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Annual Evapotranspiration of a Forested Wetland Watershed, SC

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Abstract. *In this study, hydro-meteorological data collected from 1964 to 1976 on an approximately 5,000 ha predominantly forested coastal watershed (Turkey Creek) at the Francis Marion National Forest near Charleston, SC were analyzed to estimate annual evapotranspiration (ET) using four different empirical methods. The first one, reported by Zhang et al. (2001), that takes into account annual precipitation, potential ET (PET), and a vegetation water-use factor. The second method by Lu et al. (2003) uses annual rainfall, elevation, latitude and forest cover. The third method by Turner (1991) uses annual rainfall, coverage of the watershed by forest and non-forest vegetation. The fourth method by Calder and Newson (1979) uses annual rainfall and Penman PET for the grass vegetation, actual forest canopy cover, interception fraction, and fraction of the wet days. Results from each of these methods were compared with the measured water balance in which annual ET is a difference of measured annual rainfall and stream flow. The study period included years with annual rainfall varying from 1853 mm (wet) to 1020 mm (dry), typical to the Southeastern coastal plain. The 13-year measured mean annual ET was 983 mm and the annual ET remained to be near PET (>90% of average Thornthwaite PET of 1079 mm) for the years exceeding the long-term average rainfall and/or the years with just below the average but with the wet antecedent year. Years with consistently below average annual rainfall yielded annual ET equivalent to 80% or less of* *the annual estimated PET. Based on the statistical evaluation, Turner method yielded the best estimates with a mean annual ET of 974 mm (± 116 mm) and a Nash-Sutcliffe "E" coefficient of 0.64, followed by the Lu et al and Zhang et al methods. The mean annual (MAE) and mean absolute annual (MAAE) errors for both the Turner and Lu et al methods were less than 0.5% and 6.6%, respectively. The Calder-Newson method performed poorest (E = -0.29) among those evaluated. The highest overprediction error (<16%) in all methods, except for the CALDER, was observed in the second of the two consecutive dry (lower than near average rainfall) years, as expected, because none of these methods takes the antecedent soil water storage conditions into account. However, when comparing the mean annual ET over the 13-year period, there was no difference in estimates among the methods although all of them underestimated the measured. Results of assessing the impacts of reduction in forest cover on mean annual runoff using Turner and Lu et al methods indicated an increase of as much as 62% runoff as a result of removal of 90% forest cover on the study watershed. Although these empirical methods can be linked with GIS databases for effectively conducting "what-if" scenario analyses of land use changes, further research is warranted to assess their applications with data from other sites in the region, and to compare their utility relative to process-based ET measurements and water balance models.*

Keywords. Hydrology, Rainfall, Stream Outflow, PET, Thornthwaite, Forest Cover, Hydrologic Model

Introduction

Evapotranspiration (ET) is a major component of water balance of forested wetlands in the humid coastal plain of the Southeastern US. These landscapes are generally the low-gradient systems, where the runoff (outflow) process (magnitude, duration and timing) is dependent upon the position and dynamics of the shallow water table (hydroperiod), which in its turn is driven by rainfall and evapotranspiration (ET). An accurate quantification of ET is, therefore, critical to predicting water yield, flooding dynamics and, subsequently, the export of nutrients and sediment from these lands both of which can be affected by water management as well as forest land cover/land use changes such as harvesting, thinning, and plantation. Furthermore, in recent years, a need to better understand the relationship between catchment vegetation type and the variability of annual runoff as affected by vegetation manipulation for ET has found important implications for water resources management and development, stream ecology and fluvial geomorphology (Sun et al., 2005; Skaggs et al., 2004; Peel et al., 2002).

Evapotranspiration is not only dependent on rainfall and potential ET (PET), primarily controlled by solar energy, but also on soil properties, vegetation and its seasonal dynamics. Efforts have been made to measure ET at scales ranging from small lysimeters to field plots to calibrate the empirical models (Abtew, 1996; Jensen et al., 1990; Koerselman and Beltman, 1988; Riekerk, 1985). Unfortunately, direct measurement of ET on large watersheds is almost impossible and is complicated not only by the spatial heterogeneities in vegetation and soils but also by temporal variation in micro-meteorological and tree physiological parameters. A large number of studies, however, have been conducted in measuring and modeling ET for small fields in the upland agricultural landscapes (Shuttleworth, 2006; Federer et al., 2003; Allen et al., 1991; Jensen et al., 1990; Ritchie, 1972). It was not until last two decades when major efforts to develop methods of various levels of complexities from process-based to lumped and empirical concepts have been placed for measuring and modeling ET for various types of forests including the wetlands and upland forests (Cao et al., 2006; DeForest et al., 2006; Xu and Singh, 2005; Lu et al., 2003; Gholz and Clark, 2002; Mao et al., 2002; Zhang et al., 2001; Dias and Kan, 1999; Abtew, 1996; Turner, 1991; Koerselman and Beltman, 1988). In recent years due to advancements in computing, GIS, radar, and sensor technology more and more sophisticated measurements and modeling techniques are being developed to produce aerially-averaged ET on large eco-systems (Dias and Kan, 1999; Lu et al., 2003; Narasimhan et al., 2003; Sun et al., 2005; Szilagyi, 2002; 2001). However, only a few studies have been done on the poorly drained forested ecosystems in the coastal plain, and they use either sophisticated, expensive measurements or process-based models, which are difficult to be used in operational practice (Gholz and Clark 2002; Cao et al., 2006; DeForest et al., 2006; Amatya and Skaggs, 2001; Sun et al., 1998; McCarthy et al., 1992). Other examples of models include DRAINMOD (Skaggs, 1980) and its forestry version DRAINLOB (McCarthy et al., 1992), and FLATWOODS (Sun et al., 1998) are some of the process-based hydrology models developed for pine forests on poorly drained high water table soils. There are more lumped water balance methods or empirical models derived from lysimeter measurements to estimate ET on a monthly or seasonal basis (Xu and Singh, 2005; Mao et al., 2002; Dias and Kan, 1999; Abtew, 1996; Riekerk, 1985; Thornthwaite and Mather, 1956). However, these models require inputs on weather parameters such as radiation and wind speed, soil hydraulic properties such as hydraulic conductivity, drainable porosity, and field capacity, and tree physiological parameters such as leaf area index (LAI), canopy storage capacity, stomatal conductance, which are not always easily available. On the other hand, land managers, developers and planners are often challenged in obtaining reliable estimates of seasonal and annual ET for these forested lands.

