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Evaluation Of Methods For Estimating Daily Reference Crop Evapotranspiration At A Site In The Humid Southeast United States

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EVALUATION OF METHODS FOR ESTIMATING DAILY REFERENCE CROP EVAPOTRANSPIRATION AT A SITE IN THE HUMID SOUTHEAST UNITED STATES

R. E. Yoder, L. O. Odhiambo, W. C. Wright

ABSTRACT. Estimated daily reference crop evapotranspiration (ET$_o$) is normally used to determine the water requirement of crops using the crop factor method. Many ET$_o$ estimation methods have been developed for different types of climatic data, and the accuracy of these methods varies with climatic conditions. In this study, pair–wise comparisons were made between daily ET$_o$ estimated from eight different ET$_o$ equations and ET$_o$ measured by lysimeter to provide information helpful in selecting an appropriate ET$_o$ equation for the Cumberland Plateau located in the humid Southeast United States. Based on the standard error of the estimate ($S_{yx}$), the relationship between the estimated and measured ET$_o$ was the best using the FAO–56 Penman–Monteith equation (coefficient of determination ($r^2$) = 0.91, $S_{yx} = 0.31$ mm d$^{-1}$, and a coefficient of efficiency ($E$) = 0.87), followed by the Penman (1948) equation ($r^2 = 0.91$, $S_{yx} = 0.34$ mm d$^{-1}$, and $E = 0.88$), and Turc’s equation ($r^2 = 0.90$, $S_{yx} = 0.36$ mm d$^{-1}$, and $E = 0.88$). The FAO–24 Penman and Priestly–Taylor methods overestimated ET$_o$, while the Makkink equation underestimated ET$_o$. The results for the Hargreaves–Samani equation showed low correlation with lysimeter ET$_o$ data ($r^2 = 0.51$, $S_{yx} = 0.68$ mm d$^{-1}$, and $E = 0.20$), while those for the Kimberly Penman were reasonable ($r^2 = 0.87$, $S_{yx} = 0.40$ mm d$^{-1}$, and $E = 0.87$). These results support the adoption of the FAO–56 Penman–Monteith equation for the climatological conditions occurring in the humid Southeast. However, Turc’s equation may be an attractive alternative to the more complex Penman–Monteith method. The Turc method requires fewer input parameters, i.e., mean air temperature and solar irradiance data only.

Keywords. Evapotranspiration, Penman–Monteith, Turc.
Penman–Monteith equation yielded estimates close to measured $\text{ET}_0$ values. Following these studies, the FAO–56 Penman–Monteith method (Allen et al., 1998) was adopted as the standard method for definition and computation of $\text{ET}_0$ from a grass reference surface (cool season grass). Several other works have confirmed the validity of the Penman–Monteith equation (De Souza and Yoder, 1994; Chiew et al., 1995; Howell et al., 1997, 2000; Oliveria and Yoder, 2000; Itenfisu 2003). Motivated by the desire to bring commonality to the various $\text{ET}_0$ equations and crop coefficients now in use, the ASCE Technical Committee on Evapotranspiration in Irrigation and Hydrology recommended a standardized reference evapotranspiration equation for a grass surface ($\text{ET}_0$) along with computational procedures (Walter et al., 2000). The FAO–56 Penman–Monteith and the standardized ASCE Penman–Monteith equation for $\text{ET}_0$ are exactly the same for daily time steps. However, for hourly time steps, the standardized ASCE Penman–Monteith method uses a smaller value for surface resistance ($r_s$) during the daytime, and a larger value for $r_s$ during nighttime than does the FAO–56 Penman–Monteith equation (Allen, 2000).

