Comparison of Potential Evapotranspiration (PET) using Three Methods for a Grass Reference and a Natural Forest in Coastal Plain of South Carolina

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ABSTRACT. Potential evapotranspiration (PET) is a driving factor behind the estimates of ecosystem evapotranspiration (ET). Most of the PET methods with varying levels of complexity have been developed for a standard grass reference with unlimited soil moisture. There is only limited information examining the difference between the PET for a standard grass reference (REF-ET) and for a forest vegetation and their potential effects in water balance. Data being measured at three long-term complete weather stations located within < 10 km distance from each other on the USDA Forest Service Santee Experimental Forest (SEF) in coastal South Carolina are used in this study. The first two stations on grass reference are located at SEF headquarters (SHQ) and on Turkey Creek watershed (TC), and a third one is on a 27-m tall tower above the canopy of a pine/mixed hardwood forest on a control watershed (WS 80). In this study we evaluated (a) the observed micro-climatic conditions at those three stations and (b) the monthly and annual PET estimated by three methods with varying complexities (Penman-Monteith (P-M), Turc, and Thornthwaite (THORN)) using daily climatic data for a recent two-year (2011-2012) period. Average daily wind speed was observed to vary substantially (as much as 3 times) among the three locations, and average daily net radiation (R_n) on the WS 80 forest canopy was ~ 14% higher than the nearby SEF grass site. The effects of these differences were reflected in the PET results by the P-M method with much higher PET for the forest than the nearby grass site where the Turc method provided similar results with another grass site. Where possible and data were available, the results from these three methods were compared with pan evaporation estimates at SHQ. Results indicated that the PET estimates derived by these three methods for a single site and/or the estimates for nearby sites using a single method can vary greatly because of differences in their complexity of describing PET process, climatic factors and their interaction with site vegetation types. These differences should be considered when selecting a PET method and interpreting the results in hydrologic and water balance studies, especially for forested sites with much taller vegetation than the grass reference assumed in most PET methods in the literature.

INTRODUCTION

Potential evapotranspiration (PET) is defined as the maximum amount of water that can be removed from a land surface through evapotranspiration (ET) as sum of both evaporation and transpiration given abundant supply of soil moisture. In other words, the removal of water by ET depends only upon the available energy. PET is a driving factor in the ecosystem ET process. PET is frequently used in many hydrologic applications including water and contaminant balance, water resources development, reservoir planning and design, irrigation scheduling for crop water management, wetland hydrology restoration, and in land use and climate change studies using hydrologic modeling approaches (Allen at al., 1998; Dai et al., 2013; 2010; Federer et al., 1996; Fisher et al., 2005; Harder et al., 2007; Kim et al., 2013; McKinney and Rosenberg, 1993; Nghi et al, 2008; Prudhomme and Williamson, 2013). In last few decades several different methods varying from empirical to temperature-based to physically-based process models have been developed, tested, and applied to estimate PET for various types of land covers from soil surface to crop, water, and vegetation (Amatya et al., 1995; Archibald and Walter, 2013; Brauman et al., 2012; Douglas et al., 2009; Federer et al., 1996; Fisher et al., 2005; Hargreaves and Samani, 1985; Jensen et al., 1990; Monteith, 1965; Rao et al., 2011; Thornthwaite, 1948; Turc, 1961). Rao et al. (2011) reported that more than 50 mathematical models are currently available to estimate PET. Some of these widely used PET models include Hargreaves-Samani (1985), Penman-Monteith (Monteith, 1965), Priestlay and Taylor (P-T) (1972), Thornthwaite (1948), Turc (1961) and others as was evaluated by Jensen et al. (1990). Most of these PET models have been developed for a well-watered uniform cover of grass. In their comprehensive review on methods of estimating PET, Douglas et al. (2009) stated that the selection of one method from the many is primarily dependent on the objectives of the study and the type of data available. In recent years several studies have shown the physically-based Penman-Monteith (P-M) method (Monteith, 1965) that takes both the climatic as well as its interaction with surface vegetation characteristics into account to be the most accurate method for estimating PET for a grass reference termed as a REF-ET (Allen et al., 1998; Amatya et al., 1995; Jensen et al., 1990). Most recently, the FAO-56 Penman-Monteith model, a slight modification of the original P-M method, represents as a standard REF-ET for a grass reference to compare PET of all other crops (Allen et al., 1998; Prudhomme and Williamson, 2013).