The most straightforward estimation of ET (M L^{-2} T^{-1}) on an annual basis comes from the water balance equation (Szilagyi, 2001) applied over a watershed written as

$$ET = P - RO \quad (1)$$

where, P = precipitation (rainfall) in M L^{-2} T^{-1} and RO = runoff (stream outflow) in M L^{-2} T^{-1}. In (1) it is assumed that no significant changes occur in water storage on an annual basis, there is no other source of ground water in the watershed other than recharge from rainfall via base flow to the stream where runoff is measured. However, runoff measurements are often not available for the watersheds of interest for development, and planners/land managers often tend to rely on literature published data.

In order to address these problems more simple robust methods using the annual rainfall, annual PET, and some watershed characteristics such as elevation, forest canopy cover have been suggested for estimating annual ET (Lu et al 2003; Zhang et al., 2001; Turner, 1991; Calder-Newson, 1979). However, before applying any of these or other methods it is important to test their applicability for a given site or a region, since these empirical methods have been developed using data from different sites and geographical locations.

Therefore, the main objective of this study was to test four different methods proposed by Lu et al. (2003) (called "LU" hereinafter), Zhang et al (2001) (called "ZHANG" hereinafter), Turner (1991) (called "TURNER" hereinafter), and Calder-Newson (1979) (called "CALDER" hereinafter) for estimating annual ET of a forested watershed on poorly drained soils of the coastal plain in South Carolina. The testing was performed by evaluating the multi-year annual ET estimated by each of these methods against the measured values obtained by using equation (1). The second objective was to assess the effects of reduction in forest cover (e.g. development on the watershed) on change in runoff (stream outflows) using the two methods found to be the best predictors. This work is part of the hydrology research program at the Center for Forested Wetlands Research, and considerations of ET have been a component of that work since the mid-1960's. Accordingly, below we offer an overview of that work as a prelude to the current study.

ET Studies on the Santee Experimental Watersheds

Earlier studies have attempted to measure and estimate ET for two1st order watersheds (WS 77 and WS 80) (Fig. 1) at the Santee Experimental Forest adjacent to this study site (Turkey Creek, WS 78). Young (1968) determined ET on a biweekly basis from the 160-ha forested watershed (WS 77) from March 1964 to October 1966 by a water balance method that measured the periodic soil moisture across the watershed. The authors also compared the measured annual ET of 956 mm and 995 mm for1964 and 1965 (March to February for both years), respectively, to potential ET (PET) estimated by the Thornthwaite (1948) method and measured evaporation data. These ET values were 56% and 75% of the measured rainfall of 1701 mm and 1316 mm, respectively. The Thornthwaite PET estimates were 1223 mm and 1015 mm, respectively. Richter (1980) found the mean annual ET of 1047 mm using the pan evaporation data measured from 1965 to 1979 at the experimental forest. They found the annual ET as a difference of rainfall and stream flow remarkably consistent (1000 ± 60 mm) for the treatment watershed (WS 77) for the 15-year (1965-79) period compared to 1107 mm (± 74 mm) for the undisturbed control watershed for the 1969-80 period. These data showed that the prescribed burning treatment reducing the understory vegetation on WS 77 from 1977 to 1981 might have reduced the annual ET of as much as 107 mm on average. Similarly, Gilliam (1983) reported mean annual ET of 1030 mm and 1133 mm for the treatment watershed (WS77 that underwent prescribed burning) and the control (WS 80) for their study period of 1976-80 for an estimated PET of 1067 mm. Recently, Harder et al. (2007) obtained annual ET estimate of 917 mm using a water budget method for both the years 2003 and 2004 with annual rainfall of 1671 mm and 962 mm, respectively, for the adjacent watershed of about 150 ha. These annual ET estimates were 55% and 95% of the total annual rainfall. The annual PET estimated using Penman-Monteith method (Monteith, 1965) with hourly measured weather data for a standard grass reference was 912 mm, and 966 mm, respectively.

