Comparison of Estimation Methods for Daily Reference Evapotranspiration Under Limited Climate Data in Upper Northern Thailand

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Abstract

Reference evapotranspiration (ETo) is the evapotranspiration of a reference crop (hypothetical grass) growing on a reference surface with perfect management conditions for growing. Accurate estimation of ETo values is a key success factor for the implementation of effective agricultural production and irrigation water management in the upper Northern Thailand region. The FAO Penman-Monteith method (FAO PM) is recommended as the standard method to estimate ETo by using climatic data such as air temperature (T_{max} and T_{min}), humidity, wind speed solar radiation and other derived parameters. As weather stations in the upper Northern Thailand have been recording only daily air temperature, therefore, there is a need to evaluate alternative methods of ETo estimation for the region. This study aimed to compare three alternative methods, namely; reduced FAO PM, Hargreaves, and Thornthwaite methods, to validate and exploring the suitable methodologies under limited local climatic data. The daily climatic data set of a highland, Angkhang (ANK), and a lowland site, Chiang Mai University (CMU), were used in our study. The results shown that the ETo estimated using the reduced FAO PM method had the lowest error, with 0.5 m s^{-1} of wind speed. For the Hargreaves and the Thornthwaite methods, the good results were found by adjusting the calibration coefficient.

Keywords: Estimated Evapotranspiration/ Reference Evapotranspiration/ Upper Northern Thailand/ Reduced Penman–Monteith Method/ Hargreaves Method/ Thornthwaite method

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1. Introduction

Reference evapotranspiration (ETo) is the evapotranspiration of a reference crop (hypothetical grass) growing on a reference surface with perfect management conditions for growing. Thus, the only factors affecting ETo are climate parameters, such as air temperature, humidity, wind, and solar radiation (Allen et al., 1998). The ETo is varied regionally and seasonally, depending on solar energy conditions and weather conditions (Jensen et al., 1990). For agriculture, the ETo is an important factor for irrigation planning and management because it enables the estimation of the water demands of the crop used by multiplying the ETo with an empirical crop coefficient (Kc) to estimate the crop evapotranspiration (ETc) (Doorenbos and Pruitt, 1977; Wright, 1982). The estimated ETo is required, especially, for the scheduling of irrigation to improve water use efficiency under limited water resources in future (Howell, 1996), during the occurrence of a drought phase (Hanson, 1991), watershed assessment in the Northern Thailand (Ueangsawat and Jintrawet, 2014), Northeast Thailand (Graiprab et al, 2010), and crop water use assessment (Pongpinyopap and Mungcharoen, 2012; Rungcharoen et al., 2014). For those conditions, the estimated ETo in a short time, daily or weekly, is required.

Since ETo is a climatic parameter, it can be computed as a function of climatic data. There are many ways to estimate ETo using meteorological data (Allen et al., 1998; Jensen et al., 1990) such as Penman (1948), Penman–Monteith (Monteith, 1981), Blaney–Criddle (1962), Thornthwaite (1948), and Pan Evaporation (Doorenbos and Pruitt, 1977) methods. The FAO Penman–Monteith (PM) method is recommended as the sole method for determining ETo because the method closely approximates grass ETo which is evaluated in many locations around the world. It is physically based and explicitly incorporates both physiological and aerodynamic parameters, which it is guided to compute in FAO56 (Allen et al., 1998). However, this method requires many variables of climatic parameters. Furthermore, the FAO PM method, with missing climatic data of the parameters, were recommended in the FAO56, called the reduced FAO PM methods (Shahidian et al., 2012). The reduced FAO PM methods and the alternative methods are useful for many countries where there is a lack of availability of the climatic data required for using the standard FAO PM method. However, the values of ETo calculated from difference methods may be confusing for users, because of difference values of estimated ETo from each model, and also from each country and location (Chen et al., 2005; Xu and Singh, 2002; Rácz, et al., 2013; Patel et al., 2014). The problems can be improved by using various local calibration methods (Chen et al., 2005; Lima et al., 2013; Xu et al., 2013; Patel et al., 2014).

In Thailand, which is an agricultural country, most of the weather stations, especially in

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local areas, monitored and measured only air temperature (maximum and minimum) and rainfall. This present a major limitation for accurate estimation of ETo values with the FAO PM method. This is especially true in the upper Northern Thailand region, which is mountainous areas where the agricultural areas are distributed on lowlands of the valleys throughout the region. Under the situation of limited measured weather data sets together with increasing demand for irrigation water for various crops in the region, the estimated ETo is required for the planning and management of the irrigation schedule, but this has not been studied in the upper Northern Thailand region.

Penman (1948) model was accepted as the best method to estimate the ETo with similar values of ETo calculated by FAO PM model in Thailand (Boonyatharokul, 1975). However, the model required solar radiation and aerodynamic data, and provided a higher error than the ETo calculated by the Pan evaporation method (Vudhivanich, 1996). Additionally, using the improved Pan evaporation method, with a calibration coefficient, did not improve the accuracy of ETo in Thailand. It was also produced a higher error than the Priestley-Taylor (1972) method with a calibration fraction value (Temeepattanapongsa and Thepprasit, 2015). However, the Priestley-Taylor method also required net radiation (Rn), soil heat flux and the slope of the saturation vapor pressure-temperature curve (Δ) data set. The study recommended to use the Hargreaves method with calibration coefficients for estimate ETo under the condition of limiting climatic data in Thailand.

To validate and exploring the applicable methodologies under limited climatic data in Upper Northern Thailand region, this study aimed to compare three methods, namely; reduced FAO PM, Hargreaves and Thornthwaite methods, to estimate ETo with limited climatic data. The study focused on the methods using only the temperature data in the Chiang Mai province, the main watershed area of Ping River Basin. The results of the study should be useful for other watershed areas in the region that are facing the same issue of missing and incomplete climatic data sets.

2. Methodology

2.1. Study sites and data

The two weather stations selected for our study are located in the Chiang Mai province which is situated in upper northern Thailand. The region mainly consists of hills and valleys forming a series of north–south mountain range and plateaus interspersed with long flat river basins. The first site is situated on the highland called Angkhang (ANK), located at 19°19′19″ N latitude, 99°29′19″ E longitude with an average elevation of 1400 m.a.s.l., and the second site is situated on the lowland of Lumphun-Chiang Mai valley near Faculty of Agriculture, Chiang Mai University (CMU), located at 18°47′52″ N latitude, 98°57′54″ E longitude with an average elevation of 320 m.a.s.l. The two stations collected the meteorological data sets, which were completed for determining the standard ETo by FAO PM method. The data sets included daily climatic parameters of air temperature (maximum and minimum), maximum relative humidity (%RH), wind speed (u) at 2 m height, and actual sunshine hours (n). The data set of 2010 was used to compare three methods and the FAO PM method, and another three years weather data set between 2007 and 2013 were used for validation. The weather data from the two locations were significantly different (Table 1).

