Modeling the Monthly Water Balance of a First Order Coastal Forested Watershed

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Abstract

A study has been conducted to evaluate a spreadsheet-based conceptual Thornthwaite monthly water balance model and the process-based DRAINMOD model for their reliability in predicting monthly water budgets of a poorly drained, first order forested watershed at the Santee Experimental Forest located along the Lower Coastal Plain of South Carolina. Measured precipitation, weather, stream flow and soil hydraulic data from a 160 ha low-gradient, naturally drained watershed on a mixed pine hardwood forest (WS80) were used in the testing of the models. The Penman-Monteith and Thornthwaite based potential evapotranspiration (PET) methods were used in both models. While rooting depth and field capacity of the soil were the only parameters needed for the Thornthwaite model, complete data on soil water retention and saturated hydraulic conductivity by layers, root depths, surface storage, and drainage design parameters were needed for DRAINMOD to simulate monthly and annual hydrology. As expected, results using two and a half years (January 2003 – June 2005) of data showed that DRAINMOD was a better predictor (Nash-Sutcliffe E = 0.92 and absolute average monthly deviation, E_{aamd} = 11.0 mm) of monthly outflows compared to the Thornthwaite model (E = 0.83 and E_{aamd} = 16.8 mm). Although DRAINMOD can also be used to analyze the daily water table dynamics in contrast to the Thornthwaite model, it was not considered in this study. A DRAINMOD simulation was later conducted with a 46-year (1956-2002) weather dataset to evaluate the long-term hydrology of the watershed, specifically to describe the variability in predicted outflows as affected by the year-to-year climatic variations. Despite the limitations of these models, they can be useful tools for land managers and planners to estimate water tables, quantify monthly and seasonal water budgets as well as estimate nutrient and sediment loadings from poorly drained coastal forests.

KEYWORDS: Hydrologic models, poorly drained, DRAINMOD, Thornthwaite, runoff, ET

Introduction

Forests have an important role in controlling hydrologic patterns in the Southeastern US 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 can have negative consequences in the form of nonpoint-source pollution. Secondly, the Southeastern U.S. is expected to lose about 4.9 million forest hectares (ha) to urbanization between 1992 and 2020 with a significant part of the loss concentrated in the Atlantic Coastal Plain (Wear and Greis, 2002). A significant fraction of these ecosystems is forested wetlands, and if not properly managed, both the timber management practices and the increased development can adversely impact these ecosystems and their associated wetland functions. Land managers, developers, and regulators are faced with the challenge of finding the appropriate tools and methods to evaluate the impacts of these land use changes. Such tools and methods should be simple to understand, easy to parameterize and apply, but yet capable of reliably predicting the hydrologic dynamics of the poorly drained, low gradient forested lands of the Atlantic Coastal Plain.

One such tool land managers and regulators have often used to assess impacts of land use changes is hydrologic models. A large number of models are available in the literature for upland areas with deep water tables and processes dominated by overland surface runoff, which can be used to evaluate the hydrologic effects of land use change on these watersheds. However, there are a limited number of models which can accurately describe outflow processes and water table dynamics on low gradient lands of the Atlantic Coastal Plain. The hydrologic processes on these poorly drained, low gradient lands are dominated by shallow surface and subsurface outflow, which may be heavily dependent on water table positions. Water table, in turn, is often dependent upon rainfall and ET. DRAINMOD (Skaggs, 1978) is a hydrologic and water management model that computes the water balance based on the midpoint water table position between two parallel ditches or tile drains. It has been widely implemented for describing the hydrologic processes and evaluating the effects of land, water and crop management practices of poorly drained agricultural lands with a parallel drainage ditch pattern. McCarthy et al. (1992) modified DRAINMOD into a new version, DRAINLOB, to describe the hydrology of poorly drained pine plantations in eastern North Carolina. Modifications were made on the rainfall interception, subsurface drainage and ET components of DRAINMOD.

Application of the forestry version of DRAINMOD (DRAINLOB) has so far been very limited due to the unavailability of complete data on tree physiological parameters such as Leaf Area Index (LAI), canopy storage and stomatal conductance for non-uniform forests such as pine-hardwood mixed stands with complex understory vegetation. There has been only one study so far that has used DRAINLOB for describing the long-term hydrology of a uniform drained pine forest at the Carteret site in eastern North Carolina (Amatya and Skaggs, 2001). Recently, Diggs (2004) successfully applied DRAINMOD to describe the hydrology of drained pine forests in eastern North Carolina. The author calibrated the model using lateral saturated hydraulic conductivity for drainage rates and rooting depth parameters in the model to describe ET, a major component of the forest water balance.

