formula, using coefficients a

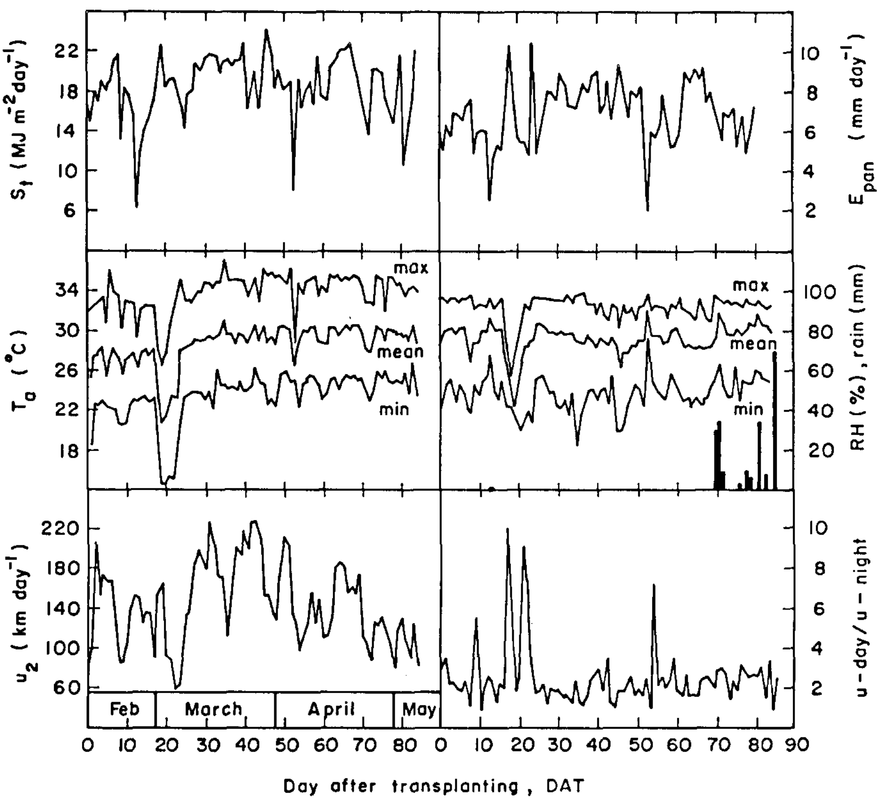

Fig. 1. Daily weather variables during the experimental period. S_t, global radiation; E_{pan}, class A pan evaporation; T_a, air temperature; RH, relative humidity; u_2, wind run at 2 m length.

and b of 0.25 and 0.5, respectively. In reasonable agreement with local conditions, the daytime period was defined as the 12-h period from 6:30 to 18:30 h.

The variation of the main weather variables during the experimental period is shown in Fig. 1. The cold spell during March 2–7 (18–23 days after transplanting) was an unusual feature.

RESULTS

Lysimeter performance

The crop phenology was similar in lysimeters and field. Tillering started on DAT 10, reaching maximum tillering around DAT 40. The reproductive stage started with panicle differentiation (30%) on DAT 40, booting (50%) was observed on DAT 55, and the ripening stage started on DAT 64 with flowering 2 days after heading (50%). Except for the first 2–3 weeks after transplanting, there was no significant (5%, t-test) difference in crop height and tiller number between the two lysimeters. However, tiller number remained significantly higher (3) in the field from DAT 56, whereas crop height generally was slightly higher (2–3 cm) in the lysimeters. This was probably due to stem borer attack, predominantly in the center of the field. Among the yield components investigated, no significant difference was found in number of panicles per hill and spikelets per panicle, grain yield, top and total dry matter, whereas the weight of 1000 grains and percent filled spikelets were higher in the field. Since the top dry matter was nearly the same in lysimeters and field, it is assumed that the leaf area measured in the field (Fig. 2) is representative of that in the lysimeters.