BACKGROUND

Recently watershed-scale eco-hydrologic models are increasingly being used to assess the water balance and hydrologic impacts of land management, land use change, climate change and variability in landscapes comprising of multiple land uses (Andreassean et al., 2012; Arnold et al., 1998; Dai et al., 2013; Kim et al., 2013). Prudhomme and Williamson (2013) noted that future changes of PET are likely to be as important as changes in precipitation patterns in determining changes in river flows. Most of those models use the grass-reference based PET methods to estimate PET as inputs for all land use types including forest to estimate/predict the actual ET, and for that matter streamflow (Arnold et al., 1998; Chescheir et al., 1994; Dai et al., 2010; 2013), while others have developed some correction factors for adjusting grass reference-based P-M PET (Kim et al., 2012). At the same time several studies have shown the sensitivity of predicted streamflows to the use of the PET method in the hydrologic model (Harder et al., 2007; Kim et al., 2012; Liciardello et al., 2011; Wang et al., 2006). Accordingly, there has been a growing concern among the eco-hydrologists about the use of such PET methods when applying the model on other land surfaces like forests, wetlands, marshes etc. to assess the hydrologic impacts as noted by Rao et al. (2011). One of the main reasons was due to the potentially different vegetation surface characteristics such as leaf area index (LAI), stomatal conductance (g_s), canopy conductance (G_s) besides the vegetation height of the forests that likely affect plant-specific stomatal and aerodynamic control of vapor transfer differently than the grass (Brauman et al., 2012; Fisher et al., 2005; McKinney and Rosenberg, 1993; Mohamed et al., 2014; Rao et al., 2011). Sun et al. (2010) showed that the PET based on the forest vegetation type can be substantially higher than the PET for the grass reference. However, there are only a limited number of studies done for estimating PET on forest vegetation (Douglas et al., 2009; Fisher et al., 2005; Rao et al., 2011;) and even fewer for the humid coastal plain landscapes (Brauman et al., 2012).

Therefore, the main objectives of this study are a) first to assess the micro-climatic characteristics among three weather stations located within < 10 km distance and b) to assess monthly and annual PET using three methods (Penman-Monteith (P-M), Turc, and Thornthwaite) for a grass reference site, and compare their results with that of the P-M method applied on an adjacent forest in a coastal South Carolina site.

METHODS

Site Description: The Santee Experimental Forest (SEF) is located in the Francis Marion National Forest near Cordesville, SC (Fig. 1).

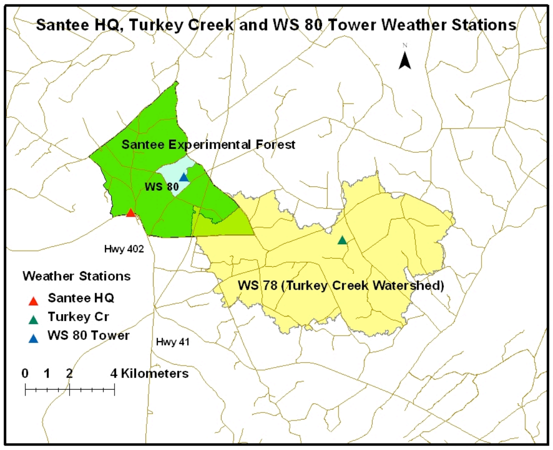


Figure 1. Location of weather stations on or near Santee Experimental Forest, Cordesville, SC.

Weather data (initially daily precipitation and max/min air temperature) have been collected at the SHQ station since 1946. A Campbell Scientific CR10X data logger and weather sensors were installed there in August 2001. A standard Class A evaporation pan was initially installed in 1964. Two first-order watersheds (WS80 - 160 ha and WS77-155 ha) were set up as a paired system in 1968, with WS 77 as the treatment and WS 80 as the control watershed. A mini-meteorological station measuring just precipitation, air, and soil temperature was installed on each watershed in 1996. A third-order 5240 ha watershed (WS78, Turkey Creek) was established in 1964 adjacent to the Santee Experimental Forest (Fig. 1). The predominant forest cover types on WS78 are pine and mixed hardwoods. A Campbell Scientific CR10X data logger and weather sensors were installed there on a grass surface in October 2005 (Fig. 3). Finally, a Campbell Scientific CR1000 data logger and weather sensors were installed in WS 80 above the forest canopy on a 90-foot tower in March 2010. The dominant vegetation around the tower is a pine and mixed hardwood stand with < 80 ft height.