Though these models have performed well on agricultural and forested lands with artificial drainage, much of the forested land along the Atlantic Coastal Plain under silvicultural management consists of lands with non-pattern natural drainage. Managed forests in the Southeast include loblolly pine, bottomland hardwood forests, pine flatwoods, and short rotation woody crops. Pine flatwoods comprise more than 400,000 ha in the Atlantic Coastal Plain (Sun et al., 1998a), while bottomland forests are nearly 120,000 ha. There are only a limited number of hydrologic and water quality models that are applicable to assess the impacts of silvicultural and developmental activities on water quantity and quality. Sun et al. (1998a, 1998b) developed and tested a distributed forest hydrologic model, FLATWOODS, to describe the hydrology of the cypress wetland-pine upland landscape on Florida flatwoods and to assess the impacts of timber harvesting on these lands. Skaggs et al. (1991) conducted a simulation study using DRAINMOD to compare the long-term hydrology of natural pocosins with that of artificially drained agricultural and forested lands in eastern North Carolina. DRAINMOD has also recently been applied to low lying forested watersheds with non-pattern drainage. Chescheir et al. (1994) calibrated the model to a 137 ha natural wetland near Plymouth, North Carolina, and were able to successfully predict daily water table dynamics and drainage outflows for an approximately two year period. Amatya et al. (2003) also presented preliminary results of the application of DRAINMOD on forested watersheds with non-pattern drainage at two sites located in north-central Florida and the coastal plain of South Carolina (WS80). The study was conducted with limited data, however, and multi-year calibration and validation are necessary to evaluate the model's reliability and usefulness for making land management decisions.

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DRAINMOD is a process-based hydrology model that requires a large number of input parameters which may not be readily available to many land managers. These inputs include complete data on soil water retention and saturated hydraulic conductivity by layers, root depths, surface storage, and drainage design parameters. The Thornthwaite model (Thornthwaite and Mather, 1955; Dingman, 2002) is a conceptually based monthly water balance model which requires only two input parameters, rooting depth and field capacity, and thus, may be a more practical model for land managers to apply in their land and water management decisions. This model is substantially less difficult to implement than DRAINMOD and computations can be performed in a simple spreadsheet program such as Microsoft® EXCEL. However, unlike DRAINMOD, this model is incapable of describing the water table dynamics and cannot take into account the day-to-day changes in soil moisture dynamics that may affect water losses and ET. The model also does not differentiate between surface and subsurface drainage.

The main objective of this study is to test the applicability and compare the performance of the DRAINMOD and Thornthwaite models in predicting monthly and annual outflows from a forested Coastal Plain watershed, WS80, located near Charleston, South Carolina. The study was conducted over a 30 month period (January 2003 – June 2005). A second objective of this study is to apply the calibrated DRAINMOD model to simulate the past hydrology on WS80 using a 47 year weather dataset (1956-2002). Specifically, the simulations will provide the year-to-year variations in predicted outflows as affected by the year-to-year variability in climatic conditions.

METHODOLOGY

Site Description

The study site is watershed WS80 (33.15° N Latitude, 79.8° W Longitude), located in the Francis Marion National Forest northeast of Charleston, SC (Figure 1). Watershed WS80, first delineated in 1968, is contained within the Santee Experimental Forest near Huger, SC and drains a first order headwater stream. The site, relatively undisturbed for over eighty years, serves as the control watershed for a paired watershed system that includes a treatment watershed (WS77). WS80 was 200 ha in size until November 2001 when a small drainage canal was diverted reducing its size to 160 ha in area. The first order stream of WS80 distributes to Fox Gulley Creek, which in turn combines with Turkey Creek, a tributary of Huger Creek which drains 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. A map of the Santee Experimental Forest with each of these watersheds and streams designated is illustrated in Figure 1.

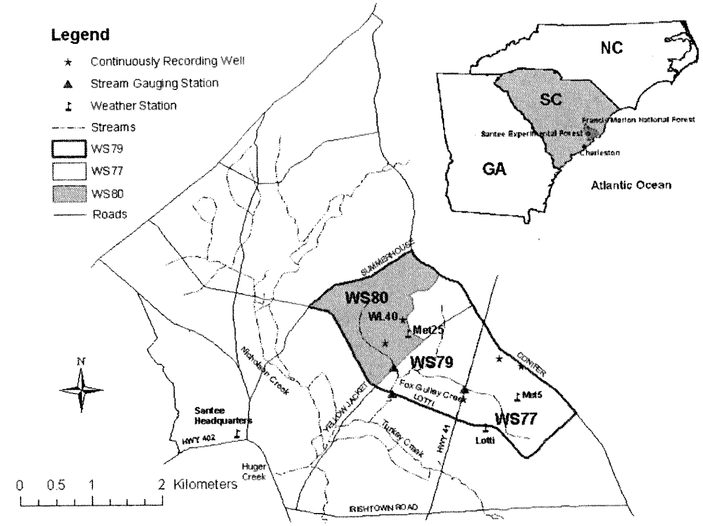


Figure 1. Location Map and Overview of WS80 and the Santee Experimental Forest

In 1989, the eye of Hurricane Hugo passed through the Francis Marion National Forest causing appreciable damage to the forest. After the hurricane, WS80 remained undisturbed except for a non-salvage harvest. The forest occupying WS80 is still in a recovery phase and the natural regeneration resulted in three general forest canopy types: pine hardwood (39%), hardwood pine (28%), and mixed hardwoods (33%). Common tree types include loblolly pine (*Pinus taeda L.*), sweetgum (*Liquidambar styraciflua*), and a variety of oak species typical of the Atlantic Coastal Plain. Most of the tree stands are 14-15 years old.

