Chapter 1

Comparison of Evapotranspiration Methods Under Limited Data

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Additional information is available at the end of the chapter

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Abstract

A limited number of parameters or a single meteorological parameter was used in this study to estimate evapotranspiration. The main objectives of this study are as follows. (1) The Penman-Monteith method was used to estimate ET. The empirical formula published by the Food and Agriculture Organization (FAO) was applied via substitution to compare situations that were missing certain meteorological parameters. (2) Radiation-based methods and temperature-based methods were compared with the Penman-Monteith method to estimate ET and discuss their applicability in the study area. With Tainan Weather Station of Taiwan as the study area, this study selected the Penman-Monteith method as well as six other radiation-based estimation formulas: Makkink, Turc, Jensen-Haise, Priestley-Taylor, Doorenbos-Pruit, and Abtew methods. The other four temperature-based estimation formulas, namely, Thornthwaite, Blaney-Criddle, Hamon, and Linacre methods, were used to estimate ET and compare the differences and the results were compared with the Penman-Monteith method. The results showed that there was little effect on estimating ET using the Penman-Monteith method when the wind speed data was missing or insufficient. The Turc method was the best among the six radiation-based estimation formulas, while the Linacre method was the best temperature-based estimation formula. Generally speaking, radiation-based estimation formulas were more accurate than temperature-based estimation formulas.

Keywords: evapotranspiration, Penman-Monteith, radiation method, temperature method

1. Introduction

Evapotranspiration (ET) is a basic element of the hydrologic cycle as well as a key factor in water balance [1]. According to statistics, global average annual rainfall is around 973 mm, and about 64% of surface water is lost through ET [2]. Therefore, ET is considered to be an indispensable parameter in hydrologic studies, such as irrigation scheduling and management, crop water demand, and environmental impact assessment [3]. Hence, effective evaluation of ET is important for the management and planning of water resources. In previous studies, many formulas of empirical or physical methods have been used to estimate ET in various climatic conditions; examples include the Makkink method [4], Priestley-Taylor method [5], lysimeter method [6], and micro-meteorological observation method [7]. The empirical formula of the Penman-Monteith method released by the Food and Agriculture Organization (FAO) is the method most internationally used [8]. This method requires consideration of a variety of meteorological parameters, such as temperature, radiation, relative humidity, and wind speed. These data, however, are frequently missing or hard to collect, resulting in difficulties in estimation [9]. In particular, reliable meteorological data, such as radiation, relative humidity, and wind speed, are rather difficult to collect in some areas. In addition, the maintenance of meteorological stations requires substantial funding and the installation is complex.

Therefore, in previous studies, many scholars have used a limited number of parameters or a single meteorological parameter to easily estimate ET and simplify the estimation methods, which are classified into five major categories based on the required meteorological parameters: (1) water balance method, (2) mass transfer method, (3) mixing method, (4) radiation-based method, and (5) temperature-based method [10]. Except for the last two methods, the other three methods require a variety of meteorological parameters to estimate ET, thus causing obstacles in data collection and obtaining complete meteorological information. Furthermore, studies have found that the results of empirical methods should be compared with the Penman-Monteith method and released by FAO so as to carry out accurate estimation in each region [11].

In this study, a single meteorological parameter was applied, as well as the Penman-Monteith method, six radiation-based methods, and four temperature-based methods, to effectively estimate ET. The main objectives of this study are as follows: (1) when radiation, wind speed, and relative humidity data were missing, empirical formulas were used for substitution in the Penman-Monteith method to compare the estimation results; (2) the regional applicability of the radiation- and temperature-based methods were compared so as to make these methods more suitable for the study area.

2. Material and methods

This study mainly discussed the effective evaluation of ET using limited meteorological parameters. With the Penman-Monteith method as the standard for estimation, ET was calculated using substitution formulas when radiation, wind speed, or relative humidity data were missing in the Penman-Monteith method. Six radiation-based methods and four temperature-based methods were selected to discuss their applicability in the study area. In this study, mean bias error, root mean square error, and the Pearson-type goodness-of-fit index were used to analyze and investigate the differences among ET estimations using the empirical formulas of temperature and radiation methods. Meanwhile, this study strived to determine the method with a simpler empirical formula to address the difficulties caused by a shortage of meteorological parameter data.

2.1. Penman-Monteith method

Penman-Monteith method was recommended by the FAO in the 1998 FAO-56 report for the assessment of ET, and it is currently used internationally [12]. After years of study by domestic scholars, it is believed that the Penman-Monteith method is quite suitable in Taiwan [13–15]. Its formula can be expressed as follows:

$$\mathrm{ET} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

In Eq. (1), ET represents evapotranspiration (mm d^{-1}); Δ represents the slope of air pressure curve (kPa $°C^{-1}$); T is the average temperature (°C); R_n is net radiation (MJ m^{-2} d^{-1}); G is the soil thermal flux (MJ m^{-2} d^{-1}); γ is the humidity constant (kPa $°C^{-1}$); u_2 is the wind speed measured at the height of 2 m (m s^{-1}); and ($e_s - e_a$) is the difference between saturated and actual vapor pressure (kPa). For field applications, Eq. (1) was calculated with monthly air temperature, humidity, radiant energy, wind speed, and other parameters [12].

When data of some meteorological parameters could not be obtained or were incomplete, for instance, radiation, relative humidity, and wind speed, a calculation was conducted using the following empirical formula:

1. When data of relative humidity could not be obtained or was incomplete:

$$e_a = 0.611 \exp\left(\frac{17.27 T_{min}}{T_{min} + 237.3}\right) \tag{2}$$

In Eq. (2), T_{min} represents minimum temperature (°C).

2. When radiation data could not be obtained or was incomplete:

$$R_s = k_{Rs}\sqrt{(T_{max} - T_{min})}R_a \tag{3}$$

In Eq. (3), k_{Rs} is the empirical coefficient (k_{Rs} = 0.19); R_a is extraterrestrial solar radiation (MJ m^{-2} d^{-1}).

3. When data of wind speed could not be obtained or was incomplete:

When there is no record of wind speed in the evaluation area, the average Taiwan wind speed of 1.83 m s^{-1} was used, which was estimated with the data collected by 20 central meteorological observatories in Taiwan during 1990–2008 [15]. In addition, wind speed at a height of 2 m above the ground was primarily used in the estimation of wind speed. Provided that the measurement height was not 2 m, the following formula was applied:

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \tag{4}$$

In Eq. (4), u_z is the wind speed measured at a meteorological station (m s^{-1}); z is the height of the anemometer above the ground (m).

2.2. Radiation-based methods

Priestley and Taylor [5] proposed that the estimation of ET could be explored from the perspective of energy conversion on the water surface. Evapotranspiration increased with an increase of radiation. Hence, radiation was taken as a vital meteorological parameter for ET assessment. Radiation-based methods were mainly based on the simplified principle of energy balance to estimate ET. Therefore, ET could be evaluated using a single meteorological parameter, and, in general, the form of radiation-based methods is as follows:

$$\mathrm{ET} = \frac{C_r}{\lambda}(wR_s) \text{ or } \mathrm{ET} = \frac{C_r}{\lambda}(wR_n) \tag{5}$$

λ represents the latent heat of evaporation (MJ kg^{-1}); C_r represents the generated empirical coefficient based on the relative humidity and wind speed; w is the generated empirical coefficient in accordance with temperature and latitude; R_s represents the amount of solar radiation (MJ m^{-2} d^{-1}); and R_n is the net radiation (W m^{-2} d^{-1}).