Table 1: Average and standard deviation (in blanket) of input weather variables at monthly Angkhang (ANK) and Chiang Mai University (CMU) in upper northern Thailand.

Month	ANK					CMU				
	T_{max} °C	T_{min} °C	RHmax %	u ms^{-1}	Rs $MJm^{-2}day^{-1}$	T_{max} °C	T_{min} °C	RHmax %	u ms^{-1}	Rs $MJm^{-2}day^{-1}$
JAN	20.1(±2.3)	7.4(±2.4)	87.7(±1.1)	0.5(±0.1)	15.8(±2.1)	32.0(±1.1)	16.9(±2.5)	87.6(±10.1)	0.7(±0.2)	17.2(±2.6)
FEB	22.9(±3.2)	6.2(±2.2)	87.4(±1.8)	0.6(±0.2)	19.7(±1.2)	34.5(±0.9)	14.9(±2.1)	79.9(±6.8)	0.7(±0.2)	21.4(±3.0)
MAR	25.9(±2.0)	11.3(±2.3)	85.2(±1.6)	0.7(±0.2)	19.3(±3.2)	35.9(±1.6)	19.8(±1.8)	78.2(±8.0)	0.9(±0.3)	20.3(±3.3)
APR	28.1(±2.4)	15.3(±1.9)	82.2(±3.7)	0.9(±0.2)	21.3(±2.4)	39.4(±1.2)	23.8(±1.0)	70.8(±6.4)	1.0(±0.2)	22.8(±1.6)
MAY	26.9(±2.6)	18.5(±1.3)	81.7(±3.6)	0.9(±0.2)	19.1(±2.4)	37.6(±2.4)	24.9(±1.4)	77.2(±9.9)	1.1(±0.2)	20.1(±4.2)
JUN	24.3(±1.8)	18.5(±0.7)	84.4(±1.4)	0.8(±0.2)	16.6(±3.7)	35.8(±1.7)	24.3(±0.9)	84.0(±7.3)	1.1(±0.3)	18.1(±4.4)
JUL	23.3(±1.9)	18.4(±0.7)	84.0(±2.0)	0.7(±0.3)	15.2(±4.4)	34.1(±1.6)	24.3(±0.8)	88.8(±5.7)	0.9(±0.2)	15.9(±4.4)
AUG	22.4(±1.6)	18(±0.7)	85.8(±0.8)	0.5(±0.2)	13.6(±3.3)	31.9(±1.8)	23.5(±0.7)	91.9(±4.2)	0.9(±0.2)	13.6(±4.2)
SEP	23.1(±1.6)	17.3(±1.0)	86.5(±1.0)	0.4(±0.1)	15.2(±3.5)	33.2(±2.1)	23.3(±0.9)	90.0(±6.8)	0.8(±0.2)	15.4(±4.1)
OCT	21.5(±1.7)	16.4(±1.9)	85.1(±2.4)	0.8(±0.3)	13.2(±3.6)	32.5(±2.0)	23(±0.8)	89.9(±5.1)	0.9(±0.1)	13.9(±4.7)
NOV	20.0(±1.8)	10.1(±1.8)	88.2(±4.4)	0.5(±0.3)	16.4(±2.5)	31.8(±1.5)	18.5(±1.7)	86.1(±6.5)	0.7(±0.2)	16.2(±4.8)
DEC	20.3(±1.5)	8.7(±3.9)	88.0(±1.8)	0.5(±0.1)	14.5(±3.3)	30.8(±1.3)	17.4(±2.6)	88.4(±6.2)	0.8(±0.5)	14.6(±4.1)

(T_{max}=maximum temperature, T_{min}=minimum temperature, RHmax=maximum relative humidity, u=wind speed and Rs=income solar radiation)

2.2 Analysis methods

The alternative methods used in the study are the reduced FAO PM, Hargreaves, and Thornthwaite methods. To evaluate the ETo estimated from the alternative methods, they were compared with the ETo estimated from the FAO PM method by expressions of accuracy, precision, and error.

First of all, the daily data set, including air temperature (maximum and minimum), maximum relative humidity (%RH), wind speed (u) at 2 m height, and actual sunshine hours (n) in 2010 of the two stations (ANK and CMU), was computed for the ETo by using the standard FAO PM method. The ETo values from the standard method were used for comparing against the estimated ETo values from the alternative methods.

To understand the sensitivity of each parameter of the weather data set affecting the ETo values, the ETo estimated by the reduced FAO PM method with a missing data was tested. The reduced FAO PM methods were treated if the data sets were limited because of missing humidity (−RH); missing solar radiation (−Rs); missing wind speed (−u); missing humidity and solar radiation (−RH−Rs); missing humidity and wind speed (−RH−u); missing solar radiation (−Rs−u); and missing humidity, solar radiation, and wind speed (−RH−Rs−u). Any missing parameter was replaced by the estimated value, the estimation for which is presented in section 2.3.1.

As for the sensitivity of wind speed to ETo estimation, for the very low wind speed in the study areas (see Table 1), where the speed was usually less than 1.0 m s^{-1}, using the recommended wind speed of 2 m s^{-1} may be resulted in a higher error which was not needed in the real situation. To validate the effect of the decreasing wind speed values on the improving in the accuracy of the estimated ETo, three levels of wind speed, 2.0 m s^{-1}, 0.5 m s^{-1}, and 1.0 m s^{-1}, were tested by using the reduced FAO PM which used only the temperature data, or the treatment with −RH−Rs−u.

As for the Hargreaves and the Thornthwaite methods, their original models and their adjusted methods were validated by a comparison of the estimated ETo with the ETo from the FAO PM. The performances of the adjustment were given in section 2.3.3 and section 2.3.4.

The accuracy and precision of the examinations were evaluated by using the slope of the 1:1 line and the coefficient of determination (R^2) of the relation with the original interception (Jabloun and Sahli, 2008; Sentelhas et al., 2010) between the ETo estimated by the alternative methods and the ETo estimated by the FAO PM method. The evaluation was also considered by the mean bias error (MBE) and the root mean square error (RMSE) from the comparison between the ETo estimated by each of the alternative methods and the ETo estimated by the FAO PM method. The determination of MBE and RMSE are presented in the following equations:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(ETo_{(est)} - ETo_{(PM)}\right) \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(ETo_{(est)} - ETo_{(PM)}\right)^2} \quad (2)$$

where ETo(est) and ETo(PM) are the ETo estimated by the alternate methods and the ETo estimated by the standard FAO PM method, respectively.

2.3 Methods for estimating ETo

2.3.1 FAO Penman–Monteith (FAO PM) Method

The FAO PM method is considered to be the chosen estimation method for standard ETo (Allen et al., 1998). It is expressed as follows

$$ETo = \frac{0.408\,\Delta\,(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)} \quad (3)$$

where ET_o is the reference evapotranspiration (mm day^{-1}); *Rn* is the net income radiation at the crop surface (MJ m^{-2} day^{-1}); *G* is the soil heat flux density (MJ m^{-2} day^{-1}) which is relatively small and considered as null for daily estimation; *T* is the mean air temperature at 2 m height (°C); u_2 is the wind speed at 2 m height (m/s); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa); $(e_s – e_a)$ is the saturation vapor pressure deficit (kPa); Δ is the slope of the vapor pressure curve (kPa/°C); and γ is the psychrometric constant (kPa°C^{-1}).