The water level in the ET tank was found to oscillate with a period of $\sim$ 24 h and an amplitude of 1–2 mm, passing through a minimum at noon and recovering somewhat during the night. This is believed to be caused by resistance in

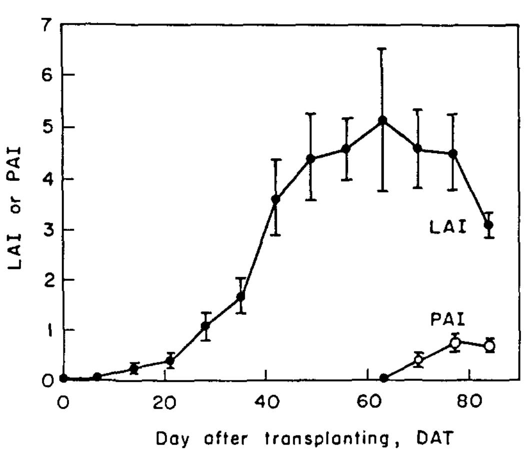

Fig. 2. Leaf (●, LAI) and panicle (○, PAI) area index. Vertical bars, ±1 SD.

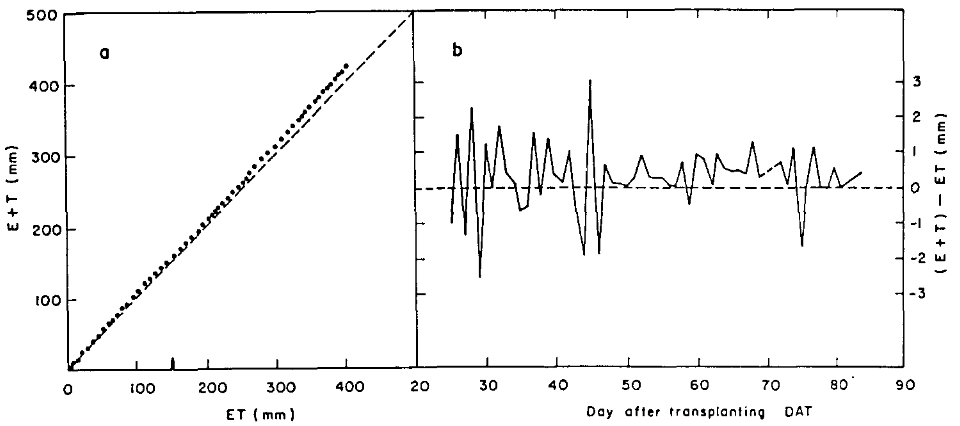

Fig. 3. Comparison of the $E + T$ and ET lysimeter systems for DAT 25–84. (a) Double mass curve; (b) residual plot.

the supply system, necessitating a greater head loss during peak demand periods for a quasi-steady supply to be established. Consequently, to calculate ET, the change in water level in the tank must be included in the lysimeter water balance equation, especially when using calculation periods of < 24 h. The T lysimeter, only open to the atmosphere through stomates, showed a rather constant loss of water from the reservoir during the night, of $\sim$ 1–2 mm. Assuming that significant transpiration only takes place during daytime hours, it was decided that the total water supply to the T tank during the 24-h period 6:30 to 6:30 h (next date) was spent on transpiration during the 6:30–18:30 h period.

Water use by the two lysimeter systems was quite similar (Fig. 3), the difference between $E + T$ and ET being only 17 mm during DAT 25–84, equivalent to 0.3 mm day^{-1} or 4% of $E + T$ (Table I). Also, the difference in daily average water temperature between the two tanks in the period DAT 48–71 was normally within $\pm$ 0.2°C, and within $\pm$ 1°C of the field water temperature. Apparently, the presence of the E tray on the T tank did not significantly alter the evapotranspiration characteristics or the energy balance. It is concluded that the lysimeters performed satisfactorily, and that the observations on daily E, T, and ET and leaf area index represent a coherent dataset for the period DAT 25–84.

