

Comparison and Recalibration of Equations for Estimating Reference Crop Evapotranspiration in Thailand

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ABSTRACT

In Thailand, the FAO-56 Penman-Monteith (FAO-56 PM) method is now widely recommended for estimating reference crop evapotranspiration (ET_0) in spite of requiring more comprehensive weather data than other methods. However, in many cases of missing climatic data, the FAO-56 PM method may not be practically employed. Therefore, this study was conducted to evaluate the performance of alternative equations which require less input data, namely, the Priestley-Taylor, Jensen-Haise, Hargreaves, and pan evaporation methods. In addition, the empirical coefficients in some of these equations were recalibrated to determine the best alternative method for ET_0 estimation under Thailand's climatic conditions. The analysis based on three datasets of 30-year monthly averaged climatic data from 125 weather stations of the Thai Meteorological Department during 1966–2011 showed that with the default values of empirical coefficients, although the pan evaporation method with an assumed constant pan coefficient may be considered the most accurate, its consistency in ET_0 prediction needs further improvement. Nonetheless, after recalibration, no significant improvement was noticeable from the pan evaporation method. Conversely, the accuracy of the Priestley-Taylor equation was significantly improved with the average relative absolute error reduced to about 5% while maintaining a high precision with both calibration and validation datasets. Therefore, the Priestley-Taylor method with a newly calibrated value of $\alpha = 1.092$ is highly recommended for using as the alternative method to the FAO-56 PM method. Nevertheless, under circumstances with very limited data, the pan evaporation and Hargreaves methods with the new empirical coefficients derived in this research resulted in about 10% of the average relative absolute error for estimating ET_0 under Thailand's climatic conditions.

Keywords: reference crop evapotranspiration, FAO-56 Penman-Monteith, Priestley-Taylor, Hargreaves, pan evaporation

INTRODUCTION

The reference crop evapotranspiration or reference evapotranspiration (ET_0) is the summation of evaporation and transpiration from a hypothetical reference surface defined by Food and Agriculture Organization of the United Nations

(Allen *et al.*, 1998) to account for the influence of weather conditions on the consumptive use of the reference crop surface. The reference surface is officially defined as a grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s.m^{-1} , and an albedo of 0.23 (Allen *et al.*, 1998).

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In Thailand, it has been recommended that the ET_0 should be calculated using the FAO-56 Penman-Monteith (FAO-56 PM) method with various elements of climatic data measured from standard weather stations (IWMD, 2011). Crop coefficients (K_c) of various crops at any growth stage, which are defined as the ratio of crop evapotranspiration (ET_c) to the ET_0 calculated using the FAO-56 PM method have been derived and published by the Royal Irrigation Department of Thailand (RID) (IWMD, 2012). Nevertheless, in many cases with limited or missing climatic data that is necessary for ET_0 calculation using the FAO-56 PM method, some other empirical equations previously proposed for determining evaporation from a water surface or evapotranspiration from some other predefined standard crops have been adopted to estimate ET_0 (Chaleeraktragoon and Punyawansiri, 2013). As a result, by not using ET_0 calculated from the FAO-56 PM method but utilizing its derived K_c as published by the RID (IWMD, 2012), without any adjustments, the estimated values of ET_c or the crop water requirement may sequentially be flawed. Depending upon the value of K_c , this may result in a large error in determining ET_c (as $ET_c = K_c \times ET_0$), if a false estimate of ET_0 is used.

Many studies have been conducted worldwide for decades to evaluate the discrepancies in ET_0 obtained from various equations against the FAO-56 PM method: in the USA (Temesgen *et al.*, 2005; Suleiman and Hoogenboom, 2007), in Canada (Sentelhas *et al.*, 2010), in Africa (Ngongondo *et al.*, 2013), in China (Xu *et al.*, 2013), in Iran (Raziei and Pereira, 2013; Tabari *et al.*, 2013), and in the Mediterranean (Todorovic *et al.*, 2013; Berti *et al.*, 2014). In Thailand, Boonyatharokul (1975) and Vudhivanich (1996) reported variations of evapotranspiration which were calculated from the equations usually adopted for ET_0 estimation. It was shown that the estimated value of ET_0 in Thailand from each equation may differ by up to 18.5% (Vudhivanich, 1996). A widely varying performance by alternative

equations could be found under diverse climatic conditions. A particular equation may provide an overestimation of ET_0 at a specified location, but an underestimation at others. Therefore, in many cases, local or regional calibrations have been carried out (Sentelhas *et al.*, 2010; Tabari and Talae, 2011; Ngongondo *et al.*, 2013; Xu *et al.*, 2013; Berti *et al.*, 2014; Heydari and Heydari 2014).