To calculate the above parameters for using in the equation of FAO PM-ETo, the following equations were recommenced by Allen et al. (1998):

$$Rn = Rns – Rnl \quad (4)$$

$$Rns = 0.77\,Rs \quad (5)$$

$$Rnl = \sigma\left[\frac{TmaxK + TminK}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left[1.35\frac{Rs}{Rso} - 0.35\right] \quad (6)$$

where Rns is the net shortwave radiation (MJ m^{-2} day^{-1}); Rnl the net outgoing longwave radiation (MJ m^{-2} day^{-1}); σ is Stefan–Boltzmann constant (4.903×10^{-9}[MJ m^{-2} day^{-1}]); T_{maxK} and T_{minK} are the absolute temperatures during the 24-hour period (°K); e_a is the actual vapor pressure (kPa); Rs is the solar radiation (MJ m^{-2} day^{-1}) calculated by Equation (7) and Rso is the clear-sky radiation (MJ m^{-2} day^{-1}) calculated by Equation (8).

$$Rs = \left(0.25 + 0.5\frac{n}{N}\right) Ra \quad (7)$$

where n is the actual and the maximum possible duration of sunshine (hours),

$$Rso = [0.75 + (2x10^{-5})\ z\ ]\ Ra \quad (8)$$

where z is the altitude (m) and Ra is the extraterrestrial radiation which is estimated from the solar constant, the solar declination, and the time of the year (MJ m^{-2} day^{-1}) (see in Allen et al., 1998).

$$P = 101.3\left(\frac{293.3 - 0.0065\,z}{293}\right)^{5.26} \quad (9)$$

$$\gamma = 0.665x10^{-3}P \quad (10)$$

where P is the atmospheric pressure (kPa) and z is the elevation above sea level (m).

$$\Delta = \frac{4098\left[0.6108exp\left(\frac{17.27\,T}{T+237.3}\right)\right]}{(T+237.3)^2} \quad (11)$$

$$e_s = \frac{e^o{}_{Tmax} + e^o{}_{Tmin}}{2} \quad (12)$$

$$e_a = e^o{}_{Tmin}\left[\frac{RHmax}{100}\right] \quad (13)$$

where $e^o{}_{Tmin}$ and $e^o{}_{Tmax}$ are the saturation vapor pressure at temperatures T_{min} and T_{max}, respectively.

2.3.2 Reduced PM Method

The reduced FAO PM method uses the same model of FAO PM in Equation (3), but the missing parameter is replaced by an estimated value such as income solar radiation (Rs), vapor pressure deficit (Δe), and wind speed which needs to be estimated. The Rn was estimated by using the solar radiation (Rs), and the Δe was estimated by actual vapor pressure (e_a). The equations for estimating Rs and e_a from the temperature data are given as follows:

$$Rs = 0.16\sqrt{(Tmax - Tmin)}\ Ra \quad (14)$$

$$e_a \cong e^o{}_{Tmin} = 0.611\ exp\left[\frac{17.27\,Tmin}{Tmin+237.3}\right] \quad (15)$$

To take care of the missing wind speed (u_2), we used the wind speed of the nearby station or using 2 m s^{-1} is recommended in FAO56 (Allen et al., 1998).

2.3.3. Hargreaves Method

The Hargreaves method (Hargreaves and Samani, 1985) of computing daily grass ETo is another empirical method that has been in use in cases where the availability of weather data is limited. The original Hargreaves equation, in 1975, calculated ETo from solar radiation (Rs) and temperature. The equation developed into a simplified equation requiring only temperature, day of the year, and latitude after they found the relation between Rs and the amplitude of temperature ($\Delta T = T_{max} - T_{min}$) (Hargreaves and Samani, 1982). The equation is given as follows:

$$ETo = 0.0023\ (T + 17.8)\ (Tmax - T\ min)^{0.5} Ra/\lambda \quad (16)$$

where Ra is the extraterrestrial radiation (MJ m^{-2} day^{-1}) which is converted to mm day^{-1} by dividing with the latent heat of vaporization (λ; 2.45 MJ kg^{-1}). T is the mean air temperature (°C).

However, it is recommended that the ETo that is estimated from Equation (16) be verified in each new region by comparing with the estimates obtained by the standard FAO PM equation by using regression analyses and by calibration with the empirical coefficients.

2.3.4. Thornthwaite Method

Thornthwaite (1948) is an alternative method for estimating ETo based on air temperature. However, the unit of ETo obtained from the Thornthwaite method is in mm per month because the ETo is computed as a function of monthly average temperature, in which the month is a standard month of 30 days, with each day having 12 hours of photoperiod. The method is applied to estimate the daily ETo by using the mean daily temperature (T_d, °C) as given in the following equation:

$$ETo, m = 1.6\left(\frac{10Td}{I}\right)^a \quad (17)$$

where ETo, m is the gross reference evapotranspiration in the unit of mm per 30 days. Td is the mean daily temperature ($0.5[T_{max}+T_{min}]$). I is the annual heat index obtained from the monthly heat indices given by the following equation:

$$I = \sum_{m=1}^{12}\left(\frac{Tm}{5}\right)^{1.514} \quad (18)$$

where Tm is the mean monthly temperature (°C) averaging from the temperatures recorded over the years and a is a function of the heat index, given by

$$a = 0.49239 + 0.01792\ I - 0.0000771I^2 + 0.000000675I^3 \quad (19)$$

The original Thornthwaite model in Equation 17 was limited when the mean temperature became over 26°C; then, it was adapted by Willmott et al. (1985) for estimating ETo if the mean temperature became higher than 26.5°C, and it is given by

$$ETo = -415.85 + 32.24T_d - 0.43T_d^2 \quad (20)$$

To convert the gross monthly ETo (*ETo,m*) with the unit of mm per month to daily ETo (mm day^{-1}), the ETo is calculated using the following expression:

$$ETo = \frac{ETo,m}{30}\frac{N}{12} \quad (21)$$

where N is the photoperiod (hours) for a given day, which is a function of the day of the year and the latitude.

The Thornthwaite method (Equation 17 and Equation 20) was improved by Camargo et al., (1999) to adjust the ETo for arid weather and very humid weather. In the improved method, the average daily temperature (*Td*) was replaced by effective temperature (T_{ef}), given by

$$T_{ef} = \beta(3Tmax - Tmin) \quad (22)$$

where β is the Camargo parameter that has a recommended value of 0.36. To improve the accuracy of ETo, local calibration of the value of β is necessary (Sentelhas et al., 2010). For this study, the β was calibrated by data from both the study sites.

