# Comparison of methods for estimating REF-ET - Closure

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D.M. Amatya
US Forest Service



R.W. Skaggs
North Carolina State University

# COMPARISON OF METHODS FOR ESTIMATING REF-ET

By D. M. Amatya,[1] Associate Member, ASCE, R. W. Skaggs,[2] and J. D. Gregory[3]

**ABSTRACT:** The Penman-Monteith, Makkink, Priestley-Taylor, Turc, Hargreaves-Samani, and Thornthwaite methods were used to estimate reference evapotranspiration (REF-ET) at three sites in eastern North Carolina. The Penman-Monteith method with grass as the reference crop was selected as the standard of comparison for evaluating the other five methods. Good correlation was found between the REF-ET values estimated by each of the five radiation- and temperature-based methods and the Penman-Monteith method, although there were some differences. Based on the statistical analyses, the methods that performed the best in estimating daily and seasonal Penman-Monteith REF-ET at each location were recommended. Reliability of the radiation methods was also evaluated when data from another site were used. Penman-Monteith estimates were used to develop correction factors for their potential use in the temperature-based Thornthwaite and Hargreaves methods at each location and in the study areas in general.

## INTRODUCTION

Most of the current hydrologic, water-management, and crop-growth models require an accurate estimate of potential evapotranspiration (PET) for reliable application (Parmele 1972; Skaggs 1980; Purisinsit 1982; McCarthy 1990; Choisnel et al. 1992). A large number of methods for calculation of PET from weather data have been developed and tested for varying geographic and climatologic conditions. These methods vary from simple empirical relationships to complex methods based on physical processes such as the Penman (1948) combination method. A review of the literature clearly indicates that the Penman method is superior when the required data are available and reliable to all other commonly used methods such as Jensen-Haise, Turc, Makkink, Priestley-Taylor, FAO Blaney-Criddle, Hargreaves-Samani, Thornthwaite, and FAO Pan evaporation for estimating PET from well-watered green grass or alfalfa among varying locations and climatic conditions. Monteith (1965) further modified the Penman method by incorporating a stomatal resistance ($r_s$) term specific to the type of crop in addition to the existing aerodynamic resistance term. This formulation is the Penman-Monteith (PM) reference evapotranspiration (REF-ET) model that estimates the PET with reference to the characteristics and surroundings of the crop. Choisnel et al. (1992) found that the $r_s$ value of an irrigated turf in the PM method decreased with the latitude indicating that it is dependent on air-saturation deficit, which increases from the north to the south of Europe. The terms REF-ET is used instead of PET for the potential evapotranspiration of a reference crop (Mohan 1991; Jensen et al. 1990) in the rest of this paper.

Reliability of the PM method for estimating REF-ET has been extensively studied (Souza and Yoder 1994; Jensen et al. 1990; Food 1990; McNaughton and Jarvis 1984). Jensen et al. (1990) ranked the PM method at the top for estimating daily and monthly reference ET in their lysimetric evaluation of 19 different methods applied in 11 different climatologic conditions. Unanimous agreement was reached in the consultation group (Food 1990) to recommend the Penman-Monteith approach as the best performing combination equation in the absence of measured data.

Although numerous studies have shown that the Penman-Monteith equation is the most reliable method when necessary weather and vegetation data are known, these inputs are difficult and expensive to obtain for many applications. In such circumstances, methods based on either radiation or on maximum and minimum temperature as suggested by Hargreaves and Samani (1985) or the Thornthwaite (1948) method are often used to estimate REF-ET. However, the former method generally overestimates the REF-ET (Jensen et al. 1990) and the latter underestimates it (Mohammad 1978; Jensen et al. 1990) for the humid locations. Because temperature data are available for most of the stations, the Thornthwaite method with correction factors is still widely used for estimating REF-ET (Smajstrla et al. 1984; Broadhead and Skaggs 1989). However, there are only a limited number of studies that have tested the reliability of these different methods for climatic conditions in the coastal plains of the southeast. Mohammad (1978) conducted a study to evaluate the reliability of Thornthwaite and the pan evaporation REF-ET estimates against the Penman method for various parts of eastern North Carolina. Less than a year of data were used to evaluate the Penman method. Smajstrla et al. (1984) conducted a similar study for humid conditions in Florida. Sadler and Camp (1986) presented a review of crop water-use data for the southeastern United States based on location, method of measurement, crop, time, duration of study, form of data, and main treatments. The authors reported that a conclusive study is lacking in the physiographic area, and insufficient data exist for a conclusive test of transferability of western irrigation management into the more humid southeast.

The main purpose of the research reported in this paper was to evaluate the reliability of five approximate REF-ET prediction methods as compared to the PM method for the grass reference using data collected in eastern North Carolina in latitudes that vary within only about 2.5° (Fig. 1). The PM method was chosen as a standard for comparison in this study because there were no measured ET data at any location. The daily, mean monthly, and annual total REF-ET values estimated by the five methods for three different locations were compared with estimates by the standard PM method. The objective for such comparisons is to examine the relationships and to determine the method that best predicted REF-ET as compared to the PM method for each of these locations. The second objective was to evaluate the reliability of the methods when data from nearby stations are used for estimating REF-ET. Third, monthly correction factors for adjusting the Hargreaves and Thornthwaite methods were developed for their potential use at the study sites.

[1]Res. Assoc., Biol. and Agric. Engrg. Dept., P.O. Box 7625, North Carolina State Univ., Raleigh, NC 27695-7625.

[2]William Neal Reynolds and Distinguished Univ. Prof., Biol. and Agric. Engrg. Dept., P.O. Box 7625, North Carolina State Univ., Raleigh, NC.

[3]Assoc. Prof., Dept. of Forestry, P.O. Box 8002, North Carolina State Univ., Raleigh, NC.

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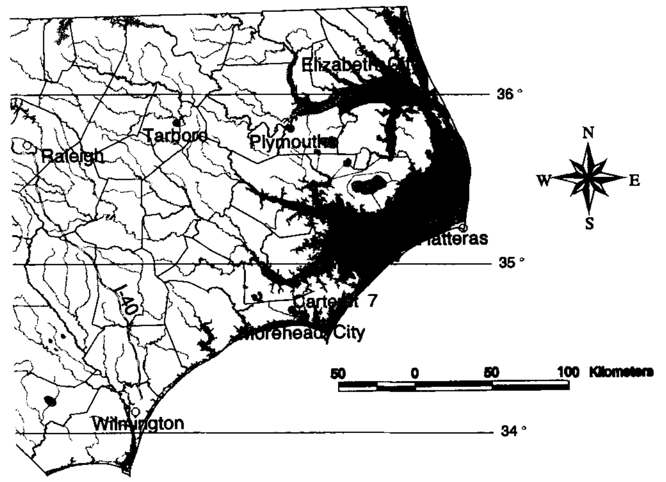


**FIG. 1. Location Map of Weather Stations in Eastern North Carolina**

**TABLE 1. Three Weather Stations in Eastern North Carolina**

| Station (1) | Carteret 7 (2) | Plymouth (3) | Tarboro (4) |
|---|---|---|---|
| County | Carteret | Washington | Edgecomb |
| Latitude (N) | 34°48′ | 35°52′ | 35°53′ |
| Longitude (W) | 76°42′ | 76°39′ | 77°32′ |
| Altitude, above mean sea level (m) | 3.0 | 6.4 | 10.7 |
| Distance from the ocean (km) | 15 | 95 | 145 |
| Wind height (m) | 12.8 | 3.65 | 2.0 |
| Humidity height (m) | 1.7 | 1.8 | 1.5 |
| Distance from Carteret 7 (km) | 0 | 115 | 145 |
| Distance from Tarboro (km) | 145 | 80 | — |
| Distance from Plymouth (km) | 115 | — | 80 |

