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HYDROLOGY AND WATER BUDGET FOR A FORESTED ATLANTIC COASTAL PLAIN WATERSHED, SOUTH CAROLINA[1]

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ABSTRACT: Increases in timber demand and urban development in the Atlantic Coastal Plain over the past decade have motivated studies on the hydrology, water quality, and sustainable management of coastal plain watersheds. However, studies on baseline water budgets are limited for the low-lying, forested watersheds of the Atlantic Coastal Plain. The purpose of this study was to document the hydrology and a method to quantify the water budget of a first-order forested watershed, WS80, located within the USDA Forest Service Santee Experimental Forest northeast of Charleston, South Carolina. Annual Rainfall for the 2003 and 2004 periods were 1,671 mm (300 mm above normal) and 962 mm (over 400 mm below normal), respectively. Runoff coefficients (outflow as a fraction of total rainfall) for the 2003 and 2004 periods were 0.47 and 0.08, respectively, indicating a wide variability of outflows as affected by antecedent conditions. A spreadsheet-based Thornthwaite monthly water balance model was tested on WS80 using three different potential evapotranspiration estimators [Hamon, Thornthwaite, and Penman-Monteith (P-M)]. The Hamon and P-M-based methods performed reasonably well with average absolute monthly deviations of 12.6 and 13.9 mm, respectively, between the measured and predicted outflows. Estimated closure errors were all within 9% for the 2003, 2004, and seasonal water budgets. These results may have implications on forest management practices and provide necessary baseline or reference information for Atlantic Coastal Plain watersheds.

KEY TERMS: Runoff; hydrologic-modeling; hydrologic-monitoring; Thornthwaite water-balance; water table, evapotranspiration.

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INTRODUCTION

Forests have an important role in controlling hydrologic patterns in the Southeastern U.S. where 55% of the region is forested (Sun *et al.*, 2002). Several factors in the past few decades have motivated studies on the hydrologic characteristics and effective management of these ecosystems. First, the timber production in the Southeast U.S. has more than doubled from 1953 to 1997 (Wear and Greis, 2002) and timber management practices including fertilizer and herbicide use, short harvesting rotations, and drainage are shown to have negative consequences in the form of

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nonpoint-source pollution (U.S. Environmental Protection Agency, USEPA, 1992; Trettin and Sheets, 1987). Secondly, the Southeastern U.S. is expected to lose about 4.9 million forest hectares (ha) to urbanization between 1992 and 2020 with a substantial part of the loss concentrated in the Atlantic Coastal Plain (Wear and Greis, 2002). A large fraction of these ecosystems are forested wetlands, and if left unchecked, both the timber management practices and the increased development can adversely impact these ecosystems and their associated wetland functions.

Sun *et al.* (2001) assessed the effects of timber management strategies on hydrologic processes in several southern-forested wetlands. The authors found that along with soils, wetland types and management practices, climate is an important factor in controlling wetland hydrology and the magnitude of disturbance impacts. In the past decade alone, the Southeast U.S. has experienced extreme climate regimes ranging from severe hurricanes causing massive flooding to severe drought. Due to the potential threat of future disturbances and the complex interactions involved in wetland environments, the understanding of the hydrology of forested wetlands is critical in the protection and management of these ecosystems. Such an understanding is enhanced by studies on undisturbed ecosystems that provide reference or baseline information.

Many hydrologic studies in the past have been conducted in upland forested watersheds where the hydrology is strongly influenced by landscape position and steep topographical gradients (Swank *et al.*, 2001; Tajchman *et al.*, 1997). However, there are fewer studies on the forested ecosystems in the lowlands of the Southeast U.S. where small topographic gradients cause hydrologic processes to be regulated predominantly by shallow water table positions. The hydrology of artificially drained forested lands with shallow water tables in eastern North Carolina have been described by Skaggs *et al.* (1980), McCarthy *et al.* (1991), and Amatya *et al.* (1996, 1998a). In addition, Chescheir *et al.* (2003) recently summarized the outflow and nutrient characteristics for over 100 site-years consisting of natural and managed pine forests in eastern NC and concluded that the median ratio of outflow to precipitation was 0.31.

Much of the Atlantic Coastal Plain that is forested, however, does not have artificial drainage. The managed forests on these lands include loblolly pine (*Pinus taeda L.*), longleaf pine (*Pinus palustris Mill.*), bottomland hardwoods, pine flatwoods, and short rotation woody crops. The monthly and annual water budget for an undrained 155 ha watershed (WS77) in the Santee Experimental Forest along the South Carolina (SC) Coastal Plain was conducted by Young (1968) and Young and Klawitter (1968). The results showed that excess water in the form of runoff could be problematic in downstream flooding and that there was no dependable base-flow generated from this undrained watershed. Riekerk *et al.* (1979) performed baseline water budgets on three watersheds containing pine flatwoods in the lower Coastal Plain of Florida, and average annual runoff, evapotranspiration (ET), and ground-water recharge, as a fraction of annual rainfall, were measured to be 0.39, 0.58, and 0.03, respectively. Chescheir *et al.* (1995) monitored water budget components over a 3-year period on an undrained forested wetland of hardwoods mixed with pine in eastern North Carolina and found that annual ET and stream outflow as a fraction of gross rainfall were 0.87 and 0.16, respectively. In addition, Sun *et al.* (2002) compared two watersheds containing forested wetlands along the Atlantic Coastal Plain to an upland watershed in the Appalachian mountains of North Carolina. The authors found that the runoff to precipitation ratio for the upland watershed was 0.53 *vs.* 0.30 and 0.13 for the coastal watersheds.

Long-term hydrologic studies of an undrained forested watershed used in this study (WS80) were presented earlier by Sun *et al.* (2000) and Amatya *et al.* (2003). Sun *et al.* (2000) analyzed the outflows from WS80 for periods from 1976 to 1980 and 1990 to October, 1992 and calculated an average annual outflow to precipitation coefficient of 0.23. For the near 3-year period after Hurricane Hugo in 1989, which caused appreciable damage to the watershed, their results indicated an increase in annual outflows, which may be due to the decreased ET caused by fallen and damaged trees. A comparative study of WS80 and a small intensely managed, drained pine forest in coastal North Carolina showed that despite WS80 having a smaller annual rainfall, this watershed had much shallower water table depths with higher frequent outflows as compared with the drained watershed (Amatya *et al.*, 2003). This study highlighted the need for long-term hydrologic data and soil water properties to adequately compare the hydrology of poorly drained coastal watersheds. A study by Miwa *et al.* (2003) on streamflow dynamics at WS80 demonstrated that headwater streamflow was highly responsive to rain events and that headwater stream processes are regulated by rainfall intervals, antecedent soil moisture, vegetation, soil types, topography, and surface water storage.

