EVALUATION OF REFERENCE EVAPOTRANSPIRATION METHODS IN ARID, SEMIARID, AND HUMID REGIONS¹

Fei Gao, Gary Feng, Ying Ouyang, Huixiao Wang, Daniel Fisher, Ardeshir Adeli, and Johnie Jenkins²

ABSTRACT: It is often necessary to find a simpler method in different climatic regions to calculate reference crop evapotranspiration (ET₀) since the application of the FAO-56 Penman-Monteith method is often restricted due to the unavailability of a comprehensive weather dataset. Seven ET₀ methods, namely the standard FAO-56 Penman-Monteith, the FAO-24 Radiation, FAO-24 Blaney Criddle, 1985 Hargreaves, Priestley-Taylor, 1957 Makkink, and 1961 Turc, were applied to calculate monthly averages of daily ET₀, total annual ET₀, and daily ET₀ in an arid region at Aksu, China, in a semiarid region at Tongchuan, China, and in a humid region at Starkville, Mississippi, United States. Comparisons were made between the FAO-56 method and the other six simple alternative methods, using the index of agreement D, modeling efficiency (EF), and root mean square error (RMSE). For the monthly averages of daily ET₀, the values of D, EF, and RMSE ranged from 0.82 to 0.98, 0.55 to 0.98, and 0.23 to 1.00 mm/day, respectively. For the total annual ET₀, the values of D, EF, and RMSE ranged from 0.21 to 0.91, −43.08 to 0.82, and 24.80 to 234.08 mm/year, respectively. For the daily ET₀, the values of D, EF, and RMSE ranged from 0.58 to 0.97, 0.57 to 0.97, and 0.30 to 1.06 mm/day, respectively. The results showed that the Priestly-Taylor and 1985 Hargreaves methods worked best in the arid and semiarid regions, while the 1957 Makkink worked best in the humid region.

(KEY TERMS: reference crop evapotranspiration; FAO-56 Penman-Monteith; alternative ET₀ methods; diverse climatic conditions.)


INTRODUCTION

Crop evapotranspiration (ETᵣ), widely used for determining crop water requirements and designing irrigation systems (Jensen and Haise, 1963; Tabari et al., 2011), is defined as the combined processes of water loss from the soil surface by evaporation and from the crop by transpiration (Allen et al., 1998). There are a number of methods for measuring crop evapotranspiration, such as energy balance methods (Tanner, 1960), soil water balance methods (Malek and Bingham, 1993), and pan evaporation methods (Grismer et al., 2002). However, crop

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evapotranspiration is not easy to measure since it depends on weather parameters, crop type, soil type, and agricultural management. Expensive devices such as lysimeters can be used, but experienced researchers are required (Allen et al., 1998). To avoid these restrictions, Jensen (1968) introduced a method of calculating crop evapotranspiration (ETc) by multiplying reference crop evapotranspiration (ETc) by a crop-specific crop coefficient (Kc). ETc is defined as “the rate of evapotranspiration from a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s/m, and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground, and not short of water” (Allen et al., 1998). Accurate estimation of ETc is necessary for improving the use efficiency of water resources as well as increasing production for growers (Droogers and Allen, 2002).

In the past 50 years, numerous methods have been developed for calculating ETc according to the climatic conditions and weather data. Penman (1948) developed a theoretical equation to compute evaporation from open water, bare soil, and grass by combining the energy balance with a mass transfer method, but Allen et al. (1998) considered that it could also be applied for calculating ETc if resistance factors were introduced to this equation. The Penman method was modified by Monteith (1965) through incorporating the aerodynamic resistance and surface resistance factors, leading to the generation of the well-known Penman-Monteith method, which can be directly used to calculate ETc. In order to improve the performance of ETc methods, the Food and Agriculture Organization of the United Nations (FAO) recommended four methods to calculate ETc, including the Blaney-Criddle method, radiation method, modified Penman method, and pan evaporation method (Doorenbos and Pruitt, 1977). However, these methods would often give variable ETc results among different locations andhad huge deviations (Allen et al., 1998; Pereira et al., 2015). As a result, the improved FAO-56 Penman-Monteith method was recommended as the standard method for calculating ETc, which included solar radiation, air temperature, humidity, and wind speed as input parameters (Allen et al., 1998). The Evapotranspiration in Irrigation and Hydrology Committee of the American Society of Civil Engineers (ASCE) also introduced a Penman-Monteith equation for calculating both hourly and daily ETc, the form of which is identical to FAO-56 Penman-Monteith method at daily time step (Allen et al., 2005).

In addition to the methods mentioned above, there are other empirical equations that only need radiation and temperature data to calculate ETc. Makkink (1957) developed a radiation-based equation to estimate ETc which neglected the aerodynamic factors and substituted incoming shortwave solar radiation for the net radiation balance. The Turc (1961) method estimated ETc with only temperature and solar radiation data. Priestley and Taylor (1972) developed an equation derived from the original Penman (1948) equation, and has been of interest to crop modelers due to lesser data requirements (Liu and Erda, 2005). Hargreaves and Samani (1985) developed an empirical equation for arid areas which needs only temperature to calculate ETc. These and other methods widely used for ETc calculation can be classified into three groups: combination methods, radiation methods, and temperature methods (Irmak et al., 2008).