Additionally, Pereira and Pruitt (2004) found that using the photoperiodic effective daily temperature (Tef*) instead of the Td in Equation 17 and Equation 20 could improve the accuracy to obtain the best ETo,m estimated by the Thornthwaite model. Tef* as a function of day–night ratio is given by the following equation:

$$T_{ef}* = T_{ef}\frac{N}{24-N} \quad (23)$$

where N is the photoperiod on any given day (hours).

3. Results and Discussion

3.1 Validation of reduced FAO PM method

The results of the comparison and the relation between the ETo estimated from the full data set of standard FAO PM method and from each of the reduced FAO PM methods, −RH, −Rs, −u, −RH−Rs, −RH−u, −Rs−u, and −RH−Rs−u, in the two study sites, ANK and CMU (Table 2).

Table 2: Comparison the average ETo (mm day^{-1}) estimated by reduced FAO PM methods when missing data of relative humidity (−RH), solar radiation (−Rs), wind speed (−u) by the values of slope and R^2 of origin interception linear relation, value of mean bias error (MBE) and of root mean square error (RMSE) compared with ETo estimated by full data FAO PM

	Reduced FAO PM Methods						
Statistical parameters	**−RH**	**−Rs**	**−u**	**−RH−Rs**	**−RH−u**	**−Rs−u**	**−RH−Rs−u**
ANK							
Average ETo	2.91	3.01	3.61	2.87	3.24	3.57	3.20
Slope	1.05	1.01	0.85	1.05	0.94	0.85	0.93
R^2	0.99	0.84	0.90	0.80	0.83	0.71	0.58
MBE	−0.14	−0.04	0.56	−0.18	0.19	0.52	0.16
RMSE	0.16	0.34	0.62	0.41	0.41	0.72	0.59
CMU							
Average ETo	3.85	4.45	4.97	4.22	4.51	5.32	4.86
Slope	1.06	0.91	0.82	0.96	0.91	0.76	0.84
R^2	0.98	0.74	0.87	0.72	0.83	0.70	0.66
MBE	−0.23	0.37	0.89	0.14	0.43	1.21	0.78
RMSE	0.29	0.66	0.98	0.56	0.59	1.40	0.99

If the data are missing only the relative humidity data (−RH), the actual vapor pressure (e_a) was estimated from the T_{min} used in the FAO PM model. A little underestimate of ETo was found in both the study sites, of −0.14 mm day^{-1} and −0.23 mm day^{-1} of MBE, and a little average error of 0.16 mm day^{-1} and 0.29 mm day^{-1} of RMSE for ANK and CMU, respectively. On the other hand, the relationship with the ETo from the standard FAO PM showed a good fit by 1.05 and 1.06 of slope and 0.99 and 0.98 of R^2 in ANK and CMU, respectively.

If the data are missing only solar radiation (−Rs), the value of solar radiation was estimated from the interval of T_{max} and T_{min}, and used in the FAO PM. The estimated ETo was found to be a little underestimate in ANK but an overestimate in CMU by −0.04 mm day^{-1} and 0.37 mm day^{-1} of MBE, respectively, while, the RMSE of the treatment showed a higher error than that of the treatment missing only humidity (−RH) by 0.34 mm day^{-1} and 0.66 mm day^{-1} in ANK and CMU, respectively. The relationship with the ETo from the standard FAO PM just showed a good slope by 1.01 and 0.91 but showed a lower fit by 0.84 and 0.74 of R^2 in ANK and CMU, respectively.

If the data are missing only the wind speed (−u), the 2 ms^{-1} of wind speed was recommended to replace the actual wind speed for use in the FAO PM model. A significant overestimate of high error in ETo was found upon comparison with the treatments of −RH and −Rs by the values 0.56 mm day^{-1} and 0.89 mm day^{-1} of MBE and 0.62 mm day^{-1} and 0.98 mm day^{-1} of RMSE in ANK and CMU, respectively. Although the relationship with the standard FAO PM method showed higher R^2 than the treatments of −RH and −Rs, by 0.90 and 0.87, the slope showed significant decrease by 0.85 and 0.82 in ANK and CMU, respectively.

As far as the treatment of two parameters missing of the data set is concerned, the results of the treatment of missing relative humidity and solar radiation (−RH−Rs) showed a similar slope and R^2 compared with the treatment of missing only solar radiation (−Rs), by 1.05 and 0.96 of slope and by a little bit lower of R^2 as 0.80 and 0.72 in ANK and CMU, respectively. However, the changes in MBE and RMSE in ANK and CMU were found to be different. The MBE and the RMSE were found to have increased in ANK by −0.18 mm day^{-1} and 0.41 mm day^{-1} but decreased in CMU by 0.14 mm day^{-1} and 0.56 mm day^{-1}, respectively.

As for the treatments of missing relative humidity and wind speed (−RH−u), in comparison with the −u treatment, better results were found with better fit of slope by 0.94 and 0.91 and R^2 by 0.83 and 0.83 in ANK and CMU, respectively. Lower error was also found by 0.19 mm day^{-1} and 0.43 mm day^{-1} of MBE and 0.41 mm day^{-1} and 0.59 mm day^{-1} of RMSE in ANK and CMU, respectively.

In the case of the treatment of missing solar radiation and wind speed (−Rs−u), in comparison with the treatment of −Rs and −u, a decrease in the relation and an increase in the error were found by 0.85 and 0.76 for the slope and 0.71 and 0.70 for R^2 and by 0.52 mm day^{-1} and 1.21 mm day^{-1} for MBE and by 0.72 mm day^{-1} and 1.40 mm day^{-1} for RMSE in ANK and CMU, respectively. The lowest value of R^2 and the highest value of RMSE were found when a comparison was performed between the treatments of two parameters missing, −RH−Rs, −RH−u, and −Rs−u.

If only the temperature data were available in the study sites, the treatment −RH−Rs−u was used to estimate ETo. The results showed an overestimate in both the study sites by 0.16 mm day^{-1} and 0.78 mm day^{-1} of MBE and by 0.59 mm day^{-1} and 0.99 mm day^{-1} of RMSE for ANK and CMU, respectively. Additionally, the treatment showed not good fit of the relation with the standard FAO PM, with a relative low slope by 0.93 and 0.84 and of R^2 by 0.58 and 0.66 for ANK and CMU, respectively.