Six radiation-based methods that are used internationally to assess evapotranspiration were selected in this study, including Makkink [4], Turc [16], Jensen-Haise [17], Priestley and Taylor [5], Doorenbos and Pruitt [18], and Abtew [19]. The methods are described as follows:

2.2.1. *Makkink method*

$$\mathrm{ET} = \alpha \times \left(\frac{\Delta}{\Delta+\gamma}\frac{R_s}{\lambda}\right) - \beta \tag{6}$$

R_s represents the amount of solar radiation (MJ m^{-2} d^{-1}); Δ is the slope of the saturated vapor pressure curve (kPa $°C^{-1}$); γ represents the humidity constant (kPa $°C^{-1}$); λ is the latent heat of evaporation (MJ kg^{-1}); and $\alpha = 0.61$, $\beta = 0.12$.

2.2.2. *Turc method*

1. Average relative humidity $RH < 50\%$

$$\mathrm{ET} = 0.013\left(\frac{\mathrm{T}}{\mathrm{T}+15}\right) \times (\mathrm{R_s} \times 23.8846 + 50) \times \left(1 + \frac{50 - \mathrm{RH}}{70}\right) \tag{7}$$

2. Average relative humidity RH > 50%

$$\mathrm{ET} = 0.013\left(\frac{\mathrm{T}}{\mathrm{T}+15}\right)(\mathrm{R_s} \times 23.8846 + 50) \tag{8}$$

In Eq. (8), T represents the average temperature (°C); R_s is the amount of solar radiation (MJ m^{-2} d^{-1}); and RH represents average relative humidity (%).

2.2.3. *Jensen-Haise method*

$$\mathrm{ET} = \mathrm{C_T} \times (\mathrm{T} - \mathrm{T_x}) \times \mathrm{R_s} \tag{9}$$

C_T represents the temperature constant, and its calculation method is listed below:

$$\mathrm{C_T} = \frac{1}{(\mathrm{C_1} + \mathrm{C_2} \times \mathrm{C_H})} \tag{10}$$

$$\mathrm{C_1} = 68 - 3.6 \times \frac{\mathrm{h_j}}{1000} \tag{11}$$

$$\mathrm{C_2} = 13 \tag{12}$$

$$\mathrm{C_h} = \frac{50}{\mathrm{e_s(T_{max})} - \mathrm{e_s(T_{min})}} \tag{13}$$

h_j is the sea surface height of the meteorological station; $e_s(T_{max}) - e_s(T_{min})$ represents the saturated vapor pressure at the highest temperature and the lowest temperature, respectively; T is the average temperature (°F); and T_x represents the temperature-axis intercept constant, and its formula is as follows:

$$\mathrm{T_x} = 27.5 - 0.25 \times \left(\mathrm{e(T_{max})} - \mathrm{e(T_{min})}\right) - \frac{\mathrm{h}}{1000} \tag{14}$$

2.2.4. *Priestley-Taylor method*

$$\mathrm{ET} = \alpha_{\mathrm{PT}} \frac{\Delta}{\Delta + \gamma} \frac{\mathrm{R_n}}{\lambda} \tag{15}$$

Δ represents the slope of the saturated vapor pressure curve (kPa $°C^{-1}$); γ is the humidity constant (kPa $°C^{-1}$); R_n is the net radiation (W m^{-2} d^{-1}); G represents soil thermal flux (MJ m^{-2} d^{-1}); and α_{PT} represents the empirical coefficient (α_{PT} = 1.26).

2.2.5. Doorenbos-Pruitt method

$$\mathrm{ET} = \mathrm{a} + \mathrm{b} \times \left(\frac{\Delta}{\Delta + \gamma}\frac{\mathrm{R_s}}{\lambda}\right) \tag{16}$$

$$\mathrm{a} = 1.066 - 0.13 \times 10^{-2}\mathrm{RH} + 0.45\ \mathrm{U_z} - 0.2 \times 10^{-3}\mathrm{RH} \times \mathrm{U_z} - 0.315 \times 10^{-4}\mathrm{RH}^2 - 0.11 \times 10^{-2}\mathrm{U_z^2} \tag{17}$$

$$\mathrm{b} = -0.3 \tag{18}$$

R_s is the amount of solar radiation (MJ m^{-2} d^{-1}); Δ represents the slope of the saturated vapor pressure curve (kPa $°C^{-1}$); γ is the humidity constant (kPa $°C^{-1}$); λ represents the latent heat of evaporation (MJ kg^{-1}); U_z is the wind speed (m s^{-1}); and RH represents relative humidity (%).

2.2.6. Abtew method

$$\mathrm{ET} = \alpha \times \left(\frac{\mathrm{R_s}}{\lambda}\right) \tag{19}$$

In Eq. (19), R_s represents the amount of solar radiation (MJ m^{-2} d^{-1}); λ represents the latent heat of evaporation (MJ kg^{-1}); and $\alpha = 0.53$.

2.3. Temperature-based methods

Temperature was the easiest to obtain among the many meteorological parameters. Generally speaking, the form of temperature-based methods is as follows [10]:

$$\mathrm{ET} = \mathrm{c} \times \mathrm{T}^{\mathrm{n}} \text{ or } \mathrm{ET} = \mathrm{c} \times \mathrm{d} \times \mathrm{T}(\mathrm{c}_1 - \mathrm{c}_2\mathrm{h}) \tag{20}$$

In Eq. (20), T is the air temperature (°C); h represents humidity; c, c_1, and c_2 were constants; and d represents time.

Four temperature-based methods were chosen in this study to estimate ET, including the Thornthwaite [20], Blaney and Criddle [21], Hamon [22], and Linacre [23]. The methods are described below:

2.3.1. Thornthwaite method

$$\mathrm{ET} = \mathrm{C} \times 16 \times \left(\frac{10\mathrm{T}}{\mathrm{I}}\right)^{\mathrm{a}} \tag{21}$$

In Eq. (21), T represents monthly average temperature of the air (°C); I is the thermal index, and its formula is as follows:

$$I = \sum_{j=1}^{12} i_j \tag{22}$$

$$i = \left(\frac{T}{5}\right)^{1.51} \tag{23}$$

$$a = 0.000000675I^3 - 0.0000771I^2 + 0.0179I + 0.49239 \tag{24}$$

C represents the correction coefficient.

$$C = \frac{N}{360} \tag{25}$$

N represents monthly amount of daylight hours (h).

2.3.2. Blaney-Criddle method

$$ET = p \times (0.46T + 8.13) \tag{26}$$

P represents the annual daylight percentage of every month and T is the average temperature (°C).

2.3.3. Hamon method

$$ET = k \times 0.1651 \times 216.7 \times N \times \left(\frac{e_s}{T + 273.3}\right) \tag{27}$$

In Eq. (27), k represents the empirical coefficient (k = 1.0); N represents daylight hours (h); e_s is the saturated vapor pressure (kPa); and T represents average temperature (°C).

2.3.4. Linacre method

$$ET = \frac{\frac{500T_m}{100-A} + 15(T - T_d)}{(80 - T)} \tag{28}$$

$$T_m = T + 0.006h \tag{29}$$

T represents average temperature (°C); T_d is the dew point temperature (°C); and A represents latitude (°).

2.4. Statistical verification

In this study, the differences and correlations between the estimation results of the Penman-Monteith method and other formulas were compared and assessed using the following criteria:

2.4.1. Mean bias error

The bias degree of the Penman-Monteith method and the other methods was determined from the mean bias error (MBE). A smaller value indicated a lower bias degree as well as a better result. The best fit was MBE = 0, and the formula is as follows:

$$\mathrm{MBE} = \frac{\sum_{i=1}^{n}(E_i - P_i)}{n} \tag{30}$$

E_i represents the estimated value of the empirical formula; P_i represents the estimated value of the Penman-Monteith method; and n is the total number of observations.