ETc depends on and is sensitive to weather data and climate type (Zhang et al., 2010; Dinpashoh et al., 2011). In order to evaluate the performance of equations under different climatological conditions, comparisons among these methods have been carried out to identify the most suitable method for calculating ETc in a certain area. Jensen et al. (1990) assessed performance of 20 different methods compared to lysimeter data from 11 locations with variable climatological conditions, and results indicated that ETc calculated by different methods varies greatly. European research institutes (Allen et al., 1998) also studied the validity of different ETc equations in comparison with lysimeter data and came to similar conclusions. Many researchers have indicated that the FAO-56 Penman-Monteith method could be used for the calculation of ETc in a wide range of locations and climates (Kashyap and Panda, 2001; Allen et al., 2005, 2006). While the FAO-56 Penman-Monteith method has become the most accurate method for estimating ETc, the application of this method is restricted in many locations since it requires a number of weather parameters, including solar radiation, air temperature, air humidity, and wind speed. It is often not easy to obtain these weather data due to limitations of installing expensive and complicated weather stations. To resolve this problem, methods with less required meteorological data are recommended to estimate ETc in many regions. Comparisons were made by Yoder et al. (2005) between daily ETc estimated from eight different equations and measured by lysimeter in the Cumberland Plateau of the humid Southeast United States (U.S.). Their results showed that the FAO-56 Penman-Monteith method is the best method for this humid climate, followed by the Penman (1948) and Turc (1961) methods. The Turc (1961) equation was an attractive alternative because it only requires temperature and solar radiation data. Studies have indicated that the Turc equation is suitable for ETc calculation in humid and subhumid regions.
(Trajkovic and Kolakovic, 2009; Fisher and Pringle, 2013). Simple methods compared to the FAO-56 Penman-Monteith have also been tested in arid and semiarid locations. Hargreaves and Allen (2003) reported that the 1985 Hargreaves method can be used in arid and semiarid locations with only measurements of maximum and minimum air temperature. Raziei and Pereira (2013) used three different methods to calculate ET₀ using data from 40 weather stations in Iran, and found that the 1985 Hargreaves method is an appropriate alternative for estimation of ET₀ for all arid regions of Iran.

While these simpler alternative methods have been widely used in different climatic regions, Valipour (2014) cautioned about using these methods in a specific site without considering the local climatic conditions, since the performance of these methods could differ greatly even if the climates of a selected area were similar to those in previous studies. It is necessary to check the performance of the simpler methods which were tested somewhere else by making comparison with the FAO-56 Penman-Monteith method. In addition, some regions lack simpler methods to replace the FAO-56 Penman-Monteith method to estimate ET₀. In order to extend the spatial coverage for evaluating alternative methods of ET₀ estimation, it is essential to calculate ET₀ by different methods at additional synoptic stations and make comparisons from various climates in the world. To our knowledge, such studies are limited in Aksu, China (an arid region), Tongchuan, China (a semiarid region), and Starkville, Mississippi, U.S. (a humid region). Also, there is an insufficient network of weather stations in these three sites, leading to limitations in the use of the FAO-56 Penman-Monteith method for calculating ET₀. The objectives of this research were to: (1) calculate ET₀ using seven different ET₀ methods and make comparisons between six simpler alternative ET₀ methods and the FAO-56 Penman-Monteith method; and (2) to identify which simpler ET₀ methods could be a substitution for the FAO-56 Penman-Monteith method in these three locations for calculating ET₀ that could be further used in water balance models for making irrigation scheduling decisions.

MATERIALS AND METHODS

Study Areas and Weather Data

Three different climatic locations from China and the U.S. (Aksu, Tongchuan, and Starkville) were selected for this study based on climate types and weather data availability (Figure 1). Aksu, within an arid region, is located in the northwest of the Taklimakan Desert in Xinjiang province, China, while Tongchuan, within a semiarid region, is located in the south of the Loess Plateau in Shanxi province, China. Starkville, within a humid region, is located in the northeast of Mississippi, U.S. The elevation of Aksu, Tongchuan, and Starkville are 1,028, 978, and 102 m above mean sea level, and mean annual precipitation totals are 61, 630, and 1,390 mm, respectively. The average annual temperature ranges from −27.6 to 40.7°C in Aksu, 8.9 to 12.3°C in Tongchuan, and 10.4 to 23.4°C in Starkville. Average annual wind speed of Aksu, Tongchuan, and Starkville are 1.6, 2.0, and 2.6 m/s, while average annual solar radiation of Aksu, Tongchuan, and Starkville are 17.8, 14.4, and 17.5 MJ/m². Weather data comprised of daily maximum and minimum air temperatures, solar radiation, relative humidity, and wind speed were downloaded from the China Meteorological Data Sharing Service System (CMDS) (http://www.escience.gov.cn) and Natural Resources Conservation Service of the U.S. Department of Agriculture (NRCS) (http://wcc.sc.egov.usda.gov/nwcc/site?sitenum=2064).

