MODELING POTENTIAL EVAPOTRANSPIRATION OF TWO FORESTED WATERSHEDS IN THE SOUTHERN APPALACHIANS

L. Y. Rao, G. Sun, C. R. Ford, J. M. Vose

ABSTRACT. *Global climate change has direct impacts on watershed hydrology through altering evapotranspiration (ET) processes at multiple scales. There are many methods to estimate forest ET with models, but the most practical and the most popular one is the potential ET (PET) based method. However, the choice of PET methods for AET estimation remains challenging. This study explored ways to identify appropriate PET models for two small forested watersheds, one dominated by conifer plantation and one dominated by native naturally regenerated deciduous hardwoods, by using long-term hydrometeorological data collected at the Coweeta Hydrologic Laboratory in the humid Appalachians in the southeastern U.S. Our specific objectives were to: (1) contrast three common PET models (FAO-56 grass reference ET, Hamon PET, and Priestley-Taylor PET) and compare these PET estimates with measured AET at monthly and annual temporal scales, and (2) derive correction factors for the FAO-56 grass reference ET and Hamon PET models at the monthly scale using the Priestley-Taylor equation as the standard method for estimating forest PET. We found that different PET models gave significantly different PET estimates. The Priestley-Taylor equation gave the most reasonable estimates of forest PET for both watersheds. We conclude that the uncorrected Hamon and FAO PET methods would cause large underestimates of forest PET. Annual PET rates of the conifer watershed were higher than those of the native deciduous watershed due to the lower albedo (thus higher net radiation) in the former compared to the latter. Monthly correction factors provided useful tools for forest PET estimation in those areas lacking climatic data (i.e., radiation, humidity, and wind speed).*

Keywords. *FAO-56 grass reference ET, Forest potential evapotranspiration, Hamon equation, Priestley-Taylor equation.*

Global climate change has direct impacts on watershed hydrology through altering precipitation patterns and evapotranspiration (ET) processes at multiple scales (Sun et al., 2008). Predicting the impacts of altered climate on ET is especially challenging because ET not only varies with climate but also across vegetation types, ages, and structures and with differences in soil water availability. There are many methods to estimate ET, but the most popular are PET-based methods, i.e., estimating potential evapotranspiration (PET) as the maximum of actual ET and then calculating actual ET by including soil moisture and leaf area dynamics as constraints (Zhang et al., 2004; Zhou et al., 2008; Sun et al., 2011). This practice is especially common in hydrological modeling at a large scale when limited climate data are available and a process-based modeling approach that simulates water pathways in the soil-plant-atmosphere continuum is not feasible (Vorosmarty et al., 1998; Wolock and McCabe, 1999; Dai et al., 2010).

PET is defined as the amount of water that can be evaporated and transpired when soil water is sufficient to meet atmospheric demand (Allen et al., 1998). As such, this variable represents the available energy driving the water loss to the atmosphere for an ecosystem. Unfortunately, PET can be a confusing concept for some hydrologists or ecologists because PET does not clearly specify what land surface it refers to (e.g., grass vs. forest vs. cropland). For example, the potential amount of water that a forest could evaporate and transpire is typically much greater than that for a grass ecosystem under the same water unlimited conditions. The reason is that the leaf surface area of a forest is generally much higher than that of grassland (Sun et al., 2011). To minimize this confusion and normalize the vegetated land surface to which PET refers to, the term "grass reference ET" has been used as the standard way to represent the energy conditions for a reference crop in a particular region, which can be estimated by the standardized FAO-56 Penman-Monteith model (Allen et al., 1998). Using the grass reference ET thus makes PET estimates comparable worldwide (Allen et al., 1998; Yoder et al., 2005).

PET has been widely used not only in agricultural hydrology for estimating crop irrigation water needs (Allen, 2008) but also in regional biodiversity modeling by ecologists (Currie, 1991). Currently, more than 50 mathematical models are available to estimate PET. These methods can be grouped into five categories (Xu and Singh, 2002): (1) mass transfer (e.g., Harbeck, 1962),

---

Submitted for review in April 2011 as manuscript number SW 9179; approved for publication by the Soil & Water Division of ASABE in November 2011.

The authors are **Liangyi Rao,** Associate Professor, College of Soil and Water Conservation, Beijing Forestry University, Beijing, China; **Ge Sun,** Research Hydrologist, USDA Forest Service, Eastern Forest Environmental Threat Assessment Center, Raleigh, North Carolina; **Chelcy R. Ford,** Research Ecologist, and **James M. Vose,** Project Leader, USDA Forest Service, Coweeta Hydrologic Laboratory, Otto, North Carolina. **Corresponding author:** Ge Sun, USDA Forest Service, Eastern Forest Environmental Threat Assessment Center, 920 Main Campus Drive, Suite 300, Raleigh, NC 27606; phone: 919-515-9498; fax: 919-513-2978; e-mail: gesun@ncsu.edu.

(2) combination methods (e.g., Penman, 1948), (3) radiation based (e.g., Priestley and Taylor, 1972), (4) water budget (e.g., Guitjens, 1982), and (5) temperature based (e.g., Thornthwaite, 1948; Blaney and Criddle, 1950; Hamon, 1963). Xu and Singh (2002) compared five popular empirical PET equations using daily meteorological data in Switzerland. Compared with the Penman-Monteith estimates, they ranked the model's accuracy (from high to low) as: Priestley-Taylor, Makkink, Hargreaves, Blaney-Criddle, and Rohwer. Rosenberry et al. (2004) compared PET and ET estimates by 13 models with ET rates estimated by energy budget method at a prairie wetland setting in North Dakota. They found that the Priestley-Taylor and DeBruin-Keijman PET methods compared best with the energy budget method, and the Penman, Jensen-Haise, and Brutsaert-Stricker methods provided the next-best PET estimates when compared to the energy budget method, while the mass transfer, DeBruin, and Stephens-Stewart methods performed least favorably.

Lu et al. (2005) contrasted six commonly used PET methods using data from 36 forested watersheds across a physiographic gradient in the southeastern U.S. These PET models included three temperature-based (Thornthwaite, Hamon, and Hargreaves-Samani) and three radiation-based (Turc, Makkink, and Priestley-Taylor) PET methods. Although all annual PET values were highly correlated, the Priestley-Taylor, Turc, and Hamon (with correction) methods performed better than the others. Their study also indicated that PET models gave better estimates when radiation was a model input versus using temperature alone. Based on the criteria of availability of input data and correlations with actual ET values, the Priestley-Taylor, Turc, and Hamon methods were recommended for regional applications in the southeastern U.S.

Wang et al. (2006) examined how PET model choices affected runoff predictions for a cropland-dominated watershed in northwestern Minnesota by the widely used Soil and Water Assessment Tool (SWAT) hydrological model. They found that the three PET modeling methods affected model calibration parameters, and the Hargreaves PET model was slightly superior to the Priestley-Taylor and Penman-Monteith methods. Although Wang et al. (2006) found that once the SWAT model was calibrated, the choice of PET models did not significantly affect streamflow predictions, Earls and Dixon (2008) argued that characterization of PET model was critical in hydrologic budgets, rainfall-runoff models, infiltration calculations, and drought prediction models. Earls and Dixon (2008) concluded that the PET calculation methods (Penman-Monteith, Hargreaves, and Priestley-Taylor) provided by the SWAT model gave different PET results in Florida and thus might affect streamflow calculations since ET is a large component of the water balances in a humid environment.

Because PET models were developed primarily for agricultural ecosystems, it is not clear if these models are appropriate for forested ecosystems. Previous studies suggest that to model actual ET using PET, the PET models must be corrected to reflect differences in potential water loss from different land surfaces, such as forests (Lu et al., 2009), wetlands (Dolan et al., 1984; Wessel and Rouse, 1994; Bidlake, 2000; Zhou and Zhou, 2009), and vineyards (Yunusa et al., 2004; Zhang et al., 2008). PET rates for crops can be estimated by the microlysimeter method. However, estimating PET for trees or forests, which are massive above and below ground, is impractical; thus, forest PET values are rarely available. Generally, forest PET is estimated by theoretical or empirical equations, or simply derived by multiplying standard pan evaporation data with a correction coefficient (Grismer et al., 2002). Therefore, choices of forest PET methods are rather arbitrary in the hydrologic modeling community, and thus large uncertainty exists (Lu et al., 2009; Dai et al., 2010).