Further research is needed to understand the natural dynamics of water balance components in such forested systems along the Atlantic Coastal Plain to accurately assess impacts of anthropogenic disturbances and for improving forest management strategies related to water quality. Furthermore, additional research is needed on the role of low-order watersheds in evaluating best management practices along coastal stream buffers and on the estimates of nutrient loads for low-gradient coastal forests. Watershed WS80 has great potential to provide reference or baseline data for assessing disturbance impacts along the Atlantic Coastal Plain. The main objective of this study was to investigate the hydrology and conduct a water budget analysis of watershed WS80 for a 2-year period from 2003 to 2004. A second objective was to assess the performance of a Thornthwaite monthly water budget model (Dingman, 2002) for quantifying the monthly water budget of WS80.

METHODOLOGY AND DATA COLLECTION

Site Description

The study site is watershed WS80 (33.15°N Latitude and 79.8°W Longitude), located in the Francis Marion National Forest northwest of Charleston, SC (Figure 1). Watershed WS80, first delineated in 1968, drains a first-order headwater stream and is contained within the Santee Experimental Forest near Huger, SC. This site serves as the control watershed for a paired watershed system that includes a treatment watershed (WS77). WS80 is 160 ha in size and has been relatively undisturbed for over 80 years. The first-order stream of WS80 flows through Fox Gulley Creek into Turkey Creek, a tributary to Huger Creek, and drains ultimately into the East Cooper River, an estuarine river of the Atlantic Ocean. WS77 and WS80 are both parts of a second-order watershed, WS79, drained by Fox Gulley Creek.

In 1989, the eye of Hurricane Hugo passed through the Francis Marion National Forest and the hurricane caused appreciable damage to the forest. After the hurricane, WS80 remained undisturbed (no timber was harvested), while WS77 underwent a salvaged harvest where any damaged or fallen trees profitable for timber were removed. The forest occupying

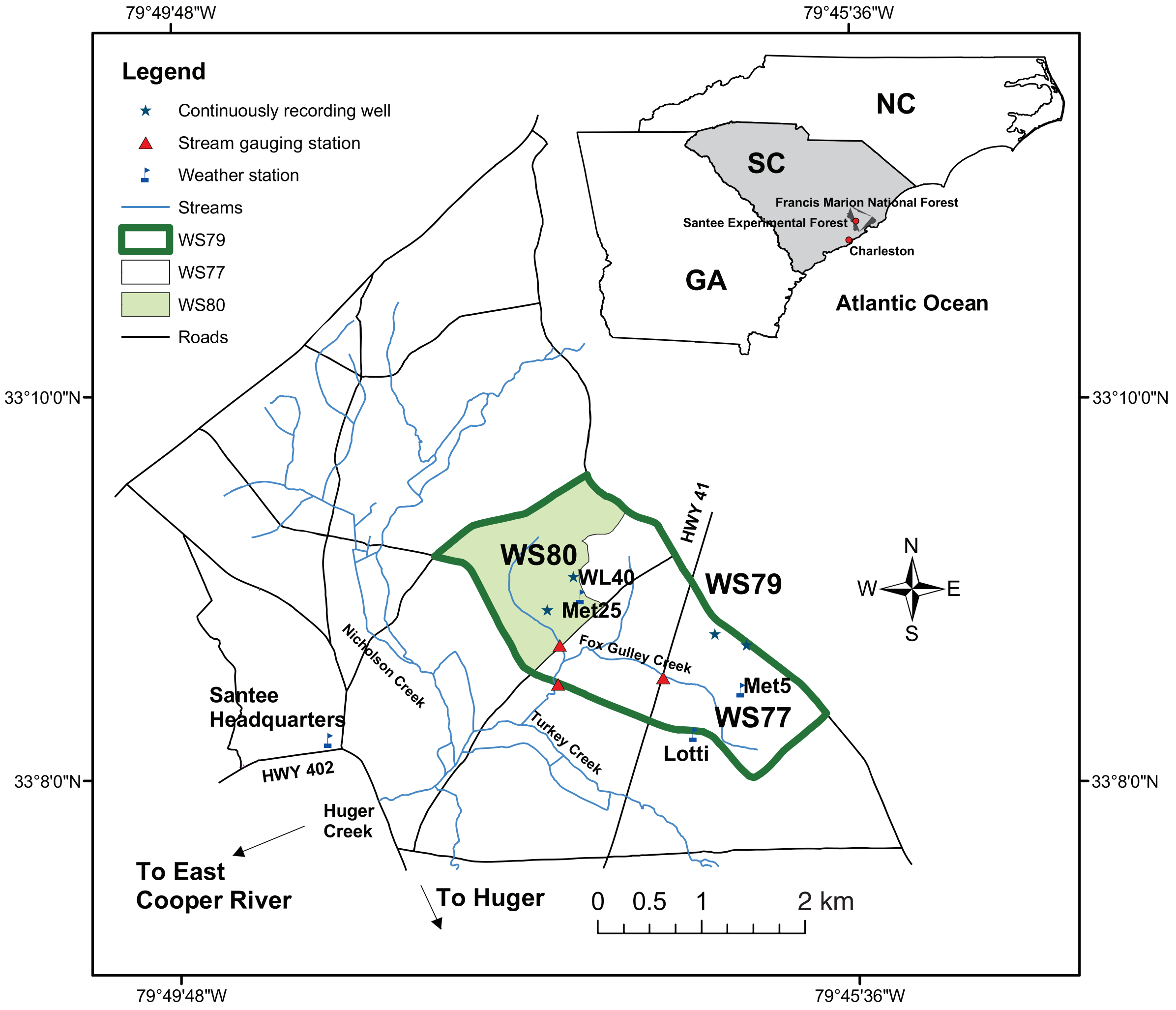

FIGURE 1. Location Map and Overview of WS80 and the Santee Experimental Forest.

WS80 is still in a recovery phase and the natural regeneration has resulted in a mix of hardwoods in the lowland areas near the stream and a mix of hardwoods and pine species in the upland areas. Common tree types include loblolly pine (*Pinus taeda L.*), sweetgum (*Liquidambar styraciflua*), and a variety of oak species (Quercus spp.) typical of the Atlantic Coastal Plain. Most of the tree stands are 14-15-years old. WS77, the treatment watershed, has not been harvested since Hugo, but subcompartments within the watershed undergo prescribed burns every 2-3 years as part of a management plan for the Red-Cockaded Woodpecker (*Picoides borealis*).