The variation in daily E, T and ET is shown in Fig. 4. Initially, evaporation at values around 4–5 mm day^{-1} predominated over transpiration. However, from DAT 35, after the crop had recovered from transplantation and developed a leaf area index of $\sim$ 1.5, transpiration was the dominant process, averaging 6.6 mm day^{-1} and with a peak of 9.0 mm day^{-1} on DAT 65 during flowering, when the maximum crop roughness due to emergence of panicles coincided with a high evaporative demand (Fig. 1). Also, panicles may contribute significantly to total transpiration (Batchelor and Roberts, 1983), although probably only for a few days. The bimodal nature of the T and ET graphs, with peaks at

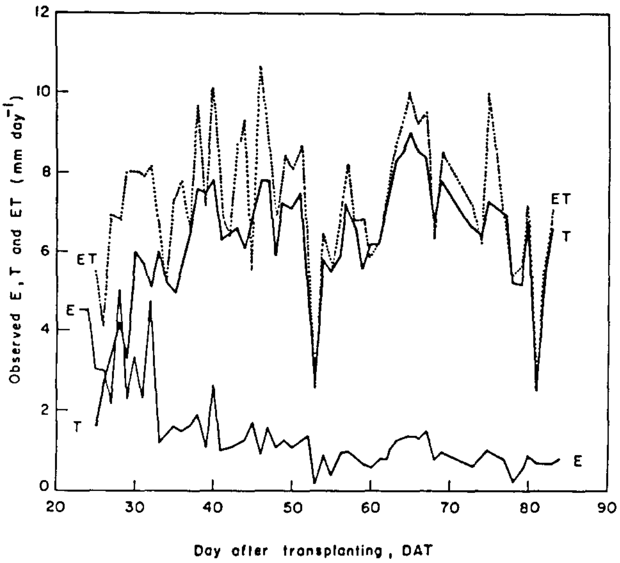

Fig. 4. Observed daily evaporation (E), transpiration (T) and evapotranspiration (ET).

maximum tillering and flowering, is often observed in wetland rice (Tomar and O'Toole, 1980). Evaporation constituted 18% of $E + T$ (Table I). By extrapolation, it is estimated that E contributed $\sim 33\%$ of total evapotranspiration for the entire crop season, in close agreement with values reported by the International Rice Research Institute (1971) and Batchelor and Roberts (1983).

In the following, the proposed E and T model is evaluated. First, the parameters required for calculating shortwave reflection are estimated. Thereafter, sub-models for transpiration and evaporation are investigated, including calibration of α_c and α_w using data from T lysimeter and the E tray, respectively. Lastly, since a truly independent dataset on crop development, water use and climate was not available, the overall model is "tested" by comparing model estimates of $E + T$ with ET observations from the ET lysimeter.

Reflection

Using the linear regression technique, k_ρ of eq. 4 was estimated for various combinations of ρ_w and ρ_c, in the ranges 0.06–0.10 and 0.20–0.22, respectively.

TABLE I

Observed evaporation (E), transpiration (T) and evapotranspiration (ET) during DAT 25–84

	E	T	$E + T$	ET
mm	77.2	345.0	422.2	405.3
mm day^{-1}	1.35	6.05	7.41	7.11
% of $E + T$	18	82	100	96

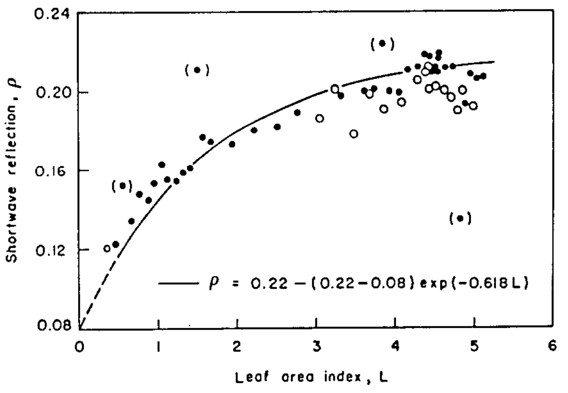

Fig. 5. Daily shortwave reflection as a function of leaf area index (●, points not considered for analysis; ○, after flowering).