Given the uncertainty of existing PET models, it is important to test the suitability of the PET models for different regions and land surface conditions. The FAO-56 grass reference ET model (henceforth FAO PET), a variant of the Penman-Monteith model for short grass surfaces, is regarded as the most dependable model, but it is difficult to use for complex landscapes at large scales because it requires numerous meteorological data, such as net radiation, wind speed, and relative humidity. As a result, empirical models that are solely driven by temperature and solar radiation or by temperature alone are still popular. Among them, the Priestley-Taylor model (henceforth P-T; Priestley and Taylor, 1972) is recommended for PET estimation in humid climate regions when radiation data are available. The Hamon equation has been used for global hydrological studies when only temperature data are available. It is unclear how the PET rates estimated by these three models (FAO, Hamon, and P-T) differ at the daily, monthly, and annual time scales.

The Coweeta Hydrologic Laboratory (fig. 1), located in the humid southern Appalachian Mountain region in the southeastern U.S., has a long record of climate and streamflow measurements and forest ecosystem studies that offer ample opportunities to evaluate PET models against actual ET at the watershed scale. No previous attempts have been made to estimate long-term forest PET using empirical equations at Coweeta. In this study, we focused on two forested watersheds: a conifer plantation forest (watershed 17), and a native deciduous forest (watershed 18). We modeled forest PET with climatic data for the time period of 1986 to 2007. We compared PET estimates by various models with actual ET derived from watershed water balances and tree-based estimates to evaluate model performance.

Our overall goal is to improve the estimation of forest ET using limited climatic data as a first step toward developing credible hydrological models for forested watersheds that can be used to project the response to a changing climate and land cover. The specific objectives of this article were to: (1) contrast three different PET models using long-term hydrometeorological data collected from two watersheds with distinct forest covers at multi-temporal scales, and (2) further develop ways to estimate forest PET across a range of data availability by relating the Hamon (i.e., least data demanding) and FAO methods (i.e., most data demanding) to the P-T method (i.e., moderate data demanding) that has been identified as the preferred PET model.

METHODS

PET MODELS

We chose three PET models that have different data requirements and complexity: Hamon (temperature based), Priestley-Taylor (radiation based), and FAO (full Penman-Monteith equation for a grass surface). The three estimates were compared and used to explore how model complexity affects PET estimates. The PET estimates were also compared to actual ET at monthly and annual scales to illustrate potential errors when PET estimates are used for hydrologic modeling. We briefly present the three models below, all of which estimate daily PET. Monthly PET was calculated by summing daily values, and annual PET was the sum of monthly PET values.

Hamon (1963) developed a simple equation to estimate PET given mean air temperature and day length. By this method, PET does not become zero when the mean air temperature is less than 0°C but provides essentially the same annual total as that of the Thornthwaite method (Federer and Lash, 1983). PET is estimated as:

$$\mathrm{PET} = 0.1651 \cdot L_{day} \cdot \varrho_{sat} \tag{1}$$

$$\varrho_{sat} = \frac{216.7 \cdot e_s}{T + 273.3} \tag{2}$$

$$e_s = 6.108 \cdot \mathrm{e}^{\frac{17.26 \cdot T}{T + 273.3}} \tag{3}$$

where

PET = daily potential evapotranspiration (mm)

L_{day} = daytime length, which is time from sunrise to sunset in multiples of 12 h

ρ_{sat} = saturated vapor density at the daily mean air temperature T (g m^{-3})

e_s = saturated vapor pressure at the given T (mbar).

The e_s equation is derived by Murray (1967), allowing air temperatures to fall below 0°C.

Priestley-Taylor equation (Priestley and Taylor, 1972) is a radiation-based semi-empirical model that was derived from the physics-based Penman-Monteith model (Monteith, 1965). The Penman-Monteith model estimates ET as a function of available energy, vapor pressure deficit, air temperature, pressure, aerodynamic resistance (a function of wind speed and plant-canopy height and roughness), and canopy resistance (a measure of resistance to vapor transport from plants). In the Priestley-Taylor model, the atmosphere is assumed to be saturated, in which case the aerodynamic term is zero. An empirically derived correction factor, α = 1.26, is often used as a coefficient for humid regions to estimate PET (Jensen et al., 1990):

$$\lambda \mathrm{PET} = \alpha \frac{\Delta}{\Delta + \gamma} R_n \tag{4}$$

$$\lambda = 2.501 - 0.002361\, T \tag{5}$$

$$\Delta = 0.200\,(0.00738\, T + 0.8072)^7 - 0.000116 \tag{6}$$

$$\gamma = \frac{c_p p}{0.622 \lambda} \tag{7}$$

$$p = 101.3 - 0.01055\ \mathrm{EL} \tag{8}$$

where

PET = daily potential evapotranspiration (mm)

λ = latent heat of vaporization (MJ kg^{-1})

T = daily mean air temperature (°C)

α = correction factor (1.26 in this study)

Δ = slope of the saturation vapor pressure versus temperature curve (kPa °C^{-1})

γ = psychrometric constant modified by the ratio of canopy resistance to atmospheric resistance (kPa °C^{-1})

c_p = specific heat of moist air at constant pressure (1.013 kJ kg^{-1} °C^{-1})

p = atmospheric pressure (kPa)

EL = elevation (m)

R_n = net radiation (MJ m^{-2} d^{-1}).

The FAO model (Allen et al., 1998) is derived from the process-based Penman-Monteith ET equation assuming a hypothetical well-watered grass that has a 0.12 m canopy height, a leaf area of 4.8 m^2 m^{-2}, a bulk surface resistance of 70 s m^{-1}, and an albedo of 0.23. Details of the computation procedures are found in Allen et al. (1998). Briefly however:

$$\mathrm{PET} = \frac{0.408 \Delta (R_n - G) + \gamma \frac{C}{T + 273} \mu_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 \mu_2)} \tag{9}$$

$$\Delta = 2503 \frac{\mathrm{e}^{\frac{17.27 T}{T + 237.3}}}{(T + 237.3)^2} \tag{10}$$

where

PET = daily Potential evapotranspiration (mm)

Δ = slope of the saturation water vapor pressure versus air temperature T (kPa °C^{-1})

R_n = total net radiation (MJ m^{-2})

G = total soil heat flux (MJ m^{-2}, assumed zero in this study)

γ = psychrometric constant (kPa °C^{-1})

e_s = saturation vapor pressure (kPa)

e_a = actual vapor pressure (kPa)

μ_2 = mean wind speed at 2 m height (m s^{-1})

C = unit conversion factor with a value of 900.

MODEL EVALUATION CRITERIA

We used two criteria to determine the appropriateness of PET models for estimating forest PET: (1) the magnitude of PET estimates, i.e., modeled PET should be higher than measured ET in the two forested watersheds; and (2) the correlation strength, i.e., modeled monthly PET should be significantly correlated with measured ET.

RESEARCH SITES AND HYDRO-METEOROLOGICAL DATABASES

The two forested watersheds (watersheds 17 and 18) selected for this modeling study are located in the Coweeta Hydrologic Laboratory in western North Carolina in the southern Appalachians (fig. 1). The climate at Coweeta is classified as marine, humid temperate (Swift et al., 1988).