## CLIMATIC CHARACTERISTICS

The three weather stations selected for this study are located in eastern North Carolina. These locations are the Carteret 7 site, Plymouth, and Tarboro, as shown in Fig. 1. Data in Table 1 describes the general characteristics of the weather stations. Although all these stations lie within the coastal plains of eastern North Carolina, climatological parameters are very similar. The long-term (1950–80) mean annual rainfall varied from 1,339 mm for the Morehead City, closest to the Carteret 7 site in the south, to 1,299 mm for the Plymouth site (adjacent to the Plymouth research site), and to 1,219 mm for the Tarboro site (closest to the Tarboro research site) in the northwest (Table 2). Nearly 50% of the annual rainfall occurs during the months May–September.

Differences in the long-term mean annual temperature are not very significant. The normal annual maximum and minimum temperatures for these three locations vary between 22.8°C to 22.3°C and 9.2°C and 12.5°C, respectively. Generally, the maximum temperatures occur during the months of June, July, and August when the region experiences large amounts of rainfall due to the intense storms and hurricanes characteristic to the humid coastal plains. The long-term annual lake evaporation normalized for the region was estimated to be 1,040 mm (Amatya et al. 1992). Thus the sites are generally wet, based on the long-term hydrometeorologic data. Relative humidity decreases somewhat with distance from the ocean.

The mean monthly weather variables for each of the three weather stations are presented in Table 3. Because the weather data come from different observation periods, direct comparison among the sites could not be made.

There are only a few other stations that continuously monitor all weather variables for estimating Penman-Monteith REF-ET in eastern North Carolina. Wilmington and Cape Hatteras are the only two class A weather stations maintained by the U.S. Weather Service Bureau where mean daily parameters on air temperature, wind speed, percentage of sunshine, and rainfall are continuously being measured. However, direct measurements of radiation data are not available for these stations. Most of the other stations, such as Plymouth, Tarboro, Morehead City, and Lumberton, simply measure rainfall and temperature (Epperson et al. 1987).

**TABLE 2. Long-Term (1950–80) Mean Monthly Temperature and Rainfall**

| | Morehead City | | Plymouth | | Tarboro | |
|---|---|---|---|---|---|---|
| Month (1) | Temperature (°C) (2) | Rain (mm) (3) | Temperature (°C) (4) | Rain (mm) (5) | Temperature (°C) (6) | Rain (mm) (7) |
| 1 | 7.5 | 105 | 5.6 | 106 | 5.1 | 102 |
| 2 | 8.1 | 101 | 6.6 | 101 | 6 | 98 |
| 3 | 11.6 | 94 | 10.5 | 106 | 10.4 | 108 |
| 4 | 16.3 | 74 | 15.7 | 80 | 16.1 | 77 |
| 5 | 20.8 | 108 | 19.8 | 118 | 20.4 | 95 |
| 6 | 24.4 | 116 | 23.5 | 115 | 24.1 | 112 |
| 7 | 26.4 | 167 | 25.6 | 160 | 26.2 | 125 |
| 8 | 26.4 | 157 | 25.2 | 148 | 25.8 | 147 |
| 9 | 24.1 | 134 | 22.2 | 117 | 22.6 | 115 |
| 10 | 18.8 | 96 | 16.4 | 85 | 16.3 | 80 |
| 11 | 13.6 | 86 | 11.3 | 79 | 10.9 | 76 |
| 12 | 9.1 | 101 | 7 | 84 | 6.3 | 84 |
| Average temperature | 17.3 | — | 15.8 | — | 15.9 | — |
| Total rain | — | 1,339 | — | 1,299 | — | 1,219 |

## METHODOLOGY

Six different methods (one combination: Penman-Monteith; three radiation-based: Makkink, Priestley-Taylor, and Turc; and two temperature-based: Hargreaves-Samani and Thornthwaite) were used to estimate REF-ET at three locations in eastern North Carolina. The general characteristics and main parameters needed for each of the methods used in this study are summarized in Table 4. The Penman-Monteith equation with grass reference [chosen as the standard for comparison of the other five methods, as given by Jensen et al. (1990)] follows:

$$\lambda E = [\Delta/(\Delta + \gamma 1)\cdot(R_n - G)] + (\gamma/(\Delta + \gamma 1)) \cdot K1\cdot(0.622\rho\lambda/P)\cdot(1/r_a)\cdot(e_z^o - e_z) \quad (1)$$

All the parameters of the first radiant energy term and the second aerodynamic term of the right-hand side are as explained in Jensen et al. (1990); it is beyond the scope of this study to describe them. The height of the reference crop chosen was 12 cm with a fixed canopy resistance of 70 sec m$^{-1}$, and albedo of 0.23 to resemble ET from an extensive surface of actively growing green grass of uniform height, completely shading the ground and not short of water (Food 1990).

The other five methods were chosen to represent REF-ET for a grass reference. These are also the methods that had been tested and applied for REF-ET estimates in the humid region (Mohammad 1978; Shih et al. 1981; Skaggs 1982; Sadler and Camp 1986; Jensen et al. 1990) when weather data on radiation, humidity, and wind speed are available. The reader is referred to Jensen et al. (1990) for detailed description of all these methods except Makkink, which is described by Jensen (1974). The Priestley-Taylor (PT) and the Har-