Soils are primarily sandy loams with clayey subsoils that have low permeability and a high available water capacity (Soil Conservation Service, SCS, 1980). Surface elevations on WS80 range from approximately 10 m above mean sea level in the upland areas to approximately 3.7 m at the stream outlet, and the watershed has topographic relief ranging from 0% to 3% slope. The climate of the region is specified as humid subtropical where winters are short and mild, and summers are long and hot (Sun *et al.*, 2000). The long-term mean annual air temperature is 18.3°C, while the mean annual precipitation is approximately 1,370 mm. The climate of the region heavily influences the hydrologic balance of the watershed, and approximately 23% of the WS80 is classified as wetlands (Sun *et al.*, 2000).

Precipitation

An on-site weather station (Met25) is equipped with an automatic tipping bucket rain gauge as well as a standard manual rain gauge (Figure 1). Intermittent periods of missing data from the automatic gauge were estimated using the manual gauge at Met 25 and a nearby weather station, Met5 (the closest of three additional gauges within the Santee Experimental Forest, located 1.8 km east of Met25). The Met5 temporal distribution of tip events was assumed the same as at Met25, but each tip amount at the Met5 station was adjusted so that its rainfall totals were equal to the manual gauge totals at Met25 for the periods of missing data.

Outflow

An automatic Teledyne ISCO-4210 flow meter, just upstream from a compound *v*-notched and flat weir (90° up to 20.3 cm height, 140° from 20.3 cm to 38.1 cm, and a flat weir spanning 8.5 m above 38.1 cm) installed in 1968 (Young, 1967), recorded stage heights above the *v*-notch bottom at 10 min intervals (Figure 1). Outflow rates (m^3s^{-1}) for the measured stage heights (cm) were determined from a stage-discharge relationship developed in the late 1960s and inserted as a lookup table into a SAS statistical software program. The stream cross section at the weir outlet is well stabilized and has changed very little since the initial construction of the weir. The stage-discharge relationship has also been independently verified using hydraulic equations for the compound weir at the site (Harder, 2004). Daily flow volumes (m^3) were calculated by integrating the 10 min interval flow rates over 24 h, and the daily outflows were then normalized to the area of the watershed (160 ha) to convert the outflows into "millimeter" depths. Most of the late spring and summer flow events in 2003 were affected by beaver activity, which caused artificially high stage heights. Equipment battery failures occurred for two large storm events in July and September, 2003 and for two minor events in January, 2004. Daily flows for periods of missing or unreliable data were estimated using a regression equation ($R^2 = 0.996$) developed from flow data measured simultaneously at WS80 and at the adjacent treatment watershed, WS77 (Figure 1), during the 2003-04 study period (Harder, 2004).

Due to equipment failures at the WS77 outlet during two large outflow events on days 183-192 and 251-255 in 2003 (both periods of which WS80 was affected by beaver activity), no measured data was available, and hence, outflows for WS80 during these events could not be estimated using WS77 outflows. Motivated by past studies documenting relationships between water table depth and outflow (Zampella *et al.*, 2001; Williams, 1979), a relationship between water table depth and outflow was developed for several late spring and summer storm events on WS80 (Harder, 2004). Daily outflows for these events were plotted *vs*. average water table positions from an on-site continuously recording well. The data were fitted with a nonlinear function of the form $y = (a)(b^x)(c^{x^\wedge 2})$ ($R^2 = 0.83$; $a = 3.697$, $p < 0.02$; $b = 1.487$, $p < 0.01$; $c = 1.023$, $p < 0.01$), and this nonlinear function was then used to estimate the daily outflows for the two large outflow events on days 183-192 and 251-255 (Figure 2). These results were also compared with estimates from the Soil Conservation Service (SCS) rainfall-runoff relationship using a curve number (CN) approach as check on the validity of the regression's predictions (McCuen, 1989).

Potential Evapotranspiration

The weather station at the Santee Headquarters, located approximately 2.8 km southwest of WS80, was equipped with an automatic CR10X Campbell

Scientific weather station (Figure 1). This station measured air temperature, rainfall, wind speed and direction, vapor pressure, humidity, net radiation, and solar radiation at half-hour intervals. The half-hour weather data were converted to daily averages and used to calculate daily Penman-Monteith (P-M) potential evapotranspiration (PET) values for a grass reference measured in "millimeter" (Amatya *et al.*, 1995). Data from the Coosawhatchie Weather Station (except for net radiation and temperature) located near Yemessee, SC, approximately 110 km southwest of the Santee Headquarters weather station was substituted for days 52-92 of 2003 during which the Santee weather station was inoperative. Missing or unreliable net radiation data for P-M PET were estimated from regression relationships developed between daily solar and net radiation for those periods in 2003 ($R^2 = 0.97$) and 2004 ($R^2 = 0.94$) that had reliable measurements of these parameters.

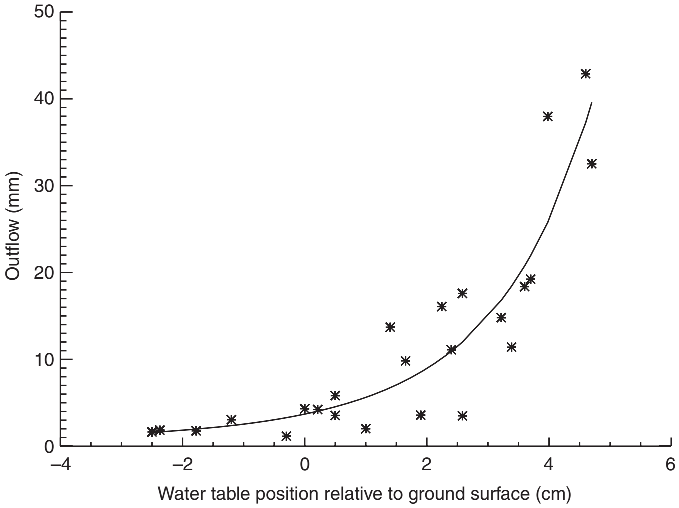

FIGURE 2. Outflow *vs.* Average Daily Water Table Position and Corresponding Nonlinear Fit, $y = (3.697)(1.487^{x})(1.023^{x\wedge 2})$ (Symbols Are Outflow/Water Table Data Points and Solid Line is the Fit).

Continuous Water Table Measurements

A continuously recording WL40 shallow monitoring well (Remote Data Systems) on WS80 recorded water table levels (maximum depth = 57.0 cm) at 4 h intervals during the study period (Figure 1). A replacement WL40, installed in March, 2004, allowed for water table measurements reaching a depth of 94.0 cm below ground surface. Data from this well site were used to estimate the change in soil water storage component of the water budget, to estimate the drainable porosity of the soils in the vicinity of the well, and to develop a relationship between water table depth and stream outflow to correct for missing event outflow data.