Soils are primarily sandy loams with clayey subsoils and are influenced by seasonally high water tables, and the argillic horizons are about 1.5 meters below ground surface with low base saturation. 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 low topographic relief ranging from 0 to 3%. 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 1370 mm. The climate of the region (annual long-term average ET of 1000 – 1050 mm) strongly influences the hydrologic balance of the watershed, and approximately 23% of the WS80 is classified as wetlands (Sun et al., 2000).

Model Descriptions and Parameterization

DRAINMOD

DRAINMOD (Skaggs, 1978) simulates the water balance in the soil profiles of poorly drained, high water table soils between two parallel ditches. Simulations are conducted on an hour-by-hour, day-by-day basis and can be applied to a long period of climatological record. Originally designed to predict the effects of drainage and related water management practices on the soil water regime and crop yields on agricultural lands, a preliminary testing of the model has been conducted to describe the hydrology of forested lands with non-pattern drainage (Chescheir et al., 1994; Amatya et al., 2003). Basic components of the model include precipitation, infiltration computed using the Green-Ampt equation, runoff as surface drainage (once the average depth of surface depression storage is satisfied), subsurface drainage by Hooghoudt's equation, evapotranspiration (ET) as a function of daily potential ET (PET) and soil water properties, soil water distribution, and rooting depth. Water management practices such as controlled drainage and subirrigation can also be simulated.

The main input variables consist of hourly precipitation and daily PET. If sufficient weather data are not available for more accurate estimates of PET such as the Penman-Monteith method (Monteith, 1965), daily minimum and maximum air temperatures can be used as inputs for calculating PET based on the Thornthwaite method (Thornthwaite, 1948). However, monthly correction factors are often used to adjust the PET to more reliable PET estimates such as the Penman-Monteith method (Amatya et al., 1995). Physical parameters required by the model include ditch spacing and depth, depth to restrictive soil layer, average surface storage, effective rooting depth, and initial water table position. Soil hydraulic properties such as saturated hydraulic conductivity, soil moisture retention data, drainable porosity, upward flux, and infiltration parameters are also required by the model. This study used DRAINMOD 5.1, a Windows based version with graphical user interfaces for managing input and output data. More details about DRAINMOD can be found at http://www.bae.ncsu.edu/soil_water/drainmod/.

An on-site weather station (Met25) includes an automatic tipping bucket rain gauge, and data from this gauge were used to obtain hourly data in DRAINMOD format for the period from January 2003 to June 2005. Separate simulations were conducted using PET estimates from the Penman-Monteith and Thornthwaite (with and without correction factors) methods. Weather data for the Penman-Monteith PET estimates were available from a weather station (Santee Headquarters) within the Santee Experimental Forest located approximately 2.8 km southwest of WS80. Daily minimum and maximum temperatures were available from an air temperature sensor/logger located at Met25 for Thornthwaite PET estimates. Correction factors were taken from a site in eastern North Carolina (Amatya et al., 1995). Soil moisture retention data for the soils on WS80 were obtained from a study by Harder (2004). Lateral saturated hydraulic conductivity was measured for the deeper layers of the soil profile using bail-down tests (Harder, 2004) while a

Table 1. Input parameters for the DRAINMOD and Thornthwaite Models

Input Parameters	WS80
DRAINMOD:	
Major Soil Type	Wahee Sandy Loam
Drainage ditch depth, cm	40
Average surface storage (S_1), cm	8
Maximum surface storage (S_m), cm	16
Depth to restrictive layer, m	1.5
Saturation water content	0.53
Wilting point	.10
Effective rooting depth, cm	30
Saturated hydraulic conductivity/Depth	5.0/30
cm/hr, cm	0.28/150
Drainage coefficient, cm/day	80
THORN:	
Rooting depth, cm	50
Field capacity	0.35
$SOIL_{max}$, mm	175
$SOIL_0$, mm	175

higher value was used for the top 30 cm of the forest soil layer. Both soil moisture retention data and saturated hydraulic conductivity were inserted into a DRAINMOD utility program (SOILPREP) that computed drainable porosity, upward flux, and infiltration parameters. An effective rooting depth of 30 cm (approximately 60% of the estimated maximum root depth of 50 cm as suggested by Skaggs, 1978) was used in the model for this forest dominated by pine hardwoods on shallow soils. An average surface depressional storage of 8 cm was assigned for the whole watershed, and a large ditch spacing of 1050 m was assumed based on the location of a nearby stream associated with the second order watershed, WS79. All other input parameters used in the model are presented in Table 1. A long-term simulation was also conducted from 1956 – 2002 based on historic precipitation and temperature data. Complete hourly and daily rainfall data were not available at the Santee Experimental Forest for 1956 – 1989, and 2001, and data from the Charleston SC Airport, located approximately 40 km southwest of WS80, were used to create hourly precipitation input files for these periods. Historic air temperature data were taken predominantly from the Santee Headquarters with any gaps filled by data from the Charleston Airport, Met25 and two other nearby stations within the Santee Experimental Forest.

