Estimating daily and seasonal evapotranspiration of a southeastern U.S. Atlantic coastal plain forest

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We tested an empirical method to estimate daily actual evapotranspiration (AET) of a forested watershed in coastal South Carolina using measured daily shallow soil moisture (SM) and potential ET (PET) estimated using weather data by two methods, i) Penman-Monteith (P-M) and ii) Priestley-Taylor (P-T), and soil field capacity during the 2015–2016 period. This work was motivated by Domec and others (2012), who found the measured annual and monthly AET by the SM and water table fluctuation methods agreed to within 10 to 20 percent of the ET from eddy covariance measurements for a managed pine forest in coastal North Carolina. Our study site is a 160-ha control watershed (WS80) (33.15° N; 79.8° W) in the paired system within the Santee Experimental Forest on the Francis Marion National Forest in coastal South Carolina (fig. 1a). This low-gradient (slope < 3 percent) watershed is on moderately well to poorly drained soils, with a restrictive layer around 2.0 m depth (Harder and others 2007). Loblolly pine (*Pinus taeda*)-mixed hardwoods, naturally regenerated since Hurricane Hugo (1989), dominate the

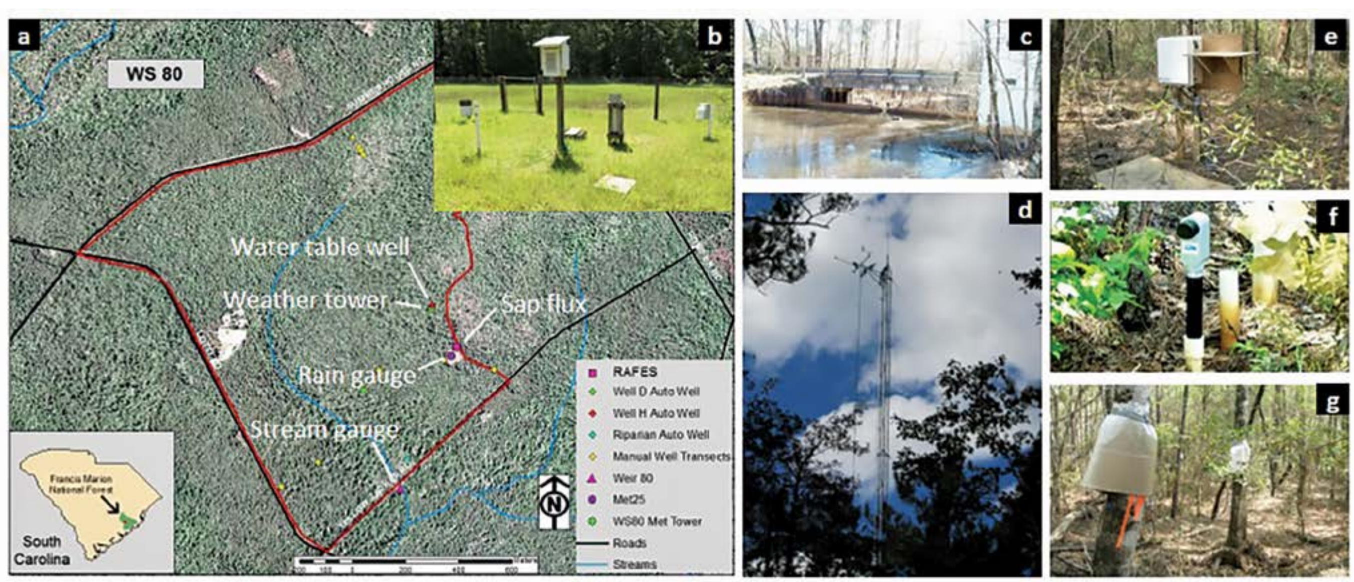

Figure 1—Location map (a) of the study watershed (WS80) (red outline). Pictured monitoring components are (b) rain gauge, (c) flow gauging station with a compound weir outlet, (d) weather station above forest canopy, (e) soil moisture sensors and datalogger, (f) recording groundwater well, and (g) sap flux sensors in trees at Santee Experimental Forest in coastal South Carolina.

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watershed, with the watershed-wide average annual leaf area index of 2.9 m^2 m^{-2} (Dai and others 2013). The site average daily temperature and annual rainfall are 17.8 °C and 1370 mm, respectively (Dai and others 2013).

