A COMPARISON OF SIX POTENTIAL EVAPOTRANSPIRATION METHODS FOR REGIONAL USE IN THE SOUTHEASTERN UNITED STATES[1]

Jianbiao Lu, Ge Sun, Steven G. McNulty, and Devendra M. Amatya[2]

ABSTRACT: Potential evapotranspiration (PET) is an important index of hydrologic budgets at different spatial scales and is a critical variable for understanding regional biological processes. It is often an important variable in estimating actual evapotranspiration (AET) in rainfall-runoff and ecosystem modeling. However, PET is defined in different ways in the literature and quantitative estimation of PET with existing mathematical formulas produces inconsistent results. The objectives of this study are to contrast six commonly used PET methods and quantify the long term annual PET across a physiographic gradient of 36 forested watersheds in the southeastern United States. Three temperature based (Thornthwaite, Hamon, and Hargreaves-Samani) and three radiation based (Turc, Makkink, and Priestley-Taylor) PET methods are compared. Long term water balances (precipitation, streamflow, and AET) for 36 forest dominated watersheds from 0.25 to 8213 km^2 in size were estimated using associated hydrometeorological and land use databases. The study found that PET values calculated from the six methods were highly correlated (Pearson Correlation Coefficient 0.85 to 1.00). Multivariate statistical tests, however, showed that PET values from different methods were significantly different from each other. Greater differences were found among the temperature based PET methods than radiation based PET methods. In general, the Priestley-Taylor, Turc, and Hamon methods performed better than the other PET methods. Based on the criteria of availability of input data and correlations with AET values, the Priestley-Taylor, Turc, and Hamon methods are recommended for regional applications in the southeastern United States.
(KEY TERMS: potential evapotranspiration; actual evapotranspiration; forest hydrology; regional hydrological modeling; southeastern United States.)

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INTRODUCTION

Although several variations of the definition exist, potential evapotranspiration (PET) can be generally defined as the amount of water that could evaporate and transpire from a vegetated landscape without restrictions other than the atmospheric demand (Thornthwaite, 1948; Penman, 1948; Jensen *et al.,* 1990). The concept of PET provides a convenient index to represent or estimate the maximum water loss to the atmosphere. Estimates of PET are necessary in many of the rainfall-runoff and ecosystem models that are used in global change studies (Band *et al.,* 1996; Hay and McCabe, 2002). Potential evapotranspiration is also used as an index to represent the available environmental energies and ecosystem productivity (Currie, 1991). For example, in the four vertebrate classes studied, Currie (1991) found that 80 to 93 percent of the variability in species richness could be statistically explained by ecosystem PET.

Although the PET concept has many uses, it has been regarded as a confusing term because the reference evaporation surface, usually the vegetation type, is vaguely defined (Nokes, 1995). Consequently, the PET concept has been gradually replaced in the past decade by other more narrowly defined terms, such as reference crop evapotranspiration (Jensen *et al.,* 1990), or surface dependent evapotranspiration (Federer *et al.,* 1996). Typically, reference crops are grass and alfalfa because most equations were developed for agricultural purposes, but a land surface can contain

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any designated vegetation types. Potential evapotranspiration can be measured directly by lysimeters, but generally, it is estimated by theoretical or empirical equations, or derived simply by multiplying standard pan evaporation data by a coefficient (Grismer *et al.,* 2002). Because of the large size of a tree, there have been few attempts to directly measure forest PET or AET by lysimeter studies and develop associated equations to estimate PET or AET (Stein *et al.,* 1995; Riekerk, 1985). Forest PET values at stand or landscape levels are often indirectly estimated using modified mathematical models that were developed for free water surface or short crops, such as the Thornthwaite equation (Thornthwaite and Mather, 1955; Kolka and Wolf, 1998).

There are approximately 50 methods or models available to estimate PET, but these methods or models give inconsistent values due to their different assumptions and input data requirements, or because they were often developed for specific climatic regions (Grismer *et al.,* 2002). Past studies at multiple scales have suggested that different PET methods may give significantly different results (Crago and Brutsaert, 1992; Amatya *et al.,* 1995; Federer *et al.,* 1996; Vörösmarty *et al.,* 1998). By using intensive meteorological data from three sites in eastern North Carolina, Amatya *et al.* (1995) contrasted six PET computation methods, which included one combination method (Penman-Monteith), three radiation based (Makkink, Priestley-Taylor, and Turc) and two temperature based (Thornthwaite and Hargreaves-Samani) methods. They found that the Thornthwaite method performed the worst, and that the Makkink and Priestley-Taylor methods performed the best when compared to the Penman-Monteith predictions, which were used as the standard for comparisons. Federer *et al.* (1996) compared five reference surface PET methods (Thornthwaite, Hamon, Jensen-Haise, Turc, and Penman) and four surface dependent PET methods (Priestley-Taylor, McNaughton-Black, Penman-Monteith, and Shuttleworth-Wallace) using data from seven locations across a large climatic gradient in the continental United States and Puerto Rico. They defined reference surface PET as the evapotranspiration that would occur from a land surface specified as a "reference crop" (usually defined as a short, complete, green plant cover) in designated weather conditions if plant surfaces were externally dry and soil water was at field capacity; and surface dependent PET was defined as the evapotranspiration that would occur from a designated land surface in designated weather conditions if all surfaces were externally wetted, as by rain (Federer *et al.,* 1996). They concluded that, although all nine methods agreed in general magnitude of PET values on an annual basis over a wide range of climates, differences of hundreds of millimeters for a particular location or a cover type were found. For hot and dry areas, the differences of PET among the methods exceeded 700 mm/yr. They also concluded that PET for grasslands, savanna, and conifer surfaces did not differ systematically from reference PET for short green crops. Vörösmarty *et al.* (1998) extended this point-level comparison study to the conterminous United States by comparing the sensitivity of PET methods to the AET estimated by a macro-scale hydrologic model. They found that monthly water balance calculations were sensitive to the PET method used and warned that a PET method should be validated in the field before it is used.

A large proportion of precipitation (50 to 80 percent) is returned to the atmosphere as evapotranspiration in the southeastern United States, a region that is largely covered by forests and has diverse topographic features (i.e., coastal plains, piedmonts, and hilly mountains) (Sun *et al.,* 2002; Liang *et al.,* 2002; Lu *et al.,* 2003). Streamflows, water quality, and ecosystem processes can respond substantially to small changes in precipitation or evapotranspiration. This is especially true for the coastal regions where evapotranspiration is the dominant factor on surface and ground water flow patterns. Thus, it is important to identify the differences among the PET methods when PET is used to predict AET, because different PET methods give widely different annual values at particular locations as demonstrated in previous studies (Federer *et al.,* 1996). Even for the PET methods that give similar values, the method or methods that require the least input parameters/variables are most useful and practical for regional scale studies (Fennessey and Vogel, 1996). There do not appear to be previous studies on how the commonly used PET methods perform across the warm and humid forested southeastern United States. Therefore, the objectives of this study are to: (1) contrast six commonly used PET methods that have potential to be incorporated into regional scale hydrologic modeling in global change studies, and (2) quantify PET across the climatic gradient of the southeastern United States.

METHODS

Database Development

Databases for streamflow, climate, landcover, and watershed properties from 39 watersheds across the southeastern United States were complied. These watersheds were either small watersheds that had long term forest hydrology research records or U.S.

