Annual Evapotranspiration of a Forested Wetland Watershed, SC

Devendra M Amatya, PhD, PE
USDA Forest Service, Center for Forested Wetlands Research, 2730 Savannah Highway, Charleston, SC 29414; Email: damatya@fs.fed.us

Carl Trettin, PhD
USDA Forest Service, Center for Forested Wetlands Research, 2730 Savannah Highway, Charleston, SC 29414; Email: ctrettin@fs.fed.us

Written for presentation at the
2007 ASABE Annual International Meeting
Sponsored by ASABE
Minneapolis Convention Center
Minneapolis, Minnesota
17 - 20 June 2007

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...
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 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.
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.

Watershed 78: Turkey Creek

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
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


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:

\[
AET = P \frac{1 + w \frac{PET}{P}}{1 + \frac{P}{PET} \frac{PET}{P}}
\]

(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
transpiration losses from the forest are equal to the annual PET 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:

$$ET = PET_g + f (R \alpha - W_s \cdot PET_g)$$  \hspace{1cm} (5)

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

**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
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).

![Average Annual Measured and Calculated ET, 1964-76](image)

**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
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 with 1964-76 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
those photographs, and Andy Harrison, Hydro-Tech at Forest Service for helping process the weather and stream flow data.

References


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