Practical Estimation of Evapotranspiration in Rice Cultivation in Thailand

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Abstract:

A reliable, practical method for estimating the evapotranspiration associated with rice cultivation is vital for proper water management in Thailand. We investigated the possibility of estimating rice-related evapotranspiration using only daily air temperature and wind speed, as a practical method for local application in Thailand. By applying regression analysis to a theoretical investigation, we developed a set of daily based equations that estimated evapotranspiration of rice cultivation for a typical Thai Plains environment during the rainy season. The estimation error of the developed equations was approximately 20% on a daily scale, and 10% on a weekly scale. Although additional validation of the derived equations is needed for application at other location and at other times of the year, the developed equations show potential for use in water management of cultivation in Thailand.

KEYWORDS air temperature; evapotranspiration; irrigation; rice cultivation; Thailand; wind speed

INTRODUCTION

Rice paddies are typical components of the agroeconomic system in Asia, which accounts for a major share of the world’s grain zone. As the largest export crop, rice is the most important crop in Thailand. Cultivation of rice usually consumes large amounts of water, and thus to expand the area of rice paddies, water resources must be managed efficiently. In 1850, the total area of planted rice in Thailand was estimated to be around 0.9 million ha. By 1950, that value had increased six-fold to 5.5 million ha (Fukui et al., 2000). By 2007, Thailand had approximately 11.3 million ha of rice fields (Center of Agriculture Information, 2008). However, production was characterized by quite low productivity and high interannual and regional variability due to low water availability (Fukai et al., 1998; Wade et al., 1999). Therefore, a good estimation of actual water use for rice cultivation is vital for proper water management, improved efficiency of water use, high productivity, and efficient farming activities in Thailand.

Evapotranspiration (ET), which is an essential factor in estimating actual water use (Attarod et al., 2005), can be estimated by a number of methods. Some ET estimation methods require numerous weather variables as inputs, whereas others need fewer inputs. Among the former methods, some modified techniques have been developed, partly in response to data availability. The Food and Agriculture Organization Penman–Monteith (henceforth, FAO) method (Allen et al., 1998) is generally considered to be the best approach for estimating ET; it is based on physical principles and considers all of the climatic factors that affect ET on a daily scale (e.g., Peacock et al., 2004; Watanabe et al., 2004; Tsubo et al., 2007). A more practical application for estimating ET using a few meteorological variables, the Blaney–Criddle (BC) method (Blaney and Criddle, 1950) is a temperature-based method on a monthly scale and was empirically developed based on the assumption that temperature is an indicator of the evaporative power of the atmosphere. Comparisons among estimation models have shown the BC method to be one of the best approaches for estimating monthly ET (e.g., Xu and Singh, 1998, 2001; Lee et al., 2004). Temperature-based methods are useful when other meteorological data are unavailable; however, most temperature-based methods are based on a monthly scale, and the estimates are generally less reliable than those obtained by taking other climatic factors into account on a daily basis.

To choose an ET calculation technique, factors such as data availability, the intended use of the estimation, and the time scale required by the problem must be considered (Shih et al., 1983). In Thailand, meteorological observatories operated by local authorities (e.g., Thai Meteorological Department) generally gather basic data on daily precipitation, hourly air temperature, and hourly wind speed. In addition, the Thai bureau for water conservation and use, called the Royal Irrigation Department (RID), manages water on a weekly time scale.

Based on these data sources and uses, the available meteorological variables in Thailand should be air temperature (T) and wind speed (U). Moreover, daily averaged data are better suited to proper water management by local users and managers. Therefore, the objectives of this study were to investigate the possibility of estimating ET using only daily averaged T and U and to propose a practical method for estimating ET of rice cultivation in Thailand. The study site was a representative irrigated paddy managed by the Phitsanulok Rice Research Center (PRRC).

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STUDY SITE AND MEASUREMENT SYSTEM

Study site

Thailand is located in the Southeast Asian monsoon region, and its climate is divided into wet and dry seasons, with approximately 90% of precipitation falling during the rainy season of May to November. The average $T$ values range from 26°C to 29°C throughout Thailand, with the exception of the northern and western mountainous areas (see Figure S1). The average annual precipitation and average $T$ in the area of the PRRC (16°50′N, 100°22′E, and 44 m above mean sea level) for the period 1971–2000 were 1335.6 mm, of which 1226.0 mm was recorded during the rainy season, and 27.7°C. The PRRC is located in a typical Thai plains environment, and the studied paddy was typical of an irrigated paddy in Thailand.