Soil Hydraulic Properties

Undisturbed soil samples (7.7 cm, diameter and 7.2 cm, height) were obtained from four layers (surface, 0.30, 0.76, and 1.52 m) at three sites originally identified as a Wahee soil series, the dominant series on the watershed (Soil Conservation Service, SCS, 1980). A detailed soil profile showed that two of these pit locations were correctly identified as a Wahee soil series, while the third pit was identified as a Meggett series (Eppinette, Natural Resource Conservation Service, October 6, 2003, personal communication). To gain representative values of the soil moisture retention data on WS80, the results for only the two pits identified as a Wahee soil series were used in this analysis. Samples were transported to the Forest Service Santee Headquarters Laboratory where pressure plate and tension plate apparatuses were used to obtain soil moisture retention data (volumetric water content, $\mathrm{cm^3 cm^{-3}}$) for suctions ranging from 10 to 8000 cm. Soil moisture retention curves were used to estimate specific retention based on a method described by Brooks and Corey (1964). Specific retention was approximated by determining the break in slope of the suction on the volumetric water content curve, and then defining the specific retention as the water content at that suction. This estimate of specific retention was used to calculate the soil-water storage capacity parameter required for the Thornthwaite monthly water budget model.

The continuously recording well data was used along with rainfall storm event data to estimate the drainable porosity for the Wahee soil series at one location on the watershed. The drainable porosity (n_d), similar to specific yield, was determined by computing the ratio of event rainfall magnitude (P_e) to the corresponding rise in the water table (ΔWT),

$$n_\mathrm{d} = P_\mathrm{e}/\Delta\mathrm{WT}. \qquad (1)$$

Based on suggestions by Williams (1978), only events corresponding to water table rises in the top 1.0 m of the soil were used and the duration of water table rise had to be less than 1 day. Seven events were found suitable for this analysis from the recording well data.

An additional estimate of drainable porosity was made through a utility program in the DRAINMOD hydrologic model (Skaggs, 1978), which uses measured soil moisture retention data and saturated hydraulic conductivity (Harder, 2004) to compute drainable porosity as a function of depth below ground surface. A study testing the applicability of the processed-based DRAINMOD model on this watershed (WS80) is soon to be submitted as a companion paper.

Water Budget

The water budget equation used in this study is,

$$\mathrm{P} - \mathrm{ET} - \mathrm{Q} = \pm\Delta\mathrm{S}, \tag{2}$$

where P is precipitation, ET is actual evapotranspiration, Q is stream outflow, and ΔS is the change in soil water storage. All water budget components were measured in "millimeter." Lateral seepage in and out of the watershed was assumed to be negligible across the Forest Service roads that serve as boundaries for much of the watershed. Any net ground water and surface flow across the watershed boundary in the northeast section of the watershed (unbounded by roads) was assumed to be small in relation to the overall water balance. Deep seepage typically accounts for only a small percent of the total precipitation on similar Atlantic coastal watersheds (Heath, 1975; Riekerk *et al.* (1979), and therefore, was assumed a negligible component of the water budget.

A Thornthwaite-type monthly water balance model (Dingman, 2002) was used to estimate monthly ET values and to compare predicted outflows, available as excess soil water in the water budget, to measured outflows. The model uses estimated monthly PET values and measured monthly rainfall as inputs. The model also depends on a maximum soil-water storage capacity parameter, $\mathrm{SOIL}_{\max}$ (millimeter), which is equal to the product of the field capacity, θ_{fc}, of the soil and the vertical extent of the root zone, Z_{rz} (Dingman, 2002). Thornthwaite water balance models were conducted using three different PET estimators as inputs: the temperature-based Hamon (1963) (HAMON) and Thornthwaite (1948) (THORN) methods and the physically based P-M method (Monteith, 1965) (P-M). The model using the Thornthwaite PET as an input (THORN) incorporated monthly correction factors taken from a site in eastern North Carolina (Amatya *et al.*, 1995). Results of the estimated excess soil moisture values from the water budget were compared with the measured monthly stream outflows using both graphical plots and statistical goodness-of-fit criteria to evaluate the performance of each of the PET methods in the monthly water budget model. The goodness-of-fit criteria used were average absolute monthly deviation, E_{aamd} (millimeter), between measured and predicted monthly stream outflow (excess moisture), slope of the regression, coefficient of determination, R^2, and the Nash-Sutcliffe coefficient (coefficient of efficiency), ${R_{\mathrm{NS}}}^2$ (Amatya *et al.*, 1997). The Nash-Sutcliffe coefficient, ${R_{\mathrm{NS}}}^2$, is given by

$$R^2_{\mathrm{NS}} = 1 - \left[\sum (Q_{\mathrm{m}} - Q_{\mathrm{p}})^2 / \sum (Q_{\mathrm{m}} - Q_{\mathrm{im}})^2\right], \tag{3}$$

where Q_{m} is the measured monthly outflow, Q_{p} is the predicted monthly outflow, and Q_{im} is the average measured monthly outflow over the 30-month study period. Similar to R^2, ${R_{\mathrm{NS}}}^2$ values close to one signify good correlations and indicate the bias, if any.

Closure errors for annual and seasonal water balances were computed based on a method from McCarthy *et al.* (1991) and Chescheir *et al.* (1995). Here the percent closure error is defined as,

$$\%\ \mathrm{Error} = (\Delta\mathrm{S}_{\mathrm{calc}} - \Delta\mathrm{S}_{\mathrm{meas}})/\mathrm{F} \times 100\%, \tag{4}$$

where F is the system flux (millimeter) expressed as

$$\mathrm{F} = (\mathrm{P} + \mathrm{Q} + \mathrm{ET} + |\Delta\mathrm{S}_{\mathrm{calc}}|)/2. \tag{5}$$

The system flux is essentially the higher of the total water outflow or water inflow. The ET values were taken from the Thornthwaite monthly water budget model based on the P-M-based PET inputs. This ET value was estimated in this model using the measured rainfall and PET values for the study period and incorporated a soil water storage capacity term, which was based on results from the soil moisture retention experiments. $\Delta\mathrm{S}_{\mathrm{calc}}$ is the change in soil water storage computed as a residual in the water balance equation, while $\Delta\mathrm{S}_{\mathrm{meas}}$ is the change in soil water storage measured using water table data from the recording well and an adjacent manual well.