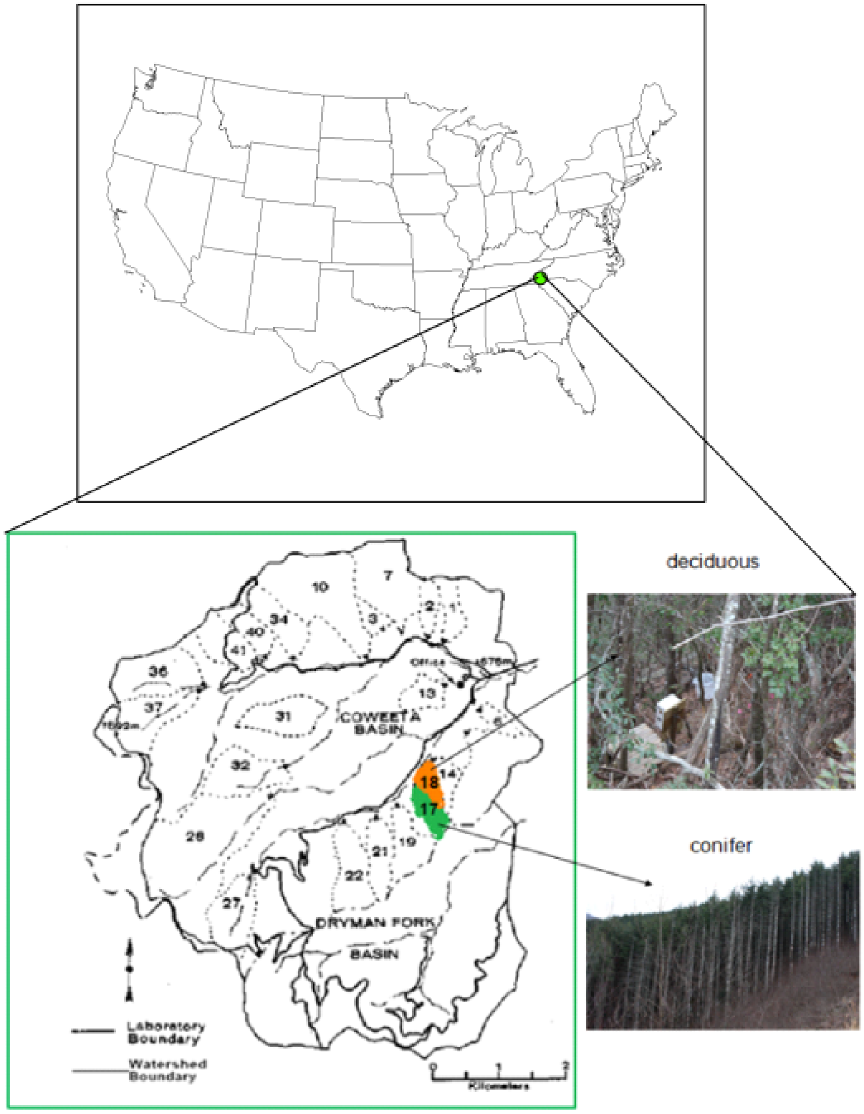

Figure 1. Location of two forested watersheds at Coweeta Hydrological Laboratory in North Carolina.

The mean annual precipitation is 2014 mm, and the mean air temperature is 13°C. Elevations in watersheds 17 and 18 range from 742 to 1021 m and from 726 to 993 m, respectively. Soils in both watersheds fall into two main series. The Saunook series, a fine-loamy, mixed, mesic Humic Hapludult, is present at streamside positions (~50 cm depth), and the Cowee-Evard complex soils, a fine loamy, mixed-oxidic, mesic, Typic Hapludult, is typically present on ridges (~70 cm depth) (Knoepp and Swank, 1994).

Watershed 17 is dominated by eastern white pine (*Pinus strobus*) plantation forest established in 1956. It is a northwest-facing 13.5 ha catchment that has an average slope of 57%. It was designated as a treatment watershed at Coweeta in the 1940s to study species conversion effects on watershed hydrology. All woody vegetation in watershed 17 was cut in January to March 1941, regrowth was cut annually thereafter in most years until 1955, and no products were removed. Eastern white pine was planted at 2 m × 2 m spacing in 1956, and competition control was applied by cutting and chemicals as necessary (Swank and Douglass, 1974). In the fall of 2001, an area of 1.2 ha was cut to halt the spread of southern pine beetle infestations. In three mid-watershed stands in 2004-2005, leaf area index was 7.2 m^2 m^{-2} and basal area was 66.5 m^2 ha^{-1} (Ford et al., 2007).

Watershed 18 is a mixed-species deciduous hardwood forest. It is a northwest-facing 12.5 ha watershed with an average slope of 53%. Watershed 18 serves as a reference watershed that has not been purposefully disturbed since being selectively logged in the early 1900s. Natural disturbance was caused by the chestnut blight that decimated American chestnut trees in the southern Appalachians in the 1920s. Plant community composition in watershed 18 is complex and closely associated with elevation, aspect, and soil moisture (Ford et al., 2011). A chestnut-oak-hickory overstory and mountain laurel understory dominate the upper slopes and drier ridges, a northern red oak-red maple-tulip poplar overstory and rhododendron understory dominate the intermediate mid-slopes, and a birch-red maple-tulip poplar overstory and rhododendron understory dominate the mesic cove and riparian areas. In two mid-watershed stands in 2004-2006, leaf area index was 6.2 m^2 m^{-2} and basal area was 39 m^2 ha^{-1} (Ford et al., 2011).

Meteorological data recorded at the main climate station (CS01) was used to estimate PET. This open-field weather station is located approximately 1 km from the two watersheds. Data acquired included daily total solar radiation (R_s) (model 8-48, Epply Lab, Inc., Newport, R.I.), precipitation (P), temperature (T), relative humidity (RH), and wind speed (W). Net radiation (R_n) for FAO grass reference surfaces and two types of forest was derived empirically from R_s using the following equations:

For FAO grass reference (Lee, 1981):

$$R_n = (0.71R_s - 41) \times 4.1868 \times 10^{-2} \tag{11}$$

For a deciduous watershed (Swift et al., 1988):

$$R_n = 0.71R_s \times 4.1868 \times 10^{-2} \tag{12}$$

For a coniferous watershed (Swift et al., 1988):

$$R_n = 0.84R_s \times 4.1868 \times 10^{-2} \tag{13}$$

where

R_n = monthly mean net radiation (MJ m^{-2} d^{-1})

R_s = monthly mean solar radiation (in Langleys; 1 Ly = 41,840 J m^{-2}).

Measured Actual Evapotranspiration (AET)

We used both monthly and annual AET data to evaluate the performance of three PET models. Annual and monthly AET rates were derived by two different methods: watershed water balance, and tree-based sapflow. The two methods have been used to estimate ET for both watersheds, and data were published by Ford et al (2007, 2011).The watershed water balance method estimates annual AET as the difference between measured precipitation (P, mm) and measured streamflow (Q, mm), assuming the change in soil water storage is negligible:

$$\text{AET} = P - Q \tag{14}$$

Streamflow data were collected by V-notch weirs at the watershed outlets. Annual AET was calculated for the years 1986-2007 that corresponded to a time period when solar radiation data were collected at CS01. We recognized that for years with extreme wet or dry years, the AET estimates may have large errors.

Monthly AET data from 2004 and 2005 for watershed 17 (Ford et al., 2007) and watershed 18 (Ford et al., 2011) were used to evaluate PET model performance at the monthly scale. In these studies, watershed-level AET was scaled from tree-level sap flux measurements representing transpiration and modeled stand-level canopy interception (Helvey, 1967). In watershed 18, 31 trees were sampled, representing four major hardwood species: *Liriodendron tulipifera*, *Carya* spp., *Quercus rubra*, and *Quercus prinus*. Due to the lack of representation of the entire watershed 18 in vegetation composition and AET data of the understory, the monthly AET values reported by Ford et al. (2011) were used for reference in the seasonal trend and correlation analysis in the growing season only. In watershed 17, annual AET estimates were developed for *Pinus strobus*. Although uncertainties exist in the monthly AET, they provide the best data for validating models. Ford et al. (2007) attributed the uncertainty of sapflow-based AET estimates to several sources, including: (1) large variability of sap flux within the sapwood of a tree, (2) variability of transpiration among trees and between plots within the catchment, and (3) variability in stand density, sapwood area, and leaf area.

Results

Modeled PET at Different Temporal Scales

Differences in temporal dynamics of modeled daily (1986-2007) PET by the different PET methods were large (fig. 2). The PET estimates by the P-T method for the conifer forest was much higher than for the deciduous forest. The P-T PET estimates for both types of forests were higher than those estimated by the Hamon and FAO methods. The annual mean daily PET was 4.1 mm d^{-1} (P-T, watershed 17), 2.9 mm d^{-1} (P-T, watershed 18), 2.2 mm d^{-1} (Hamon), and 2.4 mm d^{-1} (FAO). The largest differences of PET estimates, up to 4.0 mm d^{-1}, occurred approximately during late spring to early summer (Julian days 100 to 200). In addition, the relative magnitude of PET values shifted significantly around Julian day 190. Prior to Julian day 190, the averaged daily PET calculated by the Hamon method was lowest among the three models. After Julian day 190, the averaged daily FAO PET values were lowest among all the methods in the growing season (April to October). Except for P-T PET for conifer forest, there was little difference among the daily PET estimated by the three models after Julian day 190. The absolute differences among models during the dormant season (November to March) were smaller compared to the growing season. The seasonal differences in PET estimates show that the temperature-based model might have a large bias toward underprediction during spring and early summer when radiation dominates the ET processes. The contrast suggested that radiation might be an influential factor in affecting PET estimates during certain periods.

Similar to the contrast of PET dynamics at the daily scale, monthly PET values modeled by the P-T method for watershed 17 were higher than those for watershed 18, and the PET estimates by the P-T methods for both forest types were higher than the Hamon and FAO PET estimates (fig. 3). Generally, monthly P-T PET for the two watersheds and FAO PET had the same temporal trends, with the highest PET occurring in July and the lowest in December. In contrast, the Hamon PET estimates peaked later than those predicted by the other methods. The Hamon PET values were lowest during January to May among all three models, but higher than FAO PET starting in June. The Hamon and FAO PET models predicted 83% to 85% of the annual total PET occurring during March to October.