Rice (Chainat-5) is seeded at the PRRC in early August and harvested in early November. To provide adequate water to the rice, the PRRC irrigates paddies as follows. For the first 2 weeks, water is supplied to a height of 3 to 5 cm from the surface; water supplies are then increased in accordance with rice growth up to a height of 15 cm until 2 weeks before harvesting.

Micrometeorological measurements for obtaining $ET$ and other measurements were performed using automatic weather station systems developed by Anki et al. (1996, 1998). Data for the irrigated rice paddy were obtained during the rice growth period from August to October in 2002 and 2003. Measuring $ET$ at a tropical paddy is pivotal for this study because most studies have investigated mid-latitude temperate zone forest $ET$, and far fewer have examined $ET$ of crops in low-latitude tropical zones.

$ET$ measurement by the energy balance Bowen ratio technique

In this study, we used the energy balance Bowen ratio technique to measure $ET$ (Bowen, 1926). Because nighttime heat fluxes including $ET$ are usually quite small, we obtained daytime $ET$ as daily $ET$, following Attarod et al. (2005, 2006).

The Bowen ratio was calculated from $T$ and humidity measured by ventilated psychrometers (SCH 1010, Meteo Electronic Co., Ltd., Sapporo, Japan), which were attached to a 6-m tower and took measurements at 2 and 6 m. The net radiation at the surface ($R_n$) was measured by a net radiometer (MF-40, EKO Instruments Co., Ltd., Tokyo, Japan) mounted at 2.5 m on the tower. Soil heat flux plates (MF-81, EKO Instruments) and soil temperature sensors (E-733, Yokogawa Denshikiki Co., Ltd., Tokyo, Japan) were installed underground to measure the surface heat flux in soil ($G$). Pressure-type liquid level gauges (W-431, Yokogawa Denshikiki) and water temperature sensors (E-733, Yokogawa Denshikiki) were installed to measure the surface heat flux in water ($G_w$). For missing $G_w$ data, we applied the empirical equation developed at a rain-fed rice paddy in Thailand by Attarod et al. (2006). Data were logged every minute, averaged over 30 minutes, and recorded by a data logger (Meteo30, Meteo Electronic). Finally, all data were grouped by day, and missing data and bad quality data were objectively removed on a daily scale.

RESULTS AND DISCUSSION

Investigation of a possible method for estimating daily $ET$ using only $T$ and $U$

As noted above, a practical $ET$ estimation for Thailand would use only daily averaged $T$ and $U$ as inputs. To examine whether daily averaged $T$ and $U$ can be representative indicators of daily $ET$ related to rice cultivation in Thailand, we conducted a theoretical investigation using the PRRC data based on a study by Kondo (1994).

Given that the surfaces and surrounding environments of a paddy are fully wet during the rice-growing period, the relative humidity of the atmosphere at a reference height ($\rho$) and the evaporation efficiency ($\beta$) can be regarded as 1, following Kondo (1994). Under these specified conditions, we can derive dimensionless latent heat from the bulk formula as follows (see Document S1):

$$\frac{\ell E}{Q - \sigma T^4} = \frac{\ell \rho C_P U}{4 \sigma T^4 + C_P \rho C_H U + \ell \rho C_P U}$$

(1)

where $\ell E$ is the latent heat (Wm$^{-2}$), $\sigma$ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}$ Wm$^{-2}$K$^{-4}$), $\ell$ is the latent heat of vaporization of water (Jkg$^{-1}$), $C_P$ is the heat capacity (JK$^{-1}$kg$^{-1}$), $\rho$ is the air density (kgm$^{-3}$), $C_H$ is the bulk transfer coefficient of sensible heat, and $\Delta$ (K$^{-1}$) is the gradient of saturated specific humidity (kg kg$^{-1}$) and $T$ (K) at the reference height. $Q$ is the available incoming energy (Wm$^{-2}$) which we define as $S^* + L^* - G - \Delta \rho$, where $S^*$ and $L^*$ are downward shortwave and longwave radiation at the surface. Following Kondo (1994), we defined the dimensionless exchange rate as

$$J = (C_P \rho / \Delta \rho T^4) \rho C_H U$$

(2)

Equation (1) can then be written as

$$\frac{\ell E}{Q - \sigma T^4} = \frac{\ell / \rho C_P U}{1 + \ell / \rho C_H \Delta}$$

(3)

Here, $Q - \sigma T^4$ represents $R_{\text{in}}$ (Wm$^{-2}$), and $\frac{\ell E}{Q - \sigma T^4}$ becomes $\ell E/R_{\text{in}}$.