Geological Survey (USGS) gauged basins that had long term streamflow data (Figure 1). For the large basins, those selected were dominated by forest covers. As indicated by the long term evapotranspiration ratio (AET/precipitation) that ranges from 0.82 in Florida to 0.45 in Tennessee, the selected watersheds covered a large spectrum of hydrologic conditions (Table 1). Among the 39 watersheds, the following six were small (0.25 to 29.5 km^2): Bradford Forest (control watershed) in north-central Florida (Riekerk, 1989; Sun *et al.,* 1998); Carteret and Parker Tract watersheds on the North Carolina coast (Amatya and Skaggs, 2001; Amatya *et al.,* 2002); Walker Branch watershed in Tennessee (Johnson and Hook, 1989); Coles Forks watershed in the Robinson Experimental Forest, Kentucky (Arthur *et al.,* 1998; R. Kolka, unpublished data, 2002); and Santee Experimental Forest (Watershed 80, control watershed) on coastal South Carolina (Sun *et al.,* 2000). Both Walker Branch and Coles Forks watersheds are located on uplands of the Appalachian Mountains. The other larger gauged watersheds (200 to 8,213 km^2) include 12 in North Carolina that represent three topographic regions (coastal plains, piedmonts, and mountains), 17 studied by Liang *et al.* (2002) across the southeastern United Sates, and four selected by the same criteria as Liang *et al.* (2002) in South Carolina and Georgia. Three watersheds (Watershed IDs 10, 12, and 21) were found to be outliers where precipitation measurements were suspected of having significant errors (mismatch between weather station and watershed) or that did not meet the criteria of forest dominated land compositions. Therefore, only 36 watersheds were used in this study (Table 1).

The following watershed characteristic and meteorological variables were acquired or derived from historic hydrometeorologic records: watershed location (latitude, longitude) and elevation; annual precipitation (P) and annual streamflow (Q); and monthly mean air temperature (T), maximum temperature (T_{max}), minimum temperature (T_{min}), relative humidity (RH), solar radiation (R_s), extraterrestrial solar radiation (R_a), and net radiation (R_n). Because monthly measured net radiation (R_n) is only available for the Carteret site in North Carolina (Watershed ID 37), this variable was derived empirically from solar radiation (Castellvi *et al,* 2001) calibrated at the Carteret site. Thus, the following empirical equation was used to calculate net radiation in this study.

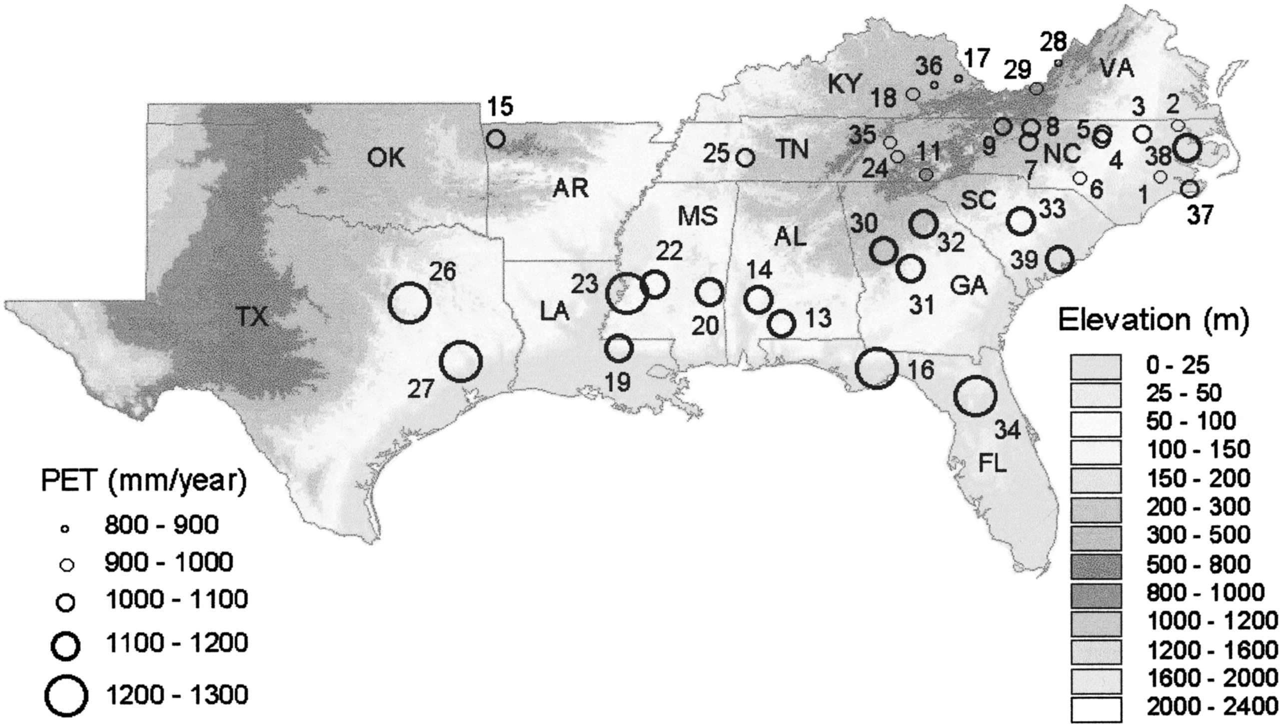

Figure 1. Long Term (5 to 30 years) Annual PET Estimated by the Priestley-Taylor Method for the 36 Watersheds in the Southeastern U.S That Were Examined During This Study. Numbers in the map represent the watershed ID in Table 1.

TABLE 1. Physical and Hydrometeorology Characteristics of Watersheds Across the Southeastern U.S.

Watershed ID	Watershed	Area (km2)	Forest Cover (percent)	Elevation (m)	No. of Years of Hydrology Data	Record Period	Annual Average Temperature (°C)	Precipitation (mm/yr)	AET (mm/yr)	AET/ Rainfall Ratio
1	Trent River, North Carolina	435.12	71.6	30	29	1961 to 1989	11.73	1,321	923	0.70
2	Potecasi Creek, North Carolina	582.75	65.2	24	30	1961 to 1990	14.17	1,151	801	0.70
3	Fishing Creek, North Carolina	458.43	82.3	47	30	1961 to 1990	15.43	1,123	799	0.71
4	Eno River, North Carolina	365.19	72.8	193	27	1964 to 1990	14.64	1,213	896	0.74
5	Flat River, North Carolina	385.91	69.1	135	30	1961 to 1990	14.27	1,122	791	0.71
6	Drown Creek, North Carolina	473.97	74.4	149	30	1961 to 1990	12.32	1,183	703	0.59
7	Hunting Creek, North Carolina	401.45	68.2	322	30	1961 to 1990	15.24	1,188	712	0.60
8	Fisher River, North Carolina	331.52	74.6	322	30	1961 to 1990	14.56	1,159	657	0.57
9	New River, North Carolina	530.95	79.6	955	29	1961 to 1990	15.65	1,441	686	0.48
11	Little Tenn., North Carolina	362.60	89.9	897	30	1961 to 1990	10.05	1,825	854	0.47
13	AL03140303	455.84	84.8	109	16	1975 to 1990	18.90	1,628	1,112	0.68
14	AL03150203	253.82	74.1	70	30	1961 to 1990	17.90	1,486	1,000	0.67
15	AR11010001	1,036.00	62.0	432	27	1964 to 1990	13.97	1,124	644	0.57
16	FL03120003	264.18	68.8	41	26	1965 to 1990	19.12	1,665	1,028	0.62
17	KY05070203	533.54	97.0	312	30	1961 to 1990	11.77	1,076	664	0.62
18	KY05100203	1,869.98	97.1	358	30	1961 to 1990	12.55	1,235	714	0.58
19	LA08070202	375.55	63.0	56	30	1961 to 1990	18.64	1,617	1,042	0.64
20	MS03170002	2,377.62	81.8	99	30	1961 to 1990	17.37	1,427	922	0.65
22	MS03180002	8,212.89	66.2	110	30	1961 to 1990	17.82	1,458	952	0.65
23	MS08060203	1,693.86	72.5	83	29	1962 to 1990	18.64	1,338	860	0.64
24	TN06010204	5,146.33	83.6	576	30	1961 to 1990	13.55	1,517	685	0.45
25	TN06040004	1,157.73	78.5	238	30	1961 to 1990	13.93	1,485	869	0.59
26	TX12030201	367.78	45.0	112	22	1969 to 1990	18.63	1,051	851	0.81
27	TX12040103	841.75	73.6	62	30	1961 to 1990	20.32	1,263	1,004	0.79
28	VA02080201	852.11	87.1	633	30	1961 to 1990	10.93	1,069	651	0.61
29	VA05050002	577.57	78.7	760	30	1961 to 1990	10.42	1,053	573	0.54
30	GA03130005	704.48	74.9	213	30	1961 to 1990	16.21	1,306	837	0.64
31	GA03070103	471.38	72.5	205	30	1961 to 1990	18.12	1,134	770	0.68
32	GA03070101	1,015.28	66.8	270	30	1961 to 1990	16.47	1,263	770	0.61
33	SC03050110	155.40	66.9	72	24	1967 to 1990	18.39	1,197	762	0.64
34	Bradford, Florida	1.40	100	44	13	1978 to 1990	20.88	1,241	1,015	0.82
35	Walker Branch, Tennessee	1.01	100	308	22	1969 to 1990	13.88	1,331	671	0.50
36	Coles Fork, Kentucky	16.60	100	378	18	1973 to 1990	11.65	1,155	778	0.67
37	Carteret, North Carolina	0.25	100	3	13	1988 to 2000	16.29	1,539	1,019	0.66
38	Parker, North Carolina	29.50	100	6	5	1996 to 2000	15.03	1,249	961	0.77
39	Santee-80, South Carolina	1.50	100	7	5	1976 to 1980	18.13	1,382	1,136	0.82