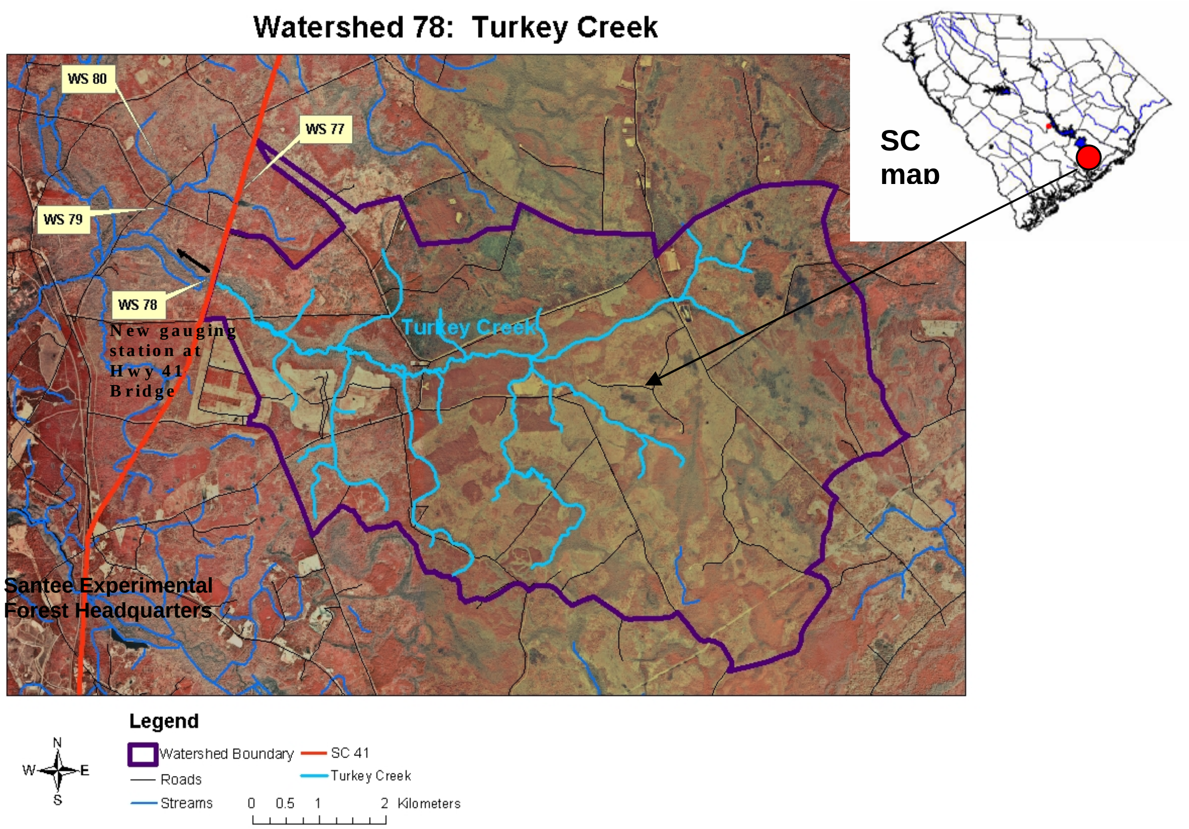

Figure 1. Aerial map of the Turkey Creek watershed (WS 78) showing its stream network and other adjacent first- (WS 77 and WS 80) and second-order (WS 79) watersheds.

This study attempts to identify empirical methods from above that are suitable for estimating the annual ET for the adjacent larger 3rd order forested watershed (Turkey Creek, WS 78) using simply rainfall, PET, forest cover and some other watershed characteristics.

Methods

Site Description

The study site is the Turkey Creek watershed (WS 78), which was established by the USDA Forest Service in 1964 and monitored until 1984. Both the rainfall and stream outflow were measured on the watershed during that period. Recognizing the importance of data from the forested watershed as a reference in a rapidly changing coastal environment, in 2004, a large-scale eco-hydrological monitoring and modeling program was initiated and the gauging of WS-78 re-established (Amatya and Trettin, 2007). The watershed was reactivated by the Forest Service, Center for Forested Wetlands Research ("Center" hereinafter) in Charleston, SC (http://www.srs.fs.usda.gov/charleston/) by installing a real-time stream flow gauging station including a rain gauge (http://waterdata.usgs.gov/sc/nwis/uv?site_no=02172035) approximately

800 m upstream of the previous gauging station in cooperation with the US Geological Survey and the College of Charleston (www.cofc.edu). This paper, however, presents the historic data collected from 1964 to 1976 only.

The Turkey Creek watershed with a third-order stream system draining an approximate area of 5,000 ha is located at 33^o 08$'$N latitude and 79^o 47$'$W longitude approximately 60 km north-west of City of Charleston near Huger, in Berkeley County of South Carolina (Fig. 1). Located at the headwaters of East Cooper River, a major tributary of the Cooper River, which drains to the Charleston Harbor System, Turkey Creek (WS 78) is typical of other watersheds in the south Atlantic coastal plain where rapid urban development is taking place. The topographic elevation of the watershed varies from 4.6 m at the stream gauging station to 14 m above mean sea level (amsl). The sub-tropical climate is characteristic of the coastal plain having hot and humid summers and moderate winter seasons. Accordingly, the minimum and maximum air temperatures, based on a 50-year (1951-2000) record at the Santee Experimental Forest, which is adjacent to Turkey Creek, were recorded as –8.5^{o}C and 37.7^{o}C, respectively, with an average daily temperature of 18.4^{o}C. Annual rainfall at the site varied from 830 mm to 1940 mm, with an average of 1370 mm based on the 50-year (1951-2000) average. Seasonally, the winter is generally wet with low intensity long duration rain events and the summer is characterized by short duration, high intensity storm events; tropical depression storms are not uncommon.

Land use within the watershed is comprised of 55% (2,728 ha) pine forest (mostly regenerated loblolly (*Pinus taeda* L.) and long leaf pine (*Pinus palustris*)), 41% (2,057 ha) wetlands and water, and 4% (215 ha) agricultural lands, roads and open areas (Amatya and Radecki-Pawlik, 2007). The watershed was heavily impacted by Hurricane Hugo in September, 1989, and the forest canopy was almost completely destroyed (Hook et al., 1991). Most of the current forests on the watershed are a mixture of remnant large trees and natural regeneration, which is approximately 17 years old. The watershed is dominated by poorly drained soils of Wahee (clayey, mixed, thermic *Aeric Ochraquults*) and Lenoir (clayey, mixed, *Thermic Aeric Paleaquults*) series (SCS, 1980). The watershed also contains small areas of somewhat poorly and moderately well drained sandy and loamy soils. Current management practices on the majority of the watershed include forestry, biomass removal for reducing fire hazards, prescribed fire and thinning for restoration of native longleaf pine and habitat management for red-cockaded woodpeckers (*Picoides borealis*), an endangered species. The watershed is also used for recreational purposes such as hunting, fishing, bird watching, hiking, canoeing, biking, historical tours, horse riding, all-terrain vehicle (ATV) use, and agriculture.