2.4.2. Error percentage

$$\text{Error percentage} = \frac{\mathrm{MBE}}{\overline{x}} \times 100 \tag{31}$$

MBE represents the mean bias error of Eq. (30); and $\overline{x}$ represents the mean value.

2.4.3. Root mean square error

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(E_i - P_i)^2}{n}} \tag{32}$$

Root mean square error (RMSE) represents the variance degree of two estimated values. The best fit was RMSE = 0. In Eq. (32), E_i is the estimated value of empirical formula; P_i represents the estimated value of the Penman-Monteith method; and n is the total number of observations.

2.4.4. Pearson-type goodness-of-fit index (R^2)

$$R^2 = \left[\frac{\sum_{i=1}^{n}(E_i - \overline{E})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n}(E_i - \overline{E})^2}\sqrt{\sum_{i=1}^{n}(P_i - \overline{P})^2}}\right] \tag{33}$$

The Pearson-type goodness-of-fit index represents the degree of correlation between two estimation methods. The best fit was R^2 = 1.0. In Eq. (33), E_i represents the estimated value of the empirical formula; $\overline{E}$ is the average estimated value of the empirical formulas; P_i represents the estimated value of the Penman-Monteith method; $\overline{P}$ is the mean estimated value of the Penman-Monteith method; and n represents the total number of observations.

2.5. Study area

There is abundant precipitation in Taiwan. Its distribution, however, is uneven in both time and space. In addition to the significant precipitation difference between the wet season and dry season, the high mountains and steep slopes in Taiwan have insufficient reservoir storage as well as ET losses that collectively result in an extremely low amount of usable water. Water resource management could be achieved by accurately estimating ET to predict available water resources. In this study, the meteorological data recorded during the period of 1961–2013 by the Tainan weather station of Taiwan and provided by the Central Weather Bureau were considered (**Figure 1**). The collected meteorological parameters included temperature, wind speed, relative humidity, solar radiation, vapor pressure difference, daylight hours, and so on. Because the climatic factors that influenced ET might change with variation in the time scale, previous researches suggested that average monthly data would lead to a better result [24]. Therefore, this study used average monthly data for estimation.

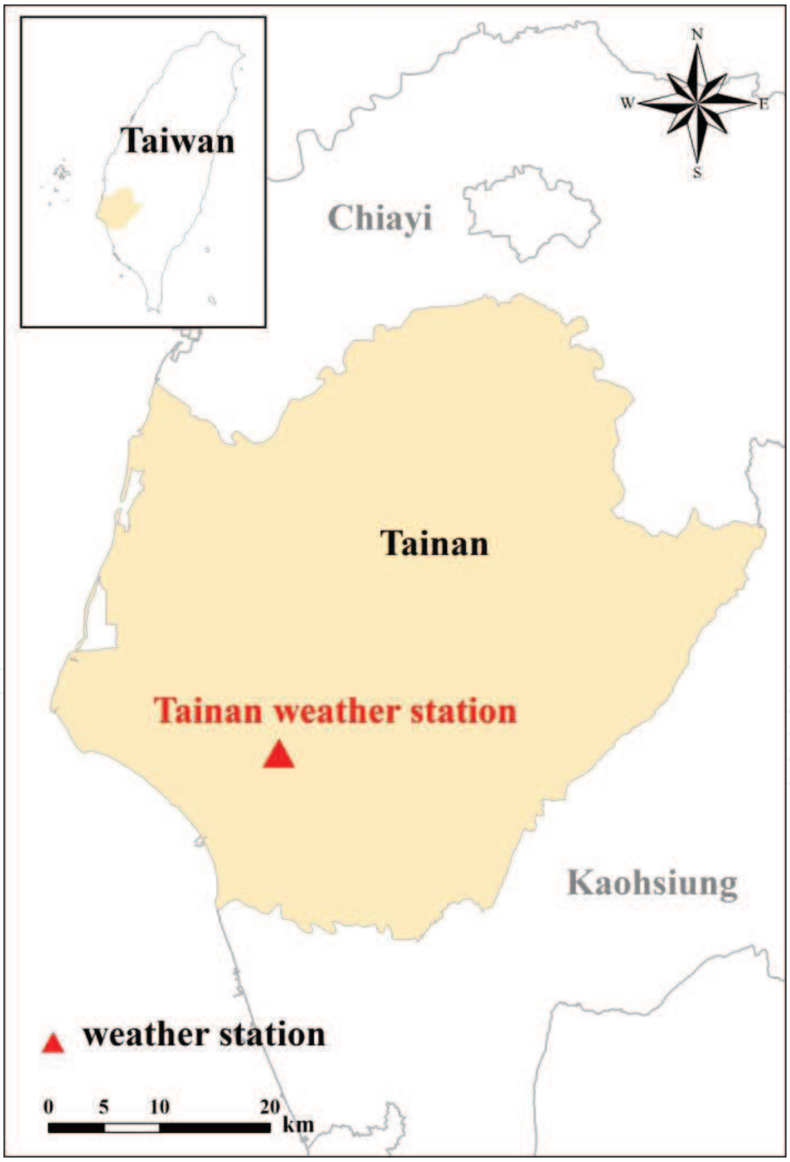


Figure 1. Location of Tainan weather station.

3. Results and discussion

3.1. Estimation of ET using Penman-Monteith method

The Penman-Monteith method is the main approach recommended internationally to estimate ET; it requires the use of meteorological parameters, such as radiation, air temperature, relative humidity, and wind speed. These parameters might be difficult to obtain and measure in many meteorological stations, with the exception of temperature. Using Taiwan as an example, only a few meteorological stations had complete data of all meteorological parameters, and still there were missing data in the observation materials. Yeh et al. [13] evaluated the ET difference between the Penman-Monteith method and evaporation pan in southern Taiwan. They used six meteorological stations in the southern part of Taiwan as case studies and collected meteorological data over a span of 15 years from 1990 to 2004 to estimate ET and ET of evaporation pans. In addition, a coefficient of evaporation pans was established. The results showed that the Penman-Monteith method and evaporation pan were highly correlated. Therefore, this study used long-term meteorological data from 1961 to 2013 from Tainan Weather Station provided by Central Weather Bureau for estimation. The estimation results calculated using the Penman-Monteith method were taken as the standard, which were named PM1. In cases where radiation data were missing or incomplete, Eq. (3) was used for substitution, which was called PM2. When wind speed data were missing or incomplete, the average wind speed of 1.83 m s^{-1} in Taiwan was used for calculation [15], which was called PM3. Eq. (2) was used for substitution in cases where relative humidity data were missing or incomplete, which was named PM4. Finally, when radiation, wind speed, and relative humidity data were all missing, all of the above substitutes were used, which was called PM5. Statistical methods of MBE, RMSE, and R^2 were applied to this study. In addition, the four models, namely PM2, PM3, PM4, and PM5, were used to estimate ET, and the results were compared with those of model PM1.

The characteristics of the ET at Tainan Weather Station estimated using different models are shown in **Table 1**. This demonstrates that maximum values are mainly concentrated in July, while minimum values are primarily concentrated in January or December. The average value was within the range of 3.42–3.61 mm/day. In addition, the ET estimated by PM models at Tainan Weather Station is shown in **Figure 2**, and the results indicate that the trend of each PM model was roughly the same as that of PM1. The comparison results between each PM model and PM1 are shown in **Figure 3**. This suggests that ET was underestimated by PM2 from July to September, while it was overestimated during other months; PM3 underestimated ET in

Scenarios	Min.	Min. (month)	Max.	Max. (month)	Mean	Standard deviation
PM1	2.26	January	4.72	July	3.54	0.92
PM2	2.35	January	4.55	July	3.61	0.85
PM3	2.22	January	4.78	July	3.58	0.95
PM4	2.15	December	4.56	July	3.42	0.89
PM5	2.24	December	4.38	July	3.49	0.81

Table 1. Various scenarios for calculating evapotranspiration using the Penman-Monteith method (mm d^{-1}).