The daily leaf area index was obtained from Fig. 2 by linear interpolation. Since the absorption of shortwave radiation increases at heading and during ripening stage, only DAT 21–63 was considered for the analysis, excluding DAT 23, 33, 44 and 59 as reflection on those days deviated grossly from the main trend (Fig. 5). The highest correlation coefficient (0.853) and smallest standard error of estimate (0.006) was obtained with $\rho_w = 0.08$ and $\rho_c = 0.22$, in agreement with values previously suggested by Uchijima (1976). The resulting k_ρ was 0.62, with a standard error of 0.02. Uchijima reported a k_ρ of 0.56, likely to vary among rice varieties, depending on leaf architecture. The model underestimates and overestimates ρ at low and high leaf area, respectively. However, the average error of estimation is only 5%.

Transpiration

To model transpiration, an extinction coefficient k_n of 0.45 was adopted, based on the previously reported range and the erectophile character of RD23. Letting $\alpha_c = 1$, daily transpiration was calculated from eq. 1b and compared with observations. The resulting general overestimation of T by $\sim 20\%$ during the full-cover period (here $L \geqslant 4$, DAT 46–69) cannot be caused by reasonable errors in k_n, since varying k_n from 0.5 to 0.4 changes the relative deviation by < 0.05. Also, the deviations are rather constant during the full-cover period, as expected from the discussion on α_c in the theoretical section. Consequently, assuming α_c to be responsible for the average deviation during the full-cover period, an α_c of 0.75 was calibrated. Apparently, due to the presence of the water surface, the rice canopy contributed only 82% of the total transfer of water vapor to the atmosphere, at an aerodynamic efficiency of 0.75.

Modelling daily transpiration for the whole period of DAT 25–85 with α_c constant and equal to 0.75, results in the correlation plot of Fig. 6a and the residual plot of Fig. 7a. The underestimation of $\sim 15\%$ by the model during DAT 30–40 may to some extent be explained by probable errors in estimating

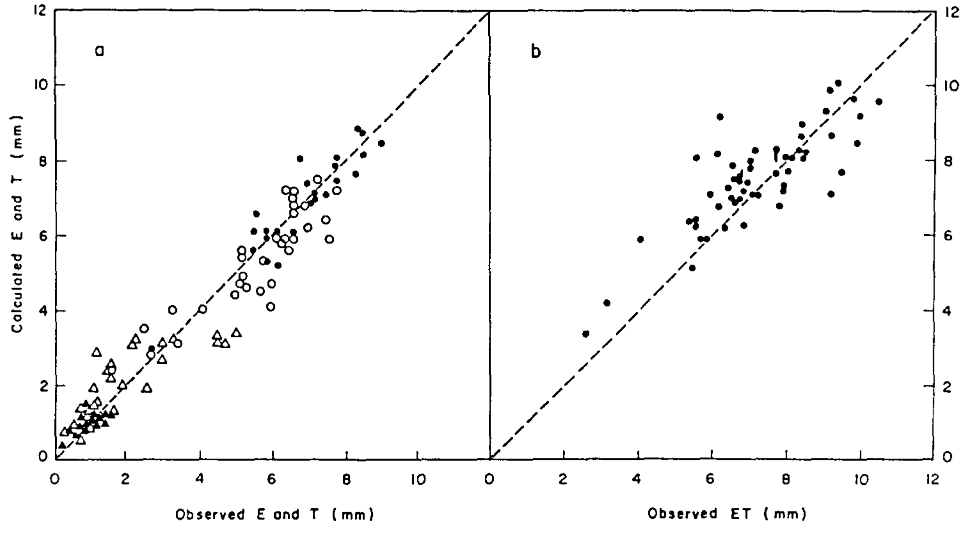

Fig. 6. Comparing observed and calculated daily values. (a) Evaporation (△, ▲), transpiration (○, ●). (▲, ●: data used for calibration.) (b) Evapotranspiration (●).