3.2. Evaluation of wind speed use

Evaluation of the wind speed use is necessary because high sensitivity of the wind speed affecting the ETo estimated by the reduce FAO PM was found, as presented in the results in section 3.1, and most of the local stations in upper northern Thailand recorded only temperature (T_{max} and T_{min}) and rainfall. The reduce FAO PM using only the temperature data for the treatment of −RH−Rs−u should be a suitable method for estimating the ETo. As shown in section 3.1, using the wind speed of 2 ms^{-1} instead of the actual value affected the decrease in the slope significantly and the R^2 of the relation between the ETo estimated by the reduced method and the ETo estimated by the standard FAO PM method. At the same time, the average daily wind speed in the study sites was less than 1.0 ms^{-1}. The wind speeds of 1.0 ms^{-1} and 0.5 ms^{-1} were tested in the reduced FAO PM using only the temperature data. The results are shown in Table 3. Changing the wind speed from 2.0 ms^{-1} to 1.0 ms^{-1} and 0.5 ms^{-1}, for ANK, a good fit of the relation was found by increasing the R^2 from 0.58 to 0.72 and 0.78, respectively, while for CMU, the R^2 rarely changed by 0.66, 0.68, and 0.66, respectively. Upon considering the error of the ETo difference from the standard value, a significant decrease in MBE and RMSE were found in CMU rather than in ANK. The value of MBE was observed to have changed from 078 to 0.22 and −0.83 in CMU, while in ANK, the value of MBE was found to have changed from 0.16 to −0.08 and −0.22. As for the value of RMSE, it was found to have changed from 0.99 to 0.61 and 0.59 in CMU, but there was only a small of change in ANK, from 0.59 to 0.45 and 0.44. However, the lowest value of RMSE in both the sites was found when the wind speed of 0.5 ms^{-1} was used. The results

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indicate that a decrease in the wind speed can improve the accuracy and precision of the ETo estimated by the reduced FAO PM using only the temperature, especially in the case of lowlands.

3.3.Validation for Hargreaves and Thornthwaite methods

Although estimating ETo with a missing weather data can improve the accuracy and precision by using the reduced FAO PM methods, the methods have complicated processes to be carried out and require many parameters to be calculated. There are some temperature base methods to estimate ETo using only the temperature data (T_{max} and T_{min}). In this study, the Hargreaves method and the Thornthwaite method were presented to test for using an alternative method for estimating the daily ETo in upper northern Thailand.

3.3.1. Hargreaves Method

The Hargreaves method, presented in Equation 16, was used to calculate ETo with the recommend coefficient by 0.0023 abbreviated as HG-Rco. Comparison with the ETo calculated by the standard FAO PM method, the overestimating of ETo estimated by the HG-Rco for ANK and CMU. The results are demonstrated in Figure 1(a) for ANK and Figure 1(c) for CMU. The results of the testing of HG-Rco showed similar slope, R^2, MBE, and RMSE to the results of the testing of the reduced FAO PM with only the temperature data, or the −RH−RS−u treatment, which are presented in section 3.2. A medium R^2 of by 0.68 was found in both the study sites, while the values of MBE and RMSE in both the sites showed a significant difference by relatively low values of 0.19 mm day^{-1} and 0.54 mm day^{-1}, respectively, for ANK and by relatively high values of 0.85 mm day^{-1} and 1.04 mm day^{-1}, respectively, for CMU. To improve the accuracy of the ETo estimated by HG-Rco, calibration of the coefficients was performed in ANK and CMU. The calibrated coefficient was 0.0021 for ANK and 0.0018 for CMU. Then, these coefficients were used instead of the recommended coefficient of 0.0023 in Equation 16. It was found that the ETo estimated using the Hargreaves model with the calibrated coefficient (HG-Cco) yielded better values than that estimated with the HG-Rco, as shown in Figure 1(b) for ANK and Figure 1(d) for CMU. The improved results showed increased accuracy, especially in CMU, in which the value of the slope, MBE, and RMSE were found to have improved significantly to 1.0 mm day^{-1}, −0.05 mm day^{-1}, and 0.57 mm day^{-1}, respectively, while in ANK, there was just a litter change to 0.97 mm day^{-1}, 0.04 mm day^{-1}, and 0.49 mm day^{-1}, respectively.

Table 3: Comparison average ETo (mm day^{-1}) estimated by reduced FAO PM using only temperature data with wind speeds 2.0 ms^{-1}, 1.0 ms^{-1}, and 0.5 ms^{-1} and values of slope and R^2 of origin interception linear relation and value of mean bias error (MBE) and of root mean square error (RMSE) compared with ETo estimated by full data FAO PM

Statistical parameters	**Wind speed (ms^{-1})**		
	2.0	**1.0**	**0.5**
ANK			
Average ETo	3.20	2.98	2.83
Slope	0.93	1.02	1.07
R^2	0.58	0.72	0.78
MBE	0.16	−0.08	−0.22
RMSE	0.59	0.45	0.44
CMU			
Average ETo	4.86	4.31	4.00
Slope	0.84	0.95	1.02
R^2	0.66	0.68	0.66
MBE	0.78	0.22	−0.08
RMSE	0.99	0.61	0.59

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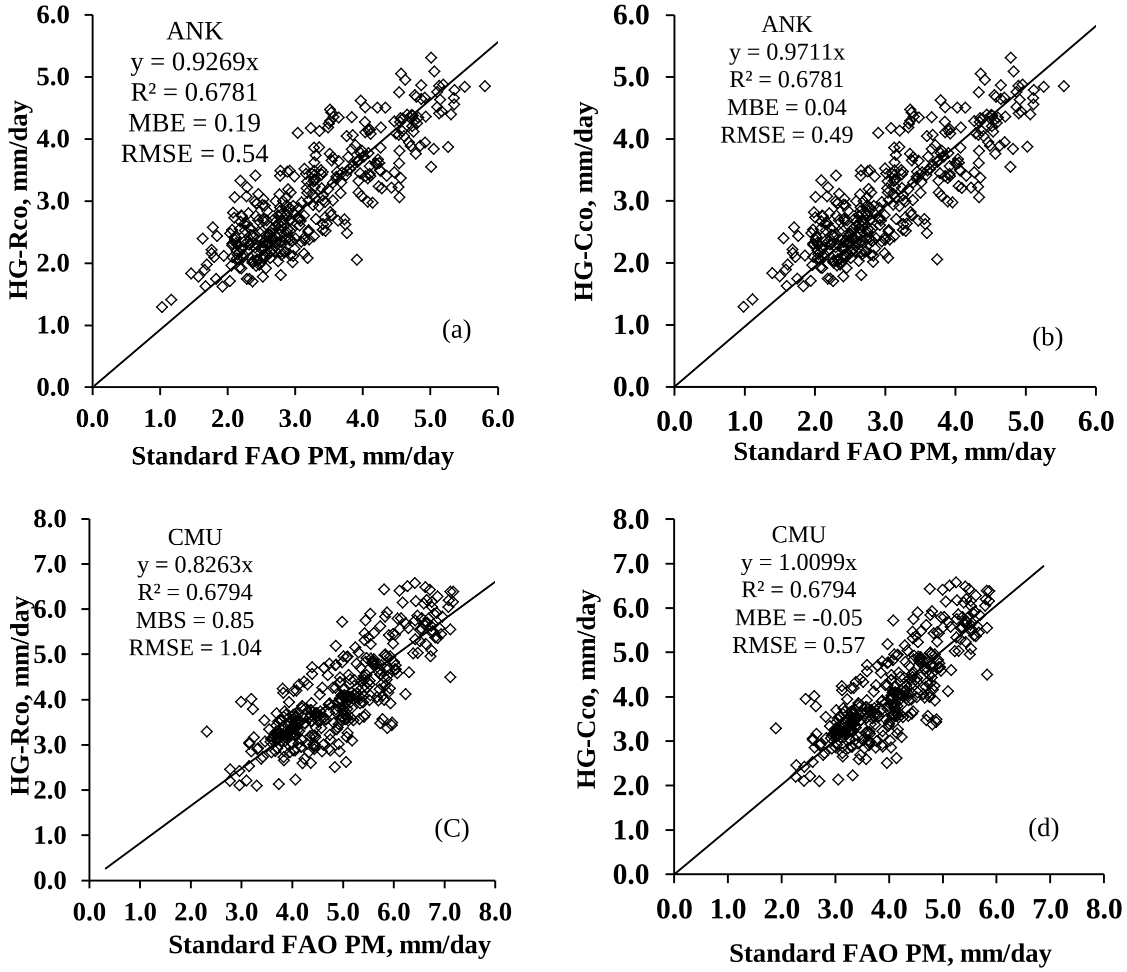