Note: Three watersheds (ID 10, 12, 21) were eliminated as outliers from the database.

$$R_n = 0.77R_s - 2.45\times10^{-9} f \times \left(0.261\times\exp\left(-7.7710\times10^{-4}T^2\right) - 0.02\right)\left(T_{\max}^4 + T_{\min}^4\right) + 0.83 \tag{1}$$

$$f = \left(1.2\times\frac{R_s}{R_a} + 0.1\right) \tag{2}$$

where R_n is the monthly mean net radiation ($MJ/m^2/day$); R_s is the monthly mean solar radiation ($MJ/m^2/day$); R_a is the monthly mean extraterrestrial solar radiation ($MJ/m^2/$ day); T is the monthly mean air temperature (K); T_{max} is the maximum monthly mean air temperature (K); and T_{min} is the minimum monthly mean air temperature (K).

To investigate how well PET values estimated by the six methods correlate with AET, long term annual watershed-scale AET was estimated by the water balance equation that assumes change in water storage is negligible (Zhang *et al.,* 2001; Church *et al.,* 1995). Thus, on the long term annual basis, AET for each watershed was simplified as the difference between precipitation and runoff. This assumption may have potential errors in the AET calculations on an annual basis due to variations in soil moisture and ground water storage. However, as the record length increases, the error from this source will decrease.

PET Methods and Comparisons

The six PET methods selected in this comparison study are commonly used and require relatively fewer input requirements than the Penman-Monteith method (Monteith, 1973). The six PET methods include three temperature based methods, Thornthwaite (1948), Hamon (1963), and Hargreaves-Samani (1985); and three radiation based methods, Turc (1961), Makkink (1957), and Priestley-Taylor (1972) (Table 2). The calibration coefficients 1.26 and 1.2 were applied to the Priestley-Taylor method (Jensen *et al.,* 1990; Federer *et al.,* 1996) and Hamon method (Federer and Lash, 1983; Sun *et al.,* 2002), respectively, while other methods were not calibrated. For detailed mathematical descriptions of the selected PET methods, refer to Jensen *et al.* (1990), Federer *et al.* (1996), Vörösmarty *et al.* (1998), and Lu (2002), or the original method citations. The Appendix summarizes the six PET methods. The data needed for the radiation based methods are more difficult to obtain because historical direct radiation measurements are still not readily available for many regions in the United States or are more expensive to acquire. A computer program was coded to calculate monthly PET based on the six methods. The program provides monthly and annual total PET for the multiple sites and multiple years. The computer code is available upon request from the authors.

Because AET could only be calculated at an annual scale by the water balance method, the analysis had to be limited to comparisons of annual AET and PET. Multivariate statistical analysis was performed using SAS 8.2 to assist comparisons (SAS Institute Inc., 2001). Potential evapotranspiration estimates by the six PET methods for each of the 36 sites were considered as six repeated measurements across the region, and the standard assumptions (Independence, Randomness, and Multivariate Normal Distribution) of repeated measurements were applied.

TABLE 2. Monthly Variables and Parameters Required by the Six PET Methods.

Method	Temperature	Radiation	Humidity	Others
Thornthwaite (1948)	Mean Daily			Daytime Length
Hamon (1963)	Mean Daily			Daytime Length, Calibration Coefficient (1.2)
Hargreaves-Samani (1985)	Daily Maximum and Minimum Temperatures	Extraterrestrial Radiation		
Priestley-Taylor (1972)	Mean Daily	Net Radiation Derived From Solar Radiation and Extraterrestrial Radiation		Calibration Constant (1.26)
Turc (1961)	Mean Daily	Solar Radiation	Mean Daily	
Makkink (1957)	Mean Daily	Solar Radiation		

To judge the performance of the six PET methods, the following three criteria and assumptions were made. The first assumption is that PET should exceed AET on a long term annual basis for the forest dominated region; the second assumption is that a significant temporally stationary relationship exists between AET and PET; and the third assumption is that the relationship between AET and PET is linear, which is necessary to assist the statistical analysis in this study. Thus, PET methods that yield the highest correlation coefficient would be the preferred ones. In practice, these assumptions are applied as AET is often estimated as a fraction of PET (Federer *et al.,* 1996).

RESULTS

Comparisons Among Six PET Methods

The Pearson correlation coefficients were calculated among the six methods and the values ranged from 0.85 to 1.00. Among these correlation coefficients, the Thornthwaite and Hamon PET methods had the highest value (R = 1.00), while the Hargreaves-Samani PET method had the lowest values (< = 0.89) with other methods (Table 3). Multivariate statistical tests indicated that each PET method was significantly different from all the others at a 0.05 significance level.

The Thornthwaite method yielded the lowest long term averaged annual PET while the Hargreaves-Samani method predicted the highest values (Figure 2). The Hamon and Makkink method gave the largest and least annual PET variation, respectively. The PET estimated by the Thornthwaite method was even slightly lower than long-term annual AET as discussed in the next paragraph (Figure 2). Across the 36 sites, greater differences were found among the temperature based PET methods than radiation based PET methods (Figures 2, 3, and 4). The PET values predicted by the three radiation based methods were found to be similar in magnitude, especially for the Priestley-Taylor and Turc methods, which had a correlation coefficient of 0.97 between the two. The Makkink method gave the lowest PET values among the radiation based methods and had the least standard deviation (81 mm/yr) among all six methods (Figures 2 and 4).

The averaged PET values varied greatly in the study region (Figure 1). Generally, the trend follows the high/low direction from the south to the north and from the coast to the mountain. The highest PET values were found in the lower elevation areas to the south in a latitude line from Texas to Florida, while the lowest estimates were in the inland and more northern mountains in Kentucky and western Virginia.

Two experimental watersheds with full forest cover (Figures 5 and 6) and two USGS monitored basins with mixed land uses (Figures 7 and 8) were selected to explore the annual temporal patterns of the PET. For these four sites, the PET methods produced consistent results through time. Again, as discussed in the previous paragraph, the differences among the temperature based PET estimates were greater than those of the radiation based methods, with the Hargreaves-Samani and Thornthwaite giving the highest and lowest values, respectively. For radiation-based methods, the Makkink PET method predicted the lowest PET, and Priestley-Taylor and Turc were close to the mean estimates for all methods.