Even though some studies on evaluating the performance of different equations for estimating ET_0 in Thailand were reported (Boonyatharokul, 1975; Vudhivanich, 1996; Chaleeraktragoon and Punyawansiri, 2013), they were carried out using only a few weather stations. Comparison and calibration at a national scale have never been proposed. Therefore, the current study was conducted to evaluate the performance of alternative equations which require fewer input data than the FAO-56 PM method for estimating ET_0 throughout the country. The alternative equations consisted of the Priestley-Taylor, Jensen-Haise, Hargreaves, and pan evaporation methods. In addition, the empirical coefficients in some of these equations were recalibrated against the FAO-56 PM method to determine the best alternative method for ET_0 estimation under Thailand's climatic conditions.

MATERIALS AND METHODS

Data for reference crop evapotranspiration estimation

This research was conducted by employing three datasets of 30-year monthly averaged climatic data officially reported by the Thai Meteorological Department (TMD) from 125 weather stations. The three datasets, as presented in Table 1, had been derived from a measurement period of 45 years during 1966–2011 and were averaged over three consecutive 30-year periods for intervals of either 5 or 10 yr on a regular basis by the TMD.

Even though the number of weather stations reported in each dataset is different due to different establishment periods at different locations, a majority (82 out of 125 stations), which were in operation before 1995, are spatially distributed over all regions in Thailand, as presented in Figure 1.

The required input data for all the equations used for ET_o estimation in this study are shown in Table 2. The required data consist of latitude (Lat), altitude above mean sea level ($Elev$), atmospheric pressure (P_{atm}), sunshine duration (n) or cloudiness (C_c), average maximum and minimum air temperature (T_{max} , T_{min} ,

Table 1 Numbers of weather stations used in reference crop evapotranspiration estimation.

30-yr Period datasets	Total number of stations	Number of stations used in this study
1966–1995	82	70
1971–2000	85	66
1982–2011	125	110

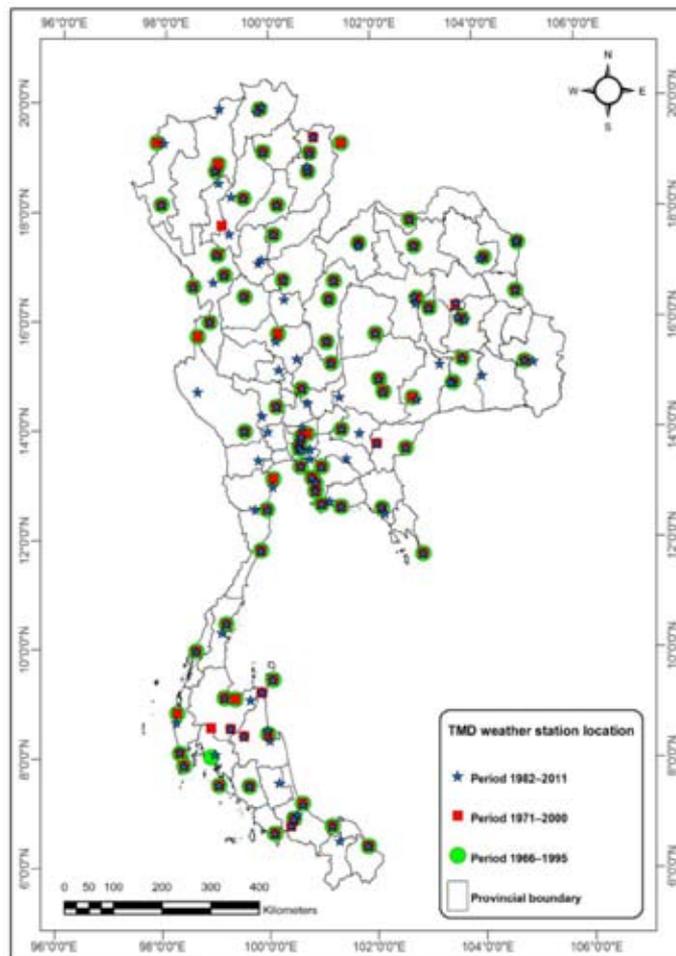


Figure 1 Spatial distribution of weather stations in Thailand from the Thai Meteorological Department (TMD).

respectively), dew point temperature (T_{dew}), wind speed with installed height z above ground surface specified (U_z), and pan evaporation (E_{pan}).