RESULTS AND DISCUSSION

Precipitation

Rainfall data for selected periods, along with data for the other water budget components, are presented in Table 1. Annual rainfall for 2003 was 1,671 mm, which is 300 mm above the long-term average rainfall (1,370 mm) at the watershed and the second highest recorded amount in the last 15 years. Monthly patterns were characterized by below average rain in the late fall and winter periods and above average rain in the spring/summer period. Approximately 70% of the annual rainfall occurred from March through July with July being the wettest month (436 mm). The rainfall of 962 mm for 2004 was over 400 mm below the long-term average. Rainfall deficits occurred in every month of 2004, except

TABLE 1. Water Budget Components and Closure Errors for Selected Periods.

Period	Rainfall P (mm)	Outflow Q (mm)	PET (mm)	ΔS Meas (mm)	ΔS Calc (mm)	ET* residual (mm)	ET† model (mm)	Closure error (%)	Q/P
2003	1,671	784	912	−30	−19	917	906	0.7	0.47
2004	962	73	966	−29	55	918	834	8.8	0.08
2003-2004	2,633	857	1,878	−59	36	1,835	1,740	3.6	0.33
Growing Season 2003	1,450	705	747	−28	9	773	736	2.6	0.49
Growing†† Season 2004	727	28	801	-	29	-	670	-	0.04
Dormant Season 2003-04	219	45	162	14	14	160	160	< 0.1	0.21

*ET estimated as the residual in the water budget equation (Equation 1), †ET estimated from the Thornthwaite monthly water budget model using Penman-Monteith PET, ††Insufficient water table position data to estimate ΔS_{meas}.

Note: ET = evapotranspiration, PET = potential evapotranspiration.

for February and August. Due to several hurricanes and tropical storms that impacted coastal SC during August of 2004, this month had the largest rainfall amount (280 mm), which was over 100 mm greater than the long-term average. The dry spring and summer period (except for August) from March through July, 2004 with a rainfall total of 339 mm contrasts greatly with the rainfall amount of 1,174 for the same period in 2003. The data are representative of the large range of precipitation variability along the Atlantic Coastal Plain.

PET

Potential evapotranspiration for 2003 as estimated from the P-M method for a standard grass reference at this location was 912 mm (Table 1). The above average amount of precipitation on WS80 during 2003 (1,671 mm) was much larger than the annual PET possibly providing surplus moisture. In such conditions, the actual evapotranspiration (AET) is generally expected to be nearly the PET. The potential for large soil moisture surpluses existed for March (P = 202 mm, PET = 60 mm), June (P = 285 mm, PET = 123 mm), July (P = 436 mm, PET = 110 mm), and September (P = 163 mm, PET = 77 mm). However, on a seasonal basis, due to the uneven distribution of monthly rainfalls at the site, there are periods where AET would possibly be less than the PET. These periods include January (P = 19 mm, PET = 48 mm), August (P = 84 mm, PET = 108 mm), and November (P = 18 mm, PET = 46 mm).

The annual PET estimate for 2004 was 966 mm, which is slightly larger than the annual rainfall for this period (962 mm). Large potential water surpluses existed for only the months of February (P = 116 mm, PET = 38 mm) and August (P = 280 mm, PET = 95 mm). Large soil water deficits were probable during March (P = 16 mm, PET = 87 mm), April (68 mm, PET = 116 mm), May (P = 57 mm, PET = 140 mm), and July (P = 61 mm, PET = 129 mm) in which the monthly PET estimates were substantially larger than the monthly rainfall amounts. During these periods, the AET is not expected to be near the monthly PET due to limited soil moisture.

Water Table

Water table positions at the on-site continuously recording well, measured as elevations above mean sea level, are illustrated along with measured daily rainfall in Figures 3 and 4. The discontinuities in the water table curves in Figures 3 and 4 are mainly due to the water level receding below the depth of the sensor. Data from Figure 3 show that the water table elevations in 2003 frequently rose above the ground surface from day 60 to day 213 (March through July). This was mainly due to 21 large storm events (>25 mm rain) dispersed through this period that caused frequent ponded conditions at this well location (typically 5-6 cm in depth). Storm events were less frequent and generally smaller in magnitude for the rest of the year beginning in August, 2003. Although some increases in the water table elevation can be seen for storm events during the latter part of 2003, only one large storm event on days 249 through 251 was able to produce ponded conditions. Data also show that daily rainfall events of 30 mm or more corresponded with the water table nearing the surface except in cases of dry antecedent conditions. This is consistent with observations made by Amatya *et al.* (1998b) for watersheds in coastal North Carolina where outlets were frequently submerged for events greater than 25 mm/day during wet winter/spring periods.

Water tables in 2004 were generally much lower than in 2003 due to the below average rainfall and its distribution (Figure 4). A series of winter storm events in February, 2004 caused water levels to rise to ponded conditions after a dry fall and early winter period. During the spring, water levels decreased substantially only reaching the surface again after a large storm event in early May. Water levels

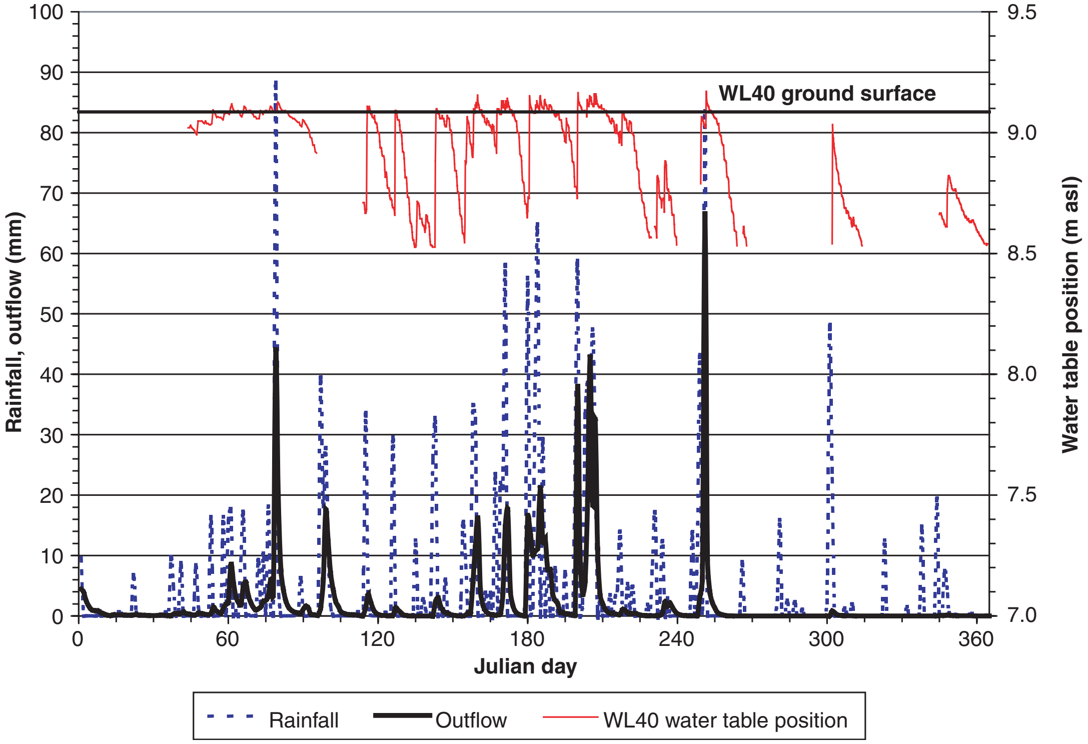

FIGURE 3. 2003 Daily Rainfalls, Outflows, and Water Table Position.