TABLE 3. Mean Monthly Weather Parameters for Three Weather Stations

| Month (1) | Temperature (°C) (2) | Relative humidity (%) (3) | Wind speed (m/s) (4) | Vapor-pressure deficit (kPa) (5) | Net radiation (MJ/m²/day) (6) | Solar radiation (MJ/m²/day) (7) |
|---|---|---|---|---|---|---|
| (a) Averaged over Five Years (1988–92) for Carteret 7 | | | | | | |
| 1 | 7.41 | 77.41 | 1.40 | 0.26 | 2.46 | 9.76 |
| 2 | 9.08 | 77.65 | 1.69 | 0.31 | 4.70 | 12.61 |
| 3 | 11.88 | 78.07 | 1.83 | 0.36 | 7.69 | 16.24 |
| 4 | 15.25 | 78.34 | 1.98 | 0.46 | 10.73 | 19.95 |
| 5 | 19.59 | 83.69 | 1.57 | 0.45 | 12.05 | 21.58 |
| 6 | 23.26 | 82.86 | 1.31 | 0.63 | 12.39 | 21.51 |
| 7 | 25.97 | 84.79 | 1.15 | 0.83 | 13.45 | 22.45 |
| 8 | 24.89 | 86.20 | 1.17 | 0.88 | 9.80 | 18.76 |
| 9 | 22.35 | 81.47 | 1.61 | 0.55 | 8.44 | 17.07 |
| 10 | 16.65 | 77.18 | 1.21 | 0.50 | 6.26 | 14.41 |
| 11 | 12.51 | 78.53 | 1.30 | 0.36 | 3.67 | 11.20 |
| 12 | 7.66 | 79.78 | 1.42 | 0.22 | 2.45 | 9.58 |
| (b) Averaged over Five Years (1990–94) for Plymouth[a] | | | | | | |
| 1 | 6.28 | 71.63 | 2.37 | 0.30 | 1.51 | 8.03 (6.26)[b] |
| 2 | 7.59 | 66.72 | 2.53 | 0.37 | 3.38 | 10.38 (8.96)[b] |
| 3 | 10.56 | 66.14 | 2.72 | 0.48 | 6.03 | 13.69 (11.77)[b] |
| 4 | 15.41 | 63.34 | 2.54 | 0.72 | 10.16 | 18.82 (16.77)[b] |
| 5 | 19.28 | 66.97 | 1.88 | 0.81 | 9.61 | 18.16 (16.62)[b] |
| 6 | 23.20 | 71.88 | 1.72 | 0.82 | 13.18 | 22.61 (18.88)[b] |
| 7 | 26.10 | 75.46 | 1.68 | 0.87 | 12.77 | 22.10 (17.77)[b] |
| 8 | 23.63 | 77.33 | 1.48 | 0.70 | 8.53 | 16.79 (14.09)[b] |
| 9 | 21.29 | 74.82 | 1.88 | 0.69 | 8.29 | 16.48 (13.98)[b] |
| 10 | 16.68 | 71.82 | 2.05 | 0.58 | 5.01 | 12.41 (10.52)[b] |
| 11 | 11.76 | 69.33 | 2.44 | 0.43 | 1.13 | 7.49 (6.48)[b] |
| 12 | 8.56 | 72.92 | 2.65 | 0.32 | −0.77 | 5.17 (4.73)[b] |
| (c) Averaged over Five Years (1982–86) for Tarboro | | | | | | |
| 1 | 3.17 | 59.01 | 2.61 | 0.31 | 1.98 | 8.60 |
| 2 | 6.38 | 61.96 | 2.76 | 0.40 | 3.43 | 10.41 |
| 3 | 10.91 | 57.67 | 3.16 | 0.56 | 7.27 | 15.21 |
| 4 | 14.80 | 52.42 | 2.70 | 0.82 | 10.49 | 19.24 |
| 5 | 20.11 | 53.27 | 1.98 | 1.11 | 13.76 | 23.32 |
| 6 | 23.88 | 58.77 | 2.12 | 1.26 | 13.07 | 22.47 |
| 7 | 25.34 | 66.75 | 1.88 | 1.12 | 11.83 | 20.91 |
| 8 | 24.53 | 60.12 | 1.64 | 1.20 | 11.16 | 20.08 |
| 9 | 21.61 | 62.18 | 1.83 | 1.07 | 7.40 | 15.37 |
| 10 | 16.89 | 62.63 | 1.97 | 0.76 | 3.16 | 10.07 |
| 11 | 11.63 | 56.90 | 2.32 | 0.63 | 2.71 | 9.51 |
| 12 | 7.57 | 56.63 | 2.39 | 0.45 | 1.04 | 7.43 |

[a]The solar radiation data for Plymouth from June 1991 to August 1994 was adjusted due to instrumental error as described in the text.
[b]Unadjusted mean monthly solar radiation for the given period.

TABLE 4. Characteristics of Methods of Estimating REF-ET

| Method of estimate (1) | Main parameters required (2) | Recommended time period (3) | Reference crop (4) | Location developed for (5) |
|---|---|---|---|---|
| Penman-Monteith[a] | $T$, RH, $W$, $R_n$, $r_c$ | Hourly, daily, weekly, monthly | Any crop | All locations |
| Makkink[b] | $T$, $R_s$ | 10 days, monthly | Grass | Cool climate, the Netherlands |
| Priestley-Taylor[a] | $T$, $R_n$ | 10 days, monthly | Rain-fed land | Australia, U.S. |
| Turc[a] | $T$, RH, $R_s$ | 10 days, monthly | Grass | Cool climate, Europe |
| Hargreaves-Samani[a] | $T_{max}$, $T_{min}$, $T$, $R_A$ | Weekly, monthly | Cool-season grass | Semiarid Western U.S. |
| Thornthwaite[a] | $T_{max}$, $T_{min}$, or $T$ | Monthly | Grass | Humid eastern U.S. |

[a]Principal reference: Jensen et al. (1990).
[b]Principal reference: Jensen (1974).

greaves-Samani (Hargreaves) methods, although developed to estimate total REF-ET for a 10-day period, have been widely used for daily periods (Jensen et al. 1990; Parmele and McGuinness 1974; Hargreaves and Samani 1985). Stanhill (1961) used the Makkink method for estimating daily REF-ET. All of these five methods were tested for their performance in predicting Penman-Monteith REF-ET.

Weather data from three eastern North Carolina research sites were used for analyzing the REF-ET methods (Fig. 1). These sites are a Weyerhaeuser Company cooperative forest water-management study in eastern Carteret county in North Carolina (Carteret 7), Tidewater Research Station at Plymouth, N.C. (Plymouth), and the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) research site near Tarboro, N.C. (Tarboro) described by Amatya et al. (1992), Chescheir et al. (1994), and Parsons et al. (1991), respectively. Air temperature, relative humidity, wind speed, net radiation, and saturation vapor pressure deficit on an hourly basis (mean of 60 readings per hour) were measured by a Campbell CR-21 data logger at the Carteret station for a five-year (1988–92) period. Daily means of these variables except for net radiation, which was replaced by solar radiation, were calculated from twice hourly measurements by Campbell CR-21 data loggers at Tarboro for approximately a five-year (1982–86) period and at Plymouth from January 1990 to May 1991. The CR-21 data logger at Plymouth was then replaced by a Campbell CR-10 data logger in June 1991. A new LICOR solar-radiation sensor was installed in the CR-10 unit in September 1994.

Because net radiation is used in combination methods and solar radiation is used in other energy-balance methods, conversion was performed by using the following regression equation suggested by Jensen et al. (1990):

$$R_n = a_3 R_s + b_3 \tag{2}$$

where $R_n$ = daily net radiation (MJ/m²/day); and $R_s$ = daily solar radiation (MJ/m²/day). The regression parameters $a_3$ = 0.80 and $b_3$ = −4.9 were for Bermuda grass and North Carolina conditions (Jensen et al. 1990).

Radiation, the most significant parameter for all combination and radiation-based REF-ET methods, was examined for its uniformity in the study region. Daily solar radiation ($R_s$) measured at the Tarboro and Plymouth sites, and the $R_s$ computed by (2) at the Carteret site were compared with the daily extraterrestrial radiation ($R_A$) and the maximum clear sky radiation ($R_{max}$) computed by the methods suggested by Jensen et al. (1990) for each of the sites. The average daily $R_s$ for the year ranged between 47% and 53% of the $R_A$ at Tarboro and 50% and 57% of the $R_A$ at the Carteret site. Similarly, $R_{max}$ ranged between 70% and 75% at the Tarboro site and 70% and 85% at the Carteret site. Somewhat higher values of $R_s$ and $R_{max}$ at the Carteret site were due to its more southern location and probably also due to use of the empirical relationships. Similarly, the average daily $R_s$ of about 50% and the $R_{max}$ of about 70–75% of $R_A$ at Plymouth for the period before the installation of the CR-10 data logger in June 1991 was consistent with data from Tarboro, the nearest station at about the same latitude (Table 1). However, the average $R_s$ and the $R_{max}$ for the period from June 1991 until the installation of a new radiation sensor in September 1994 ranged only between 35% and 38% and 50% and 55%

of the $R_A$, respectively. This resulted in values of $R_s$ [see parenthetic $R_s$ values in Table 3(*b*)] significantly lower than those from Tarboro and Carteret, as shown by the mean monthly $R_s$ (Table 3). The problem was attributed to the instrumental error in the old radiation sensor.