Summary information on location and weather data is given in Table 1. The time spans of weather datasets for the ET₀ calculation were 60 years for Aksu, 27 years for Tongchuan, and 65 years for Starkville (Table 1). Nandagiri and Kovoor (2006) used five years of weather data in India, and Yoder et al. (2005) used five years of weather data in the U.S. to conduct similar research, suggesting that the datasets used in our research should be long enough to represent weather conditions at the three locations and make comparisons of the seven ET₀ methods. The quality of the weather data at each site was assessed, using the REF-ET QA/QC (Quality Analysis and Quality Control) algorithms of Li and Allen (2012). There are some missing weather data in our study including the wind speed from 1953 to 1954, all the solar radiation and relative humidity in Aksu, and all the solar radiation and relative humidity in Tongchuan. Also, there are 1,096 samples of wind speed missing among the total samples in Starkville (Table 1). These missing data can be estimated by the RefET (Reference Evapotranspiration Calculator) software (Allen, 2013).

ET₀ Estimation Methods

The weather datasets were first input to the RefET (Reference Evapotranspiration Calculator) software (Allen, 2013) to obtain the daily ET₀ for the FAO-56 Penman-Monteith, and six alternative methods in each year. Then, the daily ET₀ estimates were input to a spreadsheet and were averaged in each month to
obtain monthly averages of daily \( ETo \). We focus on monthly averages of daily \( ETo \) because there can be considerable variability in \( ETo \) estimates from one day to the next, and averaging over longer time periods can reduce some of that variability (Allen et al., 1998). Total annual \( ETo \) were also obtained from daily \( ETo \) values since annual \( ETo \) is important for simulations of global water budgets (Federer et al., 1996). The methods used for this study are based on the required number of input weather data. The FAO-56 Penman-Monteith needs solar radiation, air temperature, humidity, and wind speed, while Priestley-Taylor and 1957 Makkink need only solar radiation and/or air temperature. The FAO-24 Radiation needs solar radiation, air temperature, and wind speed; 1985 Hargreaves needs air temperature. FAO-24 Blaney Criddle requires relative humidity, sunshine hours, wind speed and 1961 Turc method requires solar radiation, air temperature, and relative humidity. All the values of coefficients used in the \( ETo \) equations at three study sites were summarized in Table 2.

**FAO-56 Penman-Monteith Method.** The FAO-56 Penman-Monteith method (Allen et al., 1998), referred to as FAO-56 hereafter, can be expressed as follows:

\[
ETo = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{1 + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)},
\]

where \( ETo \) is the reference evapotranspiration (mm/day), \( Rn \) is the net radiation (MJ/m\(^2\)), \( G \) is the soil

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**TABLE 1. Location and Time Periods of Weather Data at Aksu, Tongchuan, and Starkville.**

<table>
<thead>
<tr>
<th></th>
<th>Aksu</th>
<th>Tongchuan</th>
<th>Starkville</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>40°10'N</td>
<td>35°05'N</td>
<td>33°27'N</td>
</tr>
<tr>
<td>Longitude</td>
<td>80°51'E</td>
<td>109°04'E</td>
<td>88°46'W</td>
</tr>
<tr>
<td>Start</td>
<td>Jan 1954</td>
<td>Jan 1973</td>
<td>Jan 1950</td>
</tr>
<tr>
<td>End</td>
<td>Dec 2013</td>
<td>Dec 1999</td>
<td>Dec 2014</td>
</tr>
<tr>
<td>Number of samples</td>
<td>21,914</td>
<td>9,858</td>
<td>23,739</td>
</tr>
</tbody>
</table>
TABLE 2. Description of the Coefficients Used in the ET₀ Equations at Three Study Sites.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Mean daily percentage of total annual daytime hours</td>
</tr>
<tr>
<td>b</td>
<td>Adjustment factor depends on minimum relative humidity, sunshine hours, and daytime wind speed</td>
</tr>
<tr>
<td>c</td>
<td>Adjustment factor depends on mean humidity and daytime wind conditions</td>
</tr>
<tr>
<td>z</td>
<td>Empirically derived constant and was defined as 1.26</td>
</tr>
<tr>
<td>a_T</td>
<td>Humidity correction coefficient</td>
</tr>
<tr>
<td>γ</td>
<td>Psychrometric constant (kPa°C)</td>
</tr>
<tr>
<td>λ</td>
<td>Latent heat of vaporization (MJ/kg)</td>
</tr>
</tbody>
</table>

heat flux (MJ/m²), T is average air temperature (°C), u₂ is the wind speed at 2-m height (m/s), e_s is the saturation vapor pressure (kPa), e_n is the actual vapor pressure (kPa), Δ is the slope of vapor pressure curve (kPa°C), and γ is the psychrometric constant (kPa°C).