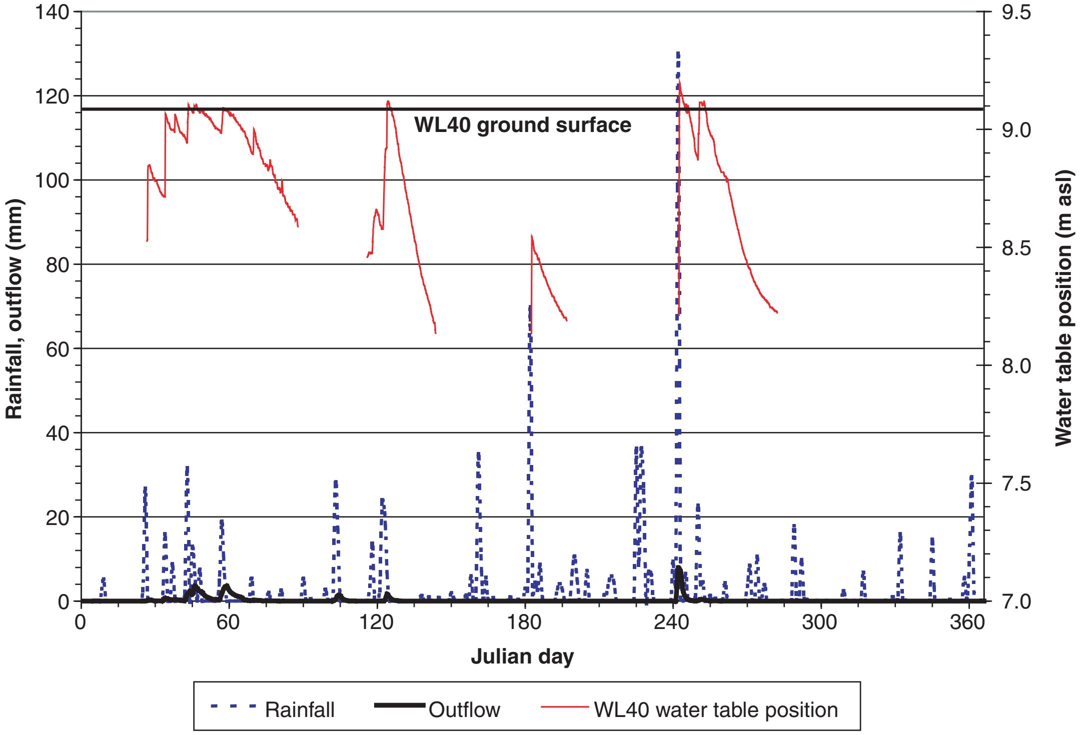

FIGURE 4. 2004 Daily Rainfalls, Outflows, and Water Table Position.

continued to drop substantially during June and July, but two large storm events in August (tropical storms Bonnie and Gaston) were able to bring the water table back to ponded conditions. After August, the water table elevation again decreased and remained below the surface for the rest of the year.

Outflow

Measured annual outflow, Q, for 2003 was 784 mm with the highest monthly outflows occurring in March, June, July, and September (Table 1). The runoff coefficient (Q/P) for 2003, estimated as the ratio of annual outflow to total rainfall (1,671 mm), was 0.47. The 2003 runoff coefficient is substantially higher than the average runoff coefficient of 0.23 (with a range of 0.13-0.33) measured by Sun *et al.* (2000) for a study that encompassed years 1976-80 and 1990-91. However, the outflow for 2003 was somewhat consistent with preliminary data reported by Amatya *et al.* (2003) at WS80 for the 1997-98 periods. Runoff coefficients were 0.44 for 1997 and 0.59 for 1998, but the watershed also experienced above average annual rainfalls for these 2 years (1,498 mm in 1997 and 1,463 mm in 1998).

As expected, months with large outflows corresponded to months with high rainfall, although the magnitude of the flows depended on the antecedent soil moisture conditions as affected by rainfall and ET. Over half of the 2003, total outflow (52%) occurred during the wet summer months of June and July. Outflow decreased considerably after September, 2003 with less than 4 mm of outflow recorded from October to December, 2003. This was consistent with the decrease of the water table elevation. The largest daily outflows (Figure 3) occurred on days 79, 183-189, 200, 205-207, and 251 of 2003, and these outflow events were associated with initial water table elevations already at or near the ground surface. However, a series of rain events between 30 and 35 mm size from days 110 to days 155 (spring months) during 2003 failed to produce significant outflow events, most likely due to deeper water table depths caused by increased ET demands on the forest. Figure 3 shows that an outflow event not only depends on the size of the rainfall event, but it is also heavily influenced by the initial water table position as well.

The annual measured outflow for 2004 was 73 mm, considerably less than the measured outflow of 784 mm in 2003. The 2004 runoff coefficient was only approximately 0.08, substantially less than runoff coefficients measured in past studies at WS80 (Sun *et al.*, 2000; Amatya *et al.*, 2003). The largest monthly outflow occurred in February (35 mm) due to a series of winter storms that created water table positions near or at the surface for much of the month. The next highest monthly outflow occurred in August (17 mm). Outflows in August and early September were mainly associated with tropical storm Gaston that passed nearby the Francis Marion National Forest on August 29. Gaston produced 130 mm of rain at WS80, but the total outflow for this event was only approximately 20 mm. This storm event along with other large rainfall events on days 103-104, 121-124, 161-162, 182, 225-228, and 360-361 (rainfall totals ranging from 38 to 107 mm) failed to produce large outflow events due to dry antecedent soil conditions prior to the rainfall events (Figure 4).