The $R_s$ data for June 1991 to August 1994 from Plymouth were then adjusted by using monthly correction factors obtained by using the average ratio of the daily 7 days' maximum value for 1990 and each of the other years for each month. The mean monthly $R_s$ with a 20% increase and the corresponding $R_n$ with a 34% increase obtained after this adjustment were then comparable to the Tarboro data (Table 3) and to the 1990–91 data at Plymouth. Similarly, the daily average adjusted $R_s$ in the range of 45 to 48% and the adjusted $R_{max}$ in the range of 70 to 80% were also comparable to data from the other two locations.

The hourly average weather data obtained at the Carteret weather station were first converted into daily means. Missing hourly data were replaced by data from the Cherry Point Marine Corps airfield which is 25 km northwest of the weather station. The method has been tested and verified by McCarthy (1990). For the Plymouth and Tarboro sites, long-term mean monthly temperatures were used to compute mean monthly REF-ET by the Thornthwaite method and these REF-ET values were used to replace the REF-ET for days with missing weather data for all methods. This was done just for computing the total annual REF-ET for all the methods. The daily values were summed and averaged to obtain total and mean daily REF-ET for each year for all three stations. Mean monthly weather data were computed from the daily means over the period of observation for the three stations (Table 3).

The soil heat storage or release can be significant over a few hours, but is usually small from day to day (Jensen et al. 1990). Therefore, this term was assumed to be negligible in both daily and monthly REF-ET computations. Vapor pressure deficit (VPDC) was computed using vapor pressure at mean air temperature ($e_z^o$) and mean relative humidity (RH) as follows (Jensen et al. 1990):

$$\mathrm{VPDC} = e_z^o(1 - \mathrm{RH}) \tag{3}$$

A simple Fortran computer program was developed to calculate reference evapotranspiration by the Penman-Monteith grass reference method, the three radiation methods, and the two temperature based methods on a daily basis using daily averaged weather data from all three stations.

The daily REF-ET (mm/day) was computed for each day using weather data for that day in the REF-ET equations. This was done using all six methods for the available period of weather data for each of the three stations. Similarly, mean monthly weather data for each year for all three sites were used to determine the mean monthly REF-ET (mm/day). The mean monthly REF-ET is a daily mean (mm/day) by month computed by using mean monthly (daily mean by month) weather data in the equations. Similarly, the mean monthly REF-ET computed by each of the five methods for the peak summer months was also compared with the standard PM method.

Regressions were performed to examine the relationships of the daily REF-ET estimates from the five methods with the daily estimates by the standard Penman-Monteith method for all three locations. Days with missing weather data were excluded in this analysis. The regression equations computed was of the form:

$$Y = mX + C \tag{4}$$

where $Y$ represents Penman-Monteith daily REF-ET; $X$ is the daily REF-ET estimated from each of the other five methods; and $m$ and $C$ are slope and intercept, respectively. Similarly, 48 observations (1988–91) for the Carteret site, 60 observations (1990–94) for the Plymouth site, and 56 observations (1982–86) for the Tarboro site were used for regressions of mean daily REF-ET for monthly periods to determine the correlation of each of the five methods with Penman-Monteith mean monthly REF-ET. Root mean square error (RMSE) was used as the main parameter for evaluating the reliability of methods in predicting PM REF-ET at each of these locations. The RMSE parameter was used to indicate the goodness-of-fit of REF-ET estimates as compared to the standard Penman-Monteith method without any adjustment. Coefficient of determination ($R^2$), the slope of the regression and the absolute average deviation between the calculated and predicted REF-ET were also computed. The best method is the one with the lowest absolute deviation, $C$ value closest to zero, $m$ value closest to 1.0, the smallest RMSE, and the highest $R^2$ (Parmele and McGuinness 1974). The regression models for predicting daily Penman-Monteith REF-ET by these five methods were then tested by comparing with estimated Penman-Monteith data for 1992 at the Carteret site.

Radiation data are not usually available for locations where ET predictions are needed. In such cases, data from nearby stations are often used to compute REF-ET. Data from the U.S. Weather Bureau class A station at Wilmington airport were applied to compute radiation for estimating the REF-ET at other location. Wilmington is the nearest (about 90 km south) class A station to the Carteret site. Since measured solar radiation was not available, published mean daily data (National 1993) for percent of sunshine hours and dew-point temperature for a two-year (1991–92) period from Wilmington were used to compute solar radiation ($R_s$) in MJ/m²/day using extraterrestrial radiation ($R_A$) in MJ/m²/day and percent sunshine ($n/N$) data (Jensen et al. 1990)

$$R_s = R_A(0.5n/N + 0.25) \tag{5}$$

Similarly, net radiation ($R_n$) in MJ/m²/day was calculated by the following empirical relationship (Jensen et al. 1990) involving solar radiation ($R_s$) calculated by (5), temperature ($T$) in °C, vapor pressure at dew point temperature ($e_d$) in kPa, and albedo ($\alpha$):

$$R_n = R_s(1 - \alpha) - [\{0.9(n/N) + 0.1\}(0.34 - 0.139\sqrt{e_d})]\sigma T^4 \tag{6}$$

where $n/N$ = percent sunshine; and $\sigma$ = Stefan-Boltzman constant. The net radiation calculated using this method was calibrated with observed net radiation at the Carteret site. Predictions by these methods using empirically calculated radiation data were compared to predictions by the Penman-Monteith method using actual data. This allowed an evaluation of the reliability of these methods when on-site radiation data were not available and data from the nearest station were used. Performance of all combination and radiation-based methods was also compared with the temperature-based Hargreaves and Thornthwaite methods.

Mean monthly correction factors for the Hargreaves and Thornthwaite methods were computed as the ratio of the monthly total PM REF-ET to the monthly total for each method averaged over the record period for each of the stations.