We used the 1) physically-based Penman-Monteith (P-M) (Monteith, 1965) with net radiation, vapor-pressure, and aerodynamic and vegetation control, 2) energy-balance based Turc (1961), and 3) temperature-based Thornthwaite (1948) methods to estimate daily, monthly, and annual PET at two grass reference sites (SHQ and TC) and one forest site (WS 80, P-M only).

Equations Used in Three Chosen PET Methods

1) Penman-Monteith (Monteith, 1965)

$$LE = \frac{\Delta(R_n - G) + \rho_a c_p (e_s - e)/r_a}{\Delta + \gamma\left(1 + {r_s}/{r_a}\right)}$$

2) Turc (1961)

for RH < 50%, and

for RH > 50%

3) Thornthwaite (1948)

Detailed description of all parameters in each of the above three methods are given by Amatya et al. (1995).

Weather parameter measurements: CR10X data loggers at SHQ and TC, and a CR1000 logger at the WS 80 were linked to various sensors at each station to measure these parameters. For example, air temperature (T) and relative humidity (RH) were measured by CS500 (Campbell Scientific) and HMP45C (Vaisala, Inc.), net radiation (R_n) by Q-7.1 (Radiation and Energy Balance Systems, Inc.) and NR-LITE (Kipp & Zonen) at the SHQ and the WS 80, respectively, solar radiation (R_s) by LI-200X (LI-COR, Inc.) at all sites, wind speed (U) and wind direction by MetOne034A and MetOne034B at SHQ and TC and WS 80, respectively. Measurements were made on a 30-sec interval, and averages were logged for each parameter on a 30-min interval at SHQ and TC and on a 15-min interval at the WS 80. These records were integrated to get the daily average weather parameters for PET estimates, except as noted, for the study period. Vapor pressure deficit was calculated by the data loggers. Sensors were periodically calibrated as recommended. All downloaded data were checked for consistencies and completeness. Approximately daily water level measurements in a Class A evaporation pan at SHQ were recorded, and the pan was refilled, emptied and cleaned as necessary.

Parameter Estimation: Because the TC station lacked a net radiometer, R_n data was estimated by a regression relationship ($R_n = 0.71*R_s - 0.77$; $R^2 = 0.89$, $P < 0.0001$) developed using daily average Rn and R_s at the SHQ station for the 2003 to 2009 period with its measured daily R_s. Also, inconsistencies in and/or missing daily average T data at the SHQ and TC stations were corrected and/or predicted using regressions developed between manual maximum and minimum thermometer readings at SHQ and the corresponding sensor data. All of these long-term climatic data are available at the Santee Experimental Forest online database, http://cybergis.uncc.edu/santee/.

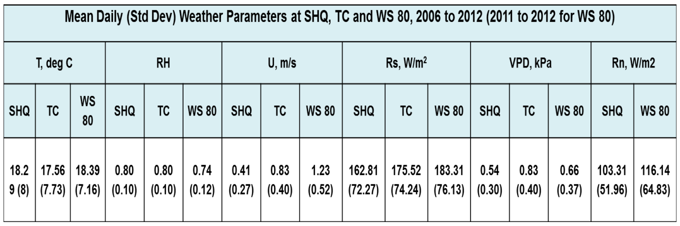
A fixed canopy resistance (r_s) value of 70 s m^{-1} was used for the standard 12 cm height grass in equation 1 for the P-M PET method (Jensen et al., 1990; Rao et al., 2011). A variable canopy resistance r_s was calculated as an inverse of the product of a fixed maximum stomatal conductance (g_{smax}) and variable leaf area index (LAI) for the tall forest canopy at the WS 80 site (Lindroth, 1985). A g_{smax} value of 90 mmoles m^2 s^{-1} (0.002 m s^{-1}) was used for a pine mixed hardwood forest for which the monthly LAI values varied from 1.7 to 4.0 m^2 m^{-2} with an average of 2.90 m^2 m^{-2} (Dai et al., 2010). The assumed g_{smax} was close to the median values of 91 mmoles m^2 s^{-1} measured by a LiCOR-1600 porometer at two plots of the forest site between March-June of 2014. This yielded a mean canopy resistance of 170 ±47 s m^{-1}, consistent with values reported in the literature (Douglas et al., 2009, Lhomme et al., 1998).

Statistical analyses of linear regression of the weather variables between the stations and standard t-tests for testing differences in PET estimates were conducted.