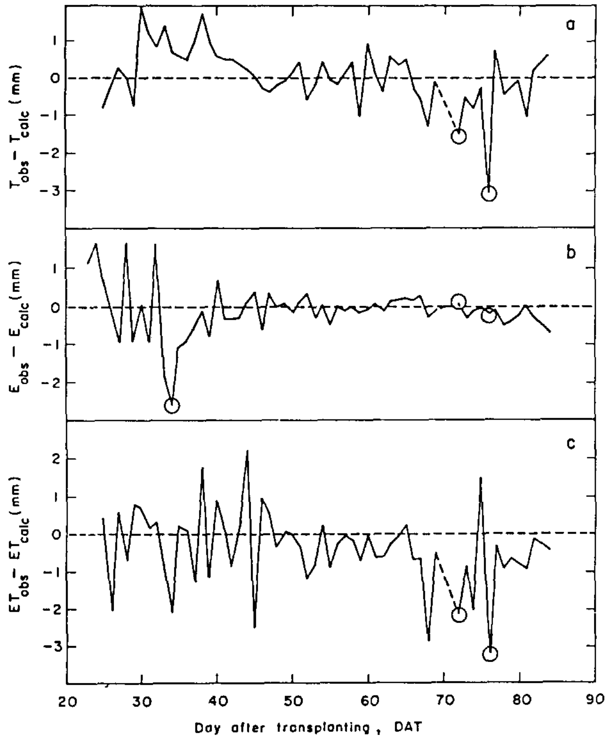

Fig. 7. Residual plots, observed minus calculated. (a) Transpiration; (b) evaporation; (c) evapotranspiration. (○, Erratic measurement.)

TABLE II

Results of linear regression analysis based on $y = bx + a$, where x and y are observed and modelled values, respectively. For E and T, the calibration period DAT 46–69 was excluded

	n	r	$s_{y \cdot x}$ (mm)	$b(s_b)$	$P(b = 1)$	$a(s_a)$ (mm)	$P(a = 0)$	$\bar{x}$ (mm)	$\bar{y}$ (mm)
Daily									
E	32	0.818	0.78	0.60(0.08)	< 0.001	0.88(0.17)	< 0.001	1.87	2.00
T	31	0.818	0.78	0.69(0.09)	0.001	1.5 (0.5)	0.005	5.62	5.39
ET	54	0.821	0.98	0.65(0.06)	< 0.001	2.8 (0.5)	< 0.001	7.30	7.55
Five days									
E	6	0.936	2.34	0.78(0.15)	0.2	2.7 (1.6)	0.18	9.73	10.27
T	6	0.871	3.78	0.8 (0.2)	0.4	5.0 (6)	0.5	27.91	26.84
ET	10	0.914	2.29	0.93(0.15)	0.5	3.7 (5)	0.5	37.14	38.24

$s_{y \cdot x} = (\Sigma(x - y)^2/n - 1)^{1/2}$
$P(b = 1)$, the probability of finding a larger t value when testing the hypothesis $b = 1$.

daily leaf area index, which changes rapidly in this period (Fig. 2) and enters the argument of the exponential function of eq. 2. A 25% underestimation of L on DAT 35 would result in an underestimation of T by ~ 0.5 mm. Also, α_c is not expected to remain constant at small leaf area indexes. The correlation between observed and calculated daily T (Fig. 6a), excluding the full-cover period used for calibration and five rainy days when lysimeters malfunctioned, is not a simple 1:1 relationship, as the regression parameters a and b are significantly different from zero and one, respectively (Table II). However, the departure from a 1:1 line is mainly caused by the positive residuals in the early period of high sensitivity to errors in the leaf area index. Also, the average estimation error is only 0.8 mm day^{-1} or 14%. Therefore, daily T can be estimated with reasonable accuracy for most practical purposes, although the model seems to slightly overestimate and underestimate daily T at low and high T, respectively.