**FAO-24 Radiation Method.** The FAO-24 Radiation method (Doorenbos and Pruitt, 1977), referred to as FAO-24 Rd hereafter, can be expressed as follows:

\[ ET₀ = c \frac{Δ}{Δ + γ} R_s, \]

where c is the adjustment factor which depends on mean humidity and daytime wind conditions, and R_s is the solar radiation (MJ/m²).

**FAO-24 Blaney-Criddle Method.** The FAO-24 Blaney-Criddle method (Doorenbos and Pruitt, 1977), referred to as FAO-24 BC hereafter, can be expressed as:

\[ ET₀ = b[a(0.46T + 8)] , \]

where a is the mean daily percentage of total annual daytime hours, and b is the adjustment factor which depends on minimum relative humidity, sunshine hours, and daytime wind speed.

**1985 Hargreaves Method.** The 1985 Hargreaves method (Hargreaves and Samani, 1985), referred to as 1985 Har hereafter, can be expressed as:

\[ ET₀ = 0.0023R_a(T + 17.8)(T_{max} - T_{min})^{0.5}, \]

where R_a is the extraterrestrial radiation (MJ/m²/day), and T_max and T_min are mean maximum and mean minimum temperatures (°C), respectively.

**Priestley-Taylor Method.** The Priestley-Taylor (1972) method, referred to as Prs-Tylr hereafter, can be expressed as:

\[ ET₀ = a \frac{Δ}{Δ + γ} R_n - G, \]

where a is the empirically derived constant and was defined as 1.26 by Priestley and Taylor (1972), and λ is the latent heat of vaporization (MJ/kg).

**1957 Makkink Method.** The 1957 Makkink (1957) method, referred to as 1957 Makk hereafter, can be expressed as:

\[ ET₀ = 0.61 \frac{Δ}{Δ + γ} R_s - 0.12 \]

**1961 Turc Method.** The 1961 Turc (1961) method, referred to as 1961 Turc hereafter, can be expressed as:

\[ ET₀ = a_T0.013 \frac{T}{T + 15} \frac{23.8856R_s + 50}{λ}. \]

The term a_T is the humidity correction coefficient and is determined by

\[ a_T = 1.0, RH_{mean} \geq 50\% \]

\[ a_T = 1.0 + \frac{50 - RH_{mean}}{70}, RH_{mean} < 50\%, \]

where RH_{mean} is mean daily relative humidity (%).

**Evaluation Criteria**

Legates and McCabe (1999) recommended that the indexes of agreement D (Willmott, 1981), modeling efficiency EF (Loague and Green, 1991), and root mean square error (RMSE) be used to evaluate the performance of the alternate ET₀ methods relative to the FAO-56 method. These criteria are defined as

\[ D = 1.0 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (|P_i - O| + |O_i - O|)^2}, \]

\[ EF = \frac{\sum_{i=1}^{n} (O_i - \bar{O})^2 - (P_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2}, \]

where O_i and P_i are observed and predicted ET₀ values, respectively.
where $D$, $EF$, and $RMSE$ are the index of agreement, modeling efficiency, and root mean square error between the $ET_o$ calculated by the FAO-56 method and six alternative $ET_o$ methods, respectively, $O_i$ is the $ET_o$ calculated by the FAO-56 method, $P_i$ is the $ET_o$ calculated by the six alternative $ET_o$ methods, $n$ is the number of calculated values, and $\bar{O}$ is average $ET_o$ calculated by the FAO-56 method. The units of $RMSE$, $O_i$, $P_i$, and $\bar{O}$ are mm/day for monthly averages of daily $ET_o$ and daily $ET_o$, and mm/year for total annual $ET_o$, while $D$ and $EF$ are dimensionless. $D$ varies from 0 to 1.0 and higher values indicate better agreement between the FAO-56 method and other $ET_o$ methods. $EF$ can be negative and have a maximum value of 1.0 and higher values indicate better agreement between the FAO-56 method and other $ET_o$ methods, while lower $RMSE$ values indicate better agreement with the FAO-56 method.

Considering this limitation, the index of agreement $D$, modeling efficiency $EF$, and root mean square error $RMSE$ were used in addition to evaluate the performance of these simple $ET_o$ methods. The values of $D$, $EF$, and $RMSE$, shown in Table 3, ranged from 0.88 to 0.98, 0.87 to 0.98, and 0.28 to 0.89 mm/day, respectively. The Prs-Tylr method gave the highest $D$ and $EF$ values, and the lowest $RMSE$, indicating that this method was the best method for calculating monthly averages of daily $ET_o$ in this arid region, followed by 1985 Har method with $D$ value of 0.97, $EF$ value of 0.96, and $RMSE$ value of 0.36 mm/day. Temporal variation of comparison statistics ($D$, $EF$, $RMSE$) on monthly averages of daily $ET_o$ for different methods are presented in Figure 3. The value of $D$, $EF$, $RMSE$ for the different methods did not experience obvious change across years except for the 1961 Turc method with the maximum $D$, $EF$, $RMSE$ of 0.99, 0.97, 1.10 mm/day and the minimum value of 0.90, 0.67, 0.33 mm/day.