Examining more closely, the relative differences in predicted PET among methods varied greatly both between watersheds and between years. For example, the Thornthwaite method gave similar PET values to the Makkink method at the Bradford watershed site in Florida (Figure 5), but the Thornthwaite predictions were more than 200 mm/yr lower than the Makkink method predictions for the other three comparison sites (Figures 6, 7, and 8). The Hamon method gave similar PET values as the Hargreaves-Samani for the Florida site (Figure 5), but it yielded

TABLE 3. Pearson Correlation Coefficients Among Six PET Methods (n = 36).

PET Methods	Thornthwaite	Hamon	Turc	Priestley-Taylor	Makkink	Hargreaves-Samani
Thornthwaite		1.00	0.96	0.94	0.93	0.89
Hamon	1.00		0.97	0.94	0.93	0.89
Turc	0.96	0.97		0.97	0.98	0.88
Priestley-Taylor	0.94	0.94	0.97		0.95	0.85
Makkink	0.93	0.93	0.98	0.95		0.85
Hargreaves-Samani	0.89	0.89	0.88	0.85	0.85	

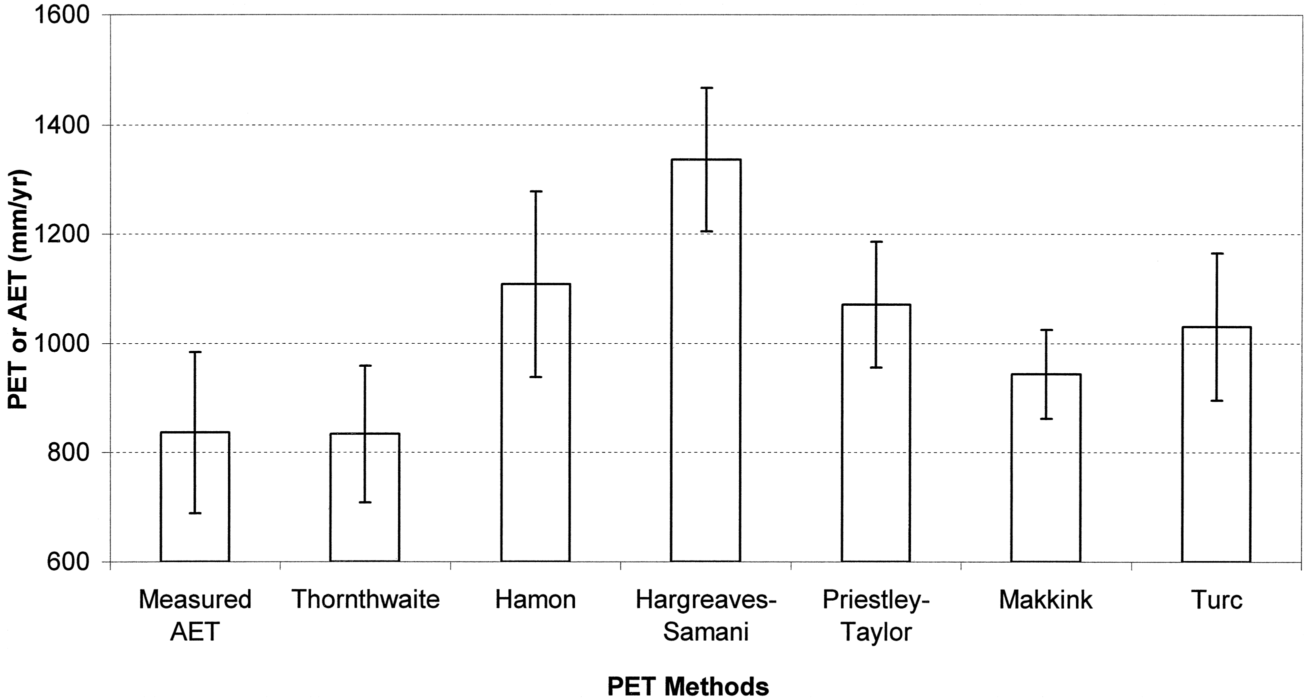

Figure 2. Long-Term (5 to 30 years) Average Annual AET Calculated From the Watershed Water Balances and PET Estimated by Six Methods Across the Southeastern United States. Error bars represent one standard deviation around the mean of the 36 watersheds in the southeastern U.S that were examined during this study.

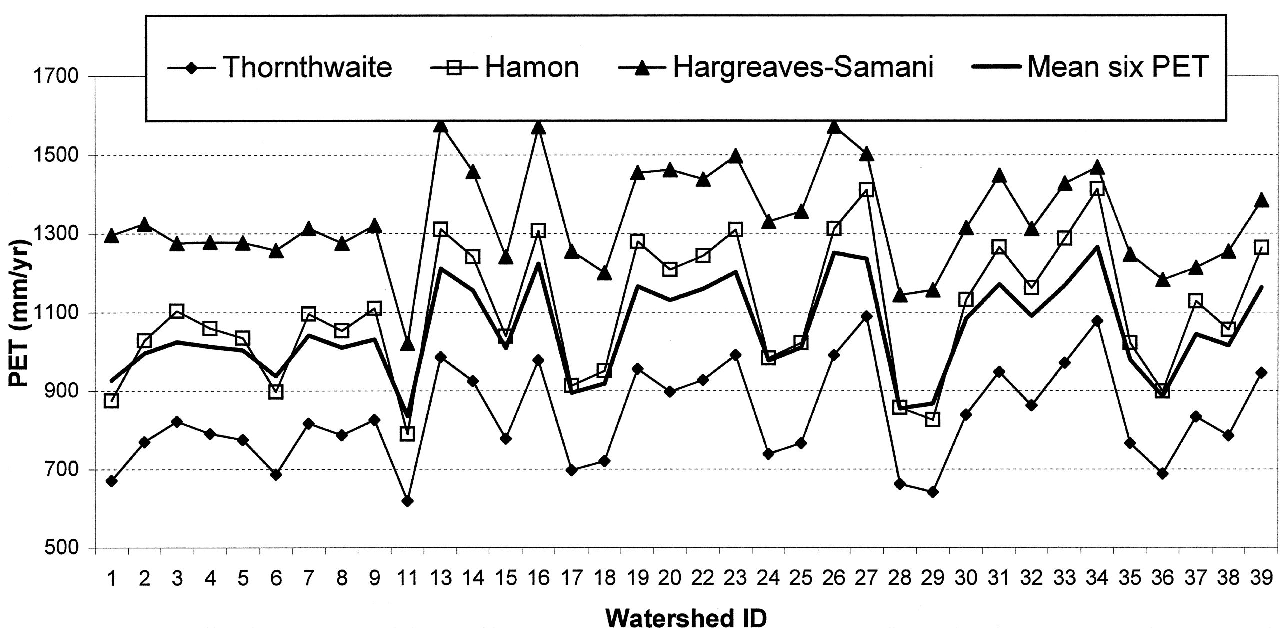

Figure 3. Mean Annual Watershed PET Simulated by the Three Temperature Based Methods.

much lower values for the other two sites (Figures 7 and 8). Among the four selected sites, the Georgia and Florida sites had the biggest and smallest variations in PET among the six tested PET methods (Figures 5 and 8). In general, the relative magnitude (or positions in the charts) of PET values predicted by each method is consistent for all sites (Figures 6, 7, and 8). Exceptions were found for the years 1988 to 1990 for