Evaporation

α_w was calibrated for the full-cover period to the data from the evaporation tray, finding $\alpha_w = 0.58$. The presence of the crop canopy, sheltering the water surface and contributing water vapor to aerodynamic exchange, has reduced the evaporation from the water surface by $\sim 85\%$ and increased the resistance to transfer of water vapor originating at the ground by a factor of 1.7. Modelling E with $\alpha_w = 0.58$ for the entire period results in the correlation plot of Fig. 6a and the residual plot of Fig. 7b. As for transpiration, a 1:1 relationship is rejected (Table II). The relatively high scatter in the daily E correlation, as compared to that for T, is due to the use of a less accurate hook gauge during the first 46 days, experimental errors carrying greater weight at smaller absolute values, and the well-known deficiency of Penman's equation in not giving special consideration to daytime and nighttime weather conditions when using weather variables averaged over day and night. The model predicts daily E with an average error of 0.8 mm day^{-1} or 42%.

Evapotranspiration

Using $\alpha_c = 0.75$ and $\alpha_w = 0.58$, daily ET was modelled as $E + T$ and compared to measured ET (Figs. 6b and 7c; Table II). As for E and T, the combined model overestimates and underestimates daily ET, at low and high ET, respectively. There is a tendency for overestimation, especially during the ripening stage, but the scatter here is increased due to the occurrence of rain. Also, the two largest deviations in Fig. 6b are associated with days of refilling the reservoir, increasing the experimental error on those days. A 1:1 relationship is rejected (Table II), although the residual standard error is only 1.0 mm day^{-1} or 13% on average. The high correlation coefficient is not surprising in view of the similar behavior of the two lysimeter systems shown in Fig. 3.

DISCUSSION

In a strict statistical sense, the calibrated models do not perform satisfactorily for daily values, although estimation errors are reasonable. [Also, the FAO-modified Penman method (Doorenbos and Pruitt, 1977) was found not to apply on daily intervals, with an estimation error of 1.2 mm day^{-1}, $r = 0.71$ and a general mid-season overestimation of $\sim 10\%$, pointing to the need for local calibration of the crop coefficients of this model.] However, for near real-time irrigation scheduling in large-scale surface irrigation systems, estimation intervals of 5 days are appropriate. Summing over 5 days, the correlations improve significantly (Fig. 8), and 1:1 relationships are statistically acceptable (Table II). The average error of estimating 5-days ET is 2.3 mm per 5-days or 6%. This error compares closely with the expected error of 1.0 mm day^{-1} and 2.2 mm per 5-days for potential evapotranspiration models (Jensen and Wright, 1978).

Being calibration factors, α_w and α_c of course tend to absorb any deficiency of the entire model complex. Elaborations in the following paragraphs are based on the assumption that any such deficiency has been of minor importance compared to the a priori assumed significance of α_w and α_c.

The apparent constancy of α_c and α_w suggests that aerodynamically, the rice crop has already reached a state of full cover at a leaf area index of ~ 1.5. Katerji and Perrier (1985) made a rather similar observation on alfalfa, where the structural resistance offered by the canopy layer to transfer of transpired water vapor was found to remain constant from a leaf area index of ~ 2. It seems that increases in transpiration due to increased canopy area available for aerodynamic interaction are opposed by increased mutual sheltering of leaves. The increasing transpiration up to a leaf area index of ~ 3 is, therefore, primarily due to increased absorption of solar radiation and a generally increasing atmospheric demand. So, energetically the rice crop reaches full cover

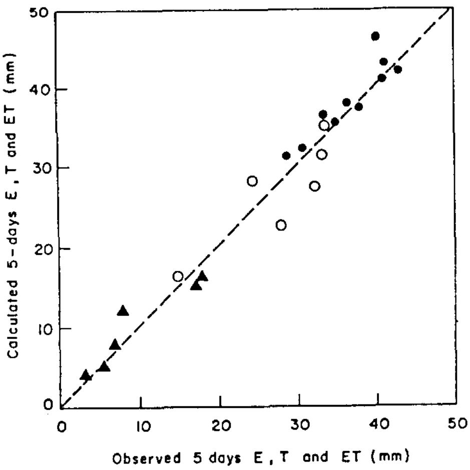

Fig. 8. Five-day sums of observed and calculated evaporation (▲), transpiration (○) and evapotranspiration (●).

at a leaf area index of ~3. Although coherent data was not collected for the initial period due to experimental difficulties, it is expected that α_c and α_w will change from zero and one, respectively, prior to transplanting, to 0.75 and 0.58 during the first 4 weeks after transplanting.