During 1986-2007, monthly PET predicted by all models fluctuated dramatically and was most variable (SD = 19.1 mm mo^{-1}) in June and least variable (SD = 4.61 mm mo^{-1}) in December. Across all models, the P-T models predicted the highest PET and highest variability, and the Hamon PET showed the least variability. The P-T PET estimates for watershed 18 had a lower standard deviation than that of the coniferous watershed in every month, with a maximum of 16.1 mm mo^{-1} in June and a minimum of 3.7 mm mo^{-1} in December. The standard deviation of the FAO PET estimates had a similar pattern: the highest variability (12.6 mm mo^{-1}) occurred in June and the lowest (2.9 mm mo^{-1}) occurred in December. The Hamon PET showed a different seasonal pattern in variability, with a maximum standard deviation (7.4 mm mo^{-1}) in May and minimum (3.4 mm mo^{-1}) in January.

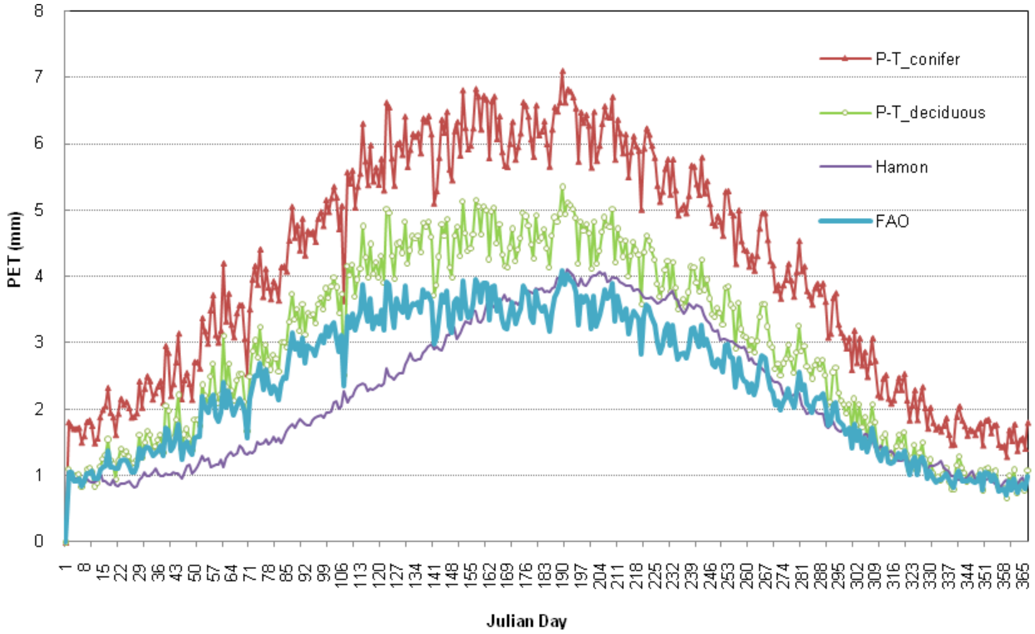

Figure 2. Long-term mean daily PET calculated by the Priestley-Taylor, Hamon, and FAO methods during 1986-2007.

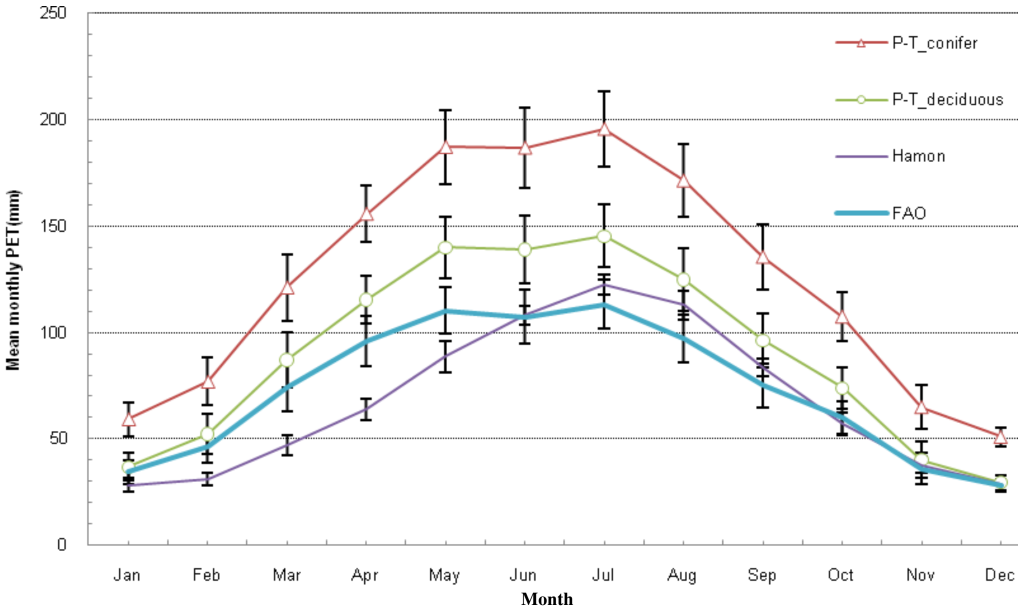

Figure 3. Long-term mean monthly PET comparison calculated by Priestley-Taylor (for conifer watershed), Priestley-Taylor (for deciduous watershed), Hamon, and FAO models. Error bars represent one standard deviation.

Similar to daily and monthly comparisons, the P-T PET method gave the highest annual PET estimates, while the Hamon method gave the lowest among the three models (table 1, fig. 4). The P-T and FAO methods gave similar interannual variation patterns but different values in magnitude. The Hamon PET had a different interannual variation patterns from the other two methods. The FAO PET estimates were consistently higher than the Hamon PET estimates but were lower than the P-T PET estimates for both conifer and deciduous forests.

Compared to measured annual AET, the PET estimates had lower interannual variation, with the maximum occurring in 1999 and the minimum in 2003 for P-T and FAO, respectively. The maximum PET occurred in 1998 and the minimum occurred in 1994 for Hamon. Mean annual PET was 1511 mm year^{-1} (P-T for watershed 17), 1079 mm year^{-1}(P-T for watershed 18), 873 mm year^{-1} (FAO ET), and 809 mm year^{-1} (Hamon). Watershed 17 had the highest PET standard deviation (SD) of 61.87 mm year^{-1}, while the SD values for P-T for watershed 18, FAO, and Hamon were 52.0, 44.4, and 28.4 mm year^{-1}, respectively.

MODEL PERFORMANCE EVALUATION

Using the two evaluation criteria (i.e., magnitude and correlation with observed data), the P-T model for watershed 17 appeared to give reasonable monthly PET values in

Table 1. Modeled PET compared with AET measured by tree-based scaling and catchment water balance approaches in conifer and deciduous watersheds.

Watershed	Year	Estimated PET (mm year^{-1})			Calculated AET[a] (mm year^{-1})	Scaled up AET[b] (mm year^{-1})
		Priestley-Taylor	FAO	Hamon		
Watershed 17 (Conifer)	2004	1424	820	832	1219	1292
	2005	1428	820	831	1088	1290
	1986 to 2007 average	1511	873	809	1509	--
Watershed 18 (Deciduous)	1986 to 2007 average	1079	873	809	1077	--

[a] Calculated by catchment water balance.

[b] Scaled up from tree-based measurements (Ford et al., 2007).