## RESULTS

The mean daily and the mean annual total REF-ET obtained by averaging the daily and annual values across the period of record for each of the three stations as well as the average for all stations are summarized in Table 5(*a*). All methods except the Thornthwaite overestimated the PM REF-

TABLE 5. Mean Daily, Annual, and Monthly Peak REF-ET Estimated by Different Methods for Three Stations in Eastern North Carolina

| Station (1) | Years of data (2) | Penman-Monteith (3) | Makkink (4) | Priestley-Taylor (5) | Turc (6) | Hargreaves-Samani (7) | Thornthwaite (8) |
|---|---|---|---|---|---|---|---|
| | | (*a*) Mean Daily (mm/day) and Mean Annual (mm) REF-ET | | | | | |
| Carteret | 1988–92 | 2.5[a] (914)[b] | 2.6[a] (943)[b] | 2.7[a] (997)[b] | 3.0[a] (1,081)[b] | 3.1[a] (1,148)[b] | 2.4[a] (884)[b] |
| Plymouth | 1990–94 | 2.6[a] (931)[b] | 2.2[a] (819)[b] | 2.3[a] (843)[b] | 2.6[a] (943)[b] | 3.1[a] (1,124)[b] | 2.3[a] (855)[b] |
| Tarboro | 1982–86 | 3.3[a] (1,197)[b] | 2.4[a] (859)[b] | 2.5[a] (913)[b] | 2.8[a] (1,030)[b] | 3.4[a] (1,223)[b] | 2.3[a] (829)[b] |
| Average | — | 2.8[a] (1,014)[b] | 2.4[a] (874)[b] | 2.5[a] (918)[b] | 2.8[a] (1,018)[b] | 3.2[a] (1,165)[b] | 2.3[a] (856)[b] |
| | | (*b*) Mean Monthly (mm/day) REF-ET during Peak Summer Months (June–August) | | | | | |
| Carteret | 1988–92 | 4.1 | 3.9 | 4.6 | 4.5 | 4.6 | 4.7 |
| Plymouth | 1990–94 | 4.0 | 3.6 | 4.3 | 4.3 | 4.6 | 4.5 |
| Tarboro | 1982–86 | 4.9 | 3.7 | 4.5 | 4.6 | 5.1 | 4.7 |
| Average | — | 4.3 | 3.7 | 4.5 | 4.5 | 4.8 | 4.6 |

[a]Daily.
[b]Annual.

ET by as much as 18% at the Carteret site. Estimates by the Makkink and PT methods were in closest agreement with the PM REF-ET at the Carteret site. However, the Turc method yielded the best estimate of the PM REF-ET both at the Plymouth and Tarboro sites. All radiation-based methods greatly underestimated PM REF-ET at the Tarboro site. This may be partly due to the higher wind speed and higher vapor-pressure deficits at that site. This result, however, supports the studies reported by Whitehead (1986) that the aerodynamic term in the Penman-Monteith equation contributes as much as 20% of REF-ET for short grass. On average, the Priestley-Taylor and Turc methods were generally the best in estimating the mean annual REF-ET. The same was true for the mean monthly REF-ET estimates for the peak summer months, as shown in Table 5(*b*). The Makkink method consistently underestimated the mean REF-ET for the peak months. The Hargreaves method overestimated REF-ET by about 2% at the Tarboro site to as much as 21% at the Plymouth site with an average of 15% for all sites. These results were in good agreement with the data reported by Jensen et al. (1990) for humid locations. On average, the Thornthwaite method underestimated the mean annual REF-ET by about 16% and overestimated the mean monthly REF-ET for the peak months by 7%.

The mean daily REF-ET values for each month averaged over given years of data, as estimated by the different methods for all three locations, are plotted in Fig. 2. The Thornthwaite method underpredicted mean daily REF-ET for November–May and overpredicted REF-ET for July–September, as compared to Penman-Monteith. All radiation-based methods predicted about the same REF-ET from January to April, although the PT method tended to underpredict from November to February at all sites. The Makkink method consistently underpredicted the REF-ET during the summer months at all sites. This was as much as 30% in May and June at the Tarboro site. The mean maximum REF-ET estimated by the PM method ranged from 5.0 to 5.5 mm/day for the three sites in the month of July for the Carteret and Plymouth sites, and in May for the Tarboro site. The PM method predicted the highest values of all methods during the winter and spring months at Tarboro. This is probably because of the high values of wind speed and vapor-pressure deficit observed at this location.

Summary statistics for regression of daily REF-ET estimated by each of the five methods against that estimated by the standard PM method are presented in Table 6 for all three

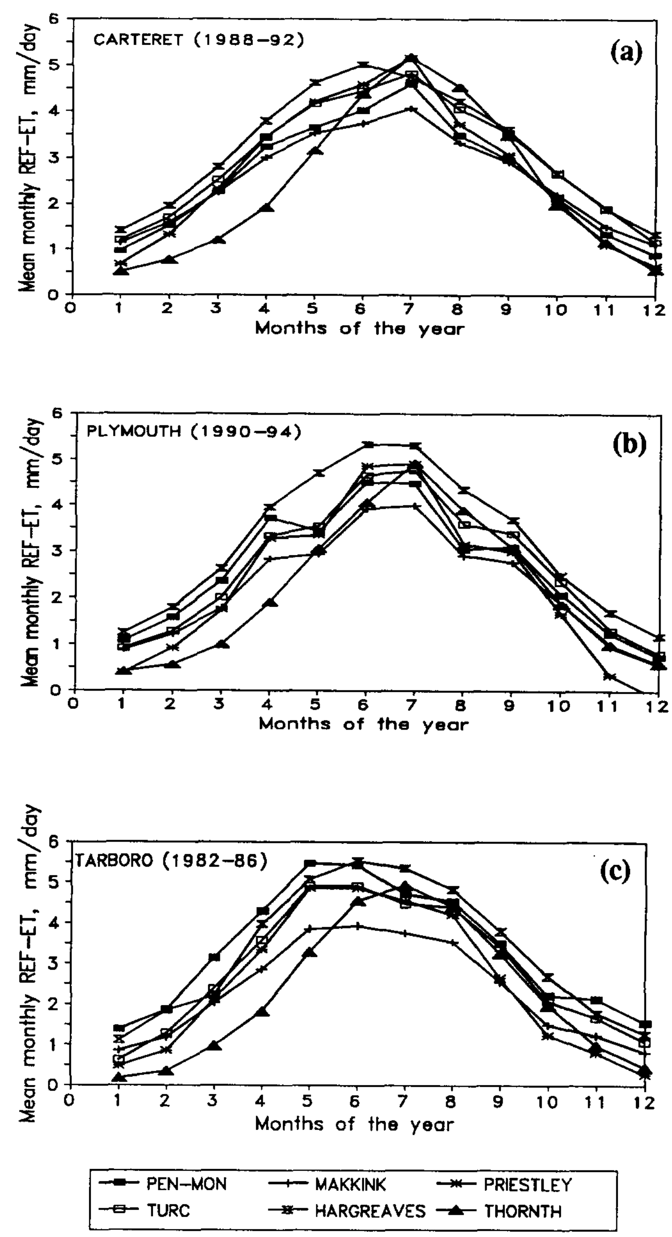


FIG. 2. Comparison of Monthly Mean Daily REF-ET Computed by Five Methods against Penman-Monteith Method