The sum of α_c and α_w exceeds one (1.33), somehow suggesting that the evaporation potential of the wetland rice field exceeds that of open water (E_o), since all the terms of the aerodynamic component of eq. 1b exceed those in eq. 1a. However, this may be counteracted by the lower reflectivity of the water surface. By accepting the model and varying the relative contribution of the aerodynamic term of eq. 1a from 20 to 40%, a ratio of ET_{rice}/E_o from 1.2 to 1.4 is found for average conditions during the full-cover period, as compared to a ratio of 0.8 for "potential" grass during summer in a temperate climate estimated by Penman (1956). This additional evaporation may result from the greater ability of the wetland rice field to extract sensible heat from the air. An average ratio $\lambda ET/R_n = 1.31$ is estimated for the period DAT 25–84, suggesting intermediate advective conditions, which may explain the tendency for underestimation of daily values by the combination approach on days of high evaporation (Fig. 6). For sites where regional climate or site exposure gives rise to a considerable advection of energy from the surroundings, like those investigated by Evans (1971; $\lambda ET/R_n = 1.71$) and Lourence and Pruitt (1971; $\lambda ET/R_n = 1.56$), the ratio between ET_{rice}/E_o may very well exceed 1.5, depending on site exposure and wind speed. For temperate, humid conditions, Uchijima (1976) reported $\lambda ET/R_n = 0.82$. Obviously, the advective condition is of major importance in determining the evaporation from rice fields, as also concluded by Linacre (1976) for evaporation from swamps.

The ratio of $\alpha_c f_c(u)$ to $\alpha_w f_w(u)$ is typically ~3, as compared to the ratio of ~25 between the structural resistances including the aerodynamic resistance to transfer of vapor from ground and stomates through the canopy layer in alfalfa at a leaf area index of 2 (Katerji and Perrier, 1985), rendering the contribution of soil evaporation to evapotranspiration negligible in alfalfa at a leaf area index > 2, as in most other upland crops. This difference between alfalfa and wetland rice may arise due to the presence of a (warm) water surface beneath the rice canopy and differences in canopy architecture, allowing eddies to develop close to the ground in the rice crop. The difference may be less pronounced in broadcast rice.

Evaporation from the water surface contributed 13% of total *ET* during the full-cover period. If water had not been freely available at the ground, the transpirational demand would have increased due to sensible heat generation in the crop leading to clothes-line effects, a generally increased vapor pressure deficit, and lack of contribution to aerodynamic transfer from the water surface. So, lack of water on the ground may induce an atmospheric moisture stress in wetland rice. The adaptation of wetland rice to transpire in the presence of an evaporating water surface and the often shallow root zone may explain why moisture stress effects generally appear already at a soil moisture depletion of 20% of the porosity (Doorenbos and Kassam, 1979), as compared to 50–75% for most upland crops. It seems that the soil–plant–atmosphere-continuum concept, emphasizing the continuity of water via roots and stomates, needs to be modified to include the active participation of the water surface in evaporation from rice fields, to be applicable as a framework for micrometeorological modelling of the wetland rice system.

CONCLUSION

Although the model was not tested on a truly independent dataset, it is concluded that the sub-models for evaporation and transpiration perform well when 5-day sums of daily evaporation and transpiration are used. The model including the calibrated aerodynamic efficiency factors, is expected to be applicable to transplanted, high-yielding rice varieties grown under wetland conditions on the rice-producing lowland plains of Asia. The model is likely to underestimate evapotranspiration on sites exposed to high energy advection, which may be the case for small irrigated areas during the dry season.

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