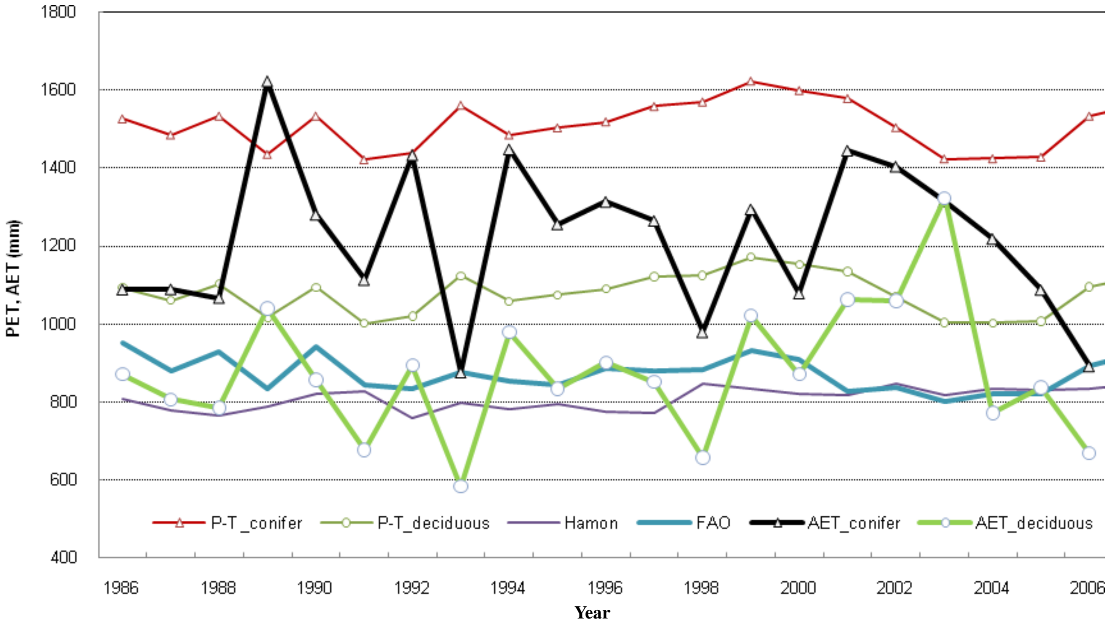

Figure 4. Comparison of annual PET estimates by three models from 1986-2007 and actual ET (AET) from 1986-2006 for two forested watersheds.

terms magnitude, being higher than AET with a moderate correlation (fig. 5a). The Hamon PET estimates were similar to measured AET, suggesting that this method perhaps underestimated forest PET. However, the R^2 value was higher for Hamon compared to P-T, suggesting that the former model explained a higher proportion of the variability of observed AET than the latter. The FAO method underestimated AET the most, and thus appears to be a poor predictor of forest PET.

Since the measured AET data reported for watershed 18 likely underestimated total AET at the watershed scale (due to not accounting for understory ET and the uncertainty of representing the entire watershed (Ford et al., 2011)), we only examined the correlation when comparing measured AET and modeled PET (fig. 5b). The R^2 values for all models were similarly low (0.43 to 0.48), but again the Hamon and P-T methods gave higher PET estimates than the FAO method, suggesting that P-T or Hamon were preferred methods for watershed 18.

To further examine if different PET models that had different input requirements provide comparable annual PET estimates, we compared aggregated PET estimates by the Hamon PET and P-T models, which require fewer climatic variables, to those by the FAO PET model, which requires complete climate data. We found that on an annual scale the temperature-based Hamon PET estimates did not correlate with the FAO PET (fig. 6a). However, the radiation-based PET estimates by FAO and P-T correlated reasonably well given the small variability of annual PET (figs. 6b and 6c) for both watersheds. This result suggested that there might be large uncertainty in PET estimates when different PET methods are used, at least at the annual time scale, and climatic variables other than air temperature, such as solar radiation, may be important to estimate PET.

Correction Factors of Three PET Models

Estimating water loss or ET of croplands can be made by multiplying the crop PET with a correction factor, or "crop coefficient" (Allen et al., 1998). Using the same logic, forest ET can be estimated by correcting forest PET if the forest ET can be modeled reasonably and sufficient forest ET measurements are available. In this study, we found that both the Hamon and FAO PET models gave lower estimates than the P-T model, and the Hamon and FAO PET estimates were even lower than the measured AET for the conifer forest (watershed 17). Obviously, the Hamon and FAO PET models cannot be used for directly estimating forest PET, so we concluded that the P-T method gave the closest plausible forest PET for both watersheds (table 1, fig. 4). Therefore, in this study, we used the P-T model estimates as a base from which correction factors for the other two models could be derived at a monthly (table 2) and annual scale. The

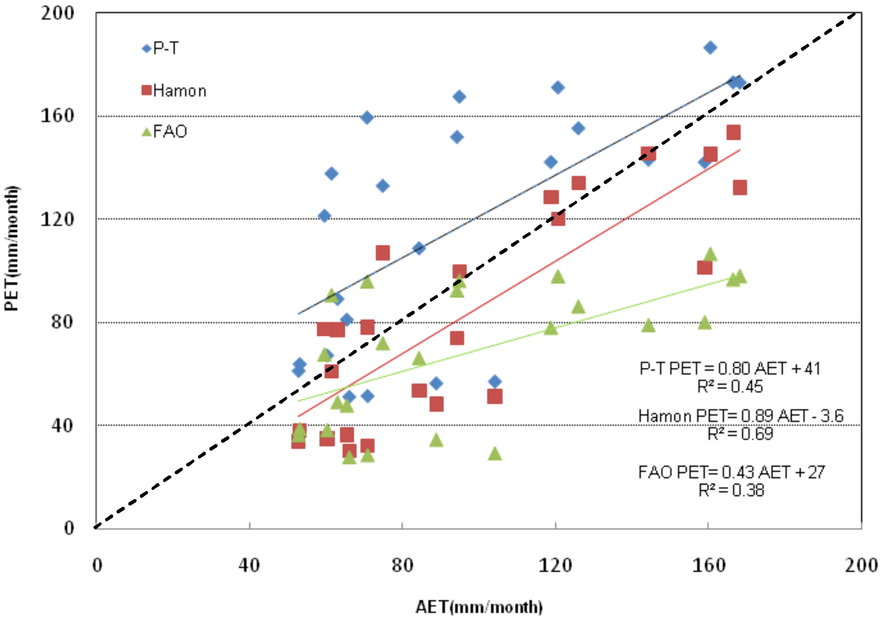

Figure 5a. Comparison between monthly AET scaled up from sapflow measurements and PET estimated by Priestley-Taylor (P-T), Hamon, and FAO for a conifer watershed in 2004 and 2005. Solid lines represent regression lines, and the dashed line is the 1:1 line.

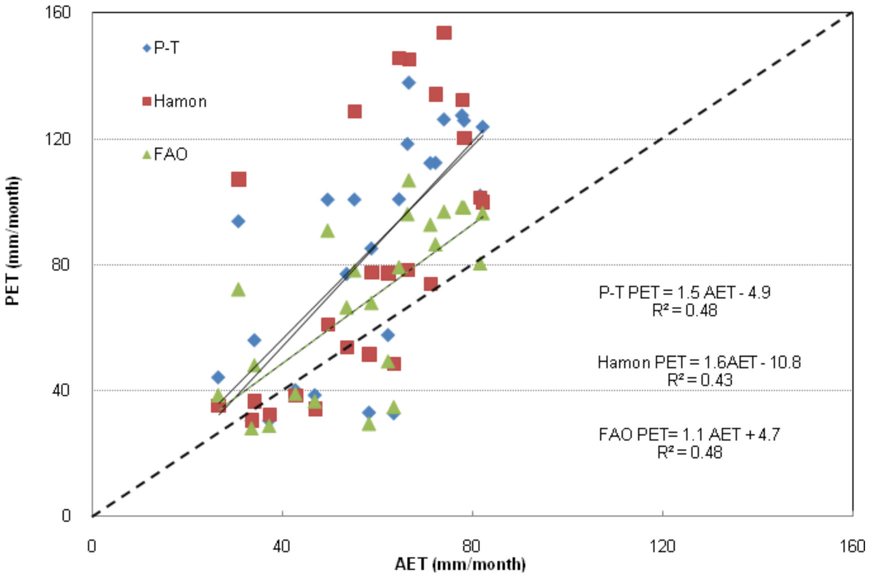

Figure 5b. Comparison between monthly AET scaled up from sapflow measurements and PET estimated by Priestley-Taylor (P-T), Hamon, and FAO for a deciduous watershed in 2004 and 2005. Solid lines represent regression lines, and the dashed line is the 1:1 line. The AET data are incomplete and do not represent the watershed-scale AET.

corrections would allow estimation of PET under different conditions of climate data availability.

The correction factors varied dramatically intra-annually for the Hamon PET model. For the conifer forest (watershed 17), the highest correction factor value was found in March (2.6) and the lowest in August (1.5). For the deciduous forest (watershed 18), the highest correction factor value was in March (1.9) and the lowest in December (1.0). Monthly correction factors for the FAO method did not vary much throughout the year. For watershed 17, the correction factors in March and April were lower than in other months. For the deciduous watershed, the lowest correction factors (1.1) appeared in the dormant season (November to February).

On an annual scale, the correction factors for the FAO and Hamon PET equations were 1.7 ±0.7 and 1.9 ±0.5 for the conifer forest, respectively. The correction factors for the two models were 1.2 ±0.8 and 1.3 ±0.5, respectively, for the deciduous watershed. This means that annual potential PET for conifer and deciduous forests could be 70% and 20% higher than grass PET, respectively. Similarly, the Hamon method would greatly underestimate forest PET if uncorrected.