Hydro-meteorologic Measurements

Rainfall

Rainfall was measured since 1946 using a manual gauge (recorded on a daily basis) at the weather station located within the Santee Experimental Forest Headquarters, which is about 4 km from the watershed (Fig. 1). Measurements at the watershed outlet are available for 1964-1984, and again starting in December, 2004 (Amatya and Trettin, 2007). In addition, an automatic CR-10X Campbell Scientific complete weather station installed by the Center in October 2005 started to record the rainfall in the middle of the watershed. At present there are five automatic tipping bucket rain gauges in and around the watershed besides the sixth one at the Santee Experimental Forest (SEF) Headquarters located about 6 km from the middle of the study site (Fig. 1). In this study daily rainfall data only from 1964 to 1976 were processed to obtain monthly and annual totals for the analysis.

Stream Outflows

The original gauging station on this watershed was located about 800 m downstream of the existing Turkey Creek Bridge on Highway 41 N (Fig. 1) near the town of Huger, SC. Stage-discharge rating curves were developed to estimate the stream flow rates recorded on a 15-minute basis when flow occurred and on a daily basis when there was no flow. Under a recent cooperative agreement with the Center, Atlanta-based Tetra-Tech, Inc. helped digitize both the instantaneous and daily historical stream flow data recorded on hard copies. Daily stream flow data measured from 1964 to 1976 were recently analyzed and reported by Amatya and Radecki-Pawlik (2007). Similarly, the instantaneous flow data are being analyzed for an ongoing companion study to evaluate the rainfall-runoff dynamics of the watershed using the storm events observed during the 1964-76 period.

A new real-time stream gauging station has been established slightly upstream of the old station in a collaborative effort with the USGS and College of Charleston (Amatya and Trettin 2007). The stage data are measured by a pressure transducer in the middle of the stream (upstream of the bridge) that is connected with a SUTRON datalogger to store the data in a 15-minute basis. Velocity measurements are done on an approximately 2-4 weekly basis to develop and update a stage discharge relationship used for computing the flow rates.

Weather parameters

A weather station consisting of a rain gauge and a temperature recorder was installed in 1946 at the Santee Experimental Forest headquarters located about 6 km from the center of the Turkey Creek watershed (Fig. 1). An evaporation pan was installed in 1963, with data collected on a daily basis. Later in 1996, a Campbell Scientific weather station with an automatic CR10X datalogger was added to measure air temperature, relative humidity, wind speed and direction, and solar radiation on an hourly basis. In 2003 a net radiometer and soil temperature sensors were also added in the system. Finally, a Campbell Scientific CR10X weather station was installed in the middle of the study site (Turkey Creek watershed) itself in October 2005 to measure air temperature, relative humidity, wind speed and direction, and solar radiation on an hourly basis.

Evapotranspiration Models and Parameter Estimates

1. Zhang et al. (2001) (ZHANG) Method

Using hydrologic data from over 250 watersheds worldwide across a wide range of climatic zones and biomes, Zhang et al. (2001) correlated mean annual actual evapotranspiration (AET), annual precipitation (P), and Priestley and Taylor equation for potential evapotranspiration (PET). The AET can be described and estimated by the following formula:

$$AET = P \frac{1 + w\frac{PET}{P}}{1 + w\frac{PET}{P} + \frac{P}{PET}} \quad (2)$$

where, w is the plant-available water coefficient and represents the relative differences of water use for transpiration. ZHANG recommended a value of 2 for forests and 0.5 for grasslands. Amatya et al. (2002) found w = 3 as the best value fitting their data for a five-year period from managed pine forested watershed in eastern NC. We used a value of 2.8 for the forest with mostly pine and hardwood as found by Sun et al. (2005) in their study of annual water yield from forestlands across the southeastern U.S.

Although ZHANG recommended net radiation-based Priestley-Taylor (1972) method to estimate PET, temperature-based Thornthwaite (1948) method was used to estimate the monthly PET as the net radiation data were not available for the site. Long-term parameter like heat index (I) in the PET method was obtained by using the long-term (1946-2004) mean monthly temperature measured at the Forest Service Santee Experimental Forest Headquarter. The monthly PET estimates were adjusted by the correction factors developed by Amatya et al. (1995) for the coastal North Carolina. Monthly values were summed to obtain the annual total PET. When calibrated with local data Thornthwaite method can also be used for reasonable estimates of grass PET (Xu and Singh, 2001; Amatya et al., 1995).

2. Lu et al. (2003) Method:

Using data from 39 different forested watersheds in the southeastern USA, Lu et al. (2003) recommended a following multivariate linear regression equation to estimate mean annual ET:

$$ET = 1098.79 + 0.31Rainfall - 0.29Elevation - 21.84Latitude + 1.96\ Forest \quad (3)$$

where, ET = Long-term mean annual evapotranspiration of the watershed, mm; Rainfall = Long-term mean annual precipitation of the watershed, mm; Latitude = Watershed latitude at the outlet, degree; Elevation = Mean watershed elevation above mean sea level, m; Forest = percentage of watershed covered by forests. The model is highly significant with all the independent variables significant at $\alpha = 0.05$ level.