Thornthwaite Monthly Water Balance Model

The Thornthwaite model (THORN) uses inputs of monthly measured precipitation and computed PET to estimate monthly water surpluses, which may be in the form of runoff, seepage, or changes in water storage. The model, thus, can be used to predict monthly outflows as water surpluses which can then be compared to measured monthly outflows. In the Thornthwaite model, inputs and outputs are summed over a monthly time step, whereas the storage component represents end of month values. Water balance computations are mainly driven by the magnitude of differences between monthly PET and rainfall values, and computations can be performed in a spreadsheet environment with little difficulty. The Thornthwaite model also depends on a soil-water storage capacity parameter, $SOIL_{max}$, 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}. This value represents the maximum amount of water that is held against gravity drainage and is available for evapotranspiration. In addition, an initial value of the soil moisture content, $SOIL_0$, must be specified in the model. Monthly direct runoff and water retention components are sometimes added to the model which can improve its accuracy (Ferguson, 1996; Dunne and Leopold, 1978). However, for the present study, predicted water surpluses were assumed to entirely result in stream outflow. Details of the model can be found in Thornthwaite and Mather (1955) and Dingman (2002).

Monthly precipitation values were taken from the Met25 weather station located on WS80 for the period from January 2003 to June 2005. As in DRAINMOD, PET inputs were estimated using both the Thornthwaite and Penman-Monteith methods using the appropriate data described above to compute monthly PET values. The field capacity value used for this study was based on specific retention values estimated from the soil moisture retention data (0.35), while the depth of the root zone was estimated at 500 mm, giving a $SOIL_{max}$ value of 175 mm. Due to wet conditions in December of 2002, the $SOIL_0$ parameter was assumed to be at $SOIL_{max}$ for the first month of the simulation (January 2003).

Model Evaluation Statistics

Monthly outflows (for a 30-month period) predicted by both the DRAINMOD and Thornthwaite water balance models were compared with the measured monthly stream outflows using both graphical plots and statistical goodness-of-fit criteria to evaluate their performance. The goodness-of-fit criteria used were average absolute monthly deviation (E_{aamd}) 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), E (Amatya et al., 1997). The Nash-Sutcliffe coefficient, E, is given by

$$E = 1 - [\Sigma(R_m - R_p)^2 / \Sigma(R_m - R_{im})^2], \quad (1)$$

Where R_m is the measured monthly outflow, R_p is the predicted monthly outflow, and R_{im} is the average monthly outflow over the 30-month study period. Similar to R^2, R_{NS}^2 values close to one signify good correlations and indicate the bias, if any.

RESULTS AND DISCUSSION

The study period was characterized by a wet year in 2003 (nearly 300 mm above normal) and a dry year in 2004 (nearly 400 mm below normal). The first six months of 2005 had a rainfall nearly 90 mm above normal. Thus, the study period provided the opportunity to test these models over a range of climatic conditions. A plot of monthly cumulative precipitation, predicted and measured outflows, and predicted ET are presented in Figures 2a and 2c for the DRAINMOD and Thornthwaite (THORN) simulations (each with the Penman-Monteith PET method), respectively. Month by month totals for precipitation and predicted and measured outflows are shown in Figures 2b and 2d for the DRAINMOD and THORN simulations, respectively.

The DRAINMOD simulation (with Penman-Monteith PET) described the monthly outflows quite well for the first six months of 2003; however, in the wettest months of July, the model overpredicted the monthly outflow by over 60 mm (Figure 2a and 2b). The model also over predicted the monthly outflows in October – December. These months contributed to the overestimate of annual outflow (889 mm) compared to the measured annual outflow (795 mm). The majority of measured flow in 2004 occurred in February (35 mm) and August (17 mm) and each of these months was preceded by a relatively dry period. The DRAINMOD simulation underpredicted these months by 15 mm (February) and 16 mm (August). Most of the measured outflow in August and September was associated with Hurricane Gaston which produced 130 mm of rain on August 29th, but due to an extremely dry summer and with deep water tables, the event only produced about 20 mm of total outflow. DRAINMOD, however, had difficulty in accurately describing this large storm event that occurred during a relatively dry period. DRAINMOD also