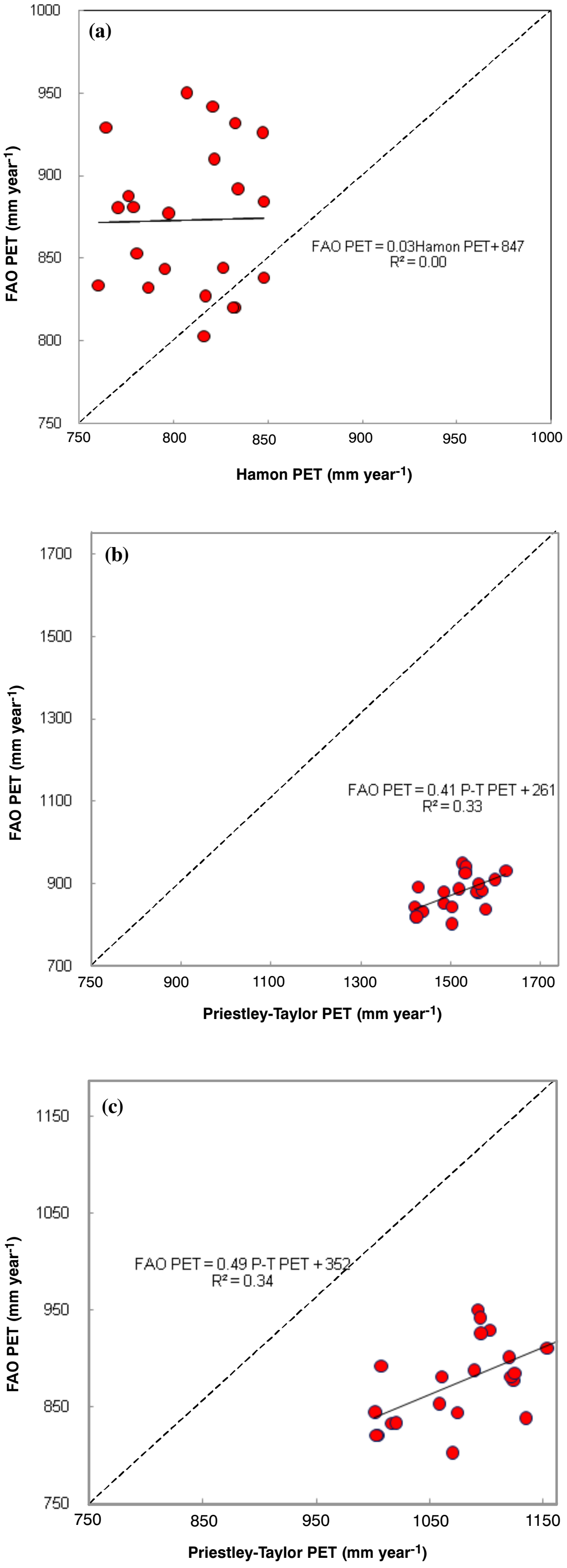

Figure 6. Correlations between PET estimate by different models: (a) Hamon vs. FAO, (b) Priestley-Taylor vs. FAO for a conifer forest (watershed 17), and (c) Priestley-Taylor vs. FAO for a deciduous forest (watershed 18).

Table 2. Monthly correction factors for two forested watersheds.

	Watershed 17 (Conifer)		Watershed 18 (Deciduous)	
Month	Hamon	FAO	Hamon	FAO
January	2.1	1.7	1.3	1.1
February	2.5	1.7	1.7	1.1
March	2.6	1.6	1.9	1.2
April	2.4	1.6	1.8	1.2
May	2.1	1.7	1.6	1.3
June	1.7	1.7	1.3	1.3
July	1.6	1.7	1.2	1.3
August	1.5	1.8	1.1	1.3
September	1.6	1.8	1.2	1.3
October	1.9	1.8	1.3	1.2
November	1.7	1.8	1.1	1.1
December	1.8	1.8	1.0	1.1

Table 3. Values of coefficient α for different surface conditions (revised from Flint and Childs, 1991).

Surface Condition	α Value	Reference
Strongly advective conditions	1.57	Jury and Tanner, 1975
Grass (soil at field capacity)	1.29	Mukammal and Neumann, 1977
Irrigated ryegrass	1.27	Davies and Allen, 1973
Saturated surface	1.26	Priestley and Taylor, 1972
Open water surface	1.26	Priestley and Taylor, 1972
Wet meadow	1.26	Stewart and Rouse, 1977
Wet Douglas fir forest	1.18	McNaughton and Black, 1973
Bare soil surface	1.04	Barton, 1979
Mixed reforestation (water-limited)	0.90	Flint and Childs, 1991
Changing grassland in Switzerland (high-latitude humid regions)	0.90	Xu and Singh, 2002
Ponderosa pine (water-limited, daytime)	0.87	Fisher et al., 2005
Douglas fir forest (unthinned)	0.84	Black, 1979
Douglas fir forest (thinned)	0.80	Black, 1979
Douglas fir forest (daytime)	0.73	Giles et al., 1985
Spruce forest (daytime)	0.72	Shuttleworth and Calder, 1979
Deciduous forest	1.16	This study
Coniferous forest	1.24	This study

DISCUSSION

MODEL PERFORMANCE

As mentioned earlier, among all three PET models examined, the P-T model gave more reasonable PET values than the Hamon and FAO models when judged by AET data derived from two different methods (i.e., watershed water balance and tree sapflow) at monthly and annual scales. Hence, the P-T model may be preferable to the Hamon and FAO models for the wet climate watersheds in the southern Appalachians when forest PET estimates are needed for regional-scale hydrologic modeling. The coefficient α in the P-T model is an empirical parameter that has been derived for many land surfaces for estimating either PET or AET. In general, a constant of 1.26 is recommended for a wide range of smooth, freely evaporating surfaces (Priestly and Taylor, 1972; Davies and Allen, 1973; Stewart and Rouse, 1977) (table 3). However, it was unclear if this parameter was appropriate for forests. Indeed, measured forest PET data are rarely available, and certainly that was the case for this study.

Thus, we could not confirm the values for either of the two watersheds. However, based on measured AET, this study suggested that 1.26 was a reasonable choice to estimate forested watershed PET for the study region.

If calibrated, the coefficient α might be used to estimate AET as well. As expected, our literature review suggested that α values could be much smaller when the P-T model was used to estimate AET for different land surfaces and climatic regimes (table 3). Values of α have been shown to vary from 0.72 to 0.9 (Flint and Childs, 1991) for dry forest conditions due to high stomatal resistance (McNaughton et al., 1979). Using the annual AET data derived from watershed water balance data, we found that the calibrated values for α were 1.16 for watershed 18 and 1.24 for watershed 17. Both values were on the high end of reported values, perhaps reflecting a wetter forest condition than those previously studied. The two values derived from the limited AET data can be used directly by the P-T equation to estimate annual AET. However, they may not be useful for monthly AET modeling since α values vary seasonally (Restrepo and Arain, 2005).

The radiation-based semi-empirical P-T model performed better than the more data-demanding FAO PET model and temperature-based Hamon PET models, both of which required substantial correction to represent the maximum evaporative demand. It is no surprise that the FAO PET model underestimated forest PET because forests have much higher leaf area index (>6 m^2 m^{-2} in this study) than grass (2.3 m^2 m^{-2}). Our findings are consistent with a recent study by Xystrakis and Matzarakis (2011), who compared 13 reference PET models to find the best model for cropland ET. They found that the use of the FAO equation was problematic because of data unavailability, and thus more empirical methods were necessary alternatives. They further concluded that radiation-based equations generally performed better than those that included only temperature-related input variables.

Our study found that the Hamon model not only underestimated forest PET but also deviated from seasonal ET patterns modeled by radiation-based methods. A few other studies indicated that the Hamon equation usually underestimated PET, especially when used for a forested surface (Xu and Singh, 2001; Alkaeed et al., 2006). The forest hydrology model BROOK, developed by Federer and Lash (1983), used Hammon's PET model but had to increase the PET values by 10% to 20% to match the streamflow measured in fully forested watersheds located in northern and southern U.S. (i.e., Hubbard Brook Forest in New Hampshire and Coweeta Experimental Station in North Carolina). Similarly, forest watershed hydrological modeling studies in Florida's pine flatwoods and cypress swamps by Sun et al. (1998) and Lu et al. (2009) recognized Hamon's deficiency of setting the upper limit of forest ET. They made corrections to the original PET model to properly model AET. However, Vorosmarty et al. (1998) performed a comparison of various PET equations including the Hamon model. Their results indicated that biases in PET estimates using the Hamon equation were smaller than those that resulted from using other equations. Model comparison studies in semi-arid regions in Europe also suggested that the Hamon equation performed well (Xystrakis and Matzarakis, 2010, 2011). These studies may indicate that climatic regime (humid vs. arid) may have a large influence on the PET model choice. It is understandable that most PET models can give PET values higher than AET in arid regions due to water limitation. As discussed earlier, this was not the case for this study. Under a humid region with high rainfall, if the Hamon or the FAO PET method were applied without corrections, they would severely underestimate actual ET.

