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Testing of DRAINMOD for Forested Watersheds with Non-Pattern Drainage

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Abstract. *Models like DRAINMOD and its forestry version, DRAINLOB, have been specifically developed as a field scale model for evaluating hydrologic effects of crops (trees), soil, and water management practices for lands with pattern drainage (i.e. with parallel ditches) on relatively flat, high water table soils. These models conduct a water balance between the ditches to predict water table depths, drainage rates, surface runoff, ET, and soil water storage. However, a vast landscape under silvicultural management in the coastal plains along the southeast and Gulf Coast region consists of lands with non-pattern drainage systems. Reliable models are needed to determine the processes and water quality impacts of management practices on these lands also.*

In this study data from two naturally drained forested watersheds without the pattern drainage in Florida and South Carolina coasts were used to test the ability of DRAINMOD to predict water table depths and drainage outflow rates. A large ditch spacing and a shallow drain depth were assumed to simulate outflows from both of these flat depressional wet sites. With minimal field calibration, the model's predictions of daily outflows from Santee watershed in South Carolina were satisfactory. The predicted outflows for Bradford watershed on Florida flatwoods with a higher level of field calibration were found to be better, as expected, for wet, dry, and normal years. The results suggest that reliable estimates of surface storage and PET inputs in DRAINMOD with a surface flow routing component may further enhance the flow predictions on these watersheds.

Keywords. Pine-Hardwood, Flatwoods, Water Table, Outflows, PET, Surface Storage, Routing.

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Introduction

A large number of models are available in the literature to evaluate hydrologic effects of land use change and management practices that occur on upland watersheds with deeper water table depths. Unlike these watersheds dominated by overland surface runoff, hydrologic processes on relatively low gradient poorly drained coastal plains are usually dominated by shallow surface and subsurface runoff (outflow) depending upon water table positions. However, there are only a few models that can accurately describe the water table dynamics and outflow processes on these lowlands. DRAINMOD (Skaggs, 1978) has been widely used for describing the water table dynamics and hydrology of poorly drained agricultural lands with a parallel drainage ditch network. The model has been modified (McCarthy et al., 1992; Amatya and Skaggs, 2001) for application on poorly drained pine plantations at Carteret site in North Carolina (Figure 1). The watershed scale model developed by linking forestry version of DRAINMOD with a stream routing component of a medium-scale model for agricultural lands (Konyha and Skaggs, 1992) was also successfully tested for large pine plantations on the lower coastal plain (Amatya et al., 1997; 1999). Approximately 1 million hectares of such plantation pine (Hughes, 1988) in the coastal plain region of the United States are drained to improve soil trafficability for harvesting and planting operations and to improve soil moisture growth conditions throughout the year.

A vast landscape under silvicultural management in the lower coastal plains along the southeast and Gulf Coast region (Figure 1) , however, consists of natural lands with non-pattern drainage systems. The types of forests managed on these lands vary widely from loblolly pine to bottomland hardwoods to pine flatwoods to even short rotation woody crops. More than one million acres in the coastal area are classified as pine flatwoods alone (Sun et al., 1998a). Bottomland hardwood forests occupy nearly 31 million acres in the southeast. With the growing demand on timber in the southeast and Gulf Coast, development and application of reliable hydrologic and water quality models for these forest systems are needed to address the issues related with management impacts on water quantity and quality. However, only a limited studies has been done to describe the processes and management impacts on hydrology and water quality of such lands (Heatwole et al., 1987a; 1987b; Capece, 1994; Sun et al., 1996; 1998a; Parsons and Trettin, 2001). Based on the COASTAL model (Sun, 1985), Sun et al. (1998a; 1998b) developed and tested a distributed forest hydrologic model, FLATWOODS, to describe the hydrology specifically for the cypress wetland-pine upland landscape on Florida flatwoods and to evaluate the impacts of forest harvesting. DRAINMOD was also modified to a new model, Field Hydrologic and Nutrient Transport Model (FHANTM), to simulate the hydrology and phosphorus movement on flatwoods (Tremwel and Campbell, 1992; Campbell et al., 1995).

Most of the outflows from a coastal watershed, in fact, drain from saturated areas where the water is either at the surface or a shallow water table is present. This means the total runoff is dependent upon the position of the water table. Therefore, in this study, we hypothesized that while flow paths (surface runoff, subsurface drainage, and ET) may differ, the theory and concepts of describing hydrologic processes based on shallow water table position between two ditches in DRAINMOD based models can also be applied to these natural forests without pattern drainage. In a simulation study using DRAINMOD to compare the long-term hydrologic effects of undrained natural pocosins to that drained with ditches near Wilmington, North Carolina, Skaggs et al. (1991) showed that average annual runoff increased as the depth of surface depressional storage was decreased. However, annual variation in runoff was much greater than all other factors. The authors discussed in detail the hydrologic processes that undergo on the natural pocosins as affected by several factors such as drainage ditches and depressional storage.