The average elevation of the site used was 8 m a.m.s.l. and the latitude is 33.1^{o}N. Using the aerial photographs of 1968 and 1973 obtained from the USDA Forest Service Francis Marion National Forest the area of the forest in the watershed is estimated as 96% (=0.96).

3. Turner (1991) Method:

This method proposed to estimate annual ET from a large unmanaged watershed as the sum of the product of annual ET rate of shrubs and trees and area covered by them plus the product of annual ET rate of herbaceous cover and area by them, both based on the annual precipitation (P) as follows:

$$ET = 2.14\ (1-C)\ P^{0.647} + 2.67\ C^{0.865}\ P^{0.677} \quad (4)$$

where, C = fraction of the watershed covered by the shrubs and trees and 1-C = fraction of the watershed covered by the herbaceous cover. The “C” value of 0.96 from the aerial photograph was again used here also as in LU’s method (2).

4. Calder and Newson (1979) Model:

A semi-empirical model was developed by Calder and Newson, as cited in Maidment (1992), for estimating both the annual and seasonal differences in runoff from afforested, upland catchments in the United Kingdom, with non-soil-water limiting conditions. This method is also tested here since the conditions on Turkey Creek watershed are similar to those catchments with poorly drained high water table soils where precipitation dominates evapotranspiration. The model requires information on annual rainfall, annual Penman ET estimates of evaporation, and the proportion of the catchment with complete canopy coverage. The assumptions are that (1) the ET losses from grassland are equal to the annual Penman (1948) PET_g for grass, (2) transpiration losses from the forest are equal to the annual PET_a value multiplied by the fraction of the year that the canopy is dry, (3) annual interception loss from the forest, with complete canopy coverage, is a simple function of the annual rainfall R, and (4) soil moisture deficits are insufficient to limit transpiration from grass or trees in the wet areas. Accordingly, the annual evapotranspiration (ET) is given by:

$$ET = PET_g + f\,(R\,\alpha - W_a\,PET_g) \qquad (5)$$

where, f = fraction of the catchment area under forest canopy cover was estimated as 0.66 times 0.96 (fraction of forested area) as suggested by the authors, W_a = fraction of the year when the canopy is wet and was estimated as a ratio of the number of rainy days to total days in each year of the study period, and α = interception fraction. This fraction was assumed equal to 0.12 estimated by Harder et al. (2007) for the forested watershed (WS 80) adjacent to the study site. As the weather data for estimating the PET using the Penman (1948) method were not available, again Thornthwaite method with correction factors were used as in ZHANG method (1) for the grass PET (PET_g) in equation (5).

Evaluation of ET Methods

Each of the four ET methods (equations 2 to 5) was tested for their reliability to predict the measured annual ET calculated (equation 1) for the 13-year (1964-76) period. The performance of each of the methods was evaluated by comparing the statistical parameters (a) average absolute annual deviation (AAAD) between the measured and estimated value, (b) mean annual error (MAE) and (c) mean absolute annual error (MAAE) in percentage between the average annual measured and estimated ET, (c) slope and intercept parameters of the regression between the ET method (X) and measured ET (y) values, (d) the standard error of estimate (SEE), and (e) Nash-Sutcliffe coefficient (E).

Impacts of Forest Removal

Two methods found to be the best predictors of the annual ET from above statistical evaluation were used for evaluating potential impacts of various levels of forest cover removal on the Turkey Creek watershed stream outflows. The levels of removal were simulated using percent areas without forest. These scenarios included 4% (existing condition with 96% forest based on the aerial photos), 15, 25, 40, 50, 60, 75, and 90 (highly developed with only a10% forest coverage). The methods were then used to estimate annual ET with the annual rainfall for the same1964-76 period for these scenarios. Annual stream outflow was then calculated as a difference of rainfall and estimated ET as was done by Sun et al. (2005). Percent increase in outflow for each forest cover removal scenario was calculated in reference to the outflow estimated for the existing base line condition with 96% forest.

Results and Discussion

Annual ET estimated by four different methods (ZHANG, LU, TURNER, and CALDER) for the Turkey Creek watershed (WS 78) for 1964-78 are presented in Table 1 together with measured ET calculated as a difference of annual rainfall and outflow. The measured annual ET ranged from 830 mm (64% of rainfall) in 1973 with an annual rainfall of 1294 mm and a PET of 1117 mm to 1333 mm (72% of rainfall) for the wettest year 1964 with the rainfall of 1851 mm and the PET of 1116 mm, with an average annual ET of 983 mm. As expected, year 1967 with the lowest observed rainfall (1020 mm) did not yield the lowest ET because of the wet antecedent conditions in the previous year (1966) with above average rain of 1505 mm. Due to the same reason with dry antecedent condition (below normal rain of 1106 mm) in 1972 the annual ET in

1973 (also with slightly below normal rain of 1290 mm) was the lowest in the study period. The annual ET remained to be near PET (>90% of PET) for the years exceeding the long-term average rainfall and/or the years with just below the average but with the wet antecedent year. Years 1972 to 1976 with consistently below average annual rainfall (Table 1) yielded annual ET equivalent to 80% or less of the annual estimated PET. ET in years 1964 and 1966 (both with above average rainfall) exceeded the estimated PET. Annual outflow yielded a higher variability with a coefficient of variation (COV) of 0.45 compared only 0.17 for rainfall and 0.14 for the ET.

Table 1. Measured annual rainfall, stream outflow and ET estimated by four different methods for the Turkey Creek watershed for 1964-76 period.