RESULTS

Daily average weather parameters for a longer period (2006 to 2012), except for the WS 80 site for 2011-2012 only are presented in Table 1. The regression plots between the daily parameters measured above the forest canopy (WS 80) and the grass site (SHQ) sites are presented in Figure 2. Some of the parameters were significantly different between the forest and grass sites that were just 5 km apart. For example, U values at TC were twice the values at the SHQ site, and at the WS 80 it was 3 times higher; Rn on WS 80 forest canopy was ~14% > than for grass at SHQ. Air temperature (T) above the forest canopy (WS 80) was lower than that for the SHQ grass for T > 19^0 C. Relative humidity (RH) at the forest canopy was lower than the grass for RH < 96% which occurs most of the times. Similarly, the vapor pressure deficit (VPDC) was also higher on the forest canopy (WS 80). There was a slight difference in solar radiation (R_s) among the sites. All regression models were statistically significant (α=0.05).

Table 1: Mean daily averages (std dev) for T, RH, U, R_s, R_n, and VPD at the three sites for 2006 to 2012, except for WS 80 with data for 2011-2012 only.



Mean Daily (Std Dev) Weather Parameters at SHQ, TC and WS 80, 2006 to 2012 (2011 to 2012 for WS 80)																
T, deg C			RH			U, m/s			Rs, W/m²			VPD, kPa			Rn, W/m2	
SHQ	TC	WS 80	SHQ	TC	WS 80	SHQ	TC	WS 80	SHQ	TC	WS 80	SHQ	TC	WS 80	SHQ	WS 80
18.29 (8)	17.56 (7.73)	18.39 (7.16)	0.80 (0.10)	0.80 (0.10)	0.74 (0.12)	0.41 (0.27)	0.83 (0.40)	1.23 (0.52)	162.81 (72.27)	175.52 (74.24)	183.31 (76.13)	0.54 (0.30)	0.83 (0.40)	0.66 (0.37)	103.31 (51.96)	116.14 (64.83)

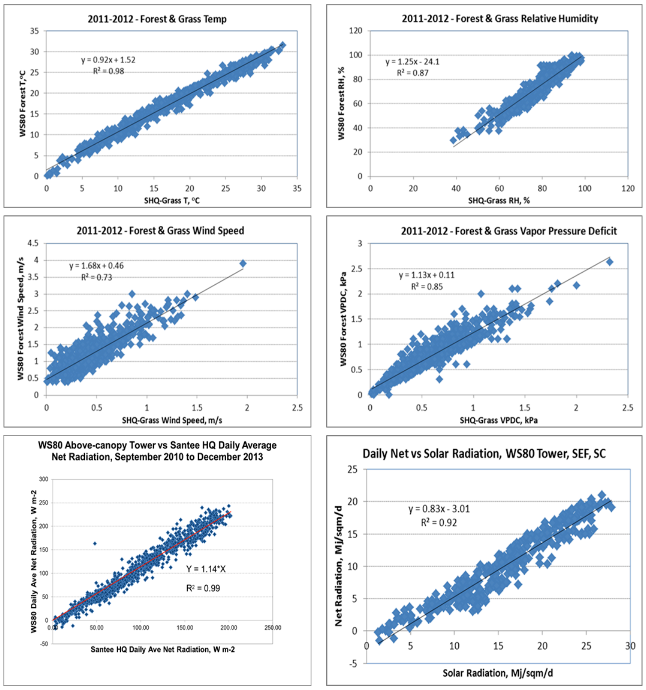


Figure 2. Regression of measured daily mean weather parameters (T, RH, U, VPDC, R_n, R_s) between the forest canopy (WS 80) and the grass vegetation (SHQ) sites.

The mean annual P-M PET estimates were highest at the forest WS 80 (1176 mm) site followed by the TC (1155 mm) and the SHQ (945 mm) sites (Fig. 3-left), while the Turc estimates at the TC site was slightly higher (1026 mm) than the SHQ grass site (997 mm). The THORN PET estimate at SHQ (986 mm) was slightly higher than at the TC (938 mm). Standard t-tests showed that mean monthly PET values (not shown) estimated by each of the three methods were significantly (α = 0.05) different between the two grass sites. When the annual P-M PET from two grass reference sites (SHQ and TC) was compared with the forest reference (WS 80) in Figure 3 (right) for two years 2011 and 2012, the WS 80 P-M PET was the highest (1228 mm) of all in 2012 but slightly lower (1176 mm) than the TC site (1190 mm) in 2011. The lowest P-M PET of 968 mm in 2011 and 955 mm in 2012 was estimated for the SHQ site. The annual P-M PET estimates of 1190 mm in 2011 and 1160 mm in 2012 were for the TC site was closer to the 1124 mm and 1228 mm for the WS 80 forest site.