It should be noted that as the T_{dew} is the temperature to which the air needs to be cooled to make the air saturated (Allen *et al.*, 1998), the actual vapor pressure (e_a) required in the FAO-56 PM method for this research was then calculated as the saturation vapor pressure at the dew point temperature rather than being derived from the relative humidity. Additionally, for the stations with no measurement of n but having C_c instead, the relationship presented as a conversion table shown in Table 3 was used to transform C_c to n (Doorenbos and Pruitt, 1977). Although not recommended by Allen *et al.* (1998), the conversion table between C_c and n has been usually adopted by the RID to calculate ET_o with the FAO-56 PM method in Thailand (IWMD, 2011).

Furthermore, to obtain unbiased data analysis, in the case of missing data for a calculation required in any equation as shown in Table 2, the estimation of ET_o was also precluded from all other equations. The number of weather stations actually

used in this study was then reduced, as presented in the last column of Table 1.

Reference crop evapotranspiration estimation methods

In 1998, the FAO-56 Penman-Monteith method (FAO-56 PM) was developed with the aim of maintaining it as the sole standard method for the computation of ET_o from meteorological data so that evapotranspiration in different periods of the year or in other regions could be compared (Allen *et al.*, 1998). The proposed equations were developed based on the definition of the reference surface proposed and the Penman-Monteith equation (Penman, 1948; Monteith, 1965) for calculating ET_o at different time steps, ranging from hours to months. A daily time step or longer is determined using Equation 1:

$$ET_o^{FAO} = \frac{0.408 \Delta(R_n - G) + \gamma \frac{900}{T + 273} U_z (e_s - e_a)}{\Delta + \gamma(1 + 0.34 U_z)} \quad (1)$$

where ET_o^{FAO} is the reference crop evapotranspiration as defined by FAO expressed in millimeters per day; R_n is the net radiation and G is the soil heat flux both in megajoules per square meter per day; T is the mean air temperature in

Table 2 Climatic data required for reference crop evapotranspiration (ET_o) estimation.

ET_o estimation method ^a	Lat	Elev	T_{max} and T_{min}	T_{dew} ^b	n , or C_c	P_{atm}	U_z	E_{pan}
FAO-56 Penman-Monteith	•		•	•	•	•	•	
Priestley-Taylor	•		•	•	•	•		
Jensen-Haise	•	•	•		•			
Hargreaves	•		•					
Pan Evaporation								•

Lat = Latitude; *Elev* = Altitude above mean sea level; *P_{atm}* = Atmospheric pressure; *n* = Sunshine duration; *C_c* = Cloudiness; *T_{max}*, *T_{min}* = Average maximum and minimum air temperatures, respectively; *T_{dew}* = Dew point temperature; *U_z* = Wind speed with installed height z above ground surface specified; *E_{pan}* = Pan evaporation.

^a = Sorted by the number of required inputs for calculation.

^b = T_{dew} was used to calculate actual vapor pressure (e_a) in this study.

Table 3 Conversion factors between sunshine duration and cloudiness. (Doorenbos and Pruitt, 1977).

C_c (1-10)	0	1	2	3	4	5	6	7	8	9	10
n/N ratio	0.95	0.85	0.80	0.75	0.65	0.55	0.50	0.40	0.30	0.15	0

C_c = Cloudiness; *n* = Sunshine duration; *N* = Maximum possible sunshine duration or daylight hours.

degrees Celcius; U_2 is the wind speed at 2 m above ground surface in meters per second; $(e_s - e_a)$ is the vapor pressure deficit in kilopascals; Δ is the slope of the saturation vapor pressure-temperature curve and γ is the psychrometric constant both in kilopascals per degree Celcius; and input variables can be calculated with the formulas in Allen *et al.* (1998).

The Priestley-Taylor equation (PT), as shown in Equation 2, was originally proposed to estimate evaporation under no or low advective conditions (Priestley and Taylor, 1972). The equation is a simplified version by neglecting the aerodynamic component in the combination equation of Penman (Penman, 1948). The energy component is normally multiplied by an empirical coefficient ($\alpha = 1.26$) to estimate evaporated water when the evaporative surface and surrounding areas are generally wet or under humid conditions (Jensen *et al.*, 1990). As a result, the equation is generally not valid for estimating ET_o without calibration.

$$ET_o^{PT} = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \quad (2)$$

where ET_o^{PT} is the reference crop evapotranspiration as defined by the Priestley-Taylor equation expressed in millimeters per day; R_n is the net radiation and G is the soil heat flux both in millimeters per day; and γ is the psychrometric constant in kilopascals per degree Celcius. The coefficient α was locally or regionally recalibrated in many studies under various climatic conditions worldwide, producing a proposed value in the range 1.01–2.14 (Temeepattanapongsa, 2004; Sentelhas *et al.*, 2010; Tabari and Talaee, 2011; Ngongondo *et al.*, 2013; Xu *et al.*, 2013).