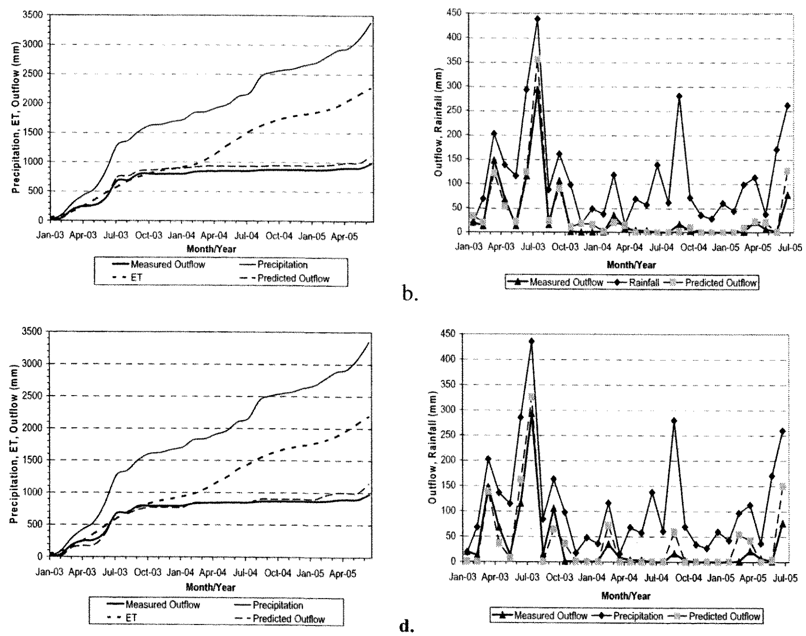


Figure 2a-d. Model Results for Calibration Period (January 2003 to June 2005): a. DRAINMOD – cumulative b. DRAINMOD – monthly c. Thornthwaite – cumulative d. Thornthwaite - monthly

failed to predict outflows for the months of April and May though there were small flows measured at the watershed outlet. The underestimation of outflow in February and August contributed to the underprediction of outflow by 25 mm in 2004. Months with the greatest measured outflows in 2005 were March and June, and the DRAINMOD simulations predicted these months to have the highest outflows as well. However, the simulation over predicted the outflow for June by nearly 50 mm, and also over predicted the months of February and April by 7 and 13 mm, respectively. The six-month measured outflow for 2005 was 108 mm compared to the prediction by DRAINMOD of 179 mm.

The THORN model with the Penman-Monteith PET input underpredicted the measured outflow for the first five-months of 2003, but overpredicted the wet months of June and July (similar to DRAINMOD) by 47 mm and 32 mm, respectively. In addition, the model underpredicted the September outflow (which was dominated by Hurricane Isabel) by over 40 mm. The net annual total predicted by the Thornthwaite model was 772 mm compared to the measured annual outflow of 795 mm. In 2004, the model predicted outflow in only the months of February and August which were the two months in this year with the greatest measured outflows. However, in these two months the measured outflows were overpredicted by 37 and 42 mm, respectively. Like DRAINMOD, the Thornthwaite model also performed poorly in predicting monthly outflows after prolonged periods of dryness and reduced water tables. The model failed to predict any of the outflows for January, March, April, May, and September though there were small outflows measured at the watershed outlet. In 2005, the model predicted large outflows for February (54 mm) and March (42 mm), however the measured outflows were only 1.5 mm and 21.8 mm respectively. In addition, the model predicted nearly 150 mm of outflow for June 2005, but the measured flow was only 77 mm. The Thornthwaite model substantially overpredicted the six-month outflow in 2005 by 142 mm.

The goodness-of-fit statistics obtained for each model using the Penman-Monteith PET input are presented in Table 2. Also included in the table are simulation results for each model obtained using the temperature based Thornthwaite PET estimate with correction factors. The DRAINMOD simulations with the Penman-Monteith and Thornthwaite (with correction factors) PET estimates performed well with Nash-Sutcliffe coefficients, E, of 0.92 and 0.94 for each of the models. The absolute average monthly deviation, E_{aamd}, for the Penman-Monteith based simulations was 11.0 mm, while the Thornthwaite with correction factors simulation resulted in an E_{aamd} value of 9.8 mm. The DRAINMOD results of applying the Thornthwaite PET method without monthly correction factors were substantially less accurate producing E and E_{aamd} values of 0.82 and 18.8 mm, respectively. The DRAINMOD results of the Thornthwaite based simulation with the correction factors validates the use of the Thornthwaite PET as inputs to the long-term simulations discussed later where Penman-Monteith weather parameters were unavailable. Use of the Thornthwaite PET with the appropriate correction factors performed slightly better than the simulations with the Penman-Monteith method which is considered to be the most reliable of PET estimators (Jensen et al., 1990).

Table 2. DRAINMOD and THORN results for selected PET inputs.