To investigate the possible application of the bulk formula on a daily basis, which is generally applied on a 30-min scale, we plotted the daily averaged results of the right-hand side of Equation (3) applied on daily and 30-min scales (see Figure S2), assuming that surfaces and surrounding environments were fully wet ($\rho = 1$ and $\beta = 1$). In addition, the value of $C_P$ was set at 0.005, based on the approximate value of the paddy studied by Kondo (1994). Considered together, all of the plots almost equaled a 1:1 line; thus, we can assume that a daily time scale can apply to the bulk formula at the PRRC.

Accordingly, we investigated the relationships of $T$ and $U$ to $\ell E$ on a daily scale. Figure 1 shows the results of the right-hand side of Equation (3) against $T$ and $U$ on a daily scale. Because $\ell E/R_{\text{in}}$ showed linear correlations with $T$ and $U$ on a daily scale in this experiment, we estimated daily $\ell E/R_{\text{in}}$ based on the linear regression of daily averaged $T$ and $U$. As $R_{\text{in}}$ was not measured at the PRRC, and $R_{\text{in}}$ showed a linear correlation with $R_n$ (see Figure S3), daily averaged data were input to plot $R_n$ instead of $R_{\text{in}}$ against $T$ and $U$ in Figure 2. Daily averaged $R_n$ showed linear correlations with daily averaged $T$ and $U$ in this experiment. Thus, estimating $R_n$, namely $R_{\text{in}}$, on a daily scale based on the linear regression of $T$ and $U$ was also appropriate. In addition, $\ell E/R_{\text{in}}$ is generally considered to be positively correlated with $T$ because the Bowen ratio is a
function only of $\Delta$ under the specific condition of $R_m = 1$. However, $\ell E/R_m \Delta$ had negative correlations with $T$ in this experiment due to a greater increase in $R_m \Delta$ than $\ell E$.

In view of the above considerations, $\ell E$, namely ET, may reasonably be considered as a function of $T$ and $U$, as both $\ell E/R_m \Delta$ and $R_m \Delta$ were linearly correlated with $T$ and $U$ (Figures 1 and 2). Therefore, the assumption that $T$ and $U$ can serve as indicators of ET for rice cultivation in Thailand was confirmed. Furthermore, daily averaged $T$ showed a linear correlation with daily averaged $U$ (see Figure S4). Hence, $\ell E/R_m \Delta$ and $R_m \Delta$ can be written as linear expressions of $T$ and $U$, respectively. Therefore, a theoretically based form of ET would appear to be a quadratic function of $T$ or $U$ with a negative quadratic slope. A form of ET for the combination of $T$ and $U$ would have a negative slope for the cross term of $T$ and $U$.

**Regression analysis for practical estimation of ET using $T$ and $U$**

Using the above theoretically based form, equations for the estimated daily ET were derived by applying regression analysis to the PRRC data during the rainy season in 2002 and 2003:

$$ET = -0.195 T^2 - 29.5 + 6.16 \quad (r = 0.72) \quad (4)$$

$$ET = -2.11 U^2 + 6.04 \quad (r = 0.73) \quad (5)$$

$$ET = -0.559 T^2 - 28.6 U - 2.3 + 6.00 \quad (r = 0.75) \quad (4)$$

Here, $r$ is the correlation coefficient of each derived equation, and units of ET, T, and U are mm day$^{-1}$, degrees C, and m s$^{-1}$, respectively. T in this experiment at the PRRC was in the range from 24.5 to 29.7°C (Figure 3), and $U$ was in the range from 0.2 to 2.1 m s$^{-1}$ (see Figure S5). As expected from consideration of the theoretically based form, Equations (4) and (5) had negative quadratic slopes, and Equation (6) had a negative slope for the cross term of $T$ and $U$. Furthermore, measured ET and $ET$ values estimated by Equations (4), (5), and (6) on a daily scale were generally the same (see Figure S6).