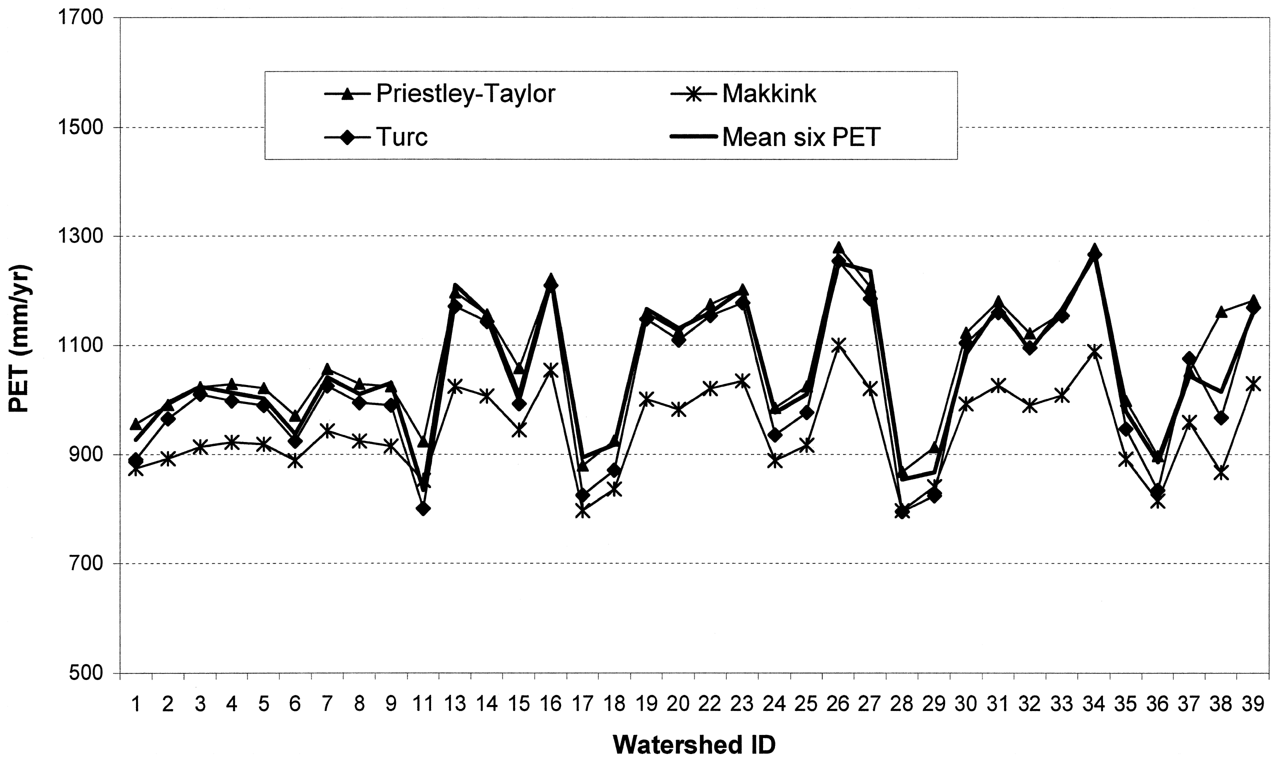

Figure 4. Mean Annual Watershed PET Simulated by the Three Radiation Based Methods.

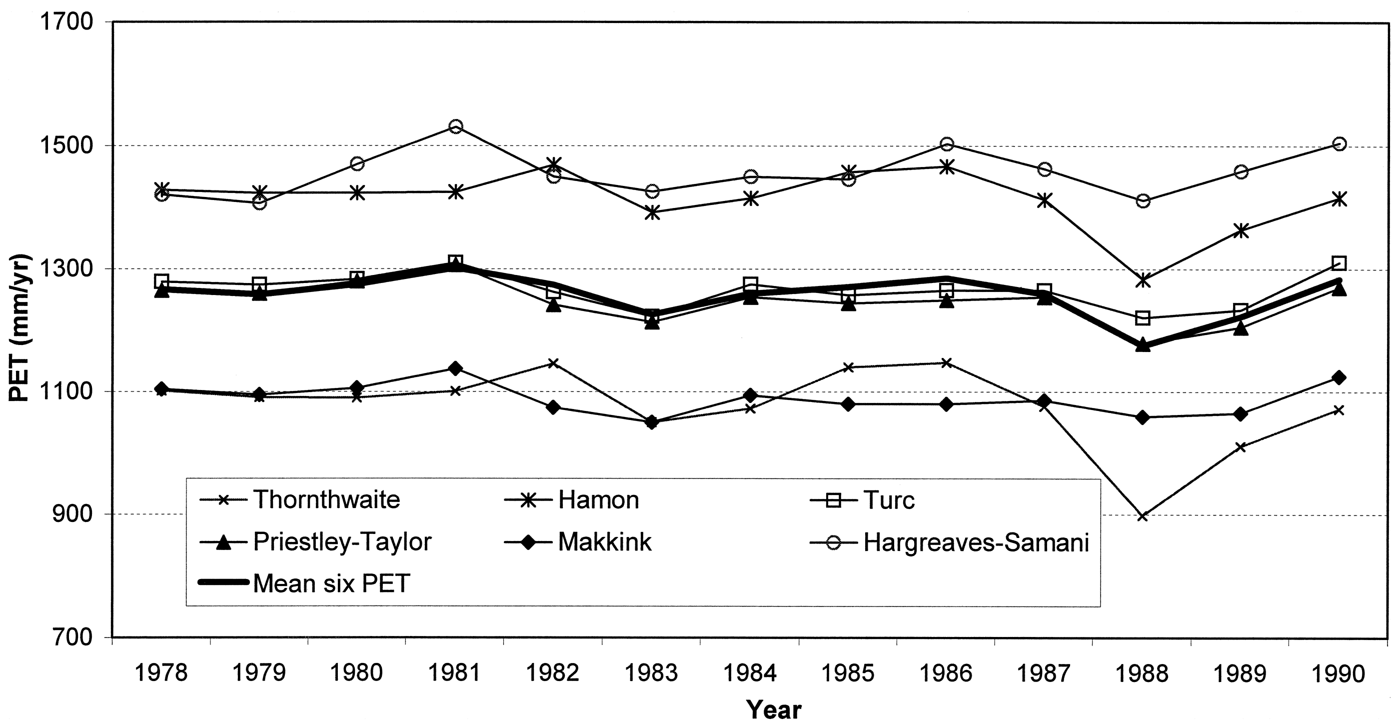

Figure 5. Comparison of Mean Annual PET by Six Methods at the Bradford Watershed on the Upper Coastal Plain in North-Central Florida (Watershed ID 34).