Year	Annual Rainfall mm	Percent Time Canopy was wet	Annual Outflow mm	Rain – Outflow mm	Annual PET mm	Estimated Annual ET, mm			
						Zhang	Lu	Turner	Calder
1964	1851	0.290	518	1333	1116	1145	1134	1229	1052
1965	1199	0.307	276	923	987	877	932	916	886
1966	1505	0.279	388	1117	927	943	1027	1068	877
1967	1020	0.238	132	888	1019	807	877	821	943
1968	1141	0.268	127	1014	1022	865	914	886	935
1969	1313	0.233	350	963	1028	938	967	974	976
1970	1362	0.260	334	1028	1117	994	983	998	1036
1971	1694	0.326	637	1057	1089	1089	1085	1157	993
1972	1106	0.224	214	892	1113	878	904	868	1039
1973	1294	0.285	464	830	1117	966	962	965	1014
1974	1175	0.249	287	888	1162	927	925	904	1068
1975	1290	0.301	431	859	1163	981	960	963	1039
1976	1202	0.243	221	981	1171	942	933	918	1082
Avg	**1320**	**0.270**	**337**	**983**	**1079**	**950**	**969**	**974**	**995**
COV	**0.18**	**0.17**	**0.45**	**0.14**	**0.07**	**0.10**	**0.08**	**0.12**	**0.07**

All methods, except for the CALDER, predicted highest annual ET in the same year 1964 with the highest rainfall consistent with the measured data. The lowest annual ET by the same three methods (ZHANG, LU, and TURNER) was estimated for the year 1967 with the lowest rainfall, as expected, as none of these methods takes the antecedent moisture conditions into account. The prediction error in annual ET ranged from +1.6 % to –16.5% with an average of 2.5% for the ZHANG method, -0.5% to 16.0% with an average of 0.5% for the LU method, 0.8% to 16% with an average of 0.3% for the TURNER method, and –0.9% to 22.2% with an average of –2.9% for the CALDER method. All methods, except for the CALDER, yielded the highest error of near -16% due to over-prediction of ET in 1973 when the measured ET was the lowest. Highest error (<16%) in all methods, except for the CALDER, was observed in the second (1973, and 1975) of the two consecutive dry (lower than near average rainfall) years resulting in over-prediction of flow, again due to error in the antecedent soil moisture conditions. The large discrepancy in 1964 in all methods was because the flows for the first two months were not available in the annual value. Another reason for discrepancies may be due to some potential errors in rainfall as affected by its spatial variability. For an example, the rainfall measured at the Santee Experimental Forest Headquarter in 1975 was 1420 mm compared to only 1290 mm measured near the study site. The 13-year (1964-76) mean annual ET by all methods was within 33 mm (for the ZHANG method) of the measured data (983 mm) (Table 1). The closest value (974 mm) was obtained for the TURNER method. All methods underpredicted the mean ET, except for the CALDER method.

The mean annual ET with their standard deviations for the measured and estimated values for all four methods are shown in Figure 2 together with the 50-year long-term rainfall and PET for the Santee Experimental Forest Headquarter. Data shows that there was no difference between the measured ET and ET by each of the four methods when compared within one standard deviation. However, all of them, except for the CALDER, slightly underestimated the measured value. The measured data shows the mean annual ET of 72 % of the long-term rainfall and 94% of the long-term PET. Compared to the 15-year (1964-79) average annual ET reported by Richter (1980), these values are about 2% less than the 1000 mm of ET for the adjacent treatment watershed (WS 77) and about 10% less than the control watershed (WS 80).

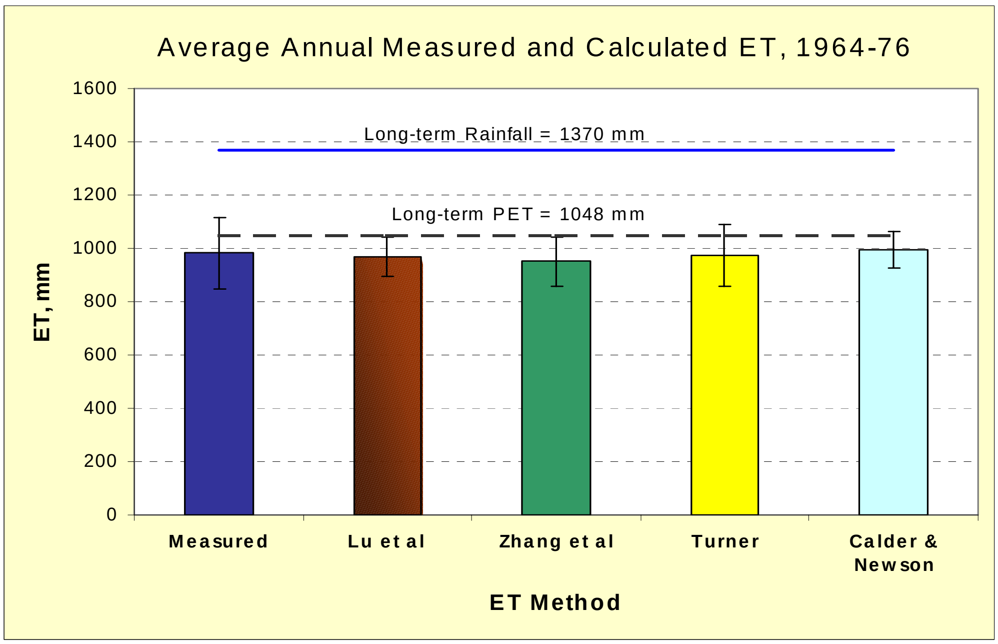

Figure 2. Measured average annual ET (Rainfall – Outflow) compared with the annual ET estimated by four methods for the Turkey Creek watershed (WS 78) using data from 1964-76.