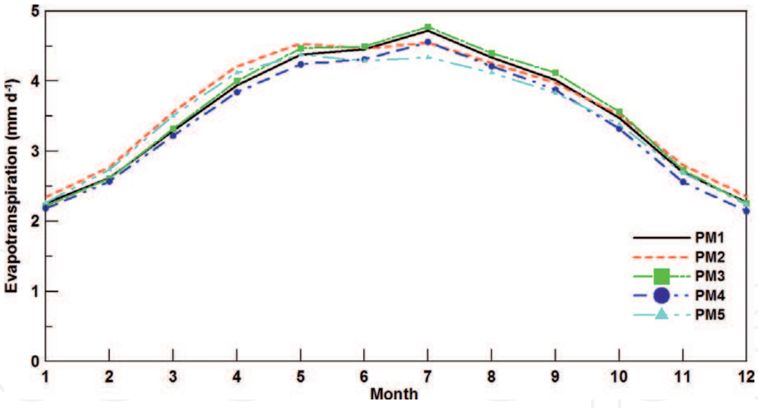


Figure 2. Comparison of monthly mean values of the Penman-Monteith method from various scenarios.

January, February, and December, and it was overestimated in the remaining months; ET was underestimated by PM4 in all months; PM5 underestimated ET in June, July, August, September, October, and December and overestimated ET in other months.

In this study, the estimated ET of PM2, PM3, PM4, and PM5 models were compared with that of the PM1 model using the statistical methods of MBE, RMSE, and R^2. Statistical verification

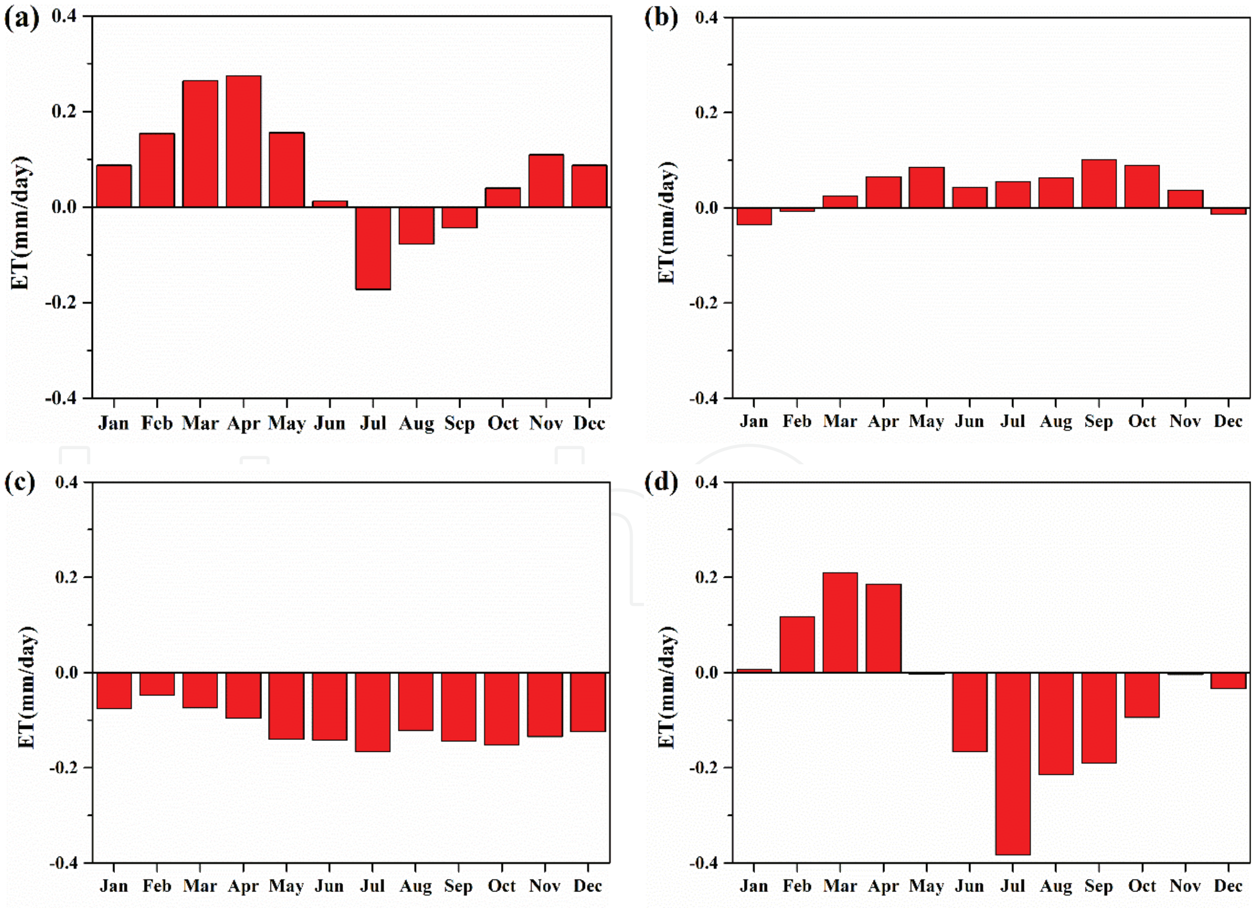


Figure 3. Monthly evapotranspiration comparison between the PM1 and the calculated values by using the various scenarios. (a) PM2; (b) PM3; (c) PM4; (d) PM5.

results of MBE showed that the MBE value was within the range of -0.12 to 0.07 mm d^{-1}, while the value of RMSE ranged from 0.09 to 0.31 mm d^{-1}. There is slight overestimation in PM2 and PM3. In contrast, there is slight underestimation in PM4 and PM5. In addition, R^2 was optimal in PM3 based on the statistical verification results. Therefore, according to the calculation results of MBE, RMSE, and R^2, the PM3 model had the optimal performance. Given the above comparison, the results of this study showed that wind speed had little effect on the assessment of ET with the Penman-Monteith method as the standard (PM1), which was similar to the conclusion drawn by Jabloun et al. [25]. The results obtained by Popova et al. [26] using the global average wind speed of 2 m s^{-1} were similar to PM1 as well. In addition, compared to missing radiation or wind speed data, the absence of relative humidity data exerted a larger impact on the estimation of ET when Penman-Monteith method was used.

3.2. The results of ET estimation using different empirical formulas

Compared with other meteorological parameters, namely radiation, relative humidity, and wind speed, temperature is relatively easy to obtain. Apart from that, radiation can be accurately measured, and yet existing measurement methods are unable to acquire precise wind speed data, especially in dry areas where the error would be relatively larger. Because the mixed evaluation methods, such as the Penman-Monteith method, require many meteorological parameters, there are some difficulties in the funding, maintenance, and construction of meteorological stations, making it difficult to acquire certain data. Therefore, it is essential to develop ET estimation methods that require fewer or a single meteorological parameter [27]. A number of scholars have proposed various methods or experiential formulas and compared them to the Penman-Monteith method in the hope of finding a relatively simple method and experiential formula to measure ET [28]. This study selected six radiation-based methods and four temperature-based methods to explore their applicability in the study area.