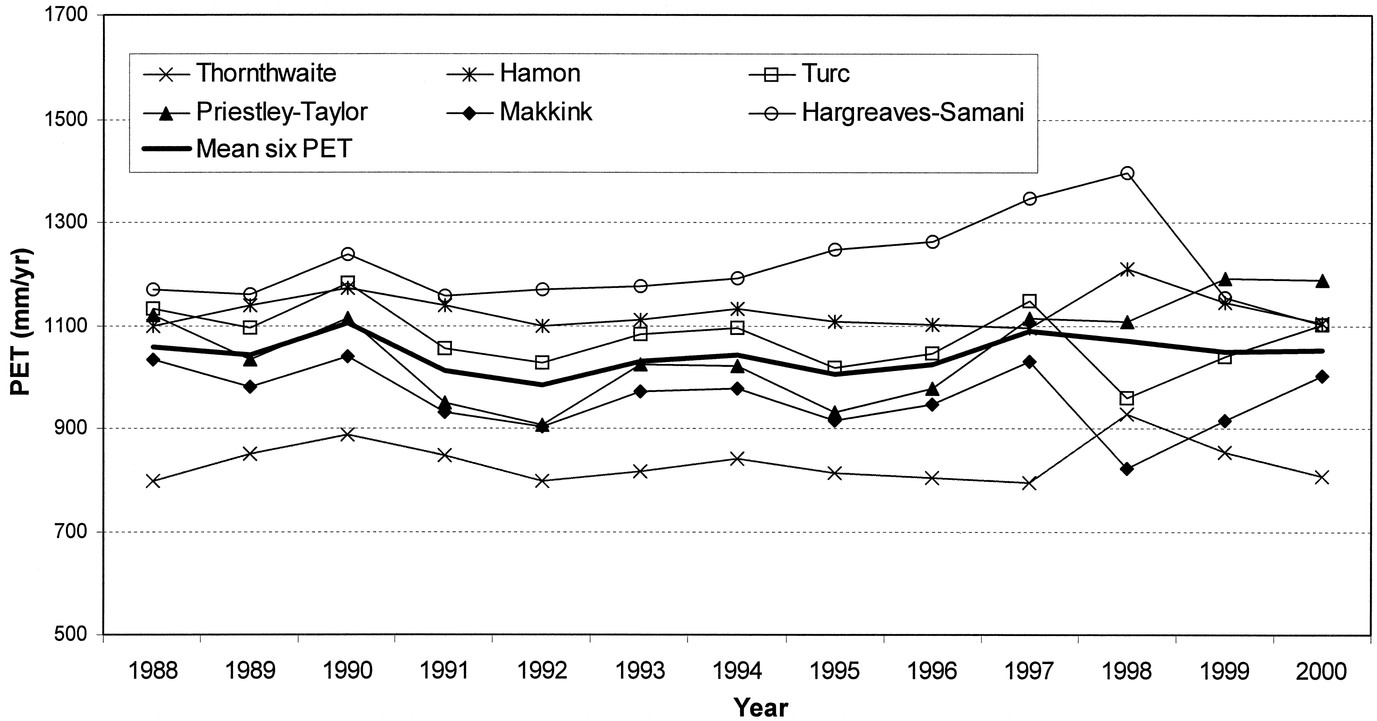

Figure 6. Comparison of Mean Annual PET by Six Methods at the Carteret Watershed on the Coast of North Carolina (Watershed ID 37).

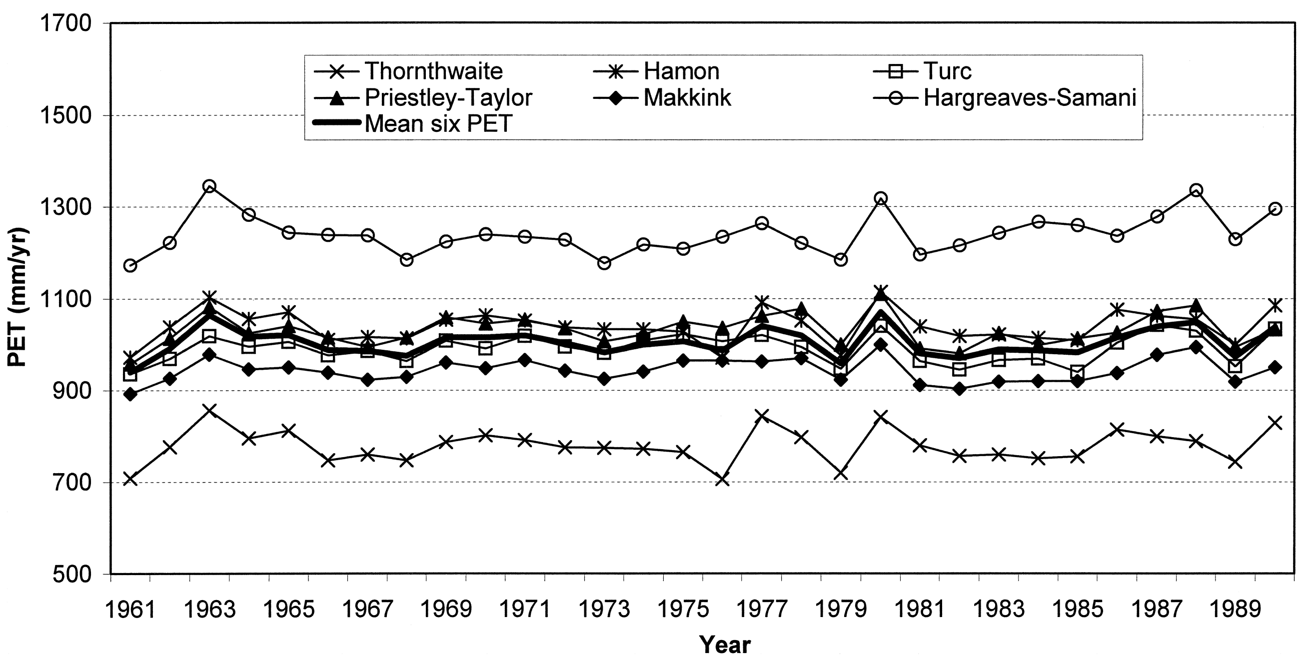

Figure 7. Comparison of Mean Annual PET by Six Methods at an Upland Watershed in Arkansas (Watershed ID 15).

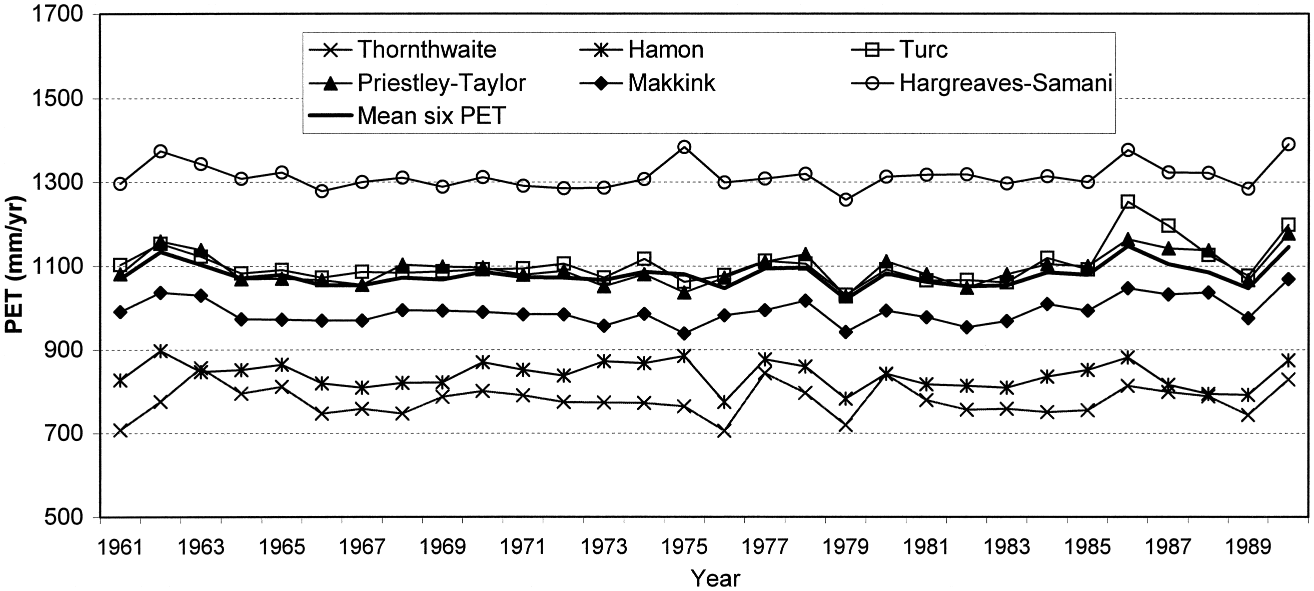

Figure 8. Comparison of Mean Annual PET by Six Methods at a Piedmont Watershed in Georgia (Watershed ID 32).

the Florida site when both the Hamon and Thornthwaite methods predicted much lower PET when compared to other years and their reference methods, Hargreaves-Samani and Makkink, respectively (Figure 5). Similar observations were found for the Carteret site in North Carolina during the period 1995 to 1998 (Figure 6). Because the six PET methods produce inconsistent results, much care must be used when selecting the appropriate method for a particular watershed.