These results demonstrate that outflow from this coastal plain watershed depends not only on the amount of rainfall but also on its temporal distribution as well. If there is adequate time between major storm events for water tables to decline substantially, these events may produce little, if any, outflow as most of the rainfall is used to replenish soil water deficits or is lost as ET. High daily flows, on the other hand, generally corresponded to initial water table positions at or above the surface. The results for 2003 and 2004 on WS80 also show the wide range of potential annual outflows (runoff coefficients of 0.47 and 0.08, respectively) on Atlantic Coastal Plain watersheds. In addition, the growing season for 2003 (March 15-November 14) had a runoff coefficient of 0.49, compared with the 2003-04 dormant season (November 15-March 14) value of 0.21.

There is some uncertainty in the monthly outflows of July and September, 2003 due to two large storm events in which beaver activity prevented reliable outflow measurements and in which no data from WS77 (used to predict WS80 outflow for other events affected by the beaver) were available. As discussed above, a water table-outflow regression was created to predict the daily outflows for these storm events. Application of the SCS rainfall-runoff relationship using a CN approach provided outflow estimates for the day 183-192 period (102 mm rain) of 84 mm compared with the result of 92 mm from the water table-outflow regression. The storm event on day 251 of 84 mm rain produced water table depths beyond the range of the regression's predictability, and the regression gave a total outflow value of 95 mm for this storm event. To reduce the uncertainty in the outflow for this event, the total outflow was set to the rainfall amount of 84 mm. Water table positions were less than 10 cm at the onset of this storm event and thus, the saturated conditions should cause a large fraction of the rainfall to leave the system as surface and shallow subsurface runoff. However, application of the SCS rainfall-runoff relationship gave an outflow estimate of 67 mm for days 251-255, suggesting that the total outflow for this storm event may be slightly overestimated.

Soil Water Storage

Soil moisture retention curves (Figure 5) were used to estimate the field capacity of the soil as an input parameter to the Thornthwaite monthly water balance model. Using a method modeled after

Brooks and Corey (1964) discussed above, field capacity (similar to specific retention) was estimated as the water content at 1,000 cm of suction (Figure 5). The field capacity was estimated at 0.35 for the 0.30 m layer, and as this layer was within the estimated rooting zone on the watershed (0.50 m), this value was used for the field capacity in the Thornthwaite model.

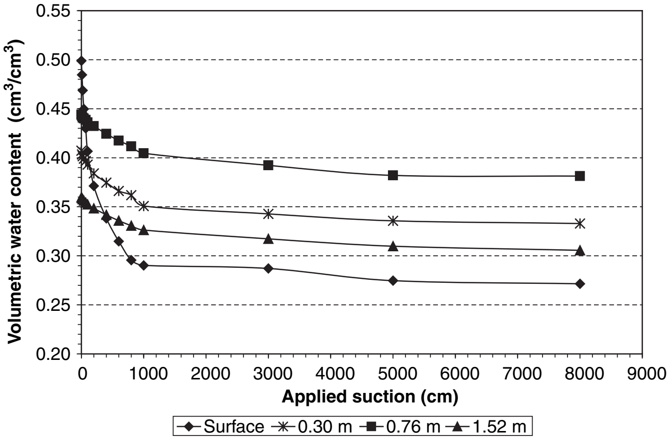

FIGURE 5. Average Soil Moisture Retention Curves for Pits 1 and 3.

Average drainable porosity, estimated from calculations of the ratio of rainfall to water table rise [Equation (1)] at the continuously recording well for several events, was 0.07. A second drainable porosity estimate can be made using soil moisture retention data for Pits 1 and 3. Using the average porosity (0.40) for the 0.30 m and 0.76 m layers at this pit, and subtracting the average specific-retention (field capacity) value of 0.35, the difference of 0.05 is the specific yield (similar to drainable porosity). To determine the soil water storage component of the water budget, an average value was taken from (1) the drainable porosity estimated from the soil moisture retention data (0.05), (2) the ratio of rainfall to water table rise (0.07), and (3) the porosity estimate (0.02) from DRAINMOD (Skaggs, 1978) simulations. This average value of 0.05 was used in conjunction with water table levels measured at the continuously recording well and the adjacent manual well to estimate the soil water storage at the beginning and end of selected water budget periods (Table 1).

Water Budget

The water budget components for WS80 for selected periods are presented in Table 1. ET was calculated as a residual in the water budget equation [Equation (2)]. The annual ET for 2003 was 917 mm, which is slightly larger than the annual PET (912 mm), and this suggests that the watershed was not moisture limited during 2003. Annual ET for 2004 was 918 mm compared with the estimated PET value of 966 mm, indicating soil moisture deficits during some periods of 2004. These periods were most likely in the spring/early summer and late fall/early winter periods.

The 2-year study period encompassing all of 2003 and 2004 provided the opportunity to compare watershed hydrology for a wet and a dry year. For 2003, rainfall was 300 mm above normal and nearly half of annual rainfall was lost from the watershed through stream outflow. However, in 2004, which had nearly 400 mm below normal rainfall, total outflow was only 8% of annual rainfall, and most of the watershed losses were through ET. The runoff coefficients for the 2003 and 2004 growing seasons also differed substantially with values of 0.49 and 0.04, respectively.

Thornthwaite Water Budget

The summary statistics, based on monthly comparisons of measured outflow and predicted water surpluses from the Thornthwaite water balance models using three PET methods (HAMON, THORN, and P-M), are presented in Table 2 along with 2 year and annual totals for both measured and predicted ET values and water surpluses. The HAMON model produced the slope closest to unity (0.92), had the lowest E_{aamd} (12.1 mm), and had R^2 and $R_{\mathrm{NS}}{}^2$ values of 0.91 and 0.90, respectively (Figure 6). The THORN model had the second closest slope to unity, however, this method produced the lowest R^2 (0.89) and $R_{\mathrm{NS}}{}^2$ (0.87) values and highest E_{aamd} (17.1 mm). The P-M model had a slope of 0.86 and the second lowest E_{aamd} of 14.1 mm, however, this method had the highest R^2 (0.93) and an $R_{\mathrm{NS}}{}^2$ value of 0.90. Based on the goodness-of-fit statistics, all three models provided reasonable results; however, the models using the P-M and HAMON methods were shown to be more reliable than the THORN method.

For the 2003-04 study period, the total predicted water surpluses for the HAMON, THORN, and P-M models were 853, 978, and 903 mm, respectively, compared with the measured outflow of 857 mm (Table 2). Thus, the HAMON model was shown to be the most reliable model for predicting the 2-year total water surplus. However, for the HAMON model, the small deviation (3 mm) in the measured and predicted outflows was, in part, due to an underestimation of water surplus in 2003 and an overestimation in 2004, which nearly balanced one another. On an annual basis the P-M model prediction for water surplus (771 mm) in 2003 was in good agreement with

TABLE 2. Comparison of Thornthwaite Water Budget Model Results Using Three PET Methods With Measured Data for Selected Periods.