Table 1 shows the root mean square errors (RMSEs) of ET values estimated with different simple moving average time scales and compares them with those of the FAO and BC methods, which are known to be two of the best estimation models. The FAO method considers $T$, $U$, humidity, and radiation for daily, weekly, or monthly calculations, and the BC method requires daily mean $T$, although it is a monthly based method (see Document S2). The error of daily estimated ET was approximately 20% for Equations (4), (5), and (6), which is between the error percentages of the FAO and BC methods. Significant differences were not recognized among estimated ET of all methods. Because a simple moving average eliminates variations, statistically significant differences were not recognized between estimated ET of each time scale not only by Equations (4), (5), and (6), but also by the FAO and BC methods; however, the estimation errors of all the methods remarkably decreased with the increased length of the moving average of time. The above results confirm that daily ET can be approximated using only daily averaged $T$ and $U$ during the rice-growing period, based on the theoretically based assumption.

To verify the derived equations, we applied Equation (4) to the Rice Experimental Field Section (REFS) located approximately 40 km north of the PRRC, where ET was observed by a lysimeter technique in July, August, and September 2006 (77 days). Because $U$ was not measured at the REFS, we could not validate Equations (5) and (6) in this experiment. T in this experiment at the REFS was in the range from 27 to 30.8°C.
Table I. Root mean square errors (mm d−1) and estimation errors (%) of estimated ET by the developed equations, the FAO Penman–Monteith (FAO) method, and the Blaney–Crumdile (BC) method for different simple moving average time scales.

|                       | 1-day scale | 7-day scale | 14-day scale |
|-----------------------|-------------|-------------|--------------|
| Equation (4)          | 1.02 (22%)  | 0.55 (12%)  | 0.41 (9%)    |
| Equation (5)          | 1.01 (21%)  | 0.43 (9%)   | 0.32 (7%)    |
| Equation (6)          | 0.97 (20%)  | 0.49 (10%)  | 0.36 (8%)    |
| FAO method            | 0.88 (19%)  | 0.49 (10%)  | 0.33 (7%)    |
| BC method             | 1.39 (29%)  | 0.65 (14%)  | 0.30 (7%)    |

The RMSEs on the daily, weekly, and 14-day scales were 0.52, 0.23, and 0.17 mm day−1, corresponding to 9, 4, and 3% of error for estimated ET, respectively. To further verify the derived equations, we applied similar equations derived from the PRRC data in only 2003 to the PRRC data in 2002. The error of estimated ET by these equations instead of Equations (4), (5), and (6) on the daily, weekly, and 14-day scales were approximately 22, 12, and 5% which were similar to the error shown in Table I.

Because Equations (4), (5), and (6) are negative quadratic equations, the range of confidence for Equations (4), (5), and (6) are between the peak and the lower root of the quadratic equations (Figure 3 and S5). In this experiment, the derived equation was validated at the REFS where T is greater than the peak of Equation (4). Moreover, the derived equations were developed at the PRRC located in a typical Thai plains environment (see Figure S1). Therefore, although additional validation is needed for application at other places and at other seasons of the year, the derived equations show potential for use in estimating ET of rice cultivation in Thailand.

CONCLUSIONS

For practical applications, a model to estimate ET associated with rice cultivation in Thailand should include only daily averaged T and U. Our theoretically based investigation confirmed that T and U are indicators of daily ET for rice cultivation in Thailand. Furthermore, this investigation suggested that ET could be represented by a quadratic function of T or U with a negative quadratic slope. In the case of ET estimation using the combination of T and U, a negative slope for the cross term of T and U was suggested. Based on the above assumptions, we derived a set of daily based equations for estimating ET using T and U, by applying regression analysis to data collected at the PRRC during the rainy season. The accuracies of the derived equations for estimating ET were acceptable compared with the FAO and BC methods, on daily, weekly, and 14-day scales.

The estimation error of the derived equations was approximately 10% on a weekly scale, which is the time scale of water management by RID. Although additional validation of the derived equations is needed for application at other places and for other seasons of the year, local authorities can use the derived equations as a practical method for estimating ET of rice cultivation in Thailand.

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SUPPLEMENTS

Supplement 1. Supplementary Documents S1 and S2 and Figures S1 to S6.

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