3.2.1. Estimation of monthly average ET using radiation-based methods

According to the radiation-based estimation methods that are used internationally, this study selected six methods, including Makkink [4], Turc [16], Jensen and Haise [17], Priestley and Taylor [5], Doorenbos and Pruitt [18], and Abtew [19]. A commonly used statistical mean error percentage was applied to the estimation so as to discuss the basic statistical differences. The data recorded by Tainan Weather Station from 1961 to 2013 were substituted into the formula, and the results are shown in **Table 2**. This demonstrates that minimum values were mainly concentrated in December and January, while maximum values were primarily concentrated in July. The mean value indicated a significant underestimation in ET calculated by the Makkink method, with an average value of 2.99 mm d^{-1} and an error percentage of -15.5%. The results of the Turc method showed a slight overestimation, with an average value of 3.66 mm d^{-1} and an error percentage of 3.4%. ET was significantly overestimated by the Jensen-Haise method, with a mean value of 5.16 mm d^{-1} and an error percentage of 45.8%. The results of the Priestley-Taylor method suggested an overestimation, with an average value of 3.96 mm d^{-1} and an error percentage of 11.9%. ET calculated by the Doorenbos-Pruitt method was the closest to the mean value of the Penman-Monteith method, with an average value of 3.43 mm d^{-1} and an

	Min.	Min. (month)	Max.	Max. (month)	Mean	Standard deviation
Penman-Monteith	2.26	January	4.72	July	3.54	0.92
Makkink (1957)	1.95	December	3.92	July	2.99	0.74
Turc (1961)	2.51	December	4.67	July	3.66	0.82
Jensen-Haise (1963)	2.91	January	7.28	July	5.16	1.63
Priestley-Taylor (1972)	2.16	December	5.53	July	3.96	1.23
Doorenbos-Pruitt (1977)	2.64	December	5.27	July	3.43	3.68
Abtew (1996)	2.69	December	4.50	July	3.68	0.70

Table 2. Performance evaluation of the radiation-based methods against Penman-Monteith (mm d^{-1}).

error percentage of −3.1%. The results of the Abtew method showed a slight overestimation, with an average value of 3.68 mm d^{-1} and an error percentage of 4.0%.

The trend of monthly average ET at Tainan Weather Station calculated by various radiation-based methods were all consistent with that of the Penman-Monteith method, which was taken as the standard, as shown in **Figure 4**. As shown in **Figure 5**, the monthly average ET was underestimated by the Makkink method, with an error percentage ranging from −16.9 to −13.7%; the Turc method slightly overestimated all the monthly average ET, with an error percentage of −1.1 to 11.1%; and the monthly average ET was significantly overestimated by the Jensen-Haise method. Especially in summer, the overestimation was far more significant, and the error percentage was up to 54.2%. The results of the Priestley-Taylor method suggest underestimation only in December and January, and overestimation in other months, with an error percentage of −4.4 to 17.2%. The Doorenbos-Pruitt method slightly underestimated ET in May, August, and September, while in other months ET was overestimated with an error percentage ranging from 11.7 to 16.8%. Compared with the Penman-Monteith method, ET was overestimated by the Abtew method, and the error percentage was within the range of −4.7 to 19%. The above results suggest that the Doorenbos-Pruitt method was the least biased in estimating ET, while the Jensen-Haise method was the most biased.

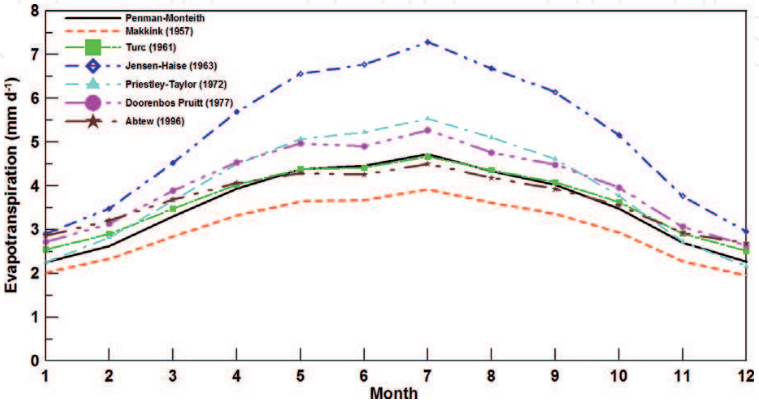
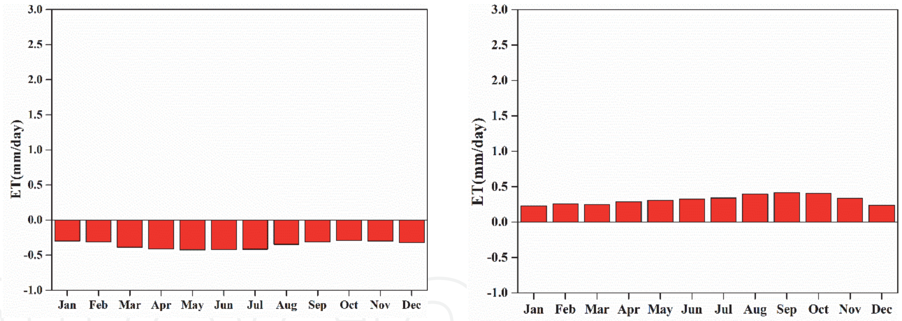
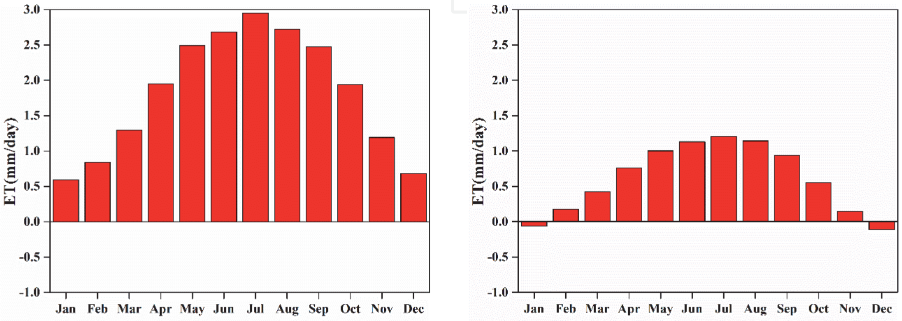


Figure 4. Monthly evapotranspiration computed by the Penman-Monteith method and six radiation-based methods.



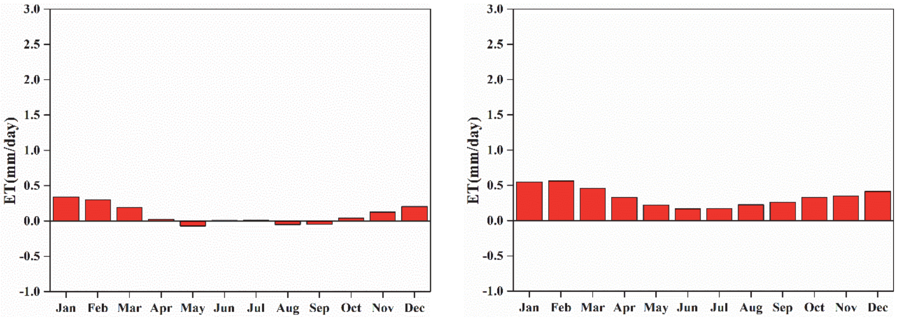
(a) Makkink (1957)

(b) Turc (1961)



(c) Jensen-Haise (1963)

(d) Priestley-Taylor (1972)



(e) Doorenbos-Pruit (1977)

(f) Abtew (1996)

Figure 5. Monthly evapotranspiration comparison between the Penman-Monteith method and the calculated values by using the radiation-based methods ((a) Makkink; (b) Turc; (c) Jensen-Haise; (d) Priestley-Taylor; (e) Doorenbos-Pruit; (f) Abtew).