Comparisons of total annual $ET_o$ calculated by the six simple methods vs. the FAO-56 method in arid region (Aksu) are presented in Figure 8a. The FAO-24 Rd method yielded the highest total annual $ET_o$, ranging from 1,054 to 1,376 mm/year during the periods of 1954 to 2013, while the 1957 Makk method estimated the lowest values, ranging from 770 to 959 mm/year. Both FAO-24 BC and 1985 Har methods gave higher total annual $ET_o$ than the FAO-56 method. The long-term average annual $ET_o$ values for Aksu for each method are presented in Table 4, and show that FAO-24 Rd, FAO-24 BC, 1985 Har, and 1961 Turc overpredicted $ET_o$ by 19%, 11%, 8%, and 1%, while Prs-Tylr and 1957 Makk underestimated by 1% and 14%, respectively. The values of $D$, $EF$, $RMSE$, and $r^2$ compared with the FAO-56 method in the arid region (Aksu) are displayed in Table 5. All the values of $r^2$ between $ET_o$ calculated by the FAO-56 and estimated by the six alternative methods were 0.99, indicating that the $ET_o$ estimates calculated by six simple methods had strong correlation with the FAO-56 method. Prs-Tylr had the highest $D$ and $EF$, and the lowest $RMSE$ values ($D = 0.84$, $EF = 0.65$, $RMSE = 38.12$ mm/year), while FAO-24 Rd had the lowest $D$ and $EF$, and the highest $RMSE$ values ($D = 0.32$, $EF = -0.83$, $RMSE = 197.42$ mm/year), indicating that Prs-Tylr is the best simple method for calculating total annual $ET_o$ in the arid region followed by 1961 Turc method with $D$ value of 0.81, $EF$ value of 0.53, and $RMSE$ value of 44.03 mm/year.

Comparison of statistical analysis of estimated daily $ET_o$ between the six simple $ET_o$ methods and the FAO-56 method for Aksu are presented in Table 6. The coefficients of determination $r^2$ for each method were 0.99 except for the 1961 Turc method.

RESULTS

Arid Region

Monthly averages of daily $ET_o$ estimated by each method in an arid region (Aksu) are shown in Figure 2. The slope of regression lines ranged from 0.84 to 1.18. In general, the FAO-24 Rd, FAO-24 BC, and 1985 Har methods overpredicted $ET_o$ compared to the FAO-56 method as indicated by slopes of the regression lines >1.0, while 1957 Makk and 1961 Turc underpredicted $ET_o$. Compared to the other six alternative methods, the slope value between Prs-Tylr $ET_o$ and FAO-56 $ET_o$ of 1.02 indicated that Prs-Tylr $ET_o$ estimates had the lowest difference relative to FAO-56 $ET_o$ estimates. The coefficients of determination, $r^2$, for each method were 0.99 except for the 1961 Turc method, indicating that these alternative methods had strong relationships with the FAO-56 method. Based on the values of slope and $r^2$, Prs-Tylr was the best alternative method for estimating monthly averages of daily $ET_o$ in the arid region ($r^2 = 0.99$, slope = 1.02), but Legates and McCabe (1999) reported that $r^2$ is oversensitive to outliers and is insensitive to additive and proportional differences between estimated and measured values, which implies it is not always reliable to evaluate the "goodness-of-fit" if it only depends on $r^2$ and slope.
The Prs-Tylr method gave the highest D and EF values, and the lowest RMSE, indicating that this method was the best method for calculating daily ETo in this arid region followed by 1985 Har method with D value of 0.96, EF value of 0.94, and RMSE value of 0.48 mm/day.

**Semiarid Region**

Monthly averages of daily ETo estimated by each method in a semiarid region (Tongchuan) are shown in Figure 4. The slope of regression lines, ranging from 0.82 to 1.13, indicated that the FAO-24 Rd and 1985 Har methods overestimated ETo as compared with FAO-56 ETo, while 1957 Makk and 1961 Turc method underestimated ETo relative to the FAO-56 method. Although the slope value of FAO-24 BC is 0.99, FAO-24 BC underestimated ETo at lower ETo values and overestimated ETo at higher ETo values. Except for the FAO-24 BC ETo estimates, Prs-Tylr ETo estimates had the lowest difference compared to FAO-56 with a slope value of 1.03. The $r^2$ value of each method was 0.99 except for the FAO-24 BC and 1961 Turc methods, indicating that all the selected simple alternative methods had strong relationships with the FAO-56 method. Based on the value of $r^2$ and slope, Prs-Tylr was the best simple method for...
estimating monthly averages of daily \( E_T \) in the semiarid region \( (r^2 = 0.99, \text{ slope } = 1.03) \). The values of \( D, EF, \text{ and RMSE for Tongchuan shown in Table 3} \) ranged from 0.92 to 0.98, 0.85 to 0.97, and 0.23 to 0.55 mm/day, respectively. The 1985 Har method gave the highest \( D \) and \( EF \), and the lowest RMSE, indicating that the 1985 Har method is the best method for calculating monthly averages of daily \( E_T \) in the semiarid region followed by the Prs-Tylr method with \( D \) value of 0.97, \( EF \) value of 0.96, and RMSE value of 0.29 mm/day. Temporal variation of comparison statistics \( (D, EF, \text{ RMSE}) \) on monthly averages of daily \( E_T \) for different methods are presented in Figure 5. The value of \( D, EF, \text{ RMSE for the different methods did not experience obvious change across years except for the 1957 Makk method with the maximum } D, \text{ RMSE of 0.96, 0.89, 0.72 mm/day and the minimum value of 0.93, 0.79, 0.40 mm/day.} \)