Despite the advantages of the more physically based Penman methods, empirical $\text{ET}_0$ equations have remained in popular use because of simplicity and the smaller number of input parameters (weather data and other constants) needed for computation. The 1985 Hargreaves–Samani equation is among the empirical methods in common use. Hargreaves (1983) presented a good review of some background and abbreviated history of the development of the 1985 Hargreaves–Samani method and contrasts this method with other commonly used approaches. The method is popular in cases where the availability of data is limited, as it requires only measurements of maximum and minimum temperature, with extraterrestrial radiation calculated as a function of latitude and day of the year. The 1985 Hargreaves–Samani method is often used to provide $\text{ET}_0$ estimations for weekly or longer periods and has been shown to provide $\text{ET}_0$ estimates that compare favorably to those of the FAO–56 Penman–Monteith equation at some arid and semi-arid locations (Hargreaves, 2003).

The 1972 Priestley–Taylor, the 1957 Makkink, and the 1961 Turc equations are other commonly used empirical methods (Allen, 2000), and require only air temperature and solar irradiance as input data. However, there are no reports of studies that have been conducted to evaluate the performance of these methods against measured lysimeter $\text{ET}_0$ under the humid conditions in the southeast of the United States. Amatya et al. (1995) evaluated the reliability of the Hargreaves and Samani, Makkink, Priestly–Taylor, Turc, and Thornwaite $\text{ET}_0$ estimation methods by comparing the estimates with results from the Penman–Monteith method for conditions in eastern North Carolina, and found that Turc’s method gave the best daily $\text{ET}_0$ estimates. Irmak et al. (2003) evaluated 21 $\text{ET}_0$ estimation methods based on their daily performance under the humid climatic conditions in Florida, and found the 1948 Penman method to be the closest to the FAO–56 Penman–Monteith method, and among the temperature-based equations, Turc’s equation was ranked the best. In earlier studies by Jensen et al. (1990), the ranking of these empirical methods varied depending on local calibration and conditions.

In this study, pair–wise comparisons were made between daily $\text{ET}_0$ estimated from eight different $\text{ET}_0$ equations and $\text{ET}_0$ measured by lysimeter to provide information helpful in selecting appropriate $\text{ET}_0$ equation for climates similar to the Cumberland Plateau located in the humid southeast of the United States.

**MATERIALS AND METHODS**

**STUDY AREA AND DATA MEASUREMENTS**

The Cumberland Plateau is the southern portion of the Appalachian plateau, and extends in a southwesterly direction from the eastern portion of Kentucky and parts of Virginia, running through middle Tennessee to the northern part of Alabama (fig. 1). The elevation ranges from 200 to 1200 m above mean sea level (MSL). The weather of the Cumberland Plateau is influenced by cold dry continental air masses from Canada, and warm moist air from the Gulf of Mexico. The average annual precipitation is 1175 mm with 525 mm falling during the growing season (May to October). The average annual temperature is 13°C and the area has an average freeze-free period of 175 days (Soil Survey Staff, 1981).

The weather and lysimeter data used in this study were measured at the Plateau Experiment Station (University of Tennessee Agricultural Experiment Station) located on the Cumberland Plateau near Crossville, Tennessee. The site is at an elevation of 573.6 m above MSL and lies at a latitude of 35° 55' N and a longitude of 85° 07' W. An automatic weather station and one large weighing lysimeter are installed within a large, nearly level field of uniform grass cover, extending more than 100 m in all directions from the station. The grass cover was maintained at a height of less than 0.5 m, and supplied with sufficient water through precipitation and irrigation. The weather variables including air temperature (T), wind speed ($u_2$), relative humidity (RH), and solar irradiance (Rs) were measured by the weather station, and the $\text{ET}_0$ was measured by the lysimeter. The lysimeter was well watered and covered with a healthy growth of grass clipped to a height of 0.12 m. The lysimeter was calibrated before the start of each data gathering period (late April to early November) and when the grass cover was fully established. The records of lysimeter condition and maintenance were used to select days with good measured $\text{ET}_0$. Both weather and measured $\text{ET}_0$ data were recorded every 15 min and subsequently integrated to daily values for use in the study. The quality and integrity of the weather data were assessed using the guidelines given by Allen (1996) and Walter et al. (2001), and were found to be of good quality. The

![Figure 1. Location of the Cumberland Plateau covering parts of Alabama, Kentucky, Virginia, and Tennessee.](image-url)
Table 1. Monthly averages of the main climatic variables for the Plateau Experiment Station, Crossville, Tenn. (1996–2001).

