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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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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

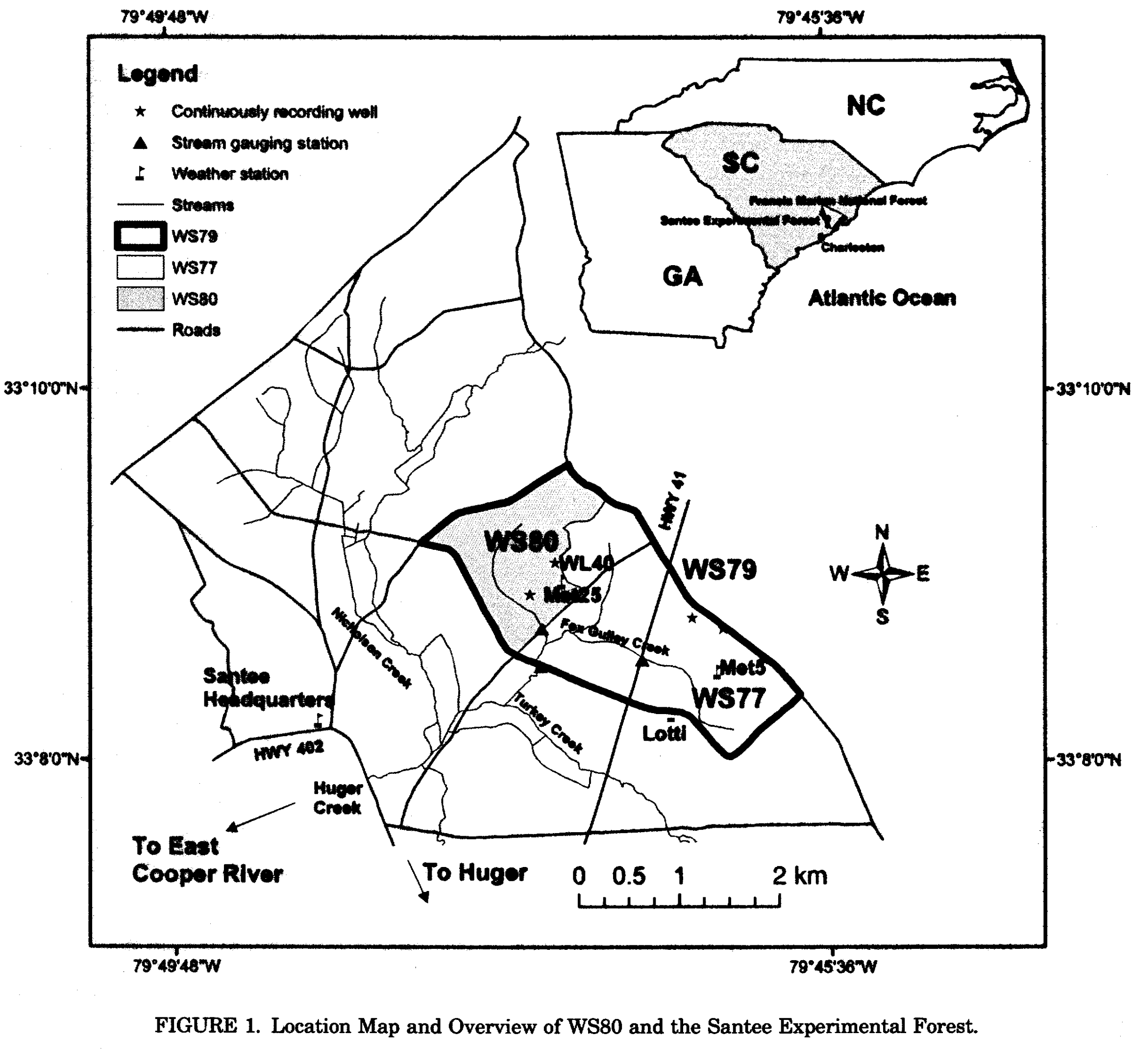


FIGURE 1. Location Map and Overview of WS80 and the Santee Experimental Forest.

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.