Figure 1: Regression between the daily ETo estimated by the standard FAO PM method and the Hargreaves method (HG) with recommended coefficient (Rco.) and locally calibrated coefficient (Cco) for ANK (a and b) and CMU (c and d), and also the mean bias error (MBE) and the root mean square error (RMSE) from the comparison between them.

3.3.2 Thornthwaite Method

Since the value of the annual average temperature in CMU was 26.7°C, it failed to fit the relation between the estimated ETo of CMU, estimated using the Thornthwaite method, in Equation 20, and the standard FAO PM by very low R^2 (0.032). Therefore, the improved model by Willmott et al. (1985), as shown in Equation 21, was used for CMU. On the other hand, for ANK where the value of the annual average temperature was found to be 17.8°C, the original Thornthwaite model in Equation 18 was used. The results of the comparative analysis are shown in Figure 2(a) for ANK and Figure 2(d) for CMU. The results revealed relatively low R^2, by 0.11 and 0.28, and too high RMSE, by 0.91 mm day^{-1} and 1.19 mm day^{-1}, in ANK and CMU, respectively. The results were observed to improve when the effective temperature (Tef) was used with the recommended β coefficient (0.36 in Equation 22), abbreviated to TW-Tef-Rco, as shown in Figure 2(b) for ANK and Figure 2(e) for CMU. Upon comparison with the ETo estimated by using the average temperature (TW-T), an evident better fitting of the relation with the standard FAO PM method was found, by increasing the R^2 to 0.57 and 0.59. For RMSE, the decreasing was found to be by 0.58 mm day^{-1} for ANK, but for CMU, the RMSE was found to decrease by a high value, of 1.26 mm day^{-1}. However, when the recommended β coefficient was replaced by the locally calibrated coefficient in the method (TW-Tef-Cco), better results were found for the slope, MBE, and RMSE. For ANK, in comparison with the results of TW-Tef-Rco, the results of TW-Tef-Cco

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showed a slight change, but for CMU, the results demonstrated a significant change of an increase in the slope by 0.95 and a decrease in the RMSE by 0.69 mm day^{-1}.

As for the last adjustment of the Thornthwaite method by using the photoperiodic effective daily temperature (Tef*), the results revealed that there was not much difference when compared with the results when Tef was used (Pereira and Pruitt, 2004) in the arid locations; however, this study found that using Tef* showed very lower accuracy and precision than using Tef, because of which the results are not presented here.

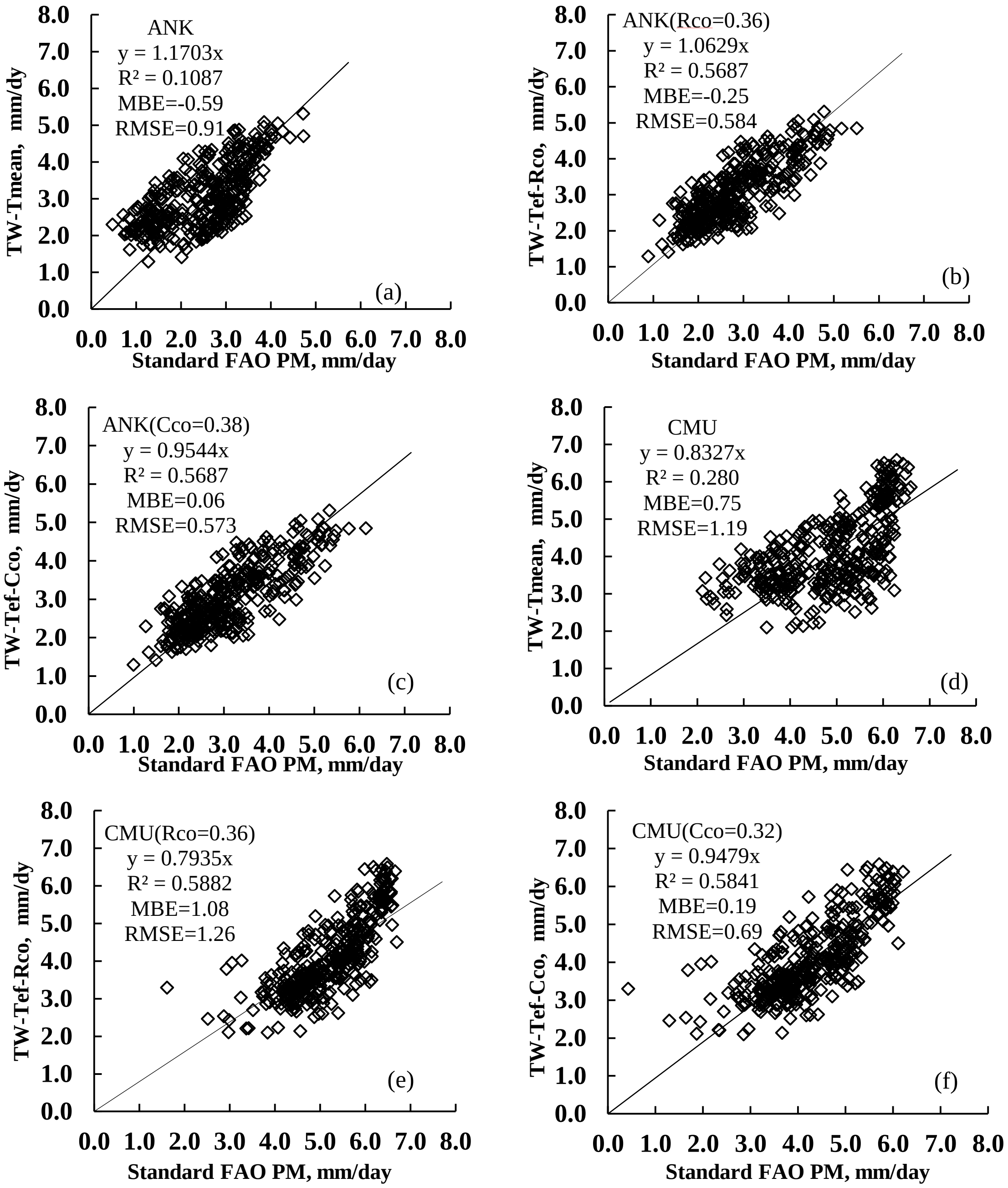

Figure 2: Regression between the daily ETo estimated by the standard FAO PM method and the Thornthwaite method (TW) with mean temperature (Tmean), effective temperature (Tef), recommended coefficient (Rco), and locally calibrated coefficient (Cco) for ANK (a, b, and c) and CMU (d, e, and f), and also the mean bias error (MBE) and the root mean square error (RMSE) from the comparison between them.