	HAMON			THORN			P-M		
	2003	2004	2003-04	2003	2004	2003-04	2003	2004	2003-04
Predicted Water Surplus (mm)	737	116	853	803	175	978	771	132	903
Measured Outflow (mm)	784	73	856	784	73	856	784	73	856
Predicted ET (mm)	945	880	1,825	868	788	1,656	906	834	1,740
ET Estimated From Water Budget (mm)	917	918	1,835	917	918	1,835	917	918	1,835
Slope*		0.92			0.91			0.86	
R^2*		0.91			0.89			0.93	
$R_{NS}{}^2$*		0.90			0.87			0.90	
E_{aamd} (mm)*		12.1			17.1			14.1	

*Based on 24 months.
Note: P-M = Penman-Monteith, ET = evapotranspiration.

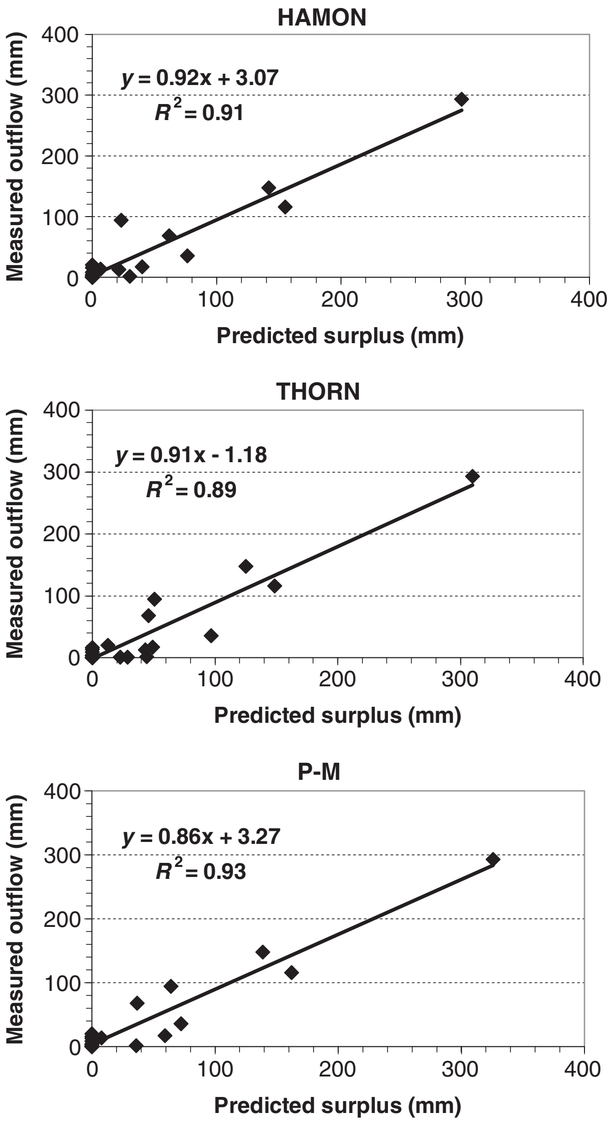

FIGURE 6. Measured Monthly Outflows Versus the Thornthwaite Model's Predicted Monthly Water Surpluses Using Three Different Potential Evapotranspiration Estimators.

the measured outflow (784 mm), and the predicted ET (906 mm) was very close to the estimated ET value of 917 mm. In 2004, the HAMON model overpredicted the water surplus by 43 mm, but the predicted ET of 880 mm was in the closest agreement to the estimated ET value of 918 mm. Based on the results from these 2 years, the Thornthwaite water balance model using the P-M method performs well for a wet period (2003), while the HAMON method works well for a dry period (2004).

Closure errors, calculated using Equation (4), were less than 1.0% for 2003 and 8.8% for 2004. The ET values used in this equation were taken from the Thornthwaite monthly water budget model based on the P-M model estimates. Despite the relative good agreement, especially for 2003, between the calculated and measured ΔS storage terms, indicating a well-balanced water budget, the results need to be cautiously interpreted due to the uncertainties in various water budget components. The change in soil water storage was calculated from a single well on a 160 ha watershed and outflow data were affected by beaver interference and equipment failures for parts of 2003. In addition, the net lateral and vertical ground-water inflow/outflow from the watershed were considered negligible in the water budget analyzes. Further studies on the lateral and vertical flow of ground water to and from the watershed are recommended to assess their importance in producing more accurate hydrologic budgets.

CONCLUSIONS

The main objective of this study was to characterize the hydrology and quantify the water budget for a first-order forested watershed (WS80) in the coastal plain of SC. Hydrologic parameters including rainfall, water table position, outflow, and PET (as a surrogate for ET) have either been measured or estimated for a 2-year study period (2003 and 2004). A Thornthwaite monthly water budget model with three different PET methods was applied to the watershed to estimate monthly ET values during the study period and to compare predicted water surpluses to measured stream outflows.

The study period provided an opportunity to compare an extremely wet year in 2003 (300 mm above average rainfall) to an extremely dry year in 2004 (400 mm below average). The runoff coefficients for 2003 and 2004 were 0.47 and 0.08, respectively, highlighting a broad range of potential outflow from a first-order forested watershed along the SC coastal plain. The P-M and Hamon PET-based Thornthwaite monthly water budget models produced the most reliable results with average absolute deviations between predicted surpluses and measured outflows of approximately 14.1 and 12.1 mm, respectively. Future work will encompass the comparison of the conceptual based Thornthwaite model with more processed-based models such as DRAINMOD (Skaggs, 1978) developed for poorly drained watersheds to assess the Thornthwaite model's utility for Southeastern Coastal Plain watersheds.

Daily outflows were shown to be sensitive to rainfall event sizes, their frequency distribution, and to the antecedent water table positions at the on-site continuously recording well. Winter and spring rain events of 25-35 mm in size during the 2003 study period failed to produce substantial outflows unless the water table was close to or at ground level, while during 2004, many large rainfall events produced little to no outflow due to dry antecedent soil moisture conditions, as indicated by deeper water table positions. Large outflow events typically corresponded to large rainfall events with water table positions already close to the surface. Thus, most of the large surface runoff events occurred under saturated soil conditions.

The results of the water budget calculations and hydrologic characterization of the watershed WS80 can serve as a reference for other similar watersheds in the Atlantic Coastal Plain of the Southeast U.S., especially for land managers who are concerned with water resources (their source, quantity, quality, and distribution) and the impacts of land management activities such as logging, clearing, and fire prescriptions, and urbanization.

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