In addition, three statistical methods, namely MBE, RMSE, and R^2, were used in this study to compare the estimation results of the Makkink, Turc, Jensen-Haise, Priestley-Taylor, Doorenbos-Pruitt, and Abtew methods with the Penman-Monteith method. The statistical verification results of MBE indicated that the value of MBE was within the range of -0.55 to 0.41 mm d^{-1} and the value of RMSE ranged from 0.23 to 1.78 mm d^{-1}. **Figure 6(a)** shows that the Makkink method underestimated ET, and the MBE value was -0.55. Furthermore, the other five methods, Turc, Jensen-Haise, Priestley-Taylor, Doorenbos-Pruitt, and Abtew methods, all overestimated ET, and the MBE values were respectively 0.12, 1.62, 0.41, 0.49, and 0.14. In particular, the overestimation of the Jensen-Haise method was the most significant. **Figure 6(b)** suggests that all six methods overestimated ET, and the values of RMSE were respectively 0.60, 0.23, 1.78, 0.55,

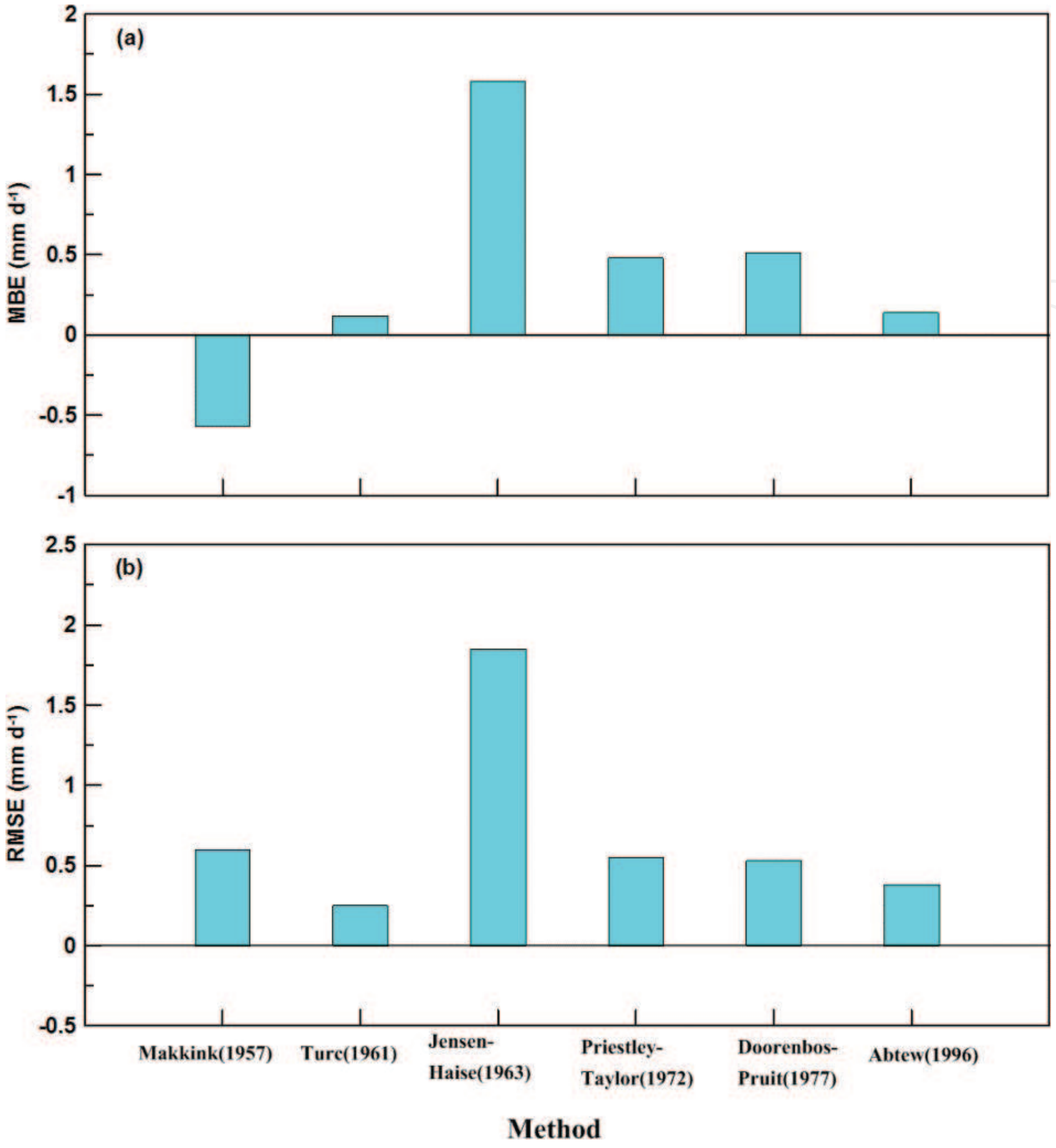


Figure 6. (a) MBE and (b) RMSE for evapotranspiration comparison between the Penman-Monteith method and six radiation-based methods.

0.53, and 0.37. Evapotranspiration was most significantly overestimated by the Jensen-Haise method as well. The statistical results showed that R^2 was within the range of 0.90–0.97. Therefore, judging from the statistical results of MBE, RMSE, and R^2, the Turc method was optimal at the Tainan Weather Station, followed by the Abtew method; the method with the worst performance was the Jensen-Haise method. Previously, Tabari et al. [29] used 31 methods to evaluate ET at a meteorological station named Rasht in a humid area of Iran. The results showed that, compared to the Penman-Monteith method, the Jensen-Haise method severely overestimated ET with a relative error of about 30%. It was also found to significantly overestimate ET in this study area, and the relative errors were respectively around 59 and 48%. Such overestimation also occurred in the humid regions of Serbia [30] and Florida of the USA [31].

3.2.2. Estimation of monthly average ET using temperature-based methods

Among the temperature-based methods that are commonly used internationally, this chapter selected four methods, including Thornthwaite [20], Blaney and Criddle [21], Hamon [22], and Linacre [23]. To begin with, the commonly used statistical mean value and error percentage were used for estimation; then this chapter discusses the basic statistical error. After the data recorded by Tainan Weather Station from 1961 to 2013 were substituted into the formulas to calculate the daily ET, the average monthly ET was calculated with month as the unit, and the results are shown in **Table 3**. At the Tainan Weather Station, minimum values were mainly concentrated in January and maximum values were primarily concentrated in July. The mean value suggests that the Thornthwaite method severely underestimated ET, with a mean value of 1.95 mm d^{-1} and an error percentage of −44.9%. The Blaney-Criddle method significantly underestimated ET as well. Its mean value was 1.61 mm d^{-1} and the error percentage was −54.5%. The Hamon method underestimated ET, with a mean value of 2.72 mm d^{-1} and an error percentage of −23.2%. Evapotranspiration was overestimated by the Linacre method, with a mean value of 4.05 mm d^{-1} and an error percentage of 14.4%.