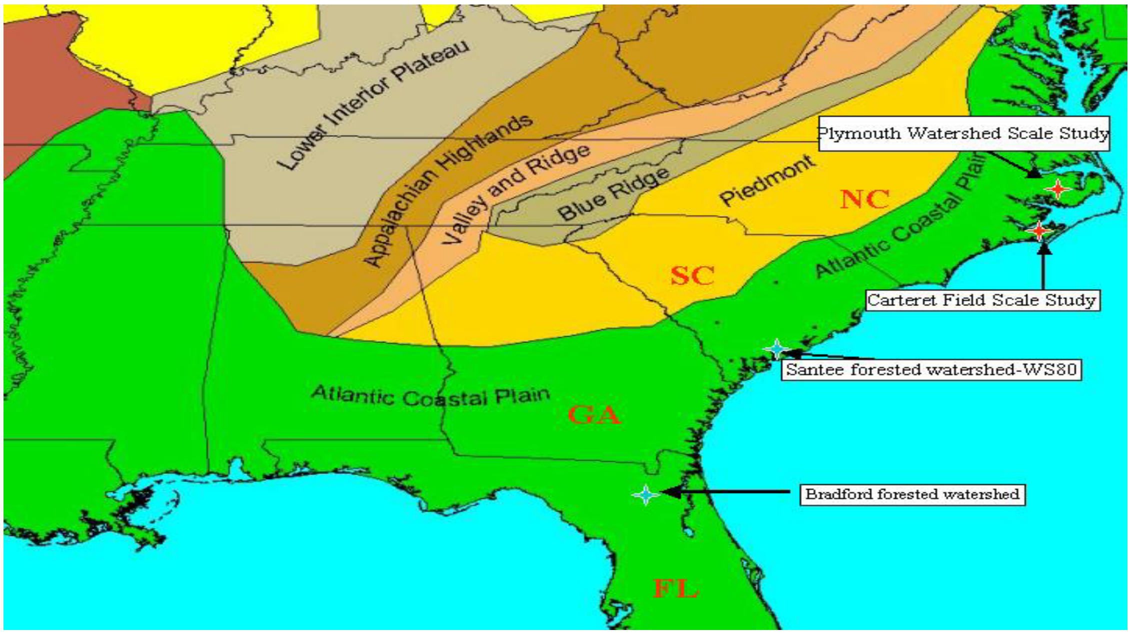


Figure 1. Location of study sites in the Southeastern Atlantic coastal plain and Gulf Coast (After Sun et al., 2000).

Chescheir et al. (1994) also successfully tested the DRAINMOD based watershed scale model on a 137 ha natural wetland near Plymouth in eastern North Carolina to predict daily water table dynamics and drainage outflows. Amatya et al. (1995) applied the DRAINMOD based watershed scale model to evaluate the effects of a wetland size and location on the hydrology of an agricultural landscape. DRAINMOD based watershed scale models were also recently tested with data from two large lower coastal plain watersheds near Plymouth in eastern North Carolina (Figure 1) (Fernandez et al., 2001; Chescheir et al., 2001; Amatya et al., 2001; 1999). These watersheds contain large areas of wetland, low lying agricultural and riparian lands, which do not have any pattern drainage like most of the other fields in the landscape. The modeling results of predicting daily flow data with a minimal field calibration were in good agreement with measured data at the watershed outlets. However, the models were not tested for their ability to predict the outflow at the in-stream outlet of these individual fields with non-pattern drainage.

Recently, Singh et al. (2001) conducted a comparative study between the simulation results of DRAINMOD/DRAINMOD-N, modified by Northcott et al. (2001), for irregular non-pattern drainage network, and Root Zone Water Quality Model (RZWQM) for tile flow from fields of a 48,900 ha little Vermillion River watershed in East Central Illinois. The authors concluded that DRAINMOD simulated results were much closer to the actual observed values than were the results predicted by the other model. All of these studies are based on only a limited data, and muti-site and multi-year validation is needed to assess the model reliability for their application on an operational basis for management decisions.

Therefore, the main objective of this study is to test the ability of DRAINMOD to predict the hydrology (drainage outflows) using measured data from two naturally drained forested watersheds without the pattern drainage in coastal Florida and South Carolina. In this study data from 1978 to 1992 were used for Bradford watershed and for only a three-year (1997 to 1999) period for Santee watershed (WS80).

Methodology

Site Description

The Bradford watershed (designated as the control watershed in a paired watershed study by the University of Florida) is located 9 km west of Starke, and 50 km northeast of Gainesville in Bradford County in north-central Florida (Figure 1). The watershed is on a typical pine flatwoods of the lower coastal plain geographic region. It has natural drainage ditches but they are not parallel, or in a uniform pattern (Figure 2). The climate is characterized by summer-wet precipitation patterns averaging 1400 mm/year, and by a mean annual temperature of 21^{o} C. The soils varied from moderately well drained to poorly drained areas. According to Riekerk et al. (1979), water table gradients average 0.1 %. The 0-4 m thick clay aquitard below the surficial water table was more leaky as suggested by Pratt (1978). Surface water drained southward through several ditches into an extensive swamp. Runoff from the watershed was measured by a long-throated recording flume. Air temperature and rainfall data were collected from a central weather station and network of seven rain gauges (Riekerk, 1989). Sun et al. (1998a) reported that the forest watershed hydrology study at the Bradford Forest site was the most complete with 15-year precipitation and runoff data in the southern coastal plain regions of the USA.