The Jensen-Haise equation (JH) was first derived by Jensen and Haise (1963) from about 3,000 observations of soil evaporation and 100 values of well-watered crops with full cover in the western USA. After repeated improvement, the equation as shown in Equation 3 was then applied to calculate the consumptive use of alfalfa under well-watered conditions (Jensen *et al.*, 1990).

$$ET_o^{JH} = K_T (T + T_x) R_s \quad (3)$$

where ET_o^{JH} is the reference crop evapotranspiration as defined by Jensen and Haise (1963) expressed in millimeters per day; R_s is the solar or shortwave radiation in millimeters per day; T is the mean air temperature in degrees Celcius; and K_T and T_x are defined by Equations 4 and 5, respectively:

$$K_T = \frac{1}{38 - \frac{2Elev}{305} + \frac{36.5}{(e_{T_{max}}^o - e_{T_{min}}^o)}} \quad (4)$$

$$T_x = 2.5 + 1.4(e_{T_{max}}^o - e_{T_{min}}^o) + \frac{Elev}{550} \quad (5)$$

where $e_{T_{max}}^o$ is the saturation vapor pressure at the maximum air temperature and $e_{T_{min}}^o$ is the saturation vapor pressure at the minimum air temperature both expressed in kilopascals; $Elev$ is the altitude of the station above mean sea level in meters.

The Hargreaves equation (HG) was first proposed by Hargreaves (1975) to estimate grass-related evapotranspiration using only shortwave solar radiation (R_s) and temperature data. The equation was derived from eight years of cool-season Alta fescue grass data measured using lysimeters at Davis, CA, USA. However, the equation was later developed to include extraterrestrial radiation (R_A) instead of R_s (Hargreaves *et al.*, 1985), as shown in Equation 6:

$$ET_o^{HG} = K_H R_A (T + 17.8) \sqrt{T_{max} - T_{min}} \quad (6)$$

where ET_o^{HG} is the reference crop evapotranspiration as defined by Hargreaves (1975) expressed in millimeters per day; R_A is the extraterrestrial solar radiation in millimeters per day; T is the mean air temperature in degrees Celcius; T_{max} is the maximum air temperature and T_{min} is the minimum air temperature both in degrees Celcius; the constant number 17.8 is the result of unit conversion from temperature in degrees Fahrenheit to degrees Celcius; and the empirical coefficient K_H in the equation has the original value of 0.0023. The coefficient K_H

was also recalibrated in many studies, producing a proposed value in the range 0.0017–0.0031 (Sentelhas *et al.*, 2010; Tabari and Talaei, 2011; Ngongondo *et al.*, 2013; Berti *et al.*, 2014; Heydari and Heydari 2014).

The ET_o may be estimated from pan evaporation (PE) using a simple proportional relationship with an empirical coefficient, as shown in Equation 7 (Jensen *et al.*, 1990):

$$ET_o^{PE} = K_p E_{pan} \quad (7)$$

where ET_o^{PE} is the reference crop evapotranspiration estimated from pan evaporation expressed in millimeters per day; E_{pan} is pan evaporation in millimeters per day; and K_p is the pan coefficient. It is important to note that the value of K_p is pan specific which may range from 0.45 to 1.1 depending on the type of pan and its installation conditions (Allen *et al.*, 1998). Then, in determining the appropriate value of K_p , not only the type of the pan, but also the ground cover at the station, its surroundings and the general wind and humidity conditions should be considered, resulting in a complex mathematical relationship, as found in Allen *et al.* (1998). Consequently, using E_{pan} to estimate ET_o may not be as simple as the form presented in Equation 7 due to the complexity inherent in the estimation of an appropriate K_p value. However, under the installation and climatic conditions in Thailand, the value of $K_p = 0.85$ has been widely used for estimating evapotranspiration over a full-cover, well-watered crop (Boonyatharokul, 1975; IWMD, 2011).

Data analysis

Before statistical data analysis occurred, estimations of ET_o were carried out using the FAO-56 PM method (Equation 1) and all of the alternative equations selected for this study (Equations 2–7). As mentioned previously, the estimations of ET_o were precluded from the calculation where data required in Table 2 were missing.

For the FAO-56 PM method, the climatic

input variables were calculated with the formulas found in Allen *et al.* (1998). Only when there was no measurement of the actual sunshine duration (n), was the relationship shown in Table 3 applied to estimate n from measured cloudiness (C_c). Unlike the FAO-56 PM method, by aiming to provide consistency in the ET_o estimation process due to the lack of standard calculation procedures originally defined, the calculation procedures presented in Allen *et al.* (1998) were adopted to calculate the climatic input data (such as R_A and R_S) required in the alternative equations used in this study (Equations 2–7).