This chapter compared the ET of Tainan Weather Station as calculated by the temperature-based methods with that of the Penman-Monteith method, and the results are as shown in **Figure 7**. The trends of the Thornthwaite, Hamon, and Linacre methods were consistent with the Penman-Monteith method, while Blaney-Criddle method suggested otherwise. The monthly average ET at Tainan Weather Station estimated by the temperature-based estimation methods was compared with Penman-Monteith method, as shown in **Figure 8**. Evapotranspiration was underestimated by Thornthwaite method, with an error percentage of −70.4 to 31.1%. The maximum error occurred in March and April. The Blaney-Criddle method underestimated monthly average ET, and the error percentage was within the range of −60.6 to 38.9%. Evapotranspiration was also underestimated by the Hamon method. The underestimation in winter was insignificant, with an error percentage of −23.5 to 18.1%. In May, the percentage reached its maximum. The Linacre method overestimated the monthly average ET. The error percentage ranged from 5.1 to 23.9% and reached maximum value in November. In light of the above results, the error percentage of Thornthwaite method was the largest.

This study used three statistical methods, namely MBE, RMSE, and R^2, to compare ET at the Tainan Weather Station estimated by the Thornthwaite, Blaney-Criddle, Hamon methods with that of the Penman-Monteith method. The value of MBE ranged from −1.93 to 0.51 mm d^{-1} and RMSE was within the range of 0.63–2.08 mm d^{-1}. The statistical results of R^2 indicated that

	Min.	Min. (month)	Max.	Max. (month)	Mean	Standard deviation
Penman-Monteith	2.26	January	4.72	July	3.54	0.92
Thornthwaite (1948)	0.67	January	3.25	July	1.95	1.02
Blaney-Criddle (1959)	1.38	January	1.86	July	1.61	0.32
Hamon (1961)	1.85	January	3.61	July	2.72	0.80
Linacre (1977)	2.80	January	4.96	July	4.05	0.82

Table 3. Performance evaluation of the temperature-based methods against Penman-Monteith (mm d^{-1}).

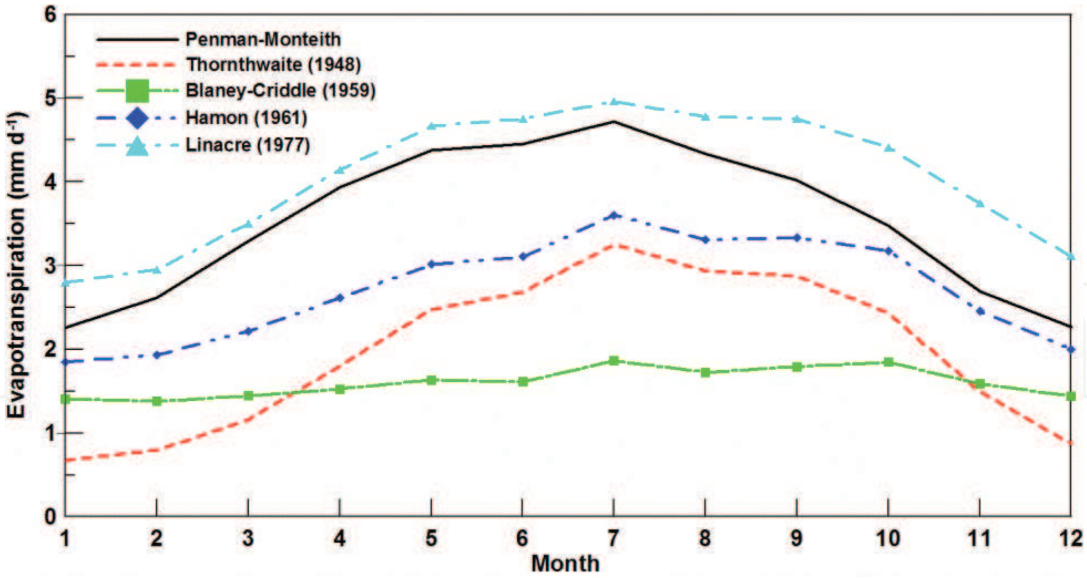
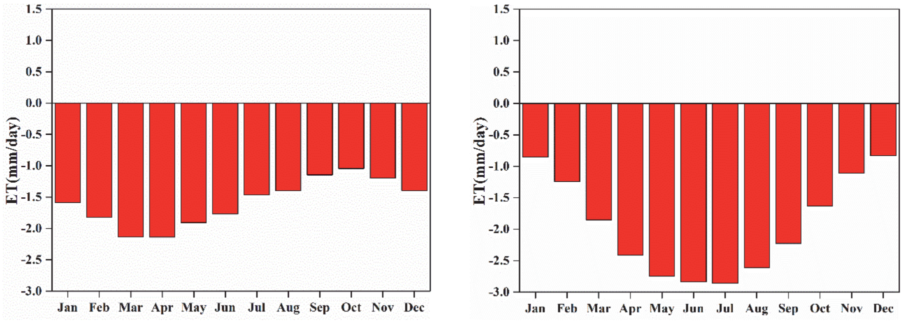
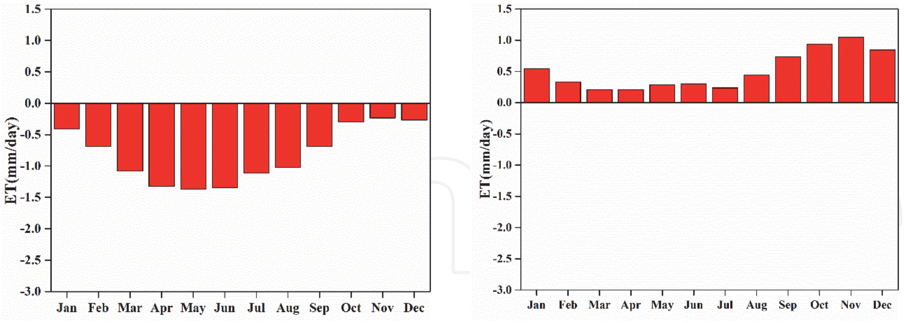


Figure 7. Monthly evapotranspiration computed by the Penman-Monteith method and four temperature-based methods.



(a)Thornthwaite (1948)

(b) Blaney-Criddle (1959)



(c) Hamon (1961)

(d) Linacre (1977)

Figure 8. Monthly evapotranspiration comparison between the Penman-Monteith method and the calculated values by using the temperature-based methods ((a) Thornthwaite; (b) Blaney-Criddle; (c) Hamon; (d) Linacre).

it was within the range of 0.36–0.83. As shown in **Figure 9(a)**, the results of Thornthwaite, Blaney-Criddle, and Hamon methods suggest underestimation, and the values of MBE were −1.58, −1.93, and −0.82, respectively. Results of the Linacre method, however, indicated overestimation with an MBE of 0.51. **Figure 9(b)** suggests overestimation in Thornthwaite,