Rainfall data were collected using automatic gauges backed up by a manual gauge (fig. 1b). A gauging station with a compound V-notch/flat weir (fig. 1c) was instrumented to measure stream stage on a 15-minute interval to compute outflow rates using an established rating curve. An on-site above-canopy tower weather station collected data on a 15-minute basis (fig. 1d). Soil hydraulic parameters for the dominant Wahee soil and additional details of hydrologic monitoring can be found elsewhere (Amatya and Trettin 2021, Harder and others 2007).

We computed monthly AET, as a residual in water budget, as Rainfall – interception – streamflow – change in storage, for the 2015–2016 period. Deep seepage was assumed negligible in this shallow system with a restrictive horizon (Harder and others 2007). Interception was estimated as 11 percent of rainfall (Harder 2004). Change in storage (ΔS) for each month was computed from a) limited hourly soil moisture (SM) measured (fig. 1e) at only a shallow 10-cm depth in three plots, which was averaged (SM-ΔS) and assumed to be representative up to 80 cm depth in this shallow system; and b) measured hourly water table depth (fig. 1f) (WT-ΔS) with average drainable porosity (0.05) (Harder and others 2007) (table 1). The limited SM and sap flux measurements (fig. 1g) were collected as a part of the Forest Service, U.S. Department of Agriculture (USDA), project on Remote Assessment of Forest Environmental Stressors (RAFES).

Daily AET for the site was independently calculated following Fisher and others (2005) as AET = f * PET, where f = SM/FC, and FC = soil moisture content at 10 kPa estimated from soil water characteristic data (Harder and others 2007). Daily PET was computed using the P-M and P-T methods with the measured daily weather data (Amatya and Harrison 2016). The method assumes daily AET = PET when the SM ≥ FC, otherwise AET = PET * SM/FC. Monthly AET, summed from daily values using each of the two PET methods, was compared with the AET as residual in the water budget (table 1). AET from each of the PET methods was also tested to predict monthly streamflow as residual in the water budget.

Both the 2-year mean monthly WT-ΔS (-0.5 mm) and WT-AET (83.6 mm) were not different ($\alpha = 0.05$) from the SM-ΔS (-0.7 mm) and SM-AET (83.9 mm), respectively, with $R^2 = 0.82$ between monthly ΔS and 0.72 between the respective monthly AET values. The mean monthly P-M AET was 92 percent of the P-M PET, dropping as low as 64 percent for May 2016 with lower rainfall and higher PET (table 1), potentially indicating a moisture stress. Results showed the R^2 and mean monthly difference in residual streamflow using each of the P-M and P-T AET methods and the observed data as 0.97 and -2.2 mm and 0.94 and 6.2 mm, respectively, indicating a better performance of the P-M PET method. Our analysis supports the WT-ΔS as a proxy for monthly SM-ΔS, as well as Fisher and others (2005) method for approximating the monthly AET on these poorly drained wetland forests, consistent with Domec and others (2012). However, the results may have been influenced by SM measurements only at a shallow depth.

Table 1—Measured/estimated monthly water budget components including Penman-Monteith (P-M) and Priestley-Taylor (P-T) PET for January 2015 to December 2016