For comparison and evaluation of the performance of each alternative equation, the desirable characteristics sought were precision and accuracy in predicting ET_o as obtained from the FAO-56 PM method. Then, in addition to general descriptive statistical parameters (minimum, maximum and mean), two statistical measures were primarily used to evaluate the performance of the alternative equations—namely, the average value of relative absolute errors (\overline{RE}) and the correlation coefficient (r) which can be computed from Equations 8 and 9:

$$\overline{RE} = \frac{\sum_{i=1}^{N_i} \left| \frac{ET_o^k(i) - ET_o^{FAO}(i)}{ET_o^{FAO}(i)} \right|}{N_i} \quad (8)$$

$$r = \frac{\sum_{i=1}^{N_i} [ET_o^k(i) - \overline{ET_o^k}] [ET_o^{FAO}(i) - \overline{ET_o^{FAO}}]}{\sqrt{\sum_{i=1}^{N_i} [ET_o^k(i) - \overline{ET_o^k}]^2} \sqrt{\sum_{i=1}^{N_i} [ET_o^{FAO}(i) - \overline{ET_o^{FAO}}]^2}} \quad (9)$$

where N_i is the number of samples, $ET_o^{FAO}(i)$ and $ET_o^k(i)$ are the reference crop evapotranspiration values calculated by the FAO-56 PM method and a particular alternative equation k for a specified month and station, respectively.

It should be noted that \overline{RE} mathematically gives equal weight to an individual absolute value of RE , as shown in Equation 8. It then indicates the overall accuracy of the estimation with a particular alternative equation ET_o^k compared to ET_o^{FAO} . There is generally no upper bound on \overline{RE} ,

and it may theoretically range from zero to infinity. Among the alternative equations, the lower the value of \overline{RE} is, the better the accuracy that can be accomplished by the equation as a substitute for the values determined using the FAO-56 PM method. On the other hand, the value of r , which can range from -1 to 1, shows the level of linear association of ET_o^{FAO} and ET_o^k . Therefore, it is used to indicate the precision of the alternative equation. The better the precision of the alternative equation that can be attained, the higher the r value that is obtained.

In the calibration process of empirical coefficients in the alternative equations, the three datasets used in this study were divided into two groups—one for calibration and the other for validation. The empirical coefficients were recalibrated using the data during 1982–2011 and least-square linear regression analysis, and validated using the other two datasets. Again, with newly calibrated empirical coefficient values, two statistical parameters (\overline{RE} and r) were then reported to show the improvement of the alternative equations and the performance comparison among the equations.

RESULTS AND DISCUSSION

Three datasets of 30-year monthly averaged climatic data during 1966–2011 were used to estimate ET_o from the equations used in this study, and the results are summarized in Table

4. It was noticed that with the FAO-56 PM method, ET_o ranged between 2.13 and 6.48 mm.d⁻¹ with an average of 3.78 mm.d⁻¹ for all three datasets. The estimation of ET_o from all of the alternative equations ranged from 1.59 to 8.75 mm.d⁻¹ for all three datasets.

From Table 4, with the default values of the empirical coefficients, most of the alternative equations tested in this study, with the exception of the pan evaporation method, tended to provide an overestimation of ET_o compared to the FAO-56 PM method. Moreover, it should be noticed that with a specific ET_o estimation method, only small variation was observed among the datasets due to the fact that the three datasets used were not totally mutually exclusive in space and time. However, the statistical parameters presented provide an overview of the range and average values of ET_o which could be found under Thailand's climate.

Comparison of reference crop evapotranspiration estimations

Figure 2 shows scatter plots comparing ET_o^{FAO} against ET_o^k estimated using the PT, JH, HG and PE methods in which the default values of empirical coefficients were used. A linear relationship between ET_o^{FAO} and ET_o^k at different degrees was observed. On average, most ET_o^k values were overestimated, except when using ET_o^{PE} from the pan evaporation method.

Table 4 Summary of reference crop evapotranspiration (ET_o) from the methods used in this study with default empirical coefficients.