Figure 8b shows the annual \( E_T \) during the periods of 1973-1999 in a semiarid region (Tongchuan). The FAO-24 Rd method had the highest total annual \( E_T \), ranging from 1,009 to 1,264 mm/year, while the 1957 Makk method gave the lowest values, ranging from 767 to 909 mm/year. The 1985 Har method estimated higher total annual \( E_T \) than FAO-56 method, while both FAO-24 BC and 1961 Turc methods estimated lower values. The long-term average annual \( E_T \) values for Tongchuan for each method are presented in Table 4, and show that FAO-24 Rd, 1985 Har, and Prs-Tylr overpredicted \( E_T \) by 12%, 3%, and 1%, while FAO-24 BC, 1957 Makk, and 1961 Turc underestimated by 6%, 17%, and 10%, respectively. The values of \( D, EF, \text{ RMSE, and } r^2 \) in comparison with FAO-56 method in the semiarid region (Tongchuan) are presented in Table 5. The values of \( r^2 \) suggest similar performance as discussed for the arid region. The Prs-Tylr method had the highest \( D \) and \( EF \) values, and the lowest RMSE values \( (D = 0.91, \text{ EF = 0.82, RMSE = 24.80 mm/year}) \), while 1957 Makk gave the lowest \( D \) and \( EF \), and the highest RMSE values \( (D = 0.40, \text{ EF = -7.99, RMSE = 172.98 mm/year}) \), suggesting that Prs-Tylr is the best simple method for calculating total annual \( E_T \) in the semiarid region followed by 1985 Har method with \( D \) value of 0.83, \( EF \) value of 0.59, and RMSE value of 37.15 mm/year.

Comparison of statistical analyses of estimated daily \( E_T \) between the six simple \( E_T \) methods and the FAO-56 method for Tongchuan are presented in Table 4, and show that FAO-24 Rd, 1985 Har, and Prs-Tylr overpredicted \( E_T \) by 12%, 3%, and 1%, while FAO-24 BC, 1957 Makk, and 1961 Turc underestimated by 6%, 17%, and 10%, respectively. The values of \( D, EF, \text{ RMSE, and } r^2 \) in comparison with FAO-56 method in the semiarid region (Tongchuan) are presented in Table 5. The values of \( r^2 \) suggest similar performance as discussed for the arid region. The Prs-Tylr method had the highest \( D \) and \( EF \) values, and the lowest RMSE values \( (D = 0.91, \text{ EF = 0.82, RMSE = 24.80 mm/year}) \), while 1957 Makk gave the lowest \( D \) and \( EF \), and the highest RMSE values \( (D = 0.40, \text{ EF = -7.99, RMSE = 172.98 mm/year}) \), suggesting that Prs-Tylr is the best simple method for calculating total annual \( E_T \) in the semiarid region followed by 1985 Har method with \( D \) value of 0.83, \( EF \) value of 0.59, and RMSE value of 37.15 mm/year.

**Humid Region**

Monthly averages of daily \( E_T \) estimated by each method in a humid region (Starkville) are shown in Figure 6. The slope of regression lines, ranging from 0.95 to 1.26, indicated that all the simple methods except the 1957 Makk method, had higher \( E_T \) than FAO-56. The \( r^2 \) values for each method were very high (0.98 or 0.99), indicating that all the selected methods had strong relationships with the FAO-56 method. Based on the value of \( r^2 \) and slope, 1957 Makk was the best simple method for estimating monthly averages of daily \( E_T \) in this humid region \( (r^2 = 0.98, \text{ slope } = 0.95) \). The values of \( D, EF, \text{ and RMSE for Starkville ranged from 0.82 to 0.95, 0.55 to 0.91, and 0.43 to 1.00 mm/day, respectively (Table 3). The 1957 Makk method had the highest } D \text{ and } EF, \)
and the lowest RMSE values, suggesting that the 1957 Makk is the best method for calculating monthly averages of daily ET₀ in the humid region. Temporal variation of comparison statistics (D, EF, RMSE) on monthly averages of daily ET₀ for different methods are presented in Figure 7. The value of D, EF, RMSE for the different methods did not experience obvious change across years except for the FAO-