<table>
<thead>
<tr>
<th>Month</th>
<th>Radiation (MJ m$^{-2}$ d$^{-1}$)</th>
<th>Air Temp. (°C)</th>
<th>Dew–Point Temp. (°C)$[a]$</th>
<th>Relative Humidity (%)</th>
<th>Wind Speed (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>21.6</td>
<td>18.2</td>
<td>13.8</td>
<td>76.8</td>
<td>1.2</td>
</tr>
<tr>
<td>June</td>
<td>21.8</td>
<td>21.1</td>
<td>17.3</td>
<td>80.4</td>
<td>1.1</td>
</tr>
<tr>
<td>July</td>
<td>20.8</td>
<td>22.9</td>
<td>19.6</td>
<td>83.5</td>
<td>1.0</td>
</tr>
<tr>
<td>August</td>
<td>19.8</td>
<td>22.1</td>
<td>18.7</td>
<td>82.4</td>
<td>0.9</td>
</tr>
<tr>
<td>September</td>
<td>17.6</td>
<td>19.4</td>
<td>15.3</td>
<td>78.2</td>
<td>1.0</td>
</tr>
<tr>
<td>October</td>
<td>14.4</td>
<td>13.9</td>
<td>9.1</td>
<td>76.4</td>
<td>1.1</td>
</tr>
</tbody>
</table>

$[a]$ Dew–point temperature is calculated.

monthly averages of the main weather variables for the period of the study (1996–2001) are given in table 1, and a description of the characteristics of the lysimeter is given in table 2.

**EVALUATION OF ET$\text{o}$ ESTIMATION METHODS**

Eight ET$\text{o}$ estimation methods comprising combination, radiation–based, and temperature–based equations were selected for comparison using weather data collected at the Plateau Experiment Station. The estimated ET$\text{o}$ values for each method were calculated using a reference crop evapotranspiration calculator (REF–ET) developed by Allen (2000). The REF–ET program supports ET$\text{o}$ computation guidelines and procedures for all the selected methods as given in Jensen et al. (1990), Wright (1982, 1996), Allen et al. (1998), and the ASCE report on standardization of reference evapotranspiration calculations (Walter et al., 2001). The specific methods used to predict net radiation, soil heat flux, and bulk resistances, and other coefficients needed in each equation are described in the REF–ET manual (Allen, 2000). The ET$\text{o}$ estimation methods selected for comparison and the representative equations as defined in REF–ET are given in table 3. The terms in these equations are defined as:

- ET$\text{o}$ = the reference crop evapotranspiration (mm d$^{-1}$)
- R$_n$ = the net radiation (MJ m$^{-2}$ d$^{-1}$)
- R$_a$ = extraterrestrial radiation (MJ m$^{-2}$ d$^{-1}$)
- $a_T = 1.0 + (50 – RH \text{mean})/70$ when RHmean < 50%
- $a_T = 1.0$ for RH mean = 50%
- $\Delta a_T = 1$ for RHmean = 75%
- $\Delta a_T = 0$ for RHmean ≥ 90%
- $u_2$ = mean daily wind speed at 2–m height (m s$^{-1}$)
- $T_{\text{max}} = $ daily maximum air temperature (°C)
- $T_{\text{min}} = $ daily minimum air temperature (°C)
- $T_{\text{mean}} = $ mean daily air temperature, computed as $(T_{\text{max}} + T_{\text{min}})/2$, °C
- $a_T = 1.0$ for RHmean = 75%
- $a_T = 0$ for RHmean ≥ 90%
- $G = $ soil heat flux (MJ m$^{-2}$ d$^{-1}$)
- $R_s = $ solar radiation (MJ m$^{-2}$ d$^{-1}$)
- $e_s = $ daily mean saturation vapor pressure (kPa)
- $e_a = $ actual vapor pressure (kPa)
- $\Delta = $ the slope of the vapor pressure curve (kPa °C$^{-1}$)
- $\gamma = $ the psychrometric constant (kPa °C$^{-1}$)
- $\lambda = $ the latent heat of vaporization (MJ kg$^{-1}$)
- $K_w = $ a units constant
- $a_w, b_w = $ wind functions
- $\alpha = $ wind functions
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- $\alpha = $ wind functions