Model/PET Input	slope	R^2	E	E_{aamd} (mm)	Outflow (mm) 2003	2004	2005*
DRAINMOD/Penman-Montieth	0.86	0.95	0.92	11.0	889	47	179
DRAINMOD/Thornthwaite with correction factors	0.92	0.95	0.94	9.8	818	72	135
DRAINMOD/Thornthwaite without correction factors	0.85	0.89	0.82	18.8	914	142	305
THORN/Penman-Monteith	0.82	0.88	0.83	16.8	771	132	251
THORN/Thornthwaite with correction factors	0.86	0.82	0.78	21.6	803	175	322
Measured Outflow	-	-	-	-	795	73	108

* Only first six months

As expected, the results of the Thornthwaite monthly water balance model (THORN) were less accurate than those of DRAINMOD for the 30-month calibration period. Nash-Sutcliffe coefficients were 0.83 and 0.78 using the THORN model with Penman-Monteith and the temperature based Thornthwaite PET estimators, respectively. The E_{aamd} for the Penman-Monteith based model was 16.8 mm, while the model using the Thornthwaite PET input was 21.6 mm. Despite the poorer monthly statistics, one may argue that the results of the THORN model ($E \geq 0.78$) show that this conceptually based water balance model may be satisfactory for describing seasonal and annual outflows (Amatya et al., 1997).

These statistical results should be approached with some caution for two reasons. First, rainfall was measured from a single gauge on the 160 ha watershed. A throughfall study on WS80 by Harder (2004) showed that significant variation in rainfall was possible during summer storm events. Thus, a single gauge may not be adequate to represent the total rainfall on a watershed as large as 160 ha. Secondly, several large outflow events in 2003 were affected by beaver interference and equipment malfunctions. Data were corrected using either a regression relationship developed for daily outflows between WS80 and the treatment watershed, WS77, or through an outflow – water table depth relationship developed for watershed WS80 using daily outflows and daily average water table positions from an on-site continuously recording well (Harder, 2004).

The DRAINMOD simulation results for this 30-month calibration period highlight some potential limitations for this model on natural forested watersheds as large as 160 ha. DRAINMOD was originally designed for relatively flat agricultural lands with well defined surface storage and crop characteristics. Watershed WS80, however, has many depressional areas which vary in depth and thus, determining an overall average surface storage parameter was a challenge. In addition, the outlet weir itself creates some surface water storage, and the water level at this outlet must rise up to the level of the v-notch before any outflow can occur. Table 3 contains simulation results using various values of the average surface storage parameter (S_I) and the maximum surface storage parameter (S_m). The table shows that as the average and maximum storage capacity parameters increase, the Nash-Sutcliffe coefficient increases and the E_{aamd} generally decreases, indicating that the larger storage parameters produce a better model. Simulated monthly and annual outflows in the 2004 – 2005 period were also more sensitive to changes in the storage parameters, S_I and S_m, and monthly and annual outflows typically decreased as these parameters were increased. The wet year of 2003 was less sensitive to changes in storage, though increasing the storage parameters led to a general increase in total annual outflow for this year. These results are expected because surface runoff will be less affected by changes in surface storage during wet periods when water tables are already at or near the surface (2003) than during dry periods when water tables have receded and the soil profile must be refilled before surface ponding occurs (2004 and 2005).

Table 3. DRAINMOD simulation results for varying values of S_I and S_m

Storage Parameters	Slope	R^2	E	E_{aamd} (mm)	Outflow (mm) 2003	2004	2005
$S_I = 2$, $S_m = 4$	0.80	0.95	0.88	12.5	837	113	240
$S_I = 4$, $S_m = 8$	0.82	0.95	0.90	11.0	852	71	231
$S_I = 6$, $S_m = 12$	0.84	0.96	0.92	10.4	870	49	199
$S_I = 8$, $S_m = 16$	0.86	0.95	0.92	11.0	889	47	179

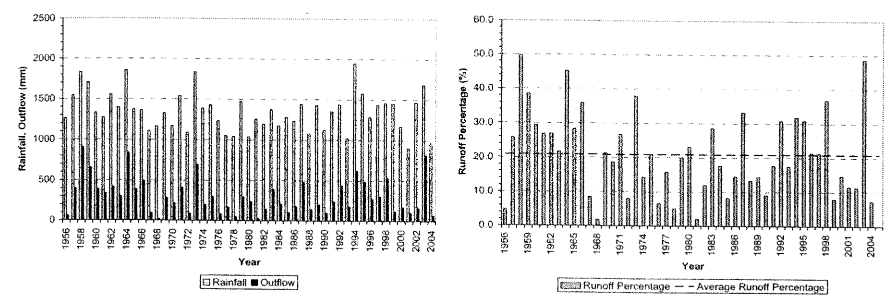
The values of $S_I = 8.0$ cm and $S_m = 16.0$ cm were optimal for simulating the outflows at WS80 over the wide range of climatic conditions over the study period, and hence, were used in the long-term hydrologic simulations from 1956 to 2002. However, the application of these storage parameters produced unrealistically high water table positions and extended ponded conditions which in part contributed to high subsurface drainage in the latter months of 2003. Water table measurements on this 160 ha watershed were limited by one continuous recording well located in an upland area, and so comparing these measurements with the simulated results is misleading. These results also suggest that using a model incorporating only average surface storage parameters may limit its effectiveness to predict reliable outflows. A watershed-scale model, such as DRAINWAT (Amatya et al., 1997; 1999) that can incorporate multiple subcatchments with localized storage parameters (and other physical parameters) within the watershed may provide a more accurate hydrologic description of coastal, low-lying forested watersheds. Lu et al. (2005) have applied a spatially distributed model (MIKE-SHE) to the watershed WS80 and are presenting their results at this conference. Furthermore, DRAINMOD may overpredict some monthly outflows for this large 160 ha watershed (especially if rain occurs on the last day of the month), as it assumes all water loss as an excess arrives at the outlet within one hour. Such an assumption is valid for only small fields. However, for larger watersheds, the excess water will have to travel on the surface for longer time periods, and part of this excess water might be lost again to retention, ET and infiltration. DRAINMOD also does not take into account canopy interception and may underestimate monthly ET, and thus, the model may overpredict the outflows for some months.