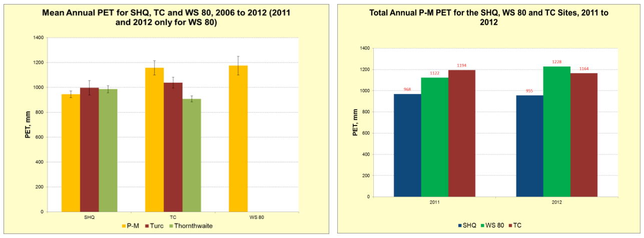


Figure 3. Mean annual PET by P-M, TURC, and THORN methods (left) and annual P-M PET for 2011-2012 (right) for three different sites.

We examined the energy (EN) and aerodynamic (AD) components of P-M PET at three sites for 2011-2012 (Figure 4). The comparison of these monthly components for two grass sites at SHQ and TC sites are shown in Figure 4(left).

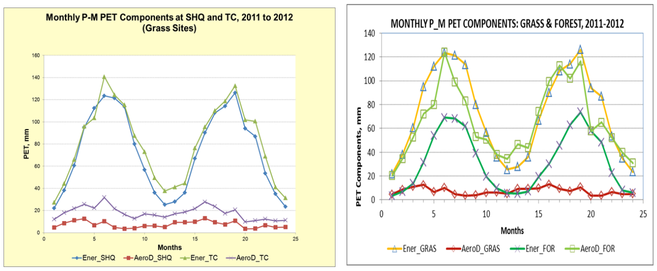


Figure 4. Comparison of estimated monthly energy and aerodynamic components of the P-M PET for two grass sites (SHQ and TC) (left) and the grass (SHQ) and the forest reference (WS 80) (right) sites in 2011 and 2012.

Both the EN and AD components were found higher at the TC site than at the SHQ. The difference in the AD component was much higher due to significantly (α =0.05) higher U (double) at the TCW than at the SHQ site within < 10 km distance. The monthly EN and AD components of the P-M PET estimated for the two nearby grass (SHQ) and the forest (WS 80) reference sites are shown in Figure 4 (right). The results are quite interesting with the AD component for the forest (WS 80) site contributing as much as120 mm close to the EN component of the grass during the peak summer and somewhat lower for the rest of the months. The AD component for the SHQ grass site was much lower than that for the forest (WS 80) with significant component of the PET made by the EN component. It was opposite for the forest site with higher AD component than the EN, with an overall higher PET than by the nearby grass site.

Where measurements were available, daily pan evaporation was calculated at SHQ grass site in 2012. The daily pan values were summed to obtain the total for the year which was then compared to the corresponding total PET by each of the three methods (Table2). The calculated PET/Pan ratios ranged from 0.90 to 0.96 with 0.92 for the P-M method using the limited data.

Table 2: Measured pan PET and estimated P-M, Turc and Thorn PET for the 323 days in 2012 at SHQ site.

Method (323 days each)	Total Estimated PET, mm	Daily Estimated PET, mm	Ratio PET/ Pan
Evaporation Pan	947.68	2.93	1
SHQ P-M	868.55	2.69	0.92
SHQ Turc	857.65	2.66	0.90
SHQ Thornthwaite	907.57	2.81	0.96

DISCUSSIONS

Although separated by only <10 km, the daily average weather parameters differed among the three sites, significantly ($\alpha = 0.05$) in some cases (Table 1). The 14% higher R_n values observed at the forest canopy (WS 80) than at the grass (SHQ) were consistent with other coastal studies (Rao et al., 2011; Sun et al., 2010). This is due to higher albedo of the grass surface (0.23) than that for the forest canopies (0.17) (Amatya et al., 2000; Jensen et al., 1990; Nghi et al., 2008). Lower humidity and higher wind speeds at the forest canopy resulted in higher VPDC, as expected. Both of these contribute to increased aerodynamic component in the P-M PET as shown in two plots of Figure 4. Solar radiation did not vary greatly at the two sites within about 5 km (Fig. 2; Table 1). There was a sensor defect at SHQ in 2012. The ~0.7^{o} C higher T observed at SHQ site than at the TC (Table 1) was likely responsible for the higher PET using the temperature-based THORN there. It is also important to note that the P-M PET estimates at the TC site might have been influenced by using the R_n extrapolated from the R_n and R_s relationship developed at the SHQ site. The higher estimated annual P-M PET at the TC grass site than the SHQ grass site was likely due to the much higher wind speed and also somewhat higher solar radiation observed at this grass site, resulting in the higher estimated EN and AD components than the SHQ grass site (Figure 4A). A possible reason of higher wind speeds at the TC site may be due to much wider opening area at the site in contrast with the SHQ grass site.