**Table 2. Characteristics of the lysimeter used in the study.**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of lysimeter</td>
<td>Weighing</td>
</tr>
<tr>
<td>Type of scale system</td>
<td>Counterbalance lever load cell</td>
</tr>
<tr>
<td>Soil profile</td>
<td>Undisturbed</td>
</tr>
<tr>
<td>Wall material</td>
<td>Steel</td>
</tr>
<tr>
<td>Surface area</td>
<td>4.0 (m$^2$)</td>
</tr>
<tr>
<td>Soil depth</td>
<td>1.8 (m)</td>
</tr>
<tr>
<td>Drainage type</td>
<td>Free drainage</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.05 (mm ET$\text{o}$)</td>
</tr>
<tr>
<td>Type of grass</td>
<td>Kentucky blue grass/fescue mix</td>
</tr>
</tbody>
</table>

**Table 3. Methods selected for comparison and the representative equations.**

<table>
<thead>
<tr>
<th>Method</th>
<th>Representative Equation$[a]$</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1948 Penman</td>
<td>$ET_o = \frac{\Delta (R_n - G) + K_w \gamma (u_2 + a_w u_2) (e_s - e_a)}{\lambda}$.</td>
<td>eq. 1</td>
</tr>
<tr>
<td>FAO–24 Penman</td>
<td>Same form as eq. 1, but with some variations in the calculation of $R_n, a_w$, and $b_w$. Also includes a correction factor.</td>
<td></td>
</tr>
<tr>
<td>1996 Kimberly Penman</td>
<td>Same form as eq. 1, but with some variations in the calculation of the coefficients $a_w$ and $b_w$.</td>
<td></td>
</tr>
<tr>
<td>FAO–56 Penman–Monteith</td>
<td>$ET_o = \frac{0.408\Delta (R_n - G) + \gamma \frac{900}{T_{\text{mean}} + 273} (e_s - e_a)}{\lambda + \gamma (0.34e_s)}$.</td>
<td>eq. 2</td>
</tr>
<tr>
<td>1985 Hargreaves–Samani</td>
<td>$ET_o = \frac{0.0023 (T_{\text{max}} - T_{\text{min}})^{1.5} (e_s + 17.8) R_n}{\lambda}$.</td>
<td>eq. 3</td>
</tr>
<tr>
<td>1957 Makik</td>
<td>$ET_o = 0.61 \frac{\Delta}{\Delta + \gamma} 2.45 - 0.12$.</td>
<td>eq. 4</td>
</tr>
<tr>
<td>1961 Turc</td>
<td>$ET_o = a_T 0.013 \frac{T_{\text{mean}}}{T_{\text{mean}} + 15} \frac{23.8586 R_n + 50}{\lambda}$.</td>
<td>eq. 5</td>
</tr>
<tr>
<td>1972 Priestly–Taylor</td>
<td>$ET_o = 1.26 \frac{\Delta}{\Delta + \gamma} 2.45 - 0.12$.</td>
<td>eq. 6</td>
</tr>
</tbody>
</table>

$[a]$ All terms in the equations are defined in the text.
where $MET_o$ is the measured $ET_o$ value, $EET_o$ is the estimated $ET_o$ value, and $\bar{MET}_o$ is the mean of the measured values. The statistic $E$ examines whether the difference between the estimated and measured data is as large as the variability in the measured data. The possible values of $E$ range from $-\infty$ to 1, with higher values indicating better agreement between the estimated and measured data. For interpretation, if $E = 0$, the observed mean is as good an estimator as the equation. If $E > 0$, the larger the positive number, the better the equation fit. The coefficient of efficiency represents an improvement over $r^2$ in that it is sensitive to differences in the measured and estimated means and variances, and will always be lower than that value (Legates and McCabe, 1999).