ET _o estimation method	ET _o (mm.d ⁻¹)								
	1982–2011			1971–2000			1966–1995		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
FAO-56 PM	5.90	2.13	3.73	6.26	2.41	3.78	6.48	2.36	3.82
Priestley-Taylor	5.96	1.93	4.29	5.90	2.83	4.25	6.04	2.84	4.23
Jensen-Haise	8.75	1.63	4.40	8.32	2.20	4.36	8.31	2.16	4.34
Hargreaves	6.99	1.94	4.68	6.90	2.94	4.66	6.93	2.95	4.66
Pan evaporation	8.08	1.59	3.60	7.14	2.03	3.80	7.43	2.03	3.90

Max = maximum; Min = Minimum; Avg = Average

Nevertheless, when compared to ET_o^{PT} , the calculated results from ET_o^{PE} were distributed more sparsely and non-linearly among the cluster of estimated ET_o values. This may result from the assumption of a constant K_p value widely used throughout Thailand even though the appropriate K_p value is, in fact, pan specific depending on the type and pan installation conditions (Allen *et al.*, 1995). With $K_p = 0.85$ as recommended by Boonyatharokul (1975) and IWMD (2011), the estimated values from ET_o^{PE} could fortunately preserve the mean of ET_o as ET_o^{FAO} for all the datasets used in this study (as shown in Table 4) due to the even scatter around the 1:1 line. This may indicate the possibility of using ET_o^{PE} as a rough estimate of ET_o for the whole country, but not for a specific site in the country. For a specific weather station, derivation of a local K_p value may be required to enhance the performance of the PE

method. Due to its inconsistency, the ET_o^{PE} with an assumed constant value of K_p , may not be the most applicable method for use as a substitute to the FAO-56 PM method.

Table 5 shows the two statistical parameters (\overline{RE} and r) which were used to evaluate the performance of each equation against the FAO-56 PM method in terms of accuracy and precision, respectively. This table shows that for all three datasets used in this study, the PE method provides the most accurate estimate of ET_o because it produces the lowest values of \overline{RE} varying from 8.4 to 9.7%. On the other hand, the PT method should be considered the most precise method for estimating ET_o with the highest values of r ranging from 0.896 to 0.927. Due to its consistency, the accuracy of the PT method could be improved if the default value of the empirical coefficient in the equation were adjusted. This indicates that the

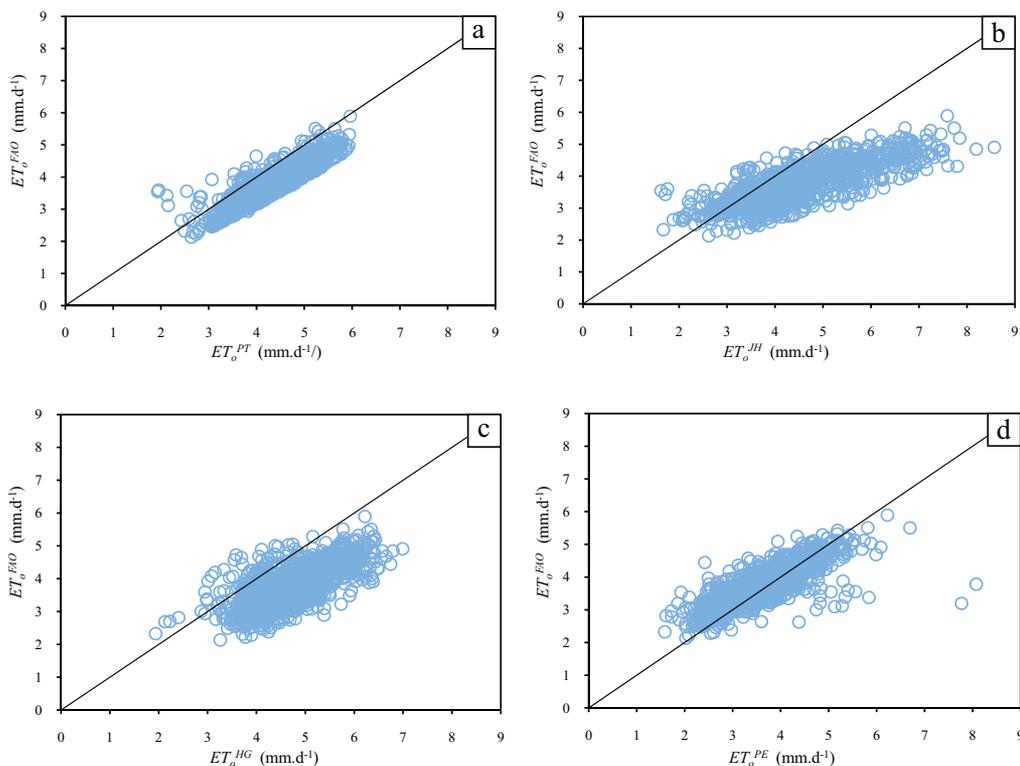


Figure 2 Comparison of reference crop evapotranspiration (ET_o^{FAO}) with default empirical coefficients using the 1982–2011 dataset for (a) Priestley-Taylor (PT); (b) Jensen-Haise (JH); (c) Hargreaves (HG); (d) Pan evaporation (PE).

formulation of the PT method could be the most preferred alternative method as a substitute for the FAO56 PM method in the estimation of ET_0 in Thailand. As a result, recalibration of the empirical coefficients was carried out, and the results are shown in the next section.