24 Rd method with the maximum $D$, $EF$, RMSE of 0.94, 0.72, 1.22 mm/day and the minimum value of 0.86, 0.35, 0.78 mm/day. Comparisons of total annual $ET_0$ estimated by the six simple methods vs. FAO-56 in a humid region (Starkville) are reported in Figure 8c. Except for the 1957 Makk method, other methods had higher total annual $ET_0$ than the FAO-56 method during the period of 1950 to 2014. The long-term average annual $ET_0$ values for Starkville for each method are presented in Table 4, and show that FAO-24 Rd, FAO-24 BC, 1985 Har, Prs-Tylr, 1957 Makk, and 1961 Turc overpredicted $ET_0$ by 34, 22, 18, 13, 2, and 13%, respectively. The values of $D$, $EF$, RMSE, and $r^2$ shown in Table 5 indicate that the 1957 Makk was the best simple method for calculating total annual $ET_0$ in the humid region ($D = 0.75$, $EF = 0.22$, RMSE = 47.34 mm/year). Comparison of statistical analysis of estimated daily $ET_0$ between six the simple $ET_0$ methods and the FAO-56 method for Starkville are presented in Table 6. The coefficients of determination $r^2$ ranged from 0.97 to 0.99. The 1957 Makk method gave the highest $D$ and $EF$ values, and the lowest RMSE, indicating that this method was the best method for calculating daily $ET_0$ in this humid region.

### DISCUSSION

Seven $ET_0$ methods, the *de facto* standard FAO-56, and six alternative methods, FAO-24 Rd, FAO-24 BC, 1985 Har, Prs-Tylr, 1957 Makk, and 1961 Turc were used to calculate monthly averages of daily $ET_0$, total annual $ET_0$, and daily $ET_0$ at Aksu in an arid region, Tongchuan in a semiarid region, and Starkville in a humid region. Comparisons between the FAO-56 method and the six simple methods were made to identify which method could be a substitution for the FAO-56 method if full weather datasets were not available at these three locations.

Calculating monthly averages of daily $ET_0$ can reduce the variability in $ET_0$ estimates from one day to the next. Although our results show similar magnitude of RMSE for monthly averages of daily $ET_0$ (0.23-1 mm/day) and daily $ET_0$ (0.30-1.06 mm/day) across all the simple $ET_0$ methods and these three sites, the RMSE for monthly averages of daily $ET_0$...
for each method is much lower than the daily ET₀ have. For example, RMSE for monthly averages of daily ET₀ for FAO-24 Rd is 0.88 in Aksu, while the RMSE for daily ET₀ is 0.72 (Tables 3 and 6). Figure 2 also showed that 1961 Turc overestimates ET₀ at lower FAO-56 ET₀ values in arid region (Aksu) which may be caused by the wind speed. Trajkovic and Stojnic (2007) reported that the performance of the 1961 Turc method depends on the wind speed and this method overpredicted FAO-56 PM ET₀ estimates at windless locations. Table 7 shows the average wind speed for each month in Aksu and the number of points which the FAO-56 PM ET₀ value ranged from 0 to 1 mm/day and 1961 Turc ET₀ >1 mm/day. It revealed that 1961 Turc overestimated ET₀ in January, February, and December when the average monthly wind speed is lowest than any other months.