**RESULTS AND DISCUSSION**

The results of the statistical analysis of equation estimated versus lysimeter measured evapotranspiration values are given in table 4. Figure 2 shows the plots of estimated $ET_o$ versus measured $ET_o$ for all methods that were analyzed. The coefficient of determination ($r^2$) has been widely used to evaluate the “goodness-of-fit” of evapotranspiration equations. However, the $r^2$ is oversensitive to extreme values (outliers) and is insensitive to additive and proportional differences between estimated and measured values (Legates and McCabe, 1999). Because of these limitations, $r^2$ values when used alone can indicate that an equation is the best estimator of $ET_o$ when it is not. For example, comparison of the equations based on the $r^2$ values alone gives a false impression that the FAO–24 Penman equation ($r^2 = 0.91$) is among the best equations for estimating $ET_o$ in this climate. Assessment of the daily average $ET_o$ values, and slope and intercept of the trend line, shows that the FAO–24 Penman, Hargreaves–Samani, and Priestly–Taylor equations overestimate $ET_o$ while the Makkink method underestimates $ET_o$. The standard error of the estimate ($S_{yx}$) represents a rough estimate of the average amount by which each $ET_o$ estimation method will either overestimate or underestimate the true $ET_o$ given by lysimeter measurements. The results show that the lowest $S_{yx}$ of the estimated daily $ET_o$ was obtained with the FAO–56 Penman–Monteith equation followed by the original Penman and Makkink equations (0.31, 0.34, and 0.34 mm d$^{-1}$). The Hargreaves–Samani method had the highest $S_{yx}$, followed by the Priestly–Taylor method, and the FAO–24 Penman method (0.68, 0.46, and 0.41 mm d$^{-1}$).

The Hargreaves (2003) reported that at humid irrigated sites, the 1985 Hargreaves–Samani method produces values for periods of five or more days that compare favorably with those of the FAO–56 Penman–Monteith equation. Based on Hargreaves (2003) findings, we further evaluated the Hargreaves–Samani equation for the conditions at our study site by direct comparison with $ET_o$ values estimated by the FAO–56 Penman–Monteith for daily and weekly time periods. The climatic data used were for the period May to October for the years 1998, 2000, and 2001. The results presented in figure 3 show that the Hargreaves–Samani equation overestimated $ET_o$ compared to the FAO–56 Penman–Monteith equation for both 1–day and weekly time periods; the $r^2$ value was better for the weekly time periods. Consideration of all the results from the analysis indicated that the relationship between the estimated and measured $ET_o$ was best using the FAO–56 Penman–Monteith equation ($r^2 = 0.91$, $S_{yx} = 0.31$ mm d$^{-1}$, and $E = 0.87$), followed by the original Penman equation ($r^2 = 0.91$, $S_{yx} = 0.34$ mm d$^{-1}$, and $E = 0.88$) and Turc’s equation ($r^2 = 0.90$, $S_{yx} = 0.36$ mm d$^{-1}$, and $E = 0.88$). The results for the Hargreaves–Samani equation showed low correlation with measured lysimeter $ET_o$ data ($r^2 = 0.51$, $S_{yx} = 0.68$ mm d$^{-1}$, and $E = 0.2$), while those of the Kimberly Penman were reasonable ($r^2 = 0.87$, $S_{yx} = 0.40$ mm d$^{-1}$, and $E = 0.87$). These results are in agreement with other studies conducted at sites in the humid southeast of the United States (Amatya et al., 1995; Irmak et al., 2003) and support the adoption of the FAO–56 Penman–Monteith equation for climatological conditions similar to those on the Cumberland Plateau. However, the little–known Turc equation may be an attractive alternative to the more complex Penman–Monteith method since only mean air temperature and solar irradiance data are required.