Recalibration of reference crop evapotranspiration equations

As an experiment to improve the performance of the alternative methods used for estimating ET_0 under Thailand’s climatic conditions, the empirical coefficients in the PT, HG and PE methods were recalibrated against ET_0^{FAO} . Due to data limitations on the pan type and installation conditions, a constant value of K_p in the PE method was assumed in the calibration. For the JH method, recalibration was not carried out due to the complexity inherently associated with the parameters K_T and T_x (as shown in Equation. 4 and 5).

The three climatic datasets were divided into two groups—calibration and validation

datasets. The most recent dataset reported for 1982–2011 was used in the calibration and the other two datasets (1971–2000 and 1966–1995) were used for validation. The calibration was analyzed based on linear regression using the least squares method. Table 6 shows the comparison of empirical coefficients newly obtained from this study and the default values in the PT, HG, and PE methods.

The values of the empirical coefficients obtained in this study were approximately in the same range as the results in the humid area ($\alpha = 1.01$ – 1.18 and $K_H = 0.0017$ – 0.0022) reported in Sentelhas *et al.* (2010) and Berti *et al.* (2014), which were lower than the default values in the original equations. However, it should be noted that no firm statement about the tendency of the coefficient values according to climatic conditions could be made. The calibration results of other humid regions may provide the opposite result with higher values than the default, as was found in Xu *et al.* (2013) with the proposed values of $\alpha = 1.34$ and $K_H = 0.0027$.

Table 5 Statistical comparison of reference crop evapotranspiration (ET_0) with default empirical coefficients against the FAO-56 PM method

ET ₀ estimation method	1982–2011		1971–2000		1966–1995	
	RE	r	RE	r	RE	r
Priestley-Taylor	16.2%	0.896	13.4%	0.927	12.2%	0.917
Jensen-Haise	19.8%	0.798	17.8%	0.801	16.8%	0.817
Hargreaves	27.4%	0.661	26.1%	0.644	25.2%	0.662
Pan Evaporation	9.7%	0.793	8.4%	0.883	8.5%	0.891

RE = Average value of relative absolute errors; r = Correlation coefficient.

Table 6 Comparison of the default values of empirical coefficients and newly calibrated values for reference crop evapotranspiration (ET_0).

ET ₀ estimation method	Empirical coefficient	Default value	Newly calibrated value
Priestley-Taylor	α	1.26	1.092
Hargreaves	K_H	0.0023	0.0018
Pan Evaporation	K_p	0.85	0.865

The statistical parameters (\overline{RE} and r) used for evaluating the performance of each equation are presented in Table 7 for the new set of empirical coefficients. It was observed that the precision in estimating ET_o of all the equations was preserved. The accuracy of the PE method was slightly changed. The \overline{RE} value decreased from 9.7 to 9.5% for the calibration dataset, but increased from 8.4 to 8.5% and 8.5 to 8.8% for the validation datasets of 1971–2000 and 1966–1995,

respectively. This may indicate signs of overfitting to the dataset used for calibration and imply that the default value of $K_p = 0.85$ may already be suitable for Thailand's climatic conditions. On the contrary, the performances of the PT and HG methods were significantly improved in terms of their accuracy. The values of \overline{RE} decreased from 12.2–16.2% to 4.9–5.1% for ET_o^{PT} and from 25.2–27.4% to 9.8–10.9% for ET_o^{HG} . These improvements are illustrated in Figure 3. The distribution of all of the

Table 7 Statistical comparison of reference crop evapotranspiration (ET_o) with newly calibrated coefficients against the FAO-56 PM method.

ET _o estimation method	Calibration dataset		Validation dataset			
	1982–2011		1971–2000		1966–1995	
	\overline{RE}	r	\overline{RE}	r	\overline{RE}	r
Priestley-Taylor	5.1%	0.896	4.9%	0.927	5.6%	0.917
Hargreaves	9.8%	0.661	10.7%	0.644	10.9%	0.662
Pan Evaporation	9.5%	0.793	8.5%	0.883	8.8%	0.891

\overline{RE} = Average value of relative absolute errors; r = Correlation coefficient.