Year-Month	Rainfall	Flow	SM-ΔS	WT-ΔS	SM AET	WTD AET	P-M AET	P-T AET	P-M PET	P-T PET
						mm				
2015-Jan.	134.1	71.5	8.1	1.3	39.8	46.5	32.5	26.5	32.5	26.5
2015-Feb.	118.8	64.8	27.6	2.3	13.3	38.6	33.2	30.6	33.2	30.6
2015-March	112.2	77.2	-24.8	-1.9	47.4	24.5	66.3	65.8	66.3	65.8
2015-April	70.6	6.7	-32.2	-3.4	88.4	59.6	90.1	92	91.8	93.7
2015-May	57.3	0.6	-104.3	-56.5	154.8	107	115.9	109.5	140.1	132.4
2015-June	213.9	3.3	62.6	44.4	124.5	142.7	152.1	131.8	179.6	155.2
2015-July	161.6	3.7	-22.3	-15.9	162.4	156	164	144.2	179	157.6
2015-Aug.	243	12.2	91.7	30.5	112.3	173.6	124.3	112.6	140.4	127.2
2015-Sep.	136.8	8.6	-10.9	0.2	124	112.9	87.1	81.2	94.7	88.1
2015-Oct.	666.7	598.9	39.4	-1.2	-5.1	35.5	61.2	58	61.2	58.1
2015-Nov.	137.1	76.9	-20.4	-5.8	65.5	50.9	43.4	40.9	43.4	40.9
2015-Dec.	119.1	43.6	6	7.4	56.4	55	36.1	31.1	36.1	31.1
2016-Jan.	75	48.3	4.2	-0.1	8.8	13	30.8	25.1	30.8	25.1
2016-Feb.	169.2	127.9	-2.3	-2.2	25.1	25	41.6	43.5	41.6	43.5
2016-March	64.7	12.8	-9.2	-2.7	53.9	47.4	83.2	75.7	83.2	75.7
2016-April	38.1	2.4	-88.2	-38.6	119.6	70	115.3	108.1	120.4	113.1
2016-May	91.4	0	-14.7	-4.2	96	85.5	87	79	135.1	122.1
2016-June	183.8	1	5.2	25.5	157.4	137.1	135	119.5	176.2	155.9
2016-July	177.5	1.7	3	-11.1	153.2	167.4	154	133	191.5	164.5
2016-Aug.	252.7	36.8	43.8	15.1	144.3	173	143.1	142.6	147.2	146.6
2016-Sep.	246.8	64.4	68.5	19.7	86.8	135.6	99.6	94.8	99.8	95
2016-Oct.	295.7	234.4	-75.3	-35.3	104	64	82.6	59	83.3	59.5
2016-Nov.	15.7	0	-53	-38.1	67	52.1	45.9	23.9	54.5	28.3
2016-Dec.	132.4	24.4	80.3	59.3	13.1	34.1	32.2	14.9	33.7	15.5
2015 Sum	**2171.2**	**968**	**20.4**	**1.5**	**983.7**	**1002.8**	**1006.3**	**924.2**	**1098.2**	**1007.1**
2015 Mean	**180.9**	**80.7**	**1.7**	**0.1**	**82**	**83.6**	**83.9**	**77**	**91.5**	**83.9**
2016 Sum	**1743**	**554.2**	**-37.7**	**-12.6**	**1029.2**	**1004.2**	**1050.3**	**919.1**	**1197.3**	**1044.8**
2016 Mean	**145.3**	**46.2**	**-3.1**	**1**	**85.8**	**83.7**	**87.5**	**76.6**	**99.8**	**87.1**
2-yr Sum	**3914.2**	**1522.2**	**-17.3**	**-11.1**	**2012.9**	**2007**	**2056.6**	**1843.3**	**2295.5**	**2051.9**
2-yr Mean	**163.1**	**63.4**	**-0.7**	**-0.5**	**83.9**	**83.6**	**85.7**	**76.8**	**95.6**	**85.5**

Note: WTD AET and SM AET are the AET as a residual in water budget using change in storage (ΔS) estimated from water table drainage volume (WT-ΔS) and measured soil moisture (SM-ΔS), respectively; P-M AET and P-T AET were obtained from independently estimated daily AET values using the approach of Fisher and others (2005) that uses PET, soil moisture, and soil field capacity; P-M and P-T are the Penman-Monteith and Priestley-Taylor based PET, respectively. The estimated annual sum of P-M AET values was greater than the sum of P-T AET values and was closer to water budget based AET (using either the SM-ΔS or WT-ΔS storage estimates) in both 2015 and 2016.

This preliminary study provides useful insights into yearly and monthly catchment water balance components of a forested wetland watershed in coastal South Carolina, USA. Among the tested methods with a short period of data including limitations of the SM measurements, application of the P-M model showed slight superiority over P-T when compared to *in-situ* AET estimates obtained as the water budget residual. The data collected in this study can be useful for validation of remote sensing-based shallow soil moisture and evapotranspiration products while the tested algorithms for AET have their application for further testing on an adjacent treatment watershed (WS77) undergoing longleaf pine restoration, as well as upscaling or development of large-scale water balance models. However, additional data collection for a longer period, primarily for soil moisture for deeper depths, on other soil types is highly recommended for reducing prediction uncertainties due to spatially distributed soil heterogeneities.

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