In their comparative study of stream flow dynamics of three (1st order (WS 80), 2nd order (WS 79) and the 3rd order (WS 78)) watersheds, Amatya and Radecki-Pawlik (2007) reported that the slightly higher (25%) mean runoff coefficient for the 3rd order watershed (WS 78) compared to only 22% for the 1st order was possibly due to reduced ET from the former with some open areas (~ 4%) covered by roads, dwellings, and farm lands. However, the annual ET estimate of only about 917 mm for a wet year (2003) and a dry year (2004) for the control watershed (WS 80) reported by Harder et al. (2007) was about 10-15% lower than that observed in 1964-79 period. This may be attributed to the effects of vegetation that was naturally regenerated after the forest canopy was severely damaged by Hurricane Hugo in September 1989 (Hook et al., 1991). These results are, however, consistent with the study reported by Amatya et al. (2002) who found the six-year (1996-02) average annual ET, calculated as difference of rainfall and outflow, to be 922 mm or 92% of the average annual PET of 1000 mm for a 3,000 ha watershed on a managed pine forest in eastern NC. That study also found the plant-available water coefficient value “w” of 3.0 (which is close to 2.8 used herein) for the ZHANG’s method (2) when calibrated with six years of calculated ET. DRAINMOD (Skaggs, 1980) hydrology simulations with a long-term (1951-2000) weather data for the adjacent forested watershed (WS 80) (Harder et al., 2006) predicted the annual ET ranging from 930 mm to 1154 mm with an average of 1058 mm for an average rainfall of 1374 mm (~4% higher than at the study site) for the same 13-year study period.

In a recent experimental study measuring water and carbon fluxes using eddy flux covariance and sap flow measurements method on a managed pine forest in eastern North Carolina, DeForest et al. (2006) reported that ET rates for the mid-rotation and clear-cut stands were similar, except during the early summer. In the same study Cao et al. (2006) found the January-September (nine-month) ET of 714 mm, equivalent to about 955 mm in the year 2005. Using the similar experimental method Gholz and Clark (2002) found measured annual ET of 959 mm and 1110 mm for a mid-rotation young and a 24-year old slash pine stands, respectively, in North Florida. Based on these studies our estimates of mean annual ET for the study site by all four methods seem to be comparable with the published data from the coastal forests.

We evaluated the performance of each of the four methods in estimating annual ET as affected by year-to-year variation in rainfall and weather defined by the PET using the various statistical measures shown in Table 2. All methods, except for the CALDER, performed fairly well based on these statistics. LU and TURNER methods performed in a fairly similar manner with about the same average absolute annual deviation (AAAD) and standard error. There was only a slight difference in mean annual (MAE) and absolute error (MAAE) between these two methods Slope of both the regression models was also significant ($p < 0.001$). However, the fact that the Nash-Sutcliffe E coefficient was > 0.6 and slope and the intercept were near unity and zero, respectively, for the Turner method indicates that it as a better performer than the LU method. ZHANG method also yielded near unity slope and near zero intercept but it yielded much higher AAAD, MAE, and MAAE, lower R^2, and higher standard error than either of the TURNER and LU methods. Therefore, it was ranked third in the performance. CALDER method performed very poor and ranked the lowest because of a negative E, highest AAAD, MAAE, MAE and standard error, and the regression slope was not significant.

Table 2. Regression equations (measured annual vs. estimated annual ET) generated for fourdifferent methods for the Turkey Creek watershed for the 1964-76 period.

Method	Regression equation and statistical parameters	AAAD mm	MAAE %	MAE %	N-S Coef. E	Standard Error mm
ZHANG	$y = 0.94x + 59.79$ ($p < 0.02$)	83	8.3	2.5	0.38	105.49
LU	$y = 1.49x – 461.54$ ($p < 0.001$)	63	6.2	0.5	0.58	82.31
TURNER	$y = 0.93x + 75.12$ ($p < 0.001$)	64	6.6	0.3	0.64	83.85
CALDER	$y = -0.07x + 1048$ ($P < 1.00$)	121	12.2	-2.9	-0.29	140.8

It is interesting that the two best predictors of annual ET were found to be TURNER and LU, both of which includes precipitation and forest cover as the major dependent variable without a PET component. LU is a linear multivariate model with elevation of the site and latitude also as the dependent variables. TURNER, a power function, just includes the rainfall and forest cover. The two other methods ZHANG and CALDER both include also the PET component. Both of these methods suggest using PET values obtained from a better process-based method such as Priestley-Taylor (1972) for the ZHANG and Penman combination (1948) method for the CALDER methods. The fact that the PET obtained from just a simple temperature-based Thornthwaite (1948) method with monthly correction factors obtained from the North Carolina study were used may have introduced errors in both of these methods. We believe that using a process-based PET parameter from the site and a calibrated “w” value may improve the estimate by ZHANG method. Similarly, CALDER although a more conceptual model with PET parameter, interception fraction, fraction of wet days in a year besides rainfall and forest cover, might have performed poorly for the similar reasons. This method, developed for the wet upland sites in United Kingdom with unlimited soil water conditions, had performed well for that region. In this study, although the site is generally wet it may sometime experience extremely dry conditions limiting the soil water conditions in this shallow soil systems as reported by Harder et al. (2007) for their WS 80 site in 2004. The interception value used herein from the same watershed may also have further introduced additional error.

The results of assessing the impacts of various intensities of forest cover removal (increase in non-forest) using the TURNER and LU methods are shown in Figure 3. Compared to the base level of 350 mm of outflow on average for 96% forest cover (4% open area), the LU method predicted a linear increase in outflow as the open area increases with reduction in forest cover. For example, for a scenario with 90% open area or only 10 % forest cover the outflow was predicted to be 519 mm, which is an increase of 48% compared to the existing scenario. However, the TURNER method, which was found to be a slightly better estimator than the LU method, predicted the increase as a power function with as much as 558 mm for the same 90% forest cover removal. This was equivalent to nearly 62% increase compared to the average annual outflow. The estimated increase was higher by TURNER method for removal of the forest cover higher than 50% (Fig. 3). These estimates are consistent with the observed increase of outflows by as much as 44% on the adjacent control watershed (WS 80) soon after the Hurricane Hugo (Wilson et al. 2006).