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3.4. Reliable methods by using only temperature data

The reliable results of the estimated daily ETo using only the temperature data were obtained when estimated using the reduced FAO PM(−RH−RS−u) with u=0.5 ms^{-1}, the Hargreaves method with the calibrated coefficient (HG-Cco), and the Thornthwaite method using the effective temperature with the calibrated coefficient (TW-Tef-Cco). The validation of the results was obtained after the three comparisons were conducted by using another three years weather data set of both sites. The results of the validations showed similar results as the first validation demonstrated in 2010 weather data set. To compare these results, the monthly ETo estimated from each method was compared with the ETo from the full data of FAO PM method, as shown in Figure 3 for ANK and Figure 4 for CMU. The results revealed that the annual distribution of the standard ETo in ANK and CMU had similar fluctuation, and that the highest value of ETo was found in April and the lowest was found in December. The annual distribution values of the monthly ETo estimated using the methods of reduced FAO PM (−RH−RS−u) by u=0.5 ms^{-1}, HG-Cco, and TW-Tef-Cco were also found in a similar pattern. Upon comparing the departure from the monthly ETo calculated using the full data FAO PM of each of the methods, it was found that the ETo obtained from the reduced FAO PM method (−RH−RS−u) with u=0.5 ms^{-1} showed the smallest values, in both ANK and CMU, in the absolute percentage departure ranges of 1.2–14.6% and 0.1–11.8%, respectively. The range of absolute departure from the standard method was found for HG Cco to be 0.6–14.9% and 2.5–19.9% and for TW-Tef-Cco to be 0.6–17.7% and 0.1–15.7% for ANK and CMU, respectively. In ANK, the overestimation of the ETo estimated by the three methods was observed mostly from January to March and in December (with the highest value being obtained by the TW-Tef-Cco method), but the underestimation was observed from May to November (with the highest value being obtained by the HG-Cco method). But at CMU, most of the ETo estimated by the three methods were seen to be overestimates, in which the highest values of estimation were in December, January, and February, yielded by the TW-Tef-Cco method, but the overestimation from March to November was by the HG-Cco method.

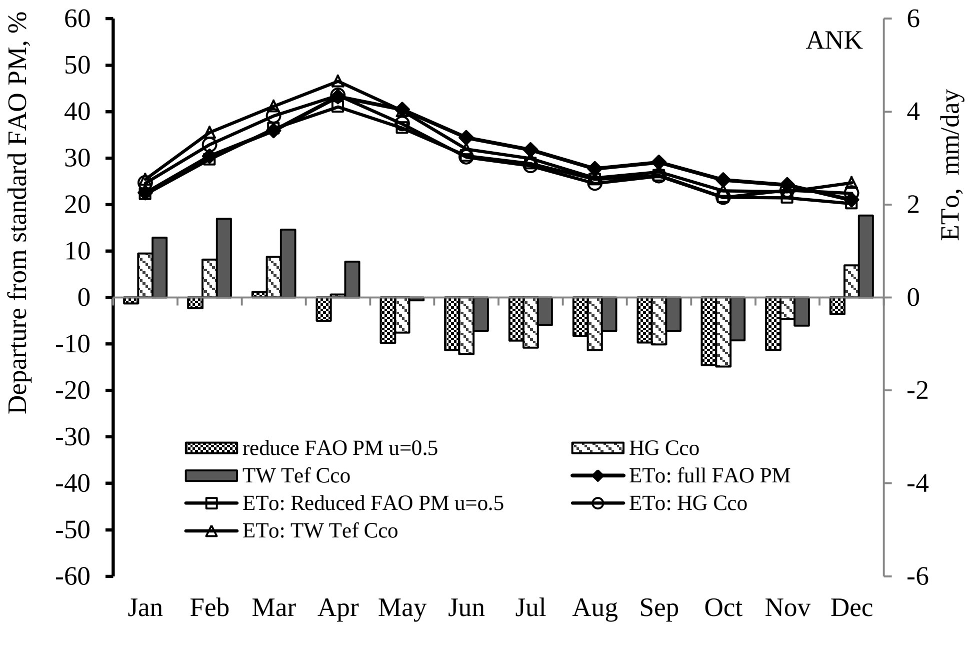

Figure 3: Comparison of the ETo values (line) and the percentage departure values from the standard ETo (bar) between the method of reduced FAO PM u=05, the Hargreaves method with calibrated coefficient (HG Cco), and the Thornthwaite method with effective temperature and calibration coefficient (TW TefCco) in the Angkhang (ANK) station.

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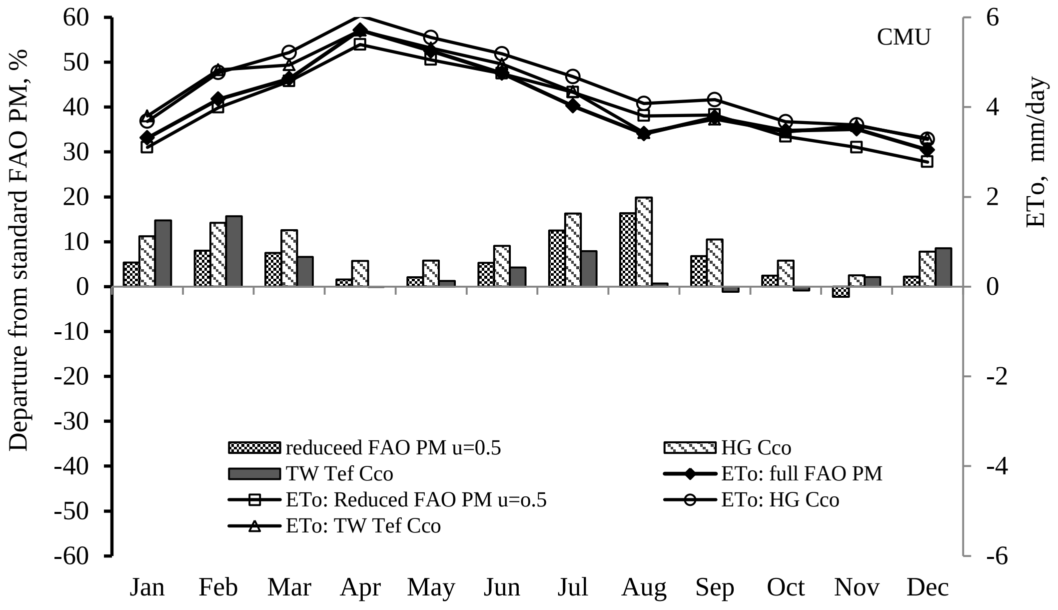

Figure 4: Comparison of the ETo values (line) and the percentage departure values from the standard ETo (bar) between the method of reduced FAO PM u=05, the Hargreaves method with calibrated coefficient (HG Cco), and the Thornthwaite method with effective temperature and calibration coefficient (TW TefCco) in the Chiang Mai University (CMU) station.