Correlations Between Estimated PET and Calculated AET by the Watershed Balance Method

As stated earlier, preferred PET methods should produce PET estimates that have high correlations with AET. To evaluate the performances of six PET methods on this criterion, long term annual PET estimated from the six methods were correlated with the AET values derived from the water balances. All PET values were highly correlated with the AET values with Pearson Correlation Coefficient ranging 0.57 to 0.65 (Table 4). The Priestley-Taylor PET estimates had the highest correlation coefficient (0.65) and the Hargreaves-Samani PET had the lowest correlation coefficient (0.57) with calculated AET. The Makkink PET had slightly lower correlation coefficient than other methods (0.60). It appears that all of the PET methods have the potential to be applied in a model to derive AET.

TABLE 4. Pearson Correlation Coefficients Between Six PET Methods and AET Estimates (n = 36).

PET Methods	R	P-Value
Thornthwaite	0.63	<0.0001
Hamon	0.63	<0.0001
Turc	0.64	<0.0001
Priestley-Taylor	0.65	<0.0001
Makkink	0.60	0.0001
Hargreaves-Samani	0.57	0.0003

DISCUSSION AND CONCLUSIONS

This study suggested that PET is difficult to estimate accurately and should be used with caution for estimating actual water loss from natural systems. The commonly used PET methods for this comparison study gave a wide range of values, showing differences in PET across the southeastern United States among six methods as high as 500 mm/yr. This magnitude of variation was also found in the previous studies by Amatya *et al.* (1995) and Federer *et al.* (1996). The study also suggested the importance of methodology used when PET values are computed in hydrological studies, and showed that spatially the estimated PET values by any of the six methods varied greatly across the southeastern United States. The annual PET values generally follow the high-low gradient from the south to the north and from the coastal plains to the piedmont, and to the Appalachian Mountains.

For a specific site or year, similar magnitudes of deviation were found for all three temperature based PET methods. The unmodified (not calibrated) Thornthwaite method yielded the lowest PET values that were even slightly lower than actual evapotranspiration, while the Hargreaves-Samani method gave the highest PET estimates. This suggests that careful calibration and verification efforts are needed when applying the Thornthwaite PET method. A recent study showed that the Hargreaves-Samani PET method, which was originally developed for the California dry climate, worked well for windy locations under the semiarid conditions in northeastern Spain (Martinez-Cob and Tejero-Juste, 2004). However, the results of the present study suggest that this method may not be appropriate in the warm, humid, southeastern United States. Greater differences were found among the three temperature based PET methods than among the three radiation based PET methods. Although it is not clear why such big differences exist among methods, it is understandable because many of the PET methods were developed for regions other than the southeastern United States. It appears that radiation based methods that were developed for warm, humid climate conditions (Priestley-Taylor and Turc methods) perform well for the southeastern United States, as expected.

Because they require less data and closely correlate with AET, we conclude that the Priestley-Taylor, Turc, and Hamon PET methods are better than the Thornthwaite, Makkink, and Hargreaves-Samani PET methods for watershed-scale applications in the southeastern United States. These three preferred methods would give stable and reasonable estimates of annual PET that could be used in hydrologic modeling in this region. Among the three methods, the Priestley-Taylor PET method is recommended if radiation data is available. Otherwise, the Hamon PET method could be used.

APPENDIX A
EXPRESSIONS FOR POTENTIAL EVAPOTRANSPIRATION

Thornthwaite (1948) Method

$$PET = 1.6 L_d \left(\frac{10T}{I} \right)^a$$

where PET is the monthly PET (cm); L_d is the daytime length, it is time from sunrise to sunset in multiples of 12 hours; T is the monthly mean air temperature (°C); $a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 0.01791 I + 0.49239$; and I is the annual heat index, which is computed from the monthly heat indices

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

where i_j is computed as

$$i_j = \left(\frac{T_j}{5} \right)^{1.514}$$

T_j is the mean air temperature in °C for month j; j = 1,…,12.

Hamon (1963) Method (PET = 0 when T < 0)

$$PET = 0.1651 \times Ld \times RHOSAT \times KPEC$$

where PET is the daily PET (mm); L_d is the daytime length, which is time from sunrise to sunset in multiples of 12 hours; RHOSAT is the saturated vapor density (g/m^3) at the daily mean air temperature (T); and where

$$\text{RHOSAT} = 216.7 \times \text{ESAT} / (\text{T} + 273.3)$$

$$\text{ESAT} = 6.108 \times \text{EXP}\,(17.26939 \times \text{T} / (\text{T} + 237.3))$$

T is the daily mean air temperature (°C); ESAT is the saturated vapor pressure (mb) at the given T; and KPEC is the calibration coefficient, which is set to 1.2 in this study.

Turc (1961) Method

RH < 50 percent

$$PET = 0.013 \left(\frac{T}{T+15} \right) (R_s + 50) \left(1 + \frac{50 - RH}{70} \right)$$

RH > 50 percent

$$PET = 0.013 \left(\frac{T}{T+15} \right) (R_s + 50)$$

where, PET is the daily PET (mm/day); T is the daily mean air temperature (°C); R_s is the daily solar radiation (ly/day or cal/cm^2/d) and where cal/cm^2/d equals (100/4.1868) MJ/m^2/day; and RH is the daily mean relative humidity (percent).

Priestley-Taylor (1972) Method

$$\lambda PET = \alpha \frac{\Delta}{\Delta + \gamma}\left(R_n - G\right)$$

where PET is the daily PET (mm/day); λ is the latent heat of vaporization (MJ/kg) and where λ = 2.501 - 0.002361 T; T is the daily mean air temperature (°C); α is the calibration constant, α = 1.26 for wet or humid conditions; Δ is the slope of the saturation vapor pressure temperature curve (kPa/°C) and where $\Delta = 0.200\ (0.00738\ T + 0.8072)^7 - 0.000116$; and γ is the psychrometric constant modified by the ratio of canopy resistance to atmospheric resistance (kPa/°C).

$$\gamma = \frac{c_p p}{0.622\lambda}$$

where c_p is the specific heat of moist air at constant pressure (kJ/kg/°C) and where c_p = 1.013 kJ/kg/°C = 0.001013 MJ/kg/°C; p is the atmospheric pressure (kPa) and where p = 101.3 - 0.01055 EL; EL is the elevation (m); Rn is the net radiation (MJ/m^2/day); and G is the heat flux density to the ground (MJ/m^2/day).

$$G = 4.2\frac{\left(T_{i+1} - T_{i-1}\right)}{\Delta t} = -4.2\frac{\left(T_{i-1} - T_{i+1}\right)}{\Delta t}$$

where T_i is the mean air temperature (°C) for the period i; and Δt is the difference of time (days) between two periods.

Makkink (1957) Method

$$PET = 0.61\left(\frac{\Delta}{\Delta + \gamma}\right)\frac{R_s}{58.5} - 0.12$$

All variables in the equation have the same meanings and units as those in the Priestley-Taylor and Turc method.

Hargreaves-Samani (1985) Method

$$\lambda PET = 0.0023 \times R_a \times TD^{0.5} \times (T + 17.8)$$

where PET is the daily PET (mm/day); λ is the latent heat of vaporization (MJ/kg); T is the daily mean air temperature (°C); R_a is the extraterrestrial solar radiation (MJ/m^2/day; and TD is the daily difference between the maximum and minimum air temperature (°C).

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LITERATURE CITED

Amatya, D.M., G.M. Chescheir, R.W. Skaggs, and G.P. Fernandez, 2002. Hydrology of Poorly Drained Coastal Watersheds in Eastern North Carolina. ASAE Paper No. 022034, St. Joseph, Michigan.