A summary of the results of the DRAINMOD simulations using a 47-year climate dataset of daily rainfall and air temperature is presented in Table 4. Year-to-year variations in rainfall and predicted outflows are depicted in Figure 3a. Annual rainfall totals ranged from nearly 450 mm below average (1349 mm) in 2001 to nearly 500 mm above average in 1994. The highest (912 mm in 1958) and lowest (22 mm in 1968) outflows did not correspond to the years with the highest and lowest rainfalls in 1994 and 2001, respectively. The coefficient of variation (standard deviation/average) for the rainfall (0.18) was substantially less than the coefficient of variation for outflow (0.70). These results indicate that the annual outflow is greatly affected by the temporal distribution of rainfall and antecedent soil moisture conditions and not just total annual rainfall. Runoff coefficients (ratio of runoff as predicted by the simulations to total rainfall) are shown in Figure 3b and ranged from 0.02 to 0.50 with an average of 0.21. This indicates that much of the rainfall (79%) is lost to ET assuming negligible deep seepage. Skaggs et al. (1991) reported somewhat higher average coefficients of 0.27 and 0.29 for long-term (1950-1982) DRAINMOD simulations in eastern North Carolina on an undrained and drained pocosin, respectively. A substantially higher average runoff coefficient of 0.31 was found by Chescheir et al. (2003) for over 100 site-years of measured outflow on natural and managed pine forests in eastern North Carolina. Sun et al. (2000) reported a value of 0.22 using measured outflow data on WS80 from 1969-1981 and 1990-1992 which agrees well with the simulation results on the watershed in this study.

Table 4. DRAINMOD simulation results for a historic climate record for the years 1956 – 2004.

	Year	Rainfall, P (mm)	Outflow, R (mm)	R/P
Maximum Rainfall	1994	1948	630	0.32
Minimum Rainfall	2001	907	105	0.12
Maximum Outflow	1958	1833	912	0.50
Minimum Outflow	1968	1164	22	0.02
Typical Year	1969	1324	282	0.21
Average	1956-2004	1349	303	0.21
Standard Deviation	1956-2004	240	221	0.12
Coefficient of Variation*	1956-2004	0.18	0.70	0.58

* Standard Deviation/Average



a. b.

Figure 3. (a) Annual rainfall and DRAINMOD predicted outflows for 1956 – 2004 (b) Runoff percentages as predicted by DRAINMOD from 1956 – 2004.

Measured monthly and annual outflow data were available for WS80 for the periods 1969-1981, 1990-1992, 1997-1998, and 2003-2004. Measured outflows for these periods are plotted versus DRAINMOD's predicted outflows in Figure 4a and 4c. Figures 4b and 4d exclude the years 1973, 1997 and 1998. The year 1973 which used rainfall data from the Charleston airport was 400 mm above the annual rainfall recorded at the Santee Experimental Forest (daily rainfall was unavailable) and the measured outflows for 1997-1998 are questionable. Excluding these three years, the high measured outflows agreed reasonably well with the predictions from DRAINMOD, and a linear fit produced an R^2 value of 0.85. The regression produced a slope of 0.85, but with a large y-intercept of 93 mm, the model tended to generally under predict the annual outflows. The monthly results, as expected, yielded a poorer regression with an R^2 of 0.59.