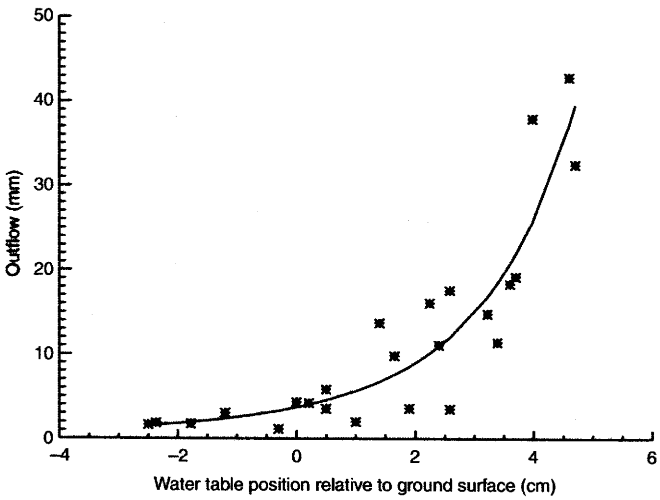


FIGURE 2. Outflow *vs.* Average Daily Water Table Position and Corresponding Nonlinear Fit, $y = (3.697)(1.487^x)(1.023^{x^2})$ (Symbols Are Outflow/Water Table Data Points and Solid Line is the Fit).

*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, $cm^3cm^{-3}$) 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 ($\Delta$WT),

$$n_d = P_e/\Delta \mathrm{WT}. \quad (1)$$

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.

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 $\Delta S_{meas}$.
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

*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

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.

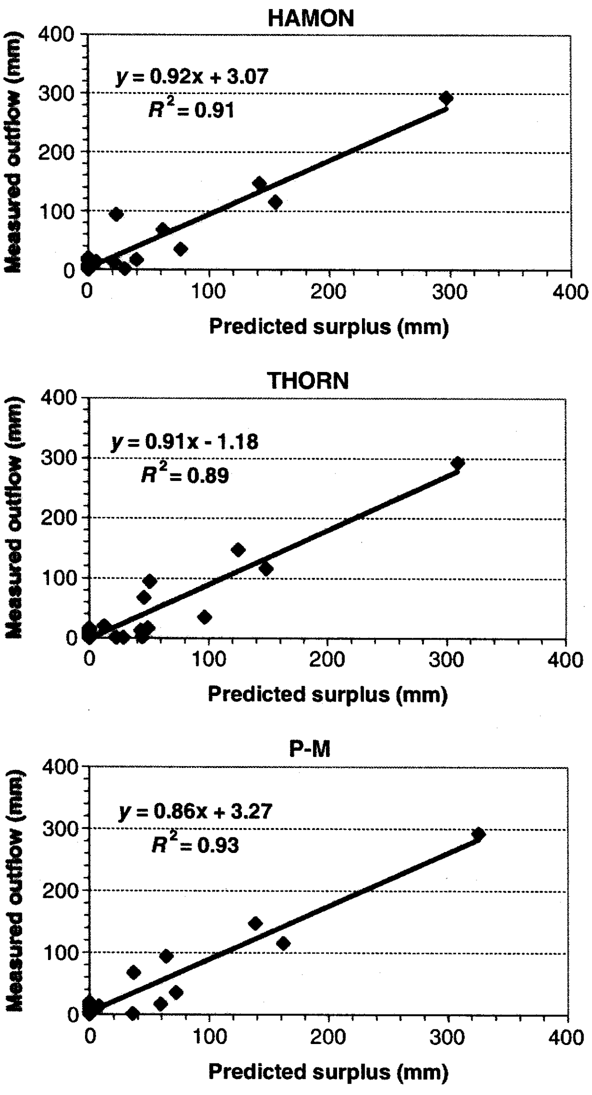


FIGURE 6. Measured Monthly Outflows Versus the Thornthwaite Model's Predicted Monthly Water Surpluses Using Three Different Potential Evapotranspiration Estimators.

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 over-predicted 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 $\Delta S$ 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

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