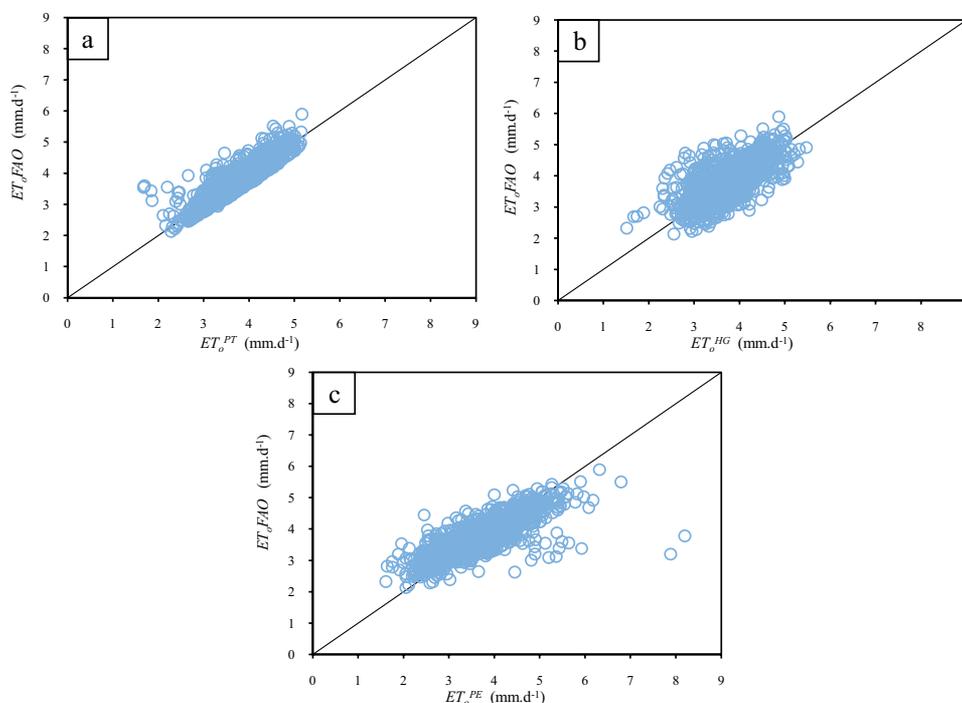


Figure 3 Comparison of reference crop evapotranspiration (ET_o) with newly calibrated empirical coefficients using the 1982–2011 dataset: (a) Priestley-Taylor (PT); (b) Hargreaves (HG); (c) Pan evaporation (PE).

data points was not changed, but the cluster of the data points was shifted and distributed closely over the 1:1 line compared with Figure 2, indicating higher accuracy while maintaining the precision. It should be noted that due to the fact that the two datasets used for validation are not totally independent in space and time due to a large portion of data overlapping with the calibration dataset, additional data may be needed to further verify the empirical coefficient calibrated in this study. However, the results from this study revealed the potential of using all the alternative methods, especially the PT method, used as a substitute to the FAO-56 PM method in cases of missing or limited input data. With the newly calibrated empirical coefficients, the statistical parameters were considerably decreased from those obtained by calculation with default empirical coefficient values.

CONCLUSION

Through the comparison of the performance of the alternative methods for estimating ET_0 against the FAO-56 PM method with default values of the empirical coefficients, this study has determined that even though the pan evaporation method with an assumed constant pan coefficient ($K_p = 0.85$) could preserve the average value of ET_0 over the three datasets with the lowest \overline{RE} value in the range 8.4–9.7%, it lacks consistency in ET_0 prediction, resulting in a lower r and less precision than the PT method. The performance of each of the HG and JH methods was mediocre. After recalibration against the FAO-56 PM method, the pan coefficient K_p value was slightly changed but the evidence was unclear regarding any performance improvement. Conversely, the performance of the PT and HG equations was considerably improved. Therefore, it is concluded that the PT method is the most applicable for estimating ET_0 with greater accuracy than all the other equations used in this study. The

results shown in this research could also be applied to facilitate the practical application of alternative methods for ET_0 estimation compared to using the FAO-56 PM method. With $\alpha = 1.092$ in the PT equation as derived from this research, the average relative absolute error reduced to 4.9–5.1% for the calibration and validation datasets while the consistency of estimation was maintained. In addition, when only either pan evaporation data or maximum and minimum air temperatures are available, the PE and HG methods with the coefficients calibrated from this study may be adopted for estimating ET_0 with the average relative absolute error at about 10%.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the Thai Meteorological Department for the reports of 30-year monthly averaged weather data used in this study. The authors would also like to thank anonymous reviewer for the constructive comments and suggestions for improving the manuscript.

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