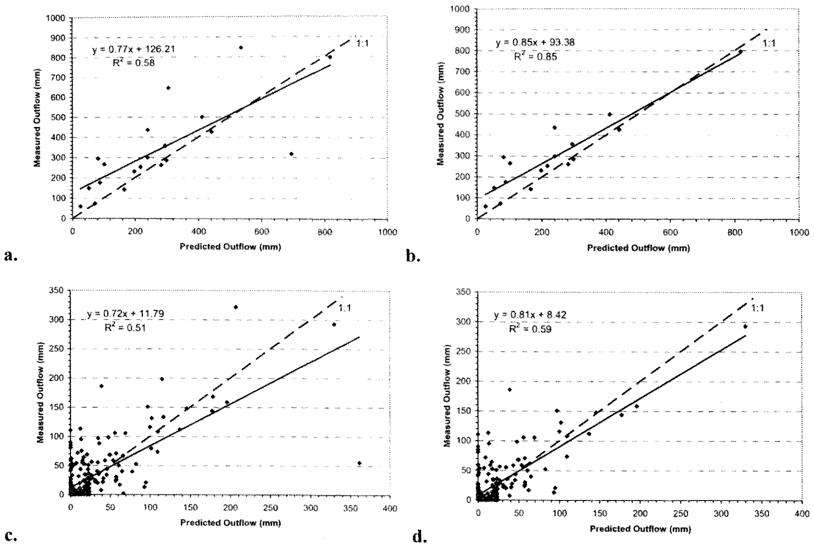


Figure 4a-d. Annual and monthly measured outflows versus DRAINMOD predictions for years 1969-1981, 1990-1992, 1997-1998, and 2003-2004. (a) Annual (b) Annual, excluding years 1973, 1997-1998 (c) monthly (d) monthly, excluding years 1973, 1997-1998.

There are two important factors to consider when comparing the monthly and annual simulated outflows to the measured values. First, daily weather data were unavailable from 1969 – 1981 from on-site weather stations and daily rainfall data from the Charleston Airport were used for these years. Due to the 40 km distance of the airport from the study site WS80, some spatial variation in rainfall is expected especially during the summer storm events. Secondly, the results of the calibration period from January 2003 to June 2005 using the Thornthwaite PET with correction factors showed that the model had difficulty predicting outflows after periods of extreme dryness. This may in part be due to the known tendency of the Thornthwaite PET method to over predict PET in the warmer summer months, leading to extremely reduced water table positions and soil water content. This phenomenon was observed in August/September of 2004 in which two large tropical storm events produced over 20 mm of measured outflow after an extremely dry summer and reduced water tables. However the DRAINMOD simulation failed to predict any outflow for these two months. The general tendency of DRAINMOD to under predict the annual outflows may in part be explained by this overestimation of ET by the Thornthwaite method which may cause erroneously low water table positions and soil moisture values. Despite several of these problems in applying the DRAINMOD model to this low-gradient, coastal plain forested watershed, there is reasonable agreement between the annual measured and predicted outflows.

CONCLUSION

The study period from January 2003 to June 2005 provided a wide range of climatic conditions from which the performance of the DRAINMOD and the THORN monthly water balance models were evaluated for a natural low-lying forested watershed along the South Carolina coastal plain. Both the graphical and statistical analyses comparing monthly measured outflows with monthly predictions for the 30-month period confirmed that DRAINMOD was superior to the THORN model. Nash Sutcliffe, E, and average absolute monthly deviation, E_{aamd}, values for the DRAINMOD simulations (with the Penman-Monteith PET inputs) were 0.92 and 11.0 mm, respectively, while the THORN model produced values of 0.83 and 16.8 mm, respectively. The monthly statistical results suggest that the THORN model may be adequate for predicting seasonal and annual outflows. Furthermore, the THORN model may be used as a preliminary tool by those who lack the resources to acquire the many input physical parameters required by DRAINMOD.

Although the results of the study demonstrate the potential for DRAINMOD to accurately describe the hydrology of low-lying forested watersheds along the Atlantic Coastal Plain, additional calibration and testing of the model is needed to improve the selection of such physical parameters as surface storage, rooting depth and saturated hydraulic conductivity. However, the results also show that the application of the field-scale model, DRAINMOD, may be limited on large watersheds with complex heterogeneous characteristics such as surface storage.

Lastly, the DRAINMOD simulation results of monthly and annual outflows using historic climate data (1956 to 2002) were found to agree reasonably well with the measured data at the study site while less agreement was found when compared on a monthly basis. Runoff coefficients as predicted by the model ranged from 0.02 to 0.5 with an average coefficient of 0.21. This is consistent with measured outflow data at the site, but smaller than simulation results for drained and undrained pocosins and pine plantations in eastern North Carolina. Years with the highest and lowest annual rainfall amounts did not correspond to the years of highest and lowest outflows which suggest that outflows are dependent upon the distribution of the rainfall and the antecedent soil moisture conditions and not just upon rainfall amount.

Acknowledgements

This work was made possible by the supports of the USDA Forest Service Center for Forested Wetlands Research (CFWR), the Department of Geology and Environmental Geosciences at the College of Charleston, and the National Council of Industries for Air & Stream Improvement, (NCASI) Inc. The work was funded in part through the USDA-Forest Service Agreement No.SRS-01-CA-11330135-513 with the College of Charleston. The authors would also like to acknowledge the assistance provided by Craig Ehde (former Hydrology Technician at the CFWR) for his help in data collection in the beginning stages of this study.

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