TABLE 6. Summary Statistics for Regression of Daily REF-ET Estimated by Five Methods against that Estimated by Penman-Monteith REF-ET Method

| Method of estimate (1) | Regression[a] (2) | R-square[b] (3) | RMSE (mm/day) (4) | AAD[c] (5) |
|---|---|---|---|---|
| (*a*) Using Mean Daily Weather Data for 1988–1991 at Carteret Site ($N$ = 1,461)[d] | | | | |
| Makkink | $Y = -0.37 + 1.16X$ | 0.93 | 0.42 | 0.34 |
| Priestley-Taylor | $Y = 0.36 + 0.79X$ | 0.94 | 0.39 | 0.47 |
| Turc | $Y = -0.08 + 0.90X$ | 0.87 | 0.56 | 0.57 |
| Hargreaves-Samani | $Y = -0.26 + 0.91X$ | 0.69 | 0.87 | 0.83 |
| Thornthwaite | $Y = 0.93 + 0.68X$ | 0.58 | 1.02 | 0.91 |
| (*b*) Using Mean Daily Weather Data for 1990–1994 at Plymouth Site ($N$ = 1,584)[d] | | | | |
| Makkink | $Y = -0.08 + 1.19X$ | 0.94 | 0.46 | 0.48 |
| Priestley-Taylor | $Y = 0.76 + 0.78X$ | 0.93 | 0.48 | 0.56 |
| Turc | $Y = 0.07 + 0.96X$ | 0.87 | 0.66 | 0.49 |
| Hargreaves-Samani | $Y = 0.03 + 0.83X$ | 0.55 | 1.23 | 1.04 |
| Thornthwaite | $Y = 0.98 + 0.68X$ | 0.42 | 1.40 | 1.23 |
| (*c*) Using Mean Daily Weather Data for 1982–1986 at Tarboro Site ($N$= 1,545)[d] | | | | |
| Makkink | $Y = 0.42 + 1.24X$ | 0.75 | 1.02 | 1.06 |
| Priestley-Taylor | $Y = 1.27 + 0.82X$ | 0.74 | 1.04 | 0.99 |
| Turc | $Y = 0.69 + 0.92X$ | 0.78 | 0.95 | 0.75 |
| Hargreaves-Samani | $Y = 0.33 + 0.87X$ | 0.56 | 1.37 | 1.07 |
| Thornthwaite | $Y = 1.69 + 0.71X$ | 0.38 | 1.60 | 1.55 |
| (*d*) Using Mean Daily Weather Data for All Three Sites Together ($N$ = 4,590)[d] | | | | |
| Makkink | $Y = -0.04 + 1.18X$ | 0.80 | 0.83 | 0.63 |
| Priestley-Taylor | $Y = 0.77 + 0.80X$ | 0.81 | 0.80 | 0.64 |
| Turc | $Y = 0.15 + 0.93X$ | 0.80 | 0.84 | 0.62 |
| Hargreaves-Samani | $Y = -0.14 + 0.90X$ | 0.62 | 1.15 | 0.97 |
| Thornthwaite | $Y = 1.14 + 0.70X$ | 0.44 | 1.40 | 1.20 |

[a]$Y$ = predicted Penman-Monteith daily REF-ET (mm/day); and $X$ = calculated daily REF-ET by each of the five methods (mm/day).

[b]R-square = coefficient of determination.

[c]AAD = average absolute deviation between predicted and calculated values (mm/day).

[d]$N$ = number of observations.

TABLE 7. Summary Statistics for Regression of Mean Monthly REF-ET Estimated by Five Methods against that Estimated by Penman-Monteith REF-ET Method

| Method of estimate (1) | Regression[a] (2) | R-square[b] (3) | RMSE (mm/day) (4) | AAD[c] (5) |
|---|---|---|---|---|
| (*a*) Using Mean Monthly Weather Data for 1988–1991 at Carteret Site ($N$ = 48)[d] | | | | |
| Makkink | $Y = -0.28 + 1.16X$ | 0.96 | 0.27 | 0.26 |
| Priestley-Taylor | $Y = 0.47 + 0.78X$ | 0.85 | 0.29 | 0.39 |
| Turc | $Y = -0.16 + 0.95X$ | 0.94 | 0.32 | 0.39 |
| Hargreaves-Samani | $Y = -0.33 + 0.94X$ | 0.88 | 0.46 | 0.59 |
| Thornthwaite | $Y = 0.94 + 0.70X$ | 0.76 | 0.65 | 0.71 |
| (*b*) Using Mean Monthly Weather Data for 1990–1994 at Plymouth Site ($N$ = 60)[d] | | | | |
| Makkink | $Y = 0.17 + 1.10X$ | 0.96 | 0.26 | 0.40 |
| Priestley-Taylor | $Y = 0.91 + 0.74X$ | 0.97 | 0.24 | 0.50 |
| Turc | $Y = 0.19 + 0.91X$ | 0.94 | 0.31 | 0.27 |
| Hargreaves-Samani | $Y = 0.00 + 0.82X$ | 0.90 | 0.41 | 0.61 |
| Thornthwaite | $Y = 1.07 + 0.70X$ | 0.73 | 0.68 | 0.73 |
| (*c*) Using Mean Monthly Weather Data for 1982–1986 at Tarboro Site ($N$ = 56)[d] | | | | |
| Makkink | $Y = 0.44 + 1.24X$ | 0.78 | 0.82 | 1.04 |
| Priestley-Taylor | $Y = 1.21 + 0.85X$ | 0.78 | 0.82 | 0.91 |
| Turc | $Y = 0.40 + 1.01X$ | 0.87 | 0.63 | 0.62 |
| Hargreaves-Samani | $Y = 0.39 + 0.86X$ | 0.67 | 0.99 | 0.83 |
| Thornthwaite | $Y = 1.73 + 0.73X$ | 0.52 | 1.20 | 1.35 |
| (*d*) Using Mean Monthly Weather Data for All Three Stations Together ($N$ = 164)[d] | | | | |
| Makkink | $Y = 0.08 + 1.17X$ | 0.80 | 0.66 | 0.56 |
| Priestley-Taylor | $Y = 0.85 + 0.79X$ | 0.82 | 0.63 | 0.58 |
| Turc | $Y = 0.08 + 0.97X$ | 0.86 | 0.56 | 0.44 |
| Hargreaves-Samani | $Y = 0.00 + 0.88X$ | 0.75 | 0.75 | 0.68 |
| Thornthwaite | $Y = 1.22 + 0.71X$ | 0.60 | 0.94 | 0.92 |

[a]$Y$ = predicted Penman-Monteith monthly REF-ET (mm/day); and $X$ = calculated monthly REF-ET by each of the five methods (mm/day).

[b]R-square = coefficient of determination.

[c]AAD = average absolute deviation between predicted and calculated monthly values (mm/day).

[d]$N$ = number of observations.

locations. Based on these results, the PT regression model ranked first with the lowest root mean square error (RMSE) and the highest coefficient of determination ($R^2$) for daily REF-ET predictions at the Carteret site. Statistics for the Makkink regression model were nearly as good, making it the second best predictor. Similarly, the Makkink model followed by the PT model performed better than other methods for the Plymouth site. The Turc model was also satisfactory based on its slope, which was close to unity, and a near zero intercept. The Turc method was ranked at the top in estimating daily REF-ET at the Tarboro site. Computed statistics were similar for all three other radiation methods. The two temperature methods, Hargreaves and Thornthwaite, generally yielded the poorest correlation with the PM estimates at all three locations. When data from all stations were analyzed together, the Turc method was as good as or better than the PT method, as revealed by the near-unity slope and near-zero intercept parameters.