All models did not perform equally well in all time periods. Generally, the P-T method gave the highest PET values, while the Hamon method gave the lowest PET values among the three models at daily, monthly, and annual time scales. However, there were big differences in PET estimation between growing season and dormant season.

MODEL CORRECTION

Although many approaches have been developed and adapted for PET estimation based on available input data, there is still a large amount of uncertainty related to which method to choose, specifically in forest PET calculations. Thus, for the purposes of establishing a relatively simple method that can provide a more accurate PET estimate with fewer input variables, we made annual and monthly corrections for the Hamon and FAO equations based on the Priestley-Taylor equation. However, due to the numerous uncertainties, the correction values for both forest watersheds should be further verified by accurately measured AET, especially for periods that have little or no soil water stress.

Correction factors for the three PET models could provide a useful method for areas that lack climatic data such as radiation, wind, and humidity. In this article, we provided the monthly correction factors for conifer and deciduous watersheds in Coweeta. The applications to other similar areas should be further confirmed by using local AET data.

EFFECTS OF FOREST TYPE ON PET

In this study, we found much higher PET in the conifer forested watershed than in the deciduous watershed due to the difference in net radiation. This is consistent with early studies that reported large differences in annual ET between deciduous and conifer forests (Swank and Douglass, 1974; Swift et al., 1975). Generally speaking, conifer forests have a greater ability to exchange mass and energy with the atmosphere than other vegetation types (Baldocchi et al., 1997) because they have year-round leaf area and are optically darker and aerodynamically rougher than broadleaved forests, shrubs, and herbaceous vegetation (Shuttleworth, 1989; Sellers et al., 1995). These attributes allow them to absorb more solar radiation and enhance their ability to transpire from forest canopies and evaporate more water from vegetation surfaces and the forest floor. Therefore, estimating PET for conifer forests requires more attention when selecting an existing PET model that was developed for general uses.

CONCLUSIONS

The FAO and Hamon PET models substantially underestimated monthly and annual forest PET. Due to the many parameters required by the FAO method, it is difficult to apply this method at the regional scale. The radiation-based P-T equation, which was developed for warm, humid climate conditions, was found to be favorable for the southeastern U.S. If radiation data are available, then the P-T PET method is recommended. There were substantial differences among the PET values estimated by the three methods. The P-T method, which used temperature and radiation as input data, gave better results for the Coweeta forest watersheds. Although the temperature-based Hamon method was easy to use, especially for regions lacking detailed meteorological data, it underestimated forest PET in a humid environment. Use of the Hamon model should be corrected with coefficients provided by this study.

This study found that annual average temperature may not be a good indicator for PET estimation. Uncertainty exists in PET values due to inherit differences in the PET equations and due to data availability. This uncertainty has implications for assessing the effects of global warming on actual water loss and understanding the hydrologic impacts of climate change. PET model choices would affect the conclusions if the PET models were not well evaluated for suitability for certain regions. Although the Hamon model has been widely used in large-scale PET estimation due to its simplicity and input data availability, future studies should examine how it performs in energy-limited hydrologic systems such as the eastern U.S.

Acknowledgements

The authors gratefully acknowledge support by the Fundamental Research Funds for the Central Universities (No. TD2011-03) and National Natural Science Foundation of China (No. 30500389) and the China Scholarship Council for the senior author's visit to the Southern Research Station, USDA Forest Service.

References

Alkaeed, O., C. Flores, K. Jinno, and A. Tsutsumi. 2006. Comparison of several reference evapotranspiration methods for Itoshima Peninsula area, Fukuoka, Japan. *Memoirs of the Faculty of Engineering, Kyushu University* 66(1): 1-14.

Allen, R. G. 2008. Why do we care about ET? *Southwest Hydrol.* 7(1): 18-19.

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Rome, Italy: United Nations FAO.

Baldocchi, D. D., C. A. Vogel, and B. Hall. 1997. Seasonal variation of energy and water vapor exchange rates above and below a boreal jack pine forest canopy. *J. Geophys. Res.* 102(D24): 28939-28951.

Barton, I. J. 1979. A parameterization of the evaporation from nonsaturated surfaces. *J. Applied Meteorol.* 18(1): 43-47.

Bidlake, W. R. 2000. Evapotranspiration from a bulrush dominated wetland in the Klamath basin, Oregon. *JAWRA* 36(6): 1309-1320.

Black, T. A. 1979. Evapotranspiration from Douglas fir stands exposed to soil water deficits. *Water Resources Res.* 15(1): 164-170.

Blaney, H. F., and W. D. Criddle. 1950. Determining water requirements in irrigated areas from climatological data and irrigation data. SCS Technical Paper 96. Washington, D.C.: USDA Soil Conservation Service.

Currie, D. J. 1991. Energy and large-scale patterns of animal and plant species richness. *American Natur.* 137(1): 27-49.

Dai, Z., C. Li, C. Trettin, G. Sun, D. Amatya, and H. Li. 2010. Bi-criteria evaluation of the MIKE SHE model for a forested watershed on the South Carolina coastal plain. *Hydrol. Earth Syst. Sci.* 14(1): 1-14.

Davies, J. A., and C. D. Allen. 1973. Equilibrium, potential, and actual evaporation from cropped surfaces in southern Ontario. *J. Applied Meteorol.* 12(4): 649-657.

Dolan, T. J., A. J. Hermann, S. E. Bayley, and J. Zoltek. 1984. Evapotranspiration from a Florida, USA, freshwater wetland. *J. Hydrol.* 74(3-4): 355-371.

Earls, J., and B. Dixon. 2008. A comparison of SWAT model-predicted potential evapotranspiration using real and modeled meteorological data. *Vadose Zone J.* 7(2): 570-580.

Federer, C. A., and D. Lash. 1983. BROOK: A hydrologic simulation model for eastern forests. Research Report 19. Durham, N.H.: Water Resource Research Center, University of New Hampshire.

Fisher, J. B., T. A. Debiase, Y. Qi, M. Xu, and A. H. Goldstein. 2005. Evapotranspiration models compared on a Sierra Nevada forest ecosystem. *Environ. Modelling and Software* 20(6): 783-796.

Flint, A. L., and S. W. Childs. 1991. Use of the Priestly-Taylor evaporation equation for soil water limited conditions in a small forest clearcut. *Agric. Forest Meteorol.* 56(3-4): 247-260.

Ford, C. R., R. M. Hubbard, B. D. Kloeppel, and J. M. Vose. 2007. A comparison of sap flux-based evapotranspiration estimates with catchment-scale water balance. *Agric. Forest Meteorol.* 145(3-4): 176-185.

Ford, C. R., R. M. Hubbard, and J. M. Vose. 2011. Quantifying structural and physiological controls on variation in canopy transpiration among planted pine and hardwood species in the southern Appalachians. *Ecohydrol.* 4(2): 183-195.

Giles, D. G., T. A. Black, and D. L. Spittlehouse. 1985. Determination of growing season soil water deficits on a forested slope using water balance analysis. *Canadian J. Forest Res.* 15(1): 107-114.

Grismer, M. E., M. Orang, R. Snyder, and R. Matyac. 2002. Pan evaporation to reference evapotranspiration conversion methods. *J. Irrig. Drain. Eng.* 128(3): 180-184.

Guitjens, J. C. 1982. Models of alfalfa yield and evapotranspiration. *J. Irrig. and Drainage Division ASCE* 108(3): 212-222.

Hamon, W. R. 1963. Computation of direct runoff amounts from storm rainfall. *Intl. Assoc. Scientific Hydrol. Publ.* 63: 52-62.

Harbeck, G. E. 1962. A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory. Geological Survey Professional Paper 272-E. Washington, D.C.: U.S. Government Printing Office.

Helvey, J. D. 1967. Interception by eastern white pine. *Water Resources Res.* 3(3): 723-729.

Jensen, M. E., R. D. Burman, and R. G. Allen. 1990. *Evapotranspiration and Irrigation Water Requirements.* ASCE Manuals and Reports on Engineering Practices No. 70. Reston, Va.: ASCE.