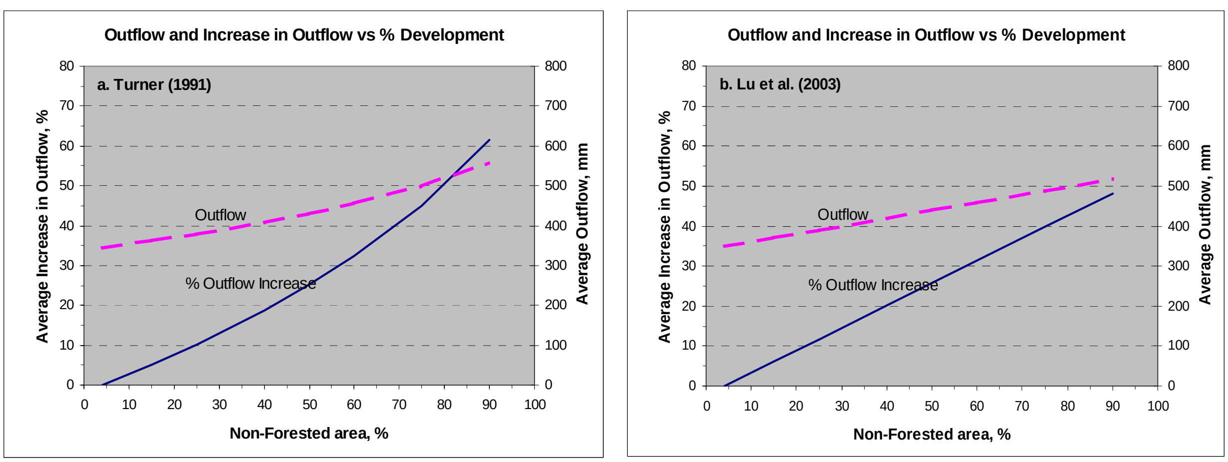

Figure 3. Average annual estimated outflow and increase in outflow for percent development (e.g. increase in non-forested open area cover) on the Turkey Creek watershed (WS 78) using (a) Turner (1979) and (b) Lu et al (2003) methods with1964-76 rainfall data from the watershed.

Conclusions and Recommendations

This paper summarized the measured annual evapotranspiration (ET) calculated as a difference of rainfall and stream flow for the 13-years (1964-76) of historic rainfall, weather and stream flow data from a 5,000 ha watershed containing a 3rd order stream, and compared the estimated annual ET using four empirical to semi-empirical methods that use annual rainfall, PET, forest cover and some other watershed characteristics against the measured data. The 13-year measured mean annual ET was 983 mm and the annual ET remained to be near PET (>90% of PET) for the years exceeding the long-term average rainfall and/or the years with just below the average but with the wet antecedent year. Years with consistently below average annual rainfall yielded annual ET equivalent to 80% or less of the annual estimated PET.

The four methods that were evaluated are: (a) Zhang et al. (2001) (ZHANG) using annual rainfall, PET, and vegetation water use coefficient, (b) Lu et al. (2003) (LU) using annual rainfall, percent forest, latitude, and elevation, (c) Turner (1991) (TURNER) using rainfall and percent forest, and (d) Calder and Newson (1979) (CALDER) using annual rainfall and Penman-based PET, percent forest canopy only, fraction of days canopy was wet, and interception coefficient. When compared with the measured annual ET for the study period, all methods performed well (within 33 mm or 3.3%) in predicting mean annual ET of 983 mm for the measured data. However, when compared on an annual basis, TURNER and LU methods were found to be the best estimators followed by the ZHANG. The method by CALDER was found to perform poorly. In all these methods use of rainfall data from a single gauge for this 5,000 ha watershed may have introduced some errors due to spatial variability. Although the first three methods performed well based on the computed statistics the errors may be high in the second year of back-to-back near or below normal rainfall as the antecedent soil water storage conditions are neglected in all methods. Scenario analysis performed to evaluate the effects of removing the forest or increasing the non-forest open areas on watershed runoff revealed 44% for LU method and 62% for TURNER method increase in average annual outflows when 90% of the forest is removed. At 50% removal level both yielded the same (25%) percentage of increase. It is important to note that although these methods are applicable only as planning level tools for estimating the long-term average ET only the TURNER and LU methods may be used for estimating the annual ET on this watershed after validation with additional data from the site.

As the next step in the ET study on this watershed we plan to validate these findings with land cover data from 1:6,000 scale high resolution images and hydro-meteorology data being collected since 2005 including the aerially averaged rainfall using nearby gauges to account for spatial variability. We also plan to test ET models such as Morton's complementary relationship of areal evapotranspiration (CRAE) as described by Xu and Singh (2003) and Szilagyi (2001) to compute watershed ET on a monthly time scale as our current weather station on this site has been continuously monitoring full weather variables such as air temperature, solar radiation, humidity, wind speed, and soil temperature needed for this method. It is also recommended that future studies should examine the ET dynamics using the eddy covariance method measuring the micrometeorological variables for these mixed pine hardwood stands on poorly drained low gradient watersheds of the coastal plain. Results from these process-based studies may help refine these empirical relationships that can also be easily integrated with GIS spatial database allowing for more effective and reliable planning tools for the analysis of land use conversion and development on this and similar other watersheds in the region.

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