Statistics for regression of mean daily REF-ET for monthly periods are summarized in Table 7 for all three locations. Although the PT and Makkink methods yielded the similar RMSE values, the latter was considered to be somewhat better because of the higher $R^2$ and a slope close to unity. Similarly, the Makkink and Priestley-Taylor methods were the best predictors of mean monthly REF-ET based on the RMSE and $R^2$ statistics at the Plymouth site. Computed statistics clearly indicated that the Turc method was superior to all other methods at the Tarboro site. When data from all three locations were considered together, the Turc method followed by the PT method ranked highest among the methods evaluated. These results are again consistent with the findings of Jensen et al. (1990), who concluded that the Turc method did the best among other radiation methods for estimating mean monthly REF-ET for humid regions. The fact that the models' computed RMSE values for Tarboro were as high as three times and the absolute deviations twice those for the Carteret and Plymouth sites clearly shows the weaker performance of the methods for the Tarboro site. Estimates of mean monthly REF-ET by the Hargreaves method was relatively better than the Thornthwaite method, which yielded the poorest correlation with the PM estimates as shown by the statistics in Table 7.

In general, good correlation was found between the daily and mean monthly REF-ET estimates computed by the radiation-based methods and the PM REF-ET at all three locations. The results, however, tend to show the preference of the PT method over the Makkink and Turc methods at the Carteret site. The reverse was true for the Plymouth and Tarboro sites. The difference was probably due to the fact that the PT method uses directly measured net radiation, whereas Makkink and Turc methods use the empirically com-

TABLE 8. Predictions of Penman-Monteith Daily and Total Annual REF-ET by Regression Models based on Carteret Data for 1988–91 Period versus Penman-Monteith Estimates Using Data for 1992

| | | Predictions by Regression Models of | | | | |
|---|---|---|---|---|---|---|
| Parameters (1) | Estimated Penman-Monteith (2) | Makkink (3) | Priestley-Taylor (4) | Turc (5) | Hargreaves-Samani (6) | Thornthwaite (7) |
| Total annual REF-ET (mm) | 780.3 | 996 | 796 | 946 | 944 | 910 |
| Mean daily REF-ET (mm) | 2.1 | 2.7 | 2.2 | 2.6 | 2.6 | 2.5 |
| Average absolute daily deviation (mm) | — | 0.6 | 0.3 | 0.7 | 0.7 | 0.7 |
| Coefficient of determination (R-square) | — | 0.94 | 0.96 | 0.80 | 0.64 | 0.63 |
| Slope | — | 0.89 | 0.84 | 0.72 | 0.73 | 0.64 |
| Intercept (mm) | — | 0.83 | 0.38 | 1.06 | 1.01 | 1.13 |
| Root mean square error (RMSE) (mm) | — | 0.29 | 0.24 | 0.49 | 0.76 | 0.68 |

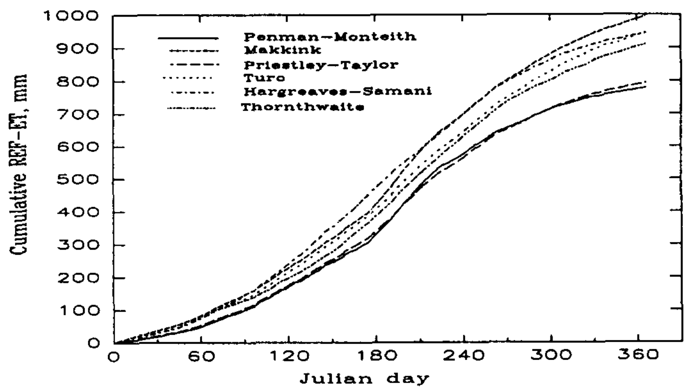


**FIG. 3. Comparison of Cumulative Penman-Monteith REF-ET Predicted by Regression Models Shown in Table 6(a) for 1992 Data at Carteret Site**

puted solar radiation at the Carteret site. This was opposite for two other sites.

The RMSE values for daily REF-ET estimates were greater by 26–53% than that for monthly estimates, indicating that the regression equations for daily REF-ET estimates are less accurate than the mean daily estimate for monthly periods for all sites taken together. This greater error of prediction is due to the wide variation in daily weather parameters as compared to the mean monthly data where variability is reduced by the averaging process.

Regression models listed in Table 6(*a*) for the Carteret site were tested by using them to predict daily REF-ET for 1992 and comparing the results with the estimates by the Penman-Monteith method using the actual data. Results are summarized in Table 8. Values predicted by the calibrated Priestley-Taylor regression model were in closest agreement with the standard Penman-Monteith estimates, having the highest $R^2$, the least absolute deviation, and the least RMSE value. Statistics for the Makkink model were nearly as good, followed by the Turc model. Both the Hargreaves and Thornthwaite models again yielded the lowest $R^2$ with the largest RMSE values. The graphical comparison of cumulative daily REF-ET predicted by the five regression models with the Penman-Monteith REF-ET estimates using actual data in Fig. 3 showed that the Priestley-Taylor model was almost in exact agreement with the Penman-Monteith cumulative REF-ET, supporting the results of the computed statistics. All other methods consistently overpredicted daily REF-ET.

The daily net radiation calculated by (6) with weather data from the Wilmington airport for the two-year period (1991–92) were correlated with measured net radiation at the Carteret site. The results yielded $R^2 = 0.71$ and slope $= 0.73$ for 594 observations analyzed. The calibration equation was

$$R_n^{\text{Carteret}} = 0.74 R_n^{\text{Wilmington}} + 0.32 \tag{7}$$

The reliability of each REF-ET method was tested by using net radiation obtained by the calibration (7) with Wilmington data for 650 days in the 1991–92 period. Days with missing radiation data at the Carteret site were omitted. Solar radiation was again computed using (5). Estimates by all six methods, using this calibrated radiation data from Wilmington, were compared to estimates by the Penman-Monteith method

TABLE 9. Comparative Statistics of Penman-Monteith Daily REF-ET Predictions by Six Methods for Period 1991–92 at Carteret Site (Number of Observations = 650)

| | | Predictions by Regression Models of | | | | | |
|---|---|---|---|---|---|---|---|
| Parameters (1) | Estimated Penman-Monteith (2) | Penman-Monteith (3) | Makkink (4) | Priestley-Taylor (5) | Turc (6) | Hargreaves-Samani (7) | Thornthwaite (8) |
| (*a*) Using Empirical Relationships with Data for Net Radiation from Wilmington Airport Station | | | | | | | |
| Total annual REF-ET (mm) | 1,396 | 1,749 | 1,688 | 1,888 | 1,958 | 2,008 | 1,483 |
| Mean dialy REF-ET (mm) | 2.1 | 2.7 | 2.6 | 2.6 | 3.0 | 3.1 | 2.3 |
| Average absolute daily deviation (mm) | — | 0.7 | 0.7 | 1.0 | 1.0 | 1.1 | 0.9 |
| Coefficient of determination (R-square) | — | 0.75 | 0.68 | 0.67 | 0.64 | 0.65 | 0.54 |
| Slope | — | 0.74 | 0.93 | 0.62 | 0.73 | 0.80 | 0.62 |
| Intercept (mm) | — | 0.15 | −0.28 | 0.34 | −0.06 | −0.33 | 0.74 |
| Root mean square error (RMSE) (mm) | — | 0.68 | 0.77 | 0.77 | 0.80 | 0.80 | 0.92 |
| (*b*) Using Actual Measured Data at Carteret Weather Station | | | | | | | |
| Total annual REF-ET (mm) | 1,396 | — | 1,581 | 1,533 | 1,840 | 2,008 | 1,483 |
| Mean daily REF-ET (mm) | 2.1 | — | 2.4 | 2.4 | 2.8 | 3.1 | 2.3 |
| Average absolute daily deviation (mm) | — | — | 0.5 | 0.4 | 0.8 | 1.1 | 0.9 |
| Coefficient of determination (R-square) | — | — | 0.85 | 0.91 | 0.77 | 0.65 | 0.54 |
| Slope | — | — | 1.23 | 0.84 | 0.92 | 0.80 | 0.62 |
| Intercept (mm) | — | — | −0.85 | 0.17 | −0.46 | −0.33 | 0.74 |
| Root mean square error (RMSE) (mm) | — | — | 0.53 | 0.41 | 0.64 | 0.80 | 0.92 |