Amatya, D.M. and R.W. Skaggs, 2001. Hydrologic Modeling of Pine Plantations on Poorly Drained Soils. Forest Science 47(1):103-114.

Amatya, D.M., R.W. Skaggs, and J.D. Gregory, 1995. Comparison of Methods for Estimating REF-ET. Journal of Irrigation and Drainage Engineering 121:427-435.

Arthur, M.A., G.B. Coltharp, and D.L. Brown, 1998. Effects of Best Management Practices on Forest Stream Water Quality in Eastern Kentucky. Journal of the American Water Resources Association (JAWRA) 34(3):481-495.

Band, L.E., D.S. Mackay, and I.F. Creed, 1996. Ecosystem Processes at the Watershed Sale: Sensitivity to Potential Climate Change. Limnol. Oceanogr. 41(5):928-938.

Castellvi, F., C.O. Stockle, P.J. Perez, and M. Ibanez, 2001. Comparison of Methods for Applying the Priestley-Taylor Equation at a Regional Scale. Hydrological Processes 15:1609-1620.

Church, M.R., G.D. Bishop, and D.L. Cassell, 1995. Maps of Regional ET and Runoff/Precipitation Ratios in the Northeast United States. Journal of Hydrology 168:283-298.

Crago, R.D. and W. Brutsaert, 1992. A Comparison of Several Evaporation Equations. Water Resour. Res. 28:951-954.

Currie, D.J., 1991. Energy and Large-Scale Patterns of Animal- and Plant-Species Richness, The American Naturalist 137(1):27-49.

Federer, C.A. and D. Lash, 1983. BROOK: A Hydrologic Simulation Model for Eastern Forests. Research Report 19, Water Resource Research Center, University of New Hampshire, Durham, New Hampshire.

Federer, C.A., C. Vörösmarty, and B. Fekete, 1996. Intercomparison of Methods for Calculating Potential Evaporation in Regional and Global Water Balance Models. Water Resources Research 32:2315-2321.

Fennessey, N.M. and R.M. Vogel, 1996. Regional Models of Potential Evaporation and Reference ET for the Northeast USA. Journal of Hydrology 184:337-354.

Grismer, M.E., M. Orang, R. Snyder, and R. Matyac, 2002. Pan Evaporation to Reference Evapotranspiration Conversion Methods. J. Irrigation and Drainage Engineering 128(3):180-184.

Hamon, W.R., 1963. Computation of Direct Runoff Amounts From Storm Rainfall. Int. Assoc. Sci. Hydrol. Pub. 63:52-62.

Hargreaves, G.H. and Z.A. Samani, 1985. Reference Crop Evapotranspiration From Temperature. Applied Engrg. in Agric. 1(2):96-99.

Hay, L.E. and G.J. McCabe, 2002. Spatial Variability in Water Balance Model Performance in the Conterminous United States. Journal of the American Water Resources Association (JAWRA) 38(3):847-860.

Jensen, M.E., R.D. Burman, and R.G. Allen, 1990. Evapotranspiration and Irrigation Water Requirements. American Society of Civil Engineers, New York, New York, 332 pp.

Johnson, D.W. and R.I.V. Hook (Editors), 1989. Analysis of Biogeochemical Cycling Processes in Walker Branch Watershed. Springer-Verlag, New York, New York.

Kolka, R.K. and A.T. Wolf, 1998. Estimating Actual Evapotranspiration for Forested Sites: Modifications to the Thornthwaite Model. Res. Note SRS-6, USDA Forest Service, Southern Research Station, Asheville, North Carolina, 7 pp.

Liang, Y., S.R. Durrans, and T. Lightsey, 2002. A Revised Version of PnET-II to Simulate the Hydrologic Cycle in Southeastern Forested Areas. Journal of the American Water Resources Association (JAWRA) 38(1):79-89.

Lu, J., 2002. Modeling Regional Evapotranspiration for Forested Watersheds Across the Southern United States. Master's Thesis, North Carolina State University, Raleigh, North Carolina, 105 pp.

Lu, J., G. Sun, S.G. McNulty, and D.M. Amatya, 2003. Modeling Actual Evapotranspiration From Forested Watersheds Across the Southeastern United States. Journal of the American Water Resources Association (JAWRA) 39(4):887-896.

Makkink, G.F., 1957. Testing the Penman Formula by Means of Lysimeters. J. Inst. of Water Eng. 11:277-288.

Martinez-Cob, A. and M. Tejero-Juste, 2004. A Wind-Based Qualitative Calibration of the Hargreaves ET0 Estimation Equation in Semiarid Regions. Agricultural Water Management 64:251-264.

Monteith, J.L., 1973. Principles of Environmental Physics. Elsevier, New York, New York, 241 pp.

Nokes, S.E., 1995. Evapotranspiration (Chapter 4). *In:* Environmental Hydrology, A.D. Ward and W.J. Elliot (Editors). Lewis Publishers, Boca Raton, Florida, pp. 91-131.

Penman, H.L., 1948. Natural Evaporation From Open Water, Bare Soil and Grass. Proc. Roy. Soc. London, A193:120-146.

Priestley, C.H.B. and R.J. Taylor, 1972. On the Assessment of Surface Heat Flux and Evaporation Using Large Scale Parameters. Mon. Weath. Rev. 100:81-92.

Riekerk, H, 1985. Lysimetric Evaluation of Pine Forest Evapotranspiration for Water Balances. In: The Forest – Atmosphere Interaction, B.A. Hutchison and B.B. Hicks (Editors). Reidel Publishing Co., Boston, Massachusetts, pp 293-308.

Riekerk, H., 1989. Influence of Silvicultural Practices on the Hydrology of Pine Flatwoods in Florida. Water Resources Research 25:713-719.

SAS Institute Inc., 2001. SAS User's Guide 8.2. SAS Institute, Inc., Cary, North Carolina.

Stein, J., R. Caissy, A.P. Plamondon, and P.Y. Bernier, 1995. Estimation of Potential Evapotranspiration With Shallow Lysimeters in a Forest Tree Nursery. The Forestry Chronicle 71(6): 755-758.

Sun, G., J. Lu, D. Gartner, M. Miwa, and C.C. Trettin, 2000. Water Budgets of Two Forested Watersheds in South Carolina. *In:* Water Quantity and Quality Issues in Coastal Areas: R.W. Higgins (Editor). Proceedings of AWRA's Annual Water Resources Conference. American Water Resources Association, Middleburg, Virginia, pp. 199-202.

Sun, G., S.G. McNulty, D.M. Amatya, R.W. Skaggs, L.W. Swift, J.P. Shepard, and H. Riekerk, 2002. A Comparison of the Hydrology of the Coastal Forested Wetlands and the Mountainous Uplands in the Southern US. J. Hydrology 263:92-104.

Sun, G., H. Riekerk, and N.B. Comerford, 1998. Modeling the Forest Hydrology of Wetland-Upland Ecosystems in Florida. Journal of the American Water Resources Association (JAWRA) 34:827-841.

Thornthwaite, C.W., 1948. An Approach Toward a Rational Classification of Climate. Geograph. Rev. 38 (1):55-94.

Thornthwaite, C.W. and J.R. Mather, 1955. The Water Balance. Publications in Climatology, Drexel Institute of Technology, Centerton, New Jersey, Vol. VIII, No. 1.

Turc, L., 1961. Evaluation de besoins en eau d'irrigation, ET potentielle, Ann. Agron. 12:13-49.

Vörösmarty, C.J., C.A. Federer, and A.L. Schloss, 1998. Potential Evaporation Functions Compared on US Watersheds: Possible Implications for Global-Scale Water Balance and Terrestrial Exosystem Modeling. Journal of Hydrology 207:147-169.

Zhang, L., W.R. Dawes, and G.R. Walker, 2001. Response of Mean Annual ET to Vegetation Changes at Catchment Scale. Water Resources Research 37 (3):701-708.