**SUMMARY AND CONCLUSION**

Pair–wise comparisons were made between daily $ET_o$ estimated with eight different $ET_o$ equations, and $ET_o$

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Table 4. Statistical analysis of estimated evapotranspiration using different methods vs. measured lysimeter evapotranspiration.

<table>
<thead>
<tr>
<th>Method</th>
<th>No. of Data</th>
<th>Average $ET_o$ (mm d$^{-1}$)</th>
<th>$r^2$</th>
<th>$E^{[a]}$</th>
<th>Slope</th>
<th>Intercept</th>
<th>$S_{yx}^{[b]}$ (mm d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lysimeter</td>
<td>296</td>
<td>3.6</td>
<td>0.91</td>
<td>0.88</td>
<td>0.84</td>
<td>0.81</td>
<td>0.34</td>
</tr>
<tr>
<td>1948 Penman</td>
<td>296</td>
<td>3.8</td>
<td>0.91</td>
<td>0.87</td>
<td>0.87</td>
<td>0.72</td>
<td>0.40</td>
</tr>
<tr>
<td>FAO–24 Penman</td>
<td>296</td>
<td>4.1</td>
<td>0.91</td>
<td>0.76</td>
<td>1.04</td>
<td>0.33</td>
<td>0.41</td>
</tr>
<tr>
<td>1996 Kimberly Penman</td>
<td>296</td>
<td>3.6</td>
<td>0.87</td>
<td>0.87</td>
<td>0.81</td>
<td>0.72</td>
<td>0.40</td>
</tr>
<tr>
<td>FAO–56 Penman–Monteith</td>
<td>296</td>
<td>3.4</td>
<td>0.91</td>
<td>0.87</td>
<td>0.76</td>
<td>0.71</td>
<td>0.31</td>
</tr>
<tr>
<td>1985 Hargreaves–Samani</td>
<td>296</td>
<td>4.3</td>
<td>0.51</td>
<td>0.20</td>
<td>0.54</td>
<td>2.38</td>
<td>0.68</td>
</tr>
<tr>
<td>1957 Makkink</td>
<td>296</td>
<td>3.1</td>
<td>0.90</td>
<td>0.74</td>
<td>0.77</td>
<td>0.36</td>
<td>0.34</td>
</tr>
<tr>
<td>1961 Turc</td>
<td>296</td>
<td>3.7</td>
<td>0.90</td>
<td>0.88</td>
<td>0.81</td>
<td>0.75</td>
<td>0.36</td>
</tr>
<tr>
<td>1972 Priestly–Taylor</td>
<td>296</td>
<td>4.0</td>
<td>0.86</td>
<td>0.78</td>
<td>0.90</td>
<td>0.74</td>
<td>0.46</td>
</tr>
</tbody>
</table>

$^{[a]}$ $E$ is coefficient of efficiency.

$^{[b]}$ $S_{yx}$ is the standard error of the estimate.
Figure 2. Comparison of daily evapotranspiration computed by eight ET₀ estimation methods vs. measured lysimeter evapotranspiration.

measured by a weighing lysimeter for conditions on the Cumberland Plateau in the humid southeast of the United States. The results indicate that the FAO–56 Penman–Monteith equation is the best method for this humid climate, followed by the original Penman equation and Turc’s equation. The FAO–24 Penman, Hargreaves–Samani, and Priestly–Taylor equations overestimated ET₀, while the Makkink method underestimated the ET₀. The results for the Hargreaves–Samani equation showed low correlation with measured lysimeter ET₀ as expected, because it was developed for arid and semi-arid climates, and for ET₀ computations for longer time periods. Hence, the Hargreaves–Samani equation is not suitable for estimating daily evapotranspiration in humid climates similar to that in this study. The Turc equation may be an attractive alternative to the more complicated Penman–Monteith method because
it requires fewer input parameters, i.e., mean air temperature and solar irradiance data only.

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The authors are grateful to the Tennessee Agricultural Experiment Station and the Plateau Experiment Station, Crossville, Tennessee, for financial and personnel support.

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