**TABLE 10. Estimated Monthly Correction Factors for Adjusting Hargreaves (HARGR) and Thornthwaite (THORN) REF-ET for Three Stations in Eastern North Carolina**

| | Carteret Site Average for 1988–1992 | | Plymouth Site Average for 1990–1994 | | Tarboro Site Average for 1982–1986 | | Average for Three Stations | |
|---|---|---|---|---|---|---|---|---|
| Month (1) | HARGR (2) | THORN (3) | HARGR (4) | THORN (5) | HARGR (6) | THORN (7) | HARGR (8) | THORN (9) |
| 1 | 0.71 | 1.9 | 0.80 | 2.27 | 1.27 | 1.65 | 0.93 | 1.94 |
| 2 | 0.79 | 1.99 | 0.85 | 2.84 | 1.09 | 2.13 | 0.91 | 2.32 |
| 3 | 0.81 | 1.88 | 0.87 | 2.12 | 1.24 | 2.27 | 0.97 | 2.09 |
| 4 | 0.85 | 1.69 | 0.91 | 1.67 | 1.10 | 1.84 | 0.95 | 1.73 |
| 5 | 0.79 | 1.15 | 0.83 | 1.11 | 1.10 | 1.44 | 0.91 | 1.23 |
| 6 | 0.80 | 0.92 | 0.85 | 1.04 | 0.98 | 1.11 | 0.88 | 1.02 |
| 7 | 0.97 | 0.89 | 0.85 | 0.87 | 0.88 | 0.92 | 0.90 | 0.89 |
| 8 | 0.83 | 0.77 | 0.75 | 0.77 | 0.94 | 0.99 | 0.84 | 0.84 |
| 9 | 0.82 | 0.85 | 0.83 | 0.94 | 0.92 | 1.05 | 0.86 | 0.95 |
| 10 | 0.80 | 1.07 | 0.84 | 1.10 | 0.83 | 1.05 | 0.82 | 1.07 |
| 11 | 0.71 | 1.16 | 0.70 | 1.05 | 1.19 | 1.47 | 0.87 | 1.23 |
| 12 | 0.66 | 1.62 | 0.55 | 1.22 | 1.26 | 1.29 | 0.82 | 1.38 |

using measured data at Carteret in Table 9(*a*). The Penman-Monteith method yielded the highest $R^2$ and the lowest RMSE values as compared to the other five methods. Although REF-ET rates estimated by all four radiation-based methods were comparable to Penman-Monteith estimates, the degree of fit of the regression on a day-by-day basis dropped considerably from that achieved with on-site measured weather data for the same period [Table 9(*b*)]. The RMSE value increased by almost 100% for the Priestley-Taylor method and by 25% for Turc. The reason was probably due to a weaker correlation ($R^2$ = 0.71) of radiation obtained by using empirical relationships with data from the Wilmington airport. These results also clearly indicated that the temperature-based Hargreaves method was nearly as good as the radiation-based methods when data from the other site were used. The Thornthwaite method still yielded the poorest correlation of all.

Mean monthly correction factors that can be used for adjusting the Hargreaves and Thornthwaite methods for their potential use at each of the stations and in the average for the study areas are summarized in Table 10.

## SUMMARY AND CONCLUSIONS

Six methods (one combination method: Penman-Monteith; three radiation methods: Makkink, Priestley-Taylor, and Turc; and two temperature-based methods: Hargreaves-Samani and Thornthwaite) were applied to estimate reference evapotranspiration using weather data from three sites in eastern North Carolina. The Penman-Monteith method with grass as the reference crop [as suggested by the Food and Agriculture Organization of the United Nations (Food 1990)] was assumed as the standard for comparing REF-ET estimates by the other five methods for all three locations. Daily, monthly, peak monthly, and annual REF-ET rates were compared for all three locations.

Mean annual REF-ET estimates by the standard Penman-Monteith method for the Carteret, Plymouth, and Tarboro sites were found to be 914 mm (2.5 mm/day), 931 mm (2.6 mm/day), and 1,197 mm (3.28 mm/day), respectively, with an average of 1,014 mm for the study region. The following conclusions and recommendations were drawn from the results of this study:

1. Turc's method yielded the best average estimate of total annual REF-ET. All other radiation methods and the temperature-based Thornthwaite method underpredicted the annual REF-ET by as much as 16%. The Hargreaves method overpredicted annual REF-ET by 15% on average.
2. Priestley-Taylor's and Turc's average estimates of the monthly REF-ET for the peak summer months were in the closest agreement with the Penman-Monteith estimate. Makkink's method consistently underpredicted the peak monthly estimates, and the temperature-based methods generally overpredicted them by as much as 11%.
3. REF-ET estimates by the Priestley-Taylor and Makkink methods were in best agreement with the daily and monthly Penman-Monteith estimates for the Carteret and Plymouth sites, respectively.
4. The best prediction model for daily and monthly REF-ET estimates at Tarboro was the Turc method.
5. On average, Turc's method was found to be the best predictor of the monthly REF-ET for all locations considered.
6. The REF-ET estimates obtained by using the temperature based Hargreaves method may be as reliable as the radiation-based methods when weather data from other stations are used.

It is highly recommended that the suggested methods for each location be calibrated first if locally measured data are available. The study showed that methods using directly measured radiation would be better than the method using calibrated data. For this reason, it is suggested that existing equations relating net and solar radiation be verified for the area of application, if possible. Either the Hargreaves method as suggested by Choisnel et al. (1992) and Jensen et al. (1990) or the Thornthwaite method with correction factors for the study region can be used in the absence of radiation, humidity, and wind-speed data. It is important to consider the type of vegetation surrounding the location when the potential ET from a given reference crop is estimated, as recommended by Choisnel et al. (1992) and Jensen et al. (1990).

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## APPENDIX II. NOTATION

*The following symbols are used in this paper:*

$a_3, b_3$ = regression coefficients;
$e_d$ = vapor pressure at dew point temperature (kPa);
$e_z^o$ = vapor pressure at mean air temperature (kPa);
$m, C$ = slope and intercept of regression equation;
$n/N$ = percent sunshine;
$R_A$ = extraterrestrial radiation (MJ/m$^2$/day);
$R_n$ = net radiation (MJ/m$^2$/day);
$R_s$ = solar radiation (MJ/m$^2$/day);
$r_c$ = canopy resistance;
RH = mean relative humidity (%);
$T$ = mean air temperature (°C);
$T_{max}, T_{min}$ = maximum and minimum air temperature (°C), respectively;
VPDC = vapor pressure deficit (kPa);
$W$ = wind speed (m/sec);
$X$ = REF-ET estimated by one of five methods (mm);
$Y$ = Penman-Monteith REF-ET (mm);
$\alpha$ = albedo value; and
$\sigma$ = Stefan-Boltzman constant.