Although some differences in PET estimates by various methods at the same site was expected based on several past studies (Amatya et al., 1995; Douglas et al., 2009; Federer et al., 1996; Rao et al., 2011), differences in PET estimates were also found even by the same method at sites located < 10 km site due to the site characteristics influencing the local micro-climate. Similarly, the difference in both the site as well as vegetation characteristics between the short grass and tall forest canopy influenced the P-M PET estimates, indicating that the P-M PET for a forest vegetation surface can be substantially higher than that for the grass reference. This may be explained by several factors including the increased net radiation, wind speed, possibly vapor pressure deficit besides the higher LAI. However, in a recent study conducted in humid tropical Hawaiian island, Brauman et al. (2012) unexpectedly found modeled PET higher from the pasture than that from the forest although ET was low in both systems. The authors reported that the interaction of the aero-dynamic and stomatal control on PET, in conjunction with tropical meteorology characterized by low wind speed and low vapor pressure deficit causes this unexpected phenomenon.

Our results of the limited two-year mean annual P-M PET of 1176 mm for the forest reference are slightly higher than the 1115 mm obtained by the Thornthwaite method for two-year (1964-1965) historic average reported by Young (1968) and the recent six-year (2003-2008) mean annual P-M PET of 1136 mm reported by Dai et al. (2010). However, the P-M PET of 940 mm average reported by Harder et al. (2007) using the data from the SHQ grass site for 2003-2004 seems to be much lower than those studies but much closer to 945 mm obtained as an average for the most recent seven-year (2006-2012) period for the SHQ grass site. Recently, in their long-term (1946-2008) study at this experimental forest, Dai et al. (2013) obtained annual PET, estimated by the Hargreaves-Samani (1985) method adjusting using the six-year (2003-08) P-M PET estimates ranging from 970 mm to 1304 mm, with an average of 1137 mm. These estimates are rather closer to the limited 2-year mean annual PET estimated by the P-M method for the forest reference in this study. Some of our results may have been affected by the extrapolation of weather data during periods of missing or inconsistent values. More reliable results of PET estimates by any method depend on regular calibration and maintenance of weather sensors and data quality control. Estimate of canopy conductance may have contributed some uncertainty in P-M PET estimate for the forest reference.

In other related studies Rao et al. (2011) reported that Priestlay-Taylor (P-T) method gave the most reasonable estimates of forest PET, when correlated with actual ET obtained from the water balance, compared to the FAO-56 Penman and Hamon methods for the grass reference for two upland forest watersheds in western North Carolina. Similarly, Fisher et al. (2005) found P-T with a well-defined α value performing remarkedly well compared to five other physically-based methods for a ponderosa forest Ameriflux site in Northern California.

The PET/Pan ratios calculated for the SEF grass site with a limited year of data were found to be somewhat higher than that typically observed in similar humid climates (0.8 to 0.88) (Maidment, 1993).

CONCLUSIONS

Local micro-climatic parameters used in estimates of potential evapotranspiration (PET) can be significantly different across weather stations located even within < 10 km based on the site characteristics. As a result, the PET by both the Penman-Monteith (P-M) and Thornthwaite methods differed significantly between the two grass reference sites. Similarly, P-M PET for the forest reference was significantly ($\alpha = 0.05$) higher than the P-M PET for a nearby grass site, indicating the potential effects of site factors and the surface vegetation characteristics on the PET estimates using the methods like P-M that take the vegetation-specific stomatal and aerodynamic control of vapor transfer into account. Additional studies are needed to better understand the canopy conductance dynamics as related to the P-M PET of this low-gradient natural forest. Analyses are being conducted using two additional methods (Hargreaves-Samani and Priestlay-Taylor) and also multi-year data for validation. The reliability of all these methods is also being assessed by applying these different PET values in DRAINMOD hydrologic model to compare the predicted streamflows with the measured data at this study site. These results may have large implications in hydrologic studies assessing hydrologic impacts of land management and climate variability and change in the urbanizing forested landscapes of the humid coastal plain.

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