Our results suggested that the 1985 Har method and Prs-Tylr method were superior to other simple methods for calculating the daily ET₀, monthly averages of daily ET₀, and total annual ET₀ in an arid region (Aksu) and semiarid region (Tongchuan). Since Hargreaves and Samani (1985) established the 1985 Har method, many comparison studies have confirmed that this method can be used to calculate ET₀ if the full weather datasets were not available in arid and semiarid regions. George et al. (2002) tested eight ET₀ estimation methods in Davis, California (an arid region) and found that, although the 1985 Har method underpredicted ET₀ by 1% compared to the FAO-56 method, it ranked in the first place among all the simple methods to calculate the daily ET₀ with SEE (standard error) value of 0.97 mm/day and r² value of 0.85. Martinez-Cob and Tejero-Juste (2004) also made comparison studies between the 1985 Har method and measured lysimeter ET₀ at a semiarid site in Spain during the period of May 1997 to October 2000, and the results suggested that the 1985 Har method could be used to estimate monthly ET₀ under the semiarid condition, with an RMSE value of 0.49 mm/day and r² value of 0.95. Lu et al. (2005) contrasted six ET₀ methods with measured ET₀ and calculated the long-term annual ET₀ over 36 forested watersheds in the southeastern U.S. They found that the 1985 Har method had the lowest r² values of 0.57 compared with other methods, and concluded that the 1985 Har method may not be appropriate in the humid southeastern U.S. since it was originally developed in arid areas. Hargreaves and Allen (2003) reported that the site aridity can affect the performance of 1985 Har method. As compared to other simple method, 1985 Har has less aridity-bias impact, especially in the arid and semiarid region. Although our results indicated that the Prs-Tylr method can be applied in an arid region, others have reported varying results, using this empirical method in different climate regions. Nandagiri and Kovoor (2006) evaluated the performance of several ET₀ methods in humid regions of India and showed that the Prs-Tylr method was reasonably good in the wetter climates, but poor in the drier climates, while Tabari (2009) reported that Prs-Tylr was poor in estimating ET₀ for all climates in Iran compared to other simple methods. The reason for this can be explained by the condition of advection in a certain place. Daneshkar and Tajrishy (2008) reported that Prs-Tylr method would give good performance in lower advection conditions which is a main restriction used in arid region. Although Aksu is an arid region in the northwest of China, Zhang (2011) revealed that advection in Aksu is at lower levels which account for the availability of Prs-Tylr method in Aksu. Priestley-Taylor (1972) suggested that the z value of 1.26 can be used to calculate ET₀.
while Daneshkar and Tajrishy (2008) reported that the range of $a$ value can be from 0.77 to 2.32. Furthermore, Singh and Taillefer (1986) reported that the performance of the Prs-Tylr method was influenced by the empirically derived constant $a$ which could differ greatly according to surfaces and surface wetness, and Lhomme (1997) also reported that the $a$ value should be higher in arid regions and lower in humid regions. For example, Barton (1979) found an $a$ value of 1.04 to be acceptable in wet regions, however, Jensen et al. (1990) recommended higher values of $a$, ranging up to 1.74 as appropriate in arid regions. The $a$ value is 1.26 for both our articles and Nandagiri and Kovoor’s paper (2006), this $a$ value of 1.26 ranked in the middle of that range which was reported by Daneshkar and Tajrishy (2008). As a result, the Prs-Tylr method would produce different results in arid and humid regions it should be advisable to compare estimates from the Prs-Tylr method and FAO-56 method at a specific site before direct use, even though Prs-Tylr has been shown to work well in previous studies. Our results also suggest that the 1957 Makk method is the best method for calculating monthly averages of daily $ET_0$, total annual $ET_0$, and daily $ET_0$ in a humid region. In order to identify a suitable alternative to the FAO-56 method for
calibrating reference evapotranspiration in northeast India, which falls under the humid subtropical ecosystem, Pandey et al. (2016) compared 17 different $ET_0$ methods, and found that the 1957 Makk was one of the 5 best methods in calculating mean daily $ET_0$ with a $D$ value of 0.85, and $r^2$ of 0.84.

**FIGURE 5.** Temporal Variation of Comparison Statistics ($D$, $EF$, root mean square error [RMSE]) on Monthly Averages of Daily $ET_0$ for Different Methods at a Semi-arid Region (Tongchuan).
Some simple ET$_0$ methods agreed well with FAO-56 method, while others did not, even in the same region. In the arid (Aksu) and semiarid region (Tongchuan), 1985 Har and Prs-Tylr agreed well with FAO-56–better than other methods, while in the humid region, 1957 Makk and 1961 Turc methods produced better results (Figures 2, 4, and 6 and Table 3). The 1961 Turc method needs relative humidity data to calculate ET$_0$ according to Jensen et al. (1990), while the 1985 Har and Prs-Tylr need temperature data, but the relative humidity data was not available in arid region (Aksu) and semiarid region (Tongchuan), and the relative humidity was available in humid region (Starkville). Furthermore, these climatic parameters were estimated by the RefET (Reference Evapotranspiration Calculator) software (Allen, 2013), which might have induced some error. As a result, the 1985 Har and Prs-Tylr agreed well with FAO-56 than 1961 Turc method did in arid and semiarid regions but it was not true in the humid region. FAO-24 Radiation did not agree well with FAO-56 method under arid and humid conditions compared to semiarid region due to the fact that the part of the missing wind speed data were estimated in arid and humid regions but observed in semiarid region. The FAO-24 Blaney-
Cridge method also did not agree well with FAO-56 method, this is due to the fact that FAO-24 Blaney-Cridge would provide good ET$_o$ estimates if 24-h measurements of wind are available. However, our wind speed data is daily time step (Allen and Pruitt, 1986).

FIGURE 7. Monthly Averages of Daily ET$_o$ Temporal Variation of D, EF, Root Mean Square Error (RMSE) for Different ET$_o$ Methods at a Humid Region (Starkville).
CONCLUSIONS

In order to select simpler ET₀ calculation methods for different climatic regions, the FAO-56 Penman-Monteith and six alternative ET₀ methods were compared based on monthly averages of daily ET₀, total annual ET₀, and daily ET₀ in Aksu (arid region), Tongchuan (semiarid region), and Starkville (humid region). The Priestley-Taylor and 1985 Hargreaves methods can be used as substitutes for the FAO-56 method for calculating monthly averages of daily ET₀, total annual ET₀, and daily ET₀ in both arid and semiarid regions, while in the humid region, the 1957 Makkink method can be used. The results suggest that different methods perform better in certain climates to calculate ET₀, and that these simple alternative methods can be used when the full weather datasets required by the FAO-56 Penman-Monteith method are not available. Results also show that caution should be used when applying these methods at a specific site since the performance of the methods may differ greatly. It is necessary to check the performance of the simpler ET₀ calculation methods for different climatic regions.
methods which were tested somewhere else by making comparison with FAO-56 method even if the climate of a selected area is similar to that tested in previous studies.

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LITERATURE CITED