The results indicated that wind speed was the major parameter affecting the increase in the dispersion of the ETo estimated using the reduced FAO PM method. Upon taking into consideration the ETo estimated using only the temperature data with the reduced FAO PM (−RH−Rs−u), it becomes clear that although the precision values presented for R^2 were not high, that was, 0.58 for ANK and 0.66 for CMU, the R^2 values found were higher than those obtained in the study sites in southern Ontario, Canada, with the same method, as those values of R^2 were very low, in the range from 0.08 to 0.47 (Sentelhas et al., 2010). However, when the reduced FAO PM (−RH−R−u) was used, the RMSE values in the study sites were found to be just too high for the evapotranspiration in a day, by 0.59 mm day^{-1} and 0.99 mm day^{-1}, respectively. The higher ETo may be an effect from the high wind speed which was always the case in hot and warm locations than in humid and warm locations (Allen et al., 1998). Thus, when the wind speed reduced to 1.0 ms^{-1} and 0.5 ms^{-1}, accuracy and precision of the daily ETo were achieved as against using 2.0 ms^{-1} as the wind speed, especially in lowlands such as CMU which was a hot location. The error in the ETo estimated from the reduced FAO PM method can be decreased by using local or regional calibrations, which has been tested in many countries (Sentelhas et al., 2010; Tabari and Talaee, 2011; Xu et al., 2013; Berti et al., 2014) including Thailand (Temeepattarapongsa and Thepprasit, 2015).

As for the Hargreaves method, the ETo was estimated by using the recommended coefficient (0.0023), and it showed too high an error in the lowland of CMU than in the highland of ANK. Such difference in error may have happened because of the fact that the Hargreaves model was developed for semi-arid environments, and when it was used for a different climate, an error occurred in the ETo value (Sentelhas et al., 2010). The high error in the ETo value estimated by the Hargreaves model could be improved by using locally calibrated coefficients (Sentelhas et al., 2010; Pereira and Pruitt, 2004). As in the study, the results showed that using locally calibrated coefficients can improve the accuracy and precision of the daily ETo estimated by the Hargreaves method to a reliable value of ETo in both the study sites, especially in lowland locations such as CMU site. Using the calibrated coefficient for each month for locations where the weather varies considerably in a year yielded very good results that were fitting to the FAO PM method (Borges and Mendiondo, 2007, Shahidian et al., 2012).

The Thornthwaite method is an empirical method for estimating ETo, and it requires only the temperature data. The Thornthwaite model used for ETo estimation usually varies, depending on the climatic conditions (Pereira and Pruitt,

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2004). Thus, the original model of the Thornthwaite method was used in highland sites such as ANK where the average temperature was relatively low, that is, about 17.8°C, but the improved method by Willmott et al. (1985) was being used for lowland sites such as CMU where the average daily air temperature was higher than 26.7°C. Both methods use the daily mean air temperature (TW-Tmean) for estimating ETo, but the results revealed high errors in both of our study sites. The high error could be improved by using the calculated coefficient in the process of estimating Tef, as found in the study of arid locations (Pereira and Pruitt, 2004). But in this study, the solution obtained by using Tef in the Thornthwaite model was significantly impacted only in highlands, such as in ANK. For lowland locations such as CMU, the acceptable results was achieved when the TW-Tef and calibrated coefficient (TW-Tef-Cco) were used.

Although, the comparison among the temperature base methods, reduced FAO PM (-RH-Rs-u) with 0.5 m s^{-1} of wind speed, HG-Cco and TW-Tef-Cco, using the weather data in 2010 gave a reliable value of ETo in ANK and CMU sites, the confidence of the results were provided after the three years validations which gave the similar results as compared with 2010 results. However, the error of ETo estimated by each methods was varied by the weather conditions of the locations and of the month, especially for the empirical model as Hargreaves and Thornthwaite methods (Sentelhas et al., 2010). The variations of the error of the estimated ETo were found in the comparison between ANK and CMU where those had a significant difference of weather by the negative error mostly found during rainy season in ANK where found a lower average temperature and smaller interval between Tmax and Tmin than in CMU. Those reasons also gave a higher error of ETo estimated by HG-Cco method than by TW-Tef-Cco in rainy season (May to October). Additionally, the comparison in the both sites found that the reduced FAO PM (-RH-Rs-u) with 0.5 ms^{-1} of wind speed gave the lowest error of monthly ETo. Most of the monthly error were within an acceptable range, which indicated by lower than 10% of the departure from the FAO PM method. The acceptable monthly ETo estimated by the HG-Cco method found in ANK than in CMU. But, the monthly ETo estimated by TW-Tef-Cco method mostly found in acceptable range, in spite of the method showed relative lower accuracy and precision than the HG-Cco method in above results.

4. Conclusions

Comparison among the temperature base methods estimating for ETo had performance in two stations located on upper northern Thailand region, ANK (highland) and CMU (lowland). The reliable values of ETo could be provided by adjusting the reduced FAO PM, Hargreaves and Thornthwaite methods. The adjustments produced slightly differences between ANK and CMU, especially for HG-Cco and TW-Tef-Cco methods. Since the sensitive of wind speed parameter affecting to the ETo value calculated by reduce FAO PM and the low wind speed found in the both study sites, the great ETo value was found by using the reduced FAO PM method (-RH-Rs-u) with 0.5 m s^{-1} wind speed at both sites. Since the differences of climate characteristics between highland and lowland sites, the adjusting for the reliable value of ETo was found by using the HG-Cco method with the calibration coefficient 0.0021 for ANK and 0.0018 for CMU, and the TW-Tef-Cco method with calibration coefficient 0.38 for ANK and 0.32 for CMU. With the local calibration process by the reduced FAO PM method with 0.5 m s^{-1} wind speed, the ETo estimated by the method gave the lowest error as compared with the ETo estimated by the HG-Cco and TW-Tef-Cco methods. The adequate estimated ETo with a simple process by HG-Cco and TW-Tef-Cco could be considered for ANK and CMU site, respectively. The results of our study can be applied to other highland watershed in Thailand and the Southeast Asia region that are facing the same issue of missing and incomplete weather data sets.

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