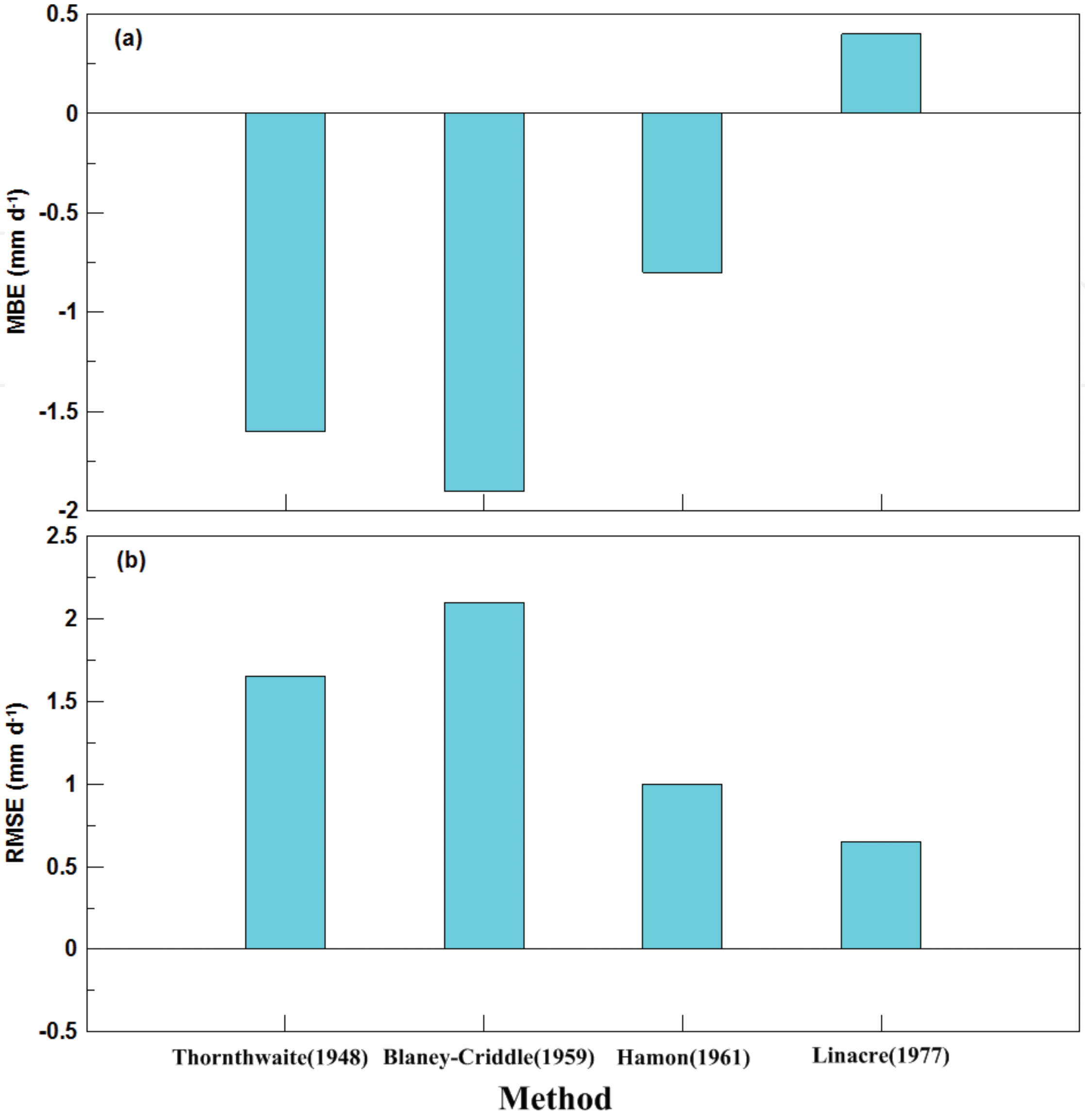


Figure 9. (a) MBE and (b) RMSE for evapotranspiration comparison between the Penman-Monteith method and four temperature-based methods.

Blaney-Criddle, Hamon, and Linacre methods, with RMSE values of 1.63, 1.31, 1.15, and 1.12, respectively. In summary, according to the statistical results of MBE, RMSE, and R^2, the Linacre method was optimal for estimating ET at the Tainan Weather Station, followed by the Hamon method. The Blaney-Criddle method was the least fit.

According to relevant studies and literature, Fontenot [32] declared that for meteorological stations near the coast, the Linacre method overestimated ET by 18.46% compared to the Penman-Monteith method. It was also pointed out that this method could be greatly affected by the dew point temperature. Compared with the Penman-Monteith method, the results of Thornthwaite, Hamon, and Blaney-Criddle methods all suggest underestimation, as these three temperature-based formulas all took daylight hours into consideration. In spite of the high temperature, the results would still be lower than the actual amount when daylight hours were insufficient, causing underestimation. Even if the daylight hours were insufficient, ET still occurred. The results of this study show that the Blaney-Criddle method underestimated ET in Tainan because it is strongly influenced by the annual daylight percentage of every month. Cruff and Thompson [33] used the Thornthwaite and Blaney-Criddle methods to estimate ET in the desert areas of the southwestern United States, and the results suggested underestimation as well.

This study compared the results of radiation-based methods with that of Penman-Monteith method and discovered that the empirical formulas of radiation-based methods were better than those of temperature-based methods. In addition, the errors of ET calculated by temperature-based methods were larger than those of the radiation-based methods. The reason is as follows: it is most likely that temperature is the only meteorological parameter used in empirical formulas of temperature-based methods. Therefore, it could be easily affected by the data of meteorological station, which would easily cause inaccuracy. Such a conclusion is similar to that of Lu et al. [34], Sentelhas et al. [8], and Gebhart et al. [35]. Moreover, the estimation results of Tukimat et al. [36] in Malaysia showed that three radiation-based methods, namely Makkink [4], Turc [16], and Priestley and Taylor [5], were more accurate than two temperature-based methods, the Thornthwaite [20] and Blaney and Criddle [21] methods. In terms of temperature-based estimation methods, many scholars have found that ET was underestimated by the Thornthwaite [20] method in humid areas compared to the Penman-Monteith method. For instance, the results of Alkaeed et al. [37] in Fukuoka of Japan, Trajkovic and Kolakovic [30] in six meteorological stations of Balkan Peninsula, and Sentelhas et al. [8] in Ontario of Canada, all showed the same conclusion. Some scholars, however, have pointed out that compared with the Penman-Monteith method, the performance of R^2 in the Thornthwaite [20] method was worse, and yet its trend was consistent with the Penman-Monteith method. The evaluation of ET conducted by [36] in Kedah of Malaysia suggested same result.

4. Conclusions

This study mainly aimed to estimate ET using a limited number of meteorological parameters. With the internationally accepted Penman-Monteith method as the standard, the estimation formulas of six radiation-based methods were compared with those of four temperature-based methods. The 53-year dataset recorded by Tainan Weather Station from 1961 to 2013 was used to discuss ET. Statistical indexes were used to analyze and discuss the differences in ET calculated by the Penman-Monteith method and other estimation formulas in the hope of discovering a simple estimation formula to solve the issue of lacking or missing meteorological data.

This study discussed situations in which meteorological data were insufficient or missing in the Penman-Monteith method. The results showed that using the average Taiwan wind speed of 1.83 m s^{-1} when wind speed data were insufficient or missing exerted little impact on ET estimation of the Penman-Monteith method. In the cases where empirical formulas were used for substitution because of the lack of relative humidity data, the estimated ET was higher than the actual data, causing overestimation. In addition, this study explored the impact on ET estimation by the Penman-Monteith method caused by insufficient or missing radiation, relative humidity, or wind speed data. It was discovered that the impact of wind speed was minimal, and the impact of relative humidity was the highest.

The six radiation-based methods selected in this study all suggested overestimation. In particular, the Turc method was optimal, followed by the Doorenbos-Pruitt method; the method with the worst performance was Jensen-Haise. This study found that ET was overestimated by the Jensen-Haise method in humid areas. In addition, among the four chosen temperature-based methods in this study, the Thornthwaite method, Hamon method, and Blaney-Criddle method all underestimated ET compared with the Penman-Monteith method, as these three temperature-based formulas all take daylight hours into consideration. In the cases where the daylight hours were insufficient, no matter how high the temperature was, underestimation would still occur. Even though the daylight hours were insufficient, ET was still occurring. The performance of the Linacre method was the best among the four estimation methods. The results of this study indicate that radiation-based estimation methods are better than temperature-based methods, as temperature is most likely to be the only meteorological parameter required in empirical formulas of temperature-based methods, making it easily affected by the data of meteorological stations, thus resulting in inaccuracy.

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