Jury, W. A., and C. B. Tanner. 1975. Advection modification of the Priestley and Taylor evapotranspiration formula. *Agron. J.* 67(6): 840-842.

Knoepp, J. D., and W. T. Swank. 1994. Long-term soil chemistry changes in aggrading forest ecosystems. *SSSA J.* 58(2): 325-331.

Lee, R. 1981. *Forest Hydrology.* New York, N.Y.: Columbia University Press.

Lu, J. B., G. Sun, S. G. McNulty, and D. M. Amatya. 2005. Modeling actual evapotranspiration from forested watersheds across the southeastern United States. *JAWRA* 39(4): 887-896.

Lu, J. B., G. Sun, S. G. McNulty, and N. Comerford. 2009. Sensitivity of pine flatwoods hydrology to climate change and forest management in Florida, USA. *Wetlands* 29(3): 826-836.

McNaughton, K. G., and T. A. Black. 1973. A study of evapotranspiration from a Douglas fir forest using the energy balance approach. *Water Resources Res.* 9(6): 1579-1590.

McNaughton, K. G., B. E. Clothier, and J. P. Kerr. 1979. Evaporation from land surfaces. In *Physical Hydrology: New*

Zealand Experience, 97-119. D. L. Murray and P. Ackroyd, eds. Wellington North, New Zealand: New Zealand Hydrological Society.

Monteith, J. L. 1965. Evaporation and environment. In *Symp. Society for Experimental Biology: The State and Movement of Water in Living Organisms*, Vol. 19: 205-234. G. E. Fogg, ed. New York, N.Y.: Academic Press.

Mukammal, E. I., and H. H. Neumann. 1977. Application of the Priestley-Taylor evaporation model to assess the influence of soil moisture on the evaporation from a large weighing lysimeter and class A pan. *Boundary-Layer Meteorol.* 12(2): 243-256.

Murray, F. W. 1967. On the computation of saturation vapor pressure. *J. Appl. Meteorol*. 6(1): 203-204.

Penman, H. L. 1948. Natural evaporation from open water, bare soil, and grass. In *Proc. Royal Soc. London A* 193(1032): 120-146.

Priestley, C. H. B, and R. J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Rev.* 100(2): 81-92.

Restrepo, N. C., and M. A. Arain. 2005. Energy and water exchanges from a temperate pine plantation forest. *Hydrol. Proc.* 19(1): 27-49.

Rosenberry, D. O., D. I. Stannard, T. C. Winter, and M. L. Martinez. 2004. Comparison of 13 equations for determining evapotranspiration from a prairie wetland, Cottonwood Lake area, North Dakota, USA.*Wetlands*. 24(3): 483-497.

Sellers, P. J., F. Hall, K. J. Ranson, H. Margolis, B. Kelly, D. Baldocchi, G. den Hartog, J. Cihlar, M. G. Ryan, B. Goodison, P. Crill, K. J. Ranson, D. Lettenmaier, and D. E. Wickland. 1995. Boreal Ecosystem-Atmosphere Study (BOREAS): An overview and early results from the 1994 field year. *Bulletin American Meteorol. Soc*. 76(9): 1549-1577.

Shuttleworth, W. J. 1989. Micrometeorology of temperate and tropical forests. *Phil. Trans. Royal Soc. London B* 324(1223): 299-334.

Shuttleworth, W. J., and I. R. Calder. 1979. Has the Priestley-Taylor equation any relevance to forest evaporation? *J. Appl. Meteorol.* 18(5): 639-646.

Stewart, R. B., and W. R. Rouse. 1977. Substantiation of the Priestly and Taylor parameter a =1.26 for potential evaporation in high latitudes. *J. Applied Meteorol*. 16(6): 649-650.

Sun, G., H. Riekerk, and N. B. Comerford. 1998. Modeling the forest hydrology of wetland-upland ecosystems in Florida. *JAWRA* 34(4): 827-841.

Sun, G., S. G. McNulty, J. A. Moore Myers, and E. C. Cohen. 2008. Impacts of multiple stresses on water demand and supply across the southeastern United States. *JAWRA* 44(6): 1441-1457.

Sun, G., K. Alstad, J. Chen, S. Chen, C. R. Ford, G. Lin, C. Liu, N. Lu, S. G. McNulty, H. Miao, A. Noormets, J. M. Vose, B. Wilske, M. Zeppel, Y. Zhang, and Z. Zhang. 2011. A general predictive model for estimating monthly ecosystem evapotranspiration. *Ecohydrol*. 4(2): 245-255.

Swank, W. T., and J. E. Douglass. 1974. Streamflow greatly reduced by converting hardwoods to pine. *Science* 185(4154): 857-859.

Swift, L. W., W. T. Swank, J. B. Mankin, R. J. Luxmoore, and R. A. Goldstein. 1975. Simulation of evapotranspiration and drainage from mature and clear-cut deciduous forests and young pine plantation. *Water Resources Res.* 11(5): 667-673.

Swift, L. W., G. B. Cunningham, and J. E. Douglass. 1988. Climate and hydrology. In *Ecological Studies, Vol. 66: Forest Hydrology and Ecology at Coweeta*, 35-55. W. T. Swank and D. A. Crossley, eds. New York, N.Y.: Springer Verlag.

Thornthwaite, C. W. 1948. An approach toward a rational classification of climate. *Geographic Review* 38(1): 55-94.

Vorosmarty, C. J., C. A. Federer, and A. L. Schloss. 1998. Potential evaporation functions compared on U.S. watersheds: Possible implications for global-scale water balance and terrestrial ecosystem modeling. *J. Hydrol*. 207(3-4): 147-169.

Wang, X., A. M. Melesse, and W. Yang. 2006. Influences of potential evapotranspiration estimation methods on SWAT's hydrologic simulation in a northwestern Minnesota watershed. *Trans. ASABE* 49(6): 1755-1771.

Wessel, D. A., and W. R. Rouse. 1994. Modelling evaporation from wetland tundra. *Boundary-Layer Meteorol*. 68(1-2): 109-130.

Wolock, D. M., and G. J. McCabe. 1999. Estimates of runoff using water balance and atmospheric general circulation models. *JAWRA* 35(6): 1341-1349.

Xu, C. Y., and V. P. Singh. 2001. Evaluation and generalization of temperature-based methods for calculating evaporation. *Hydrol. Proc.* 15(2): 305-319.

Xu, C. Y., and V. P. Singh. 2002. Cross-comparison of empirical equations for calculating potential evapotranspiration with data from Switzerland. *Water Resources Mgmt*. 16(3): 197-219.

Xystrakis, F., and A. Matzarakis. 2010. The importance of meteorological variables in the bias of potential evapotranspiration estimates in Crete, southern Greece. In *Proc. 7th Conf. on Biometeorology* 20: 96-100. A. Matzarakis, H. Mayer, and F. M. Chmielewski, eds. Freiburg, Germany: University of Freiburg Meteorological Institute.

Xystrakis, F., and A. Matzarakis. 2011. Evaluation of 13 empirical reference potential evapotranspiration equations on the island of Crete in southern Greece. *J. Irrig. Drain. Eng.* 137(4): 211-222.

Yoder, R. E., L. O. Odhiambo, and W. C. Wright. 2005. Evaluation of methods for estimating daily reference crop evapotranspiration at a site in the humid southeast United States. *Applied Eng. in Agric*. 21(2): 197-202.

Yunusa, I. A. M., R. R. Walker, and P. Lu. 2004. Evapotranspiration components from energy balance, sapflow, and microlysimetry techniques for an irrigated vineyard in inland Australia. *Agric. Forest Meteorol.* 127(1-2): 93-107.

Zhang, B. Z., S. Z. Kang, F. S. Li, and L. Zhang. 2008. Comparison of three evapotranspiration models to Bowen ratio-energy balance method for a vineyard in an arid desert region of northwest China. *Agric. Forest Meteorol.* 148(10): 1629-1640.

Zhang, L., K. Hickel, and W. R. Dawes. 2004. A rational function approach for estimating mean annual evapotranspiration. *Water Resources Res*. 40: W02502.

Zhou, G. Y., G. Sun, X. Wang, C. Y. Zhou, S. G. McNulty, J. M Vose, and D. M. Amatya. 2008. Estimating forest ecosystem evapotranspiration at multiple temporal scales with a dimension analysis approach. *JAWRA* 44(1): 208-221.

Zhou, L., and G. S. Zhou. 2009. Measurement and modeling of evapotranspiration over a reed (*Phragmites australis*) marsh in northeast China. *J. Hydrol.* 372(1-4): 41-47.