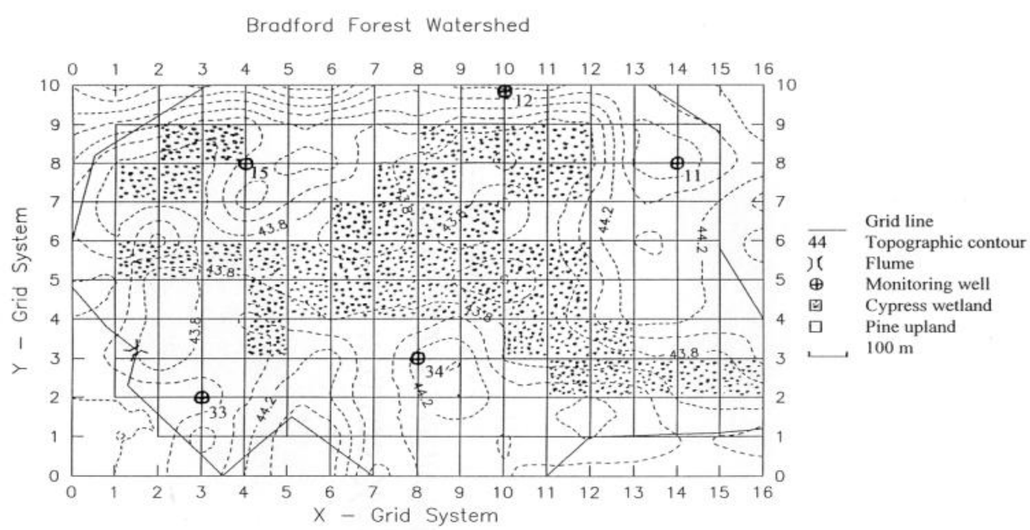


Figure 2. Schematic layout of the Bradford watershed, Florida (After Sun et al., 1998a).

The second watershed (WS80) is located at Santee experimental forest, part of Francis-Marion National Forest (USDA Forest Service) near Charleston, South Carolina (Figure 3). This is one of the paired watersheds (other one is WS77) with 206 ha in size and is on headwater stream draining to Turkey Creek on the lower Atlantic Coastal Plain on a marine terrace of the Pleistocene epoch (Gartner and Burke, 2001). The area has low topographic relief (< 4%) with surface elevations ranging from 4.0 to 10.0 m above mean sea level. Loblolly pine, longleaf pine, cypress, and sweet gum are dominant forest species in the watershed (Sun et al., 2000). Soils are primarily (sandy loams) strongly acid, infertile Aquults, characterized by seasonally high water tables and argillic horizons with low base saturation (Gartner and Burke, 2001).

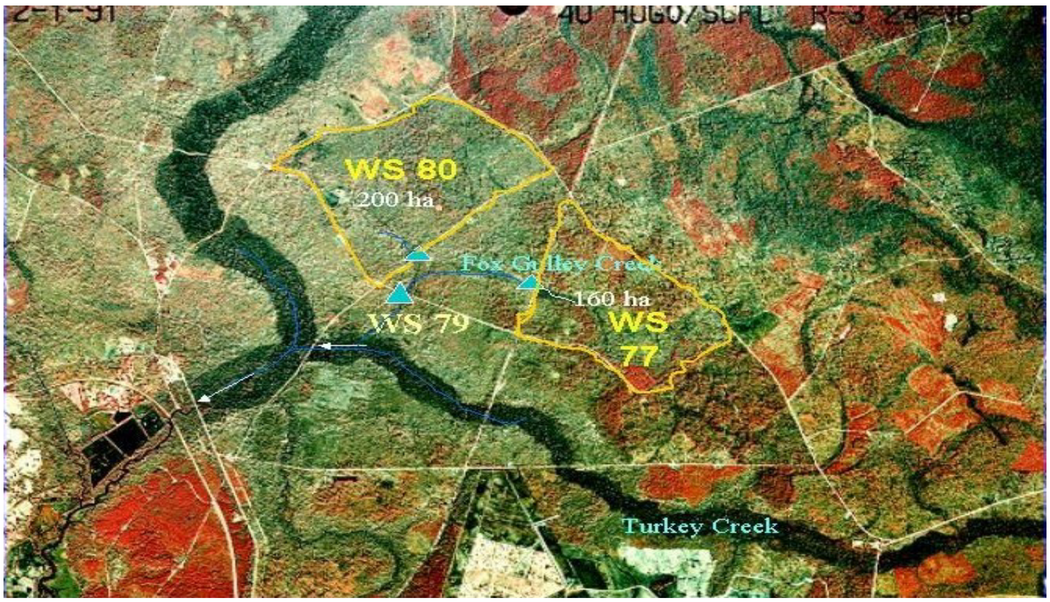


Figure 3. Satellite image with layout of Santee watershed (WS80) in South Carolina (After Sun et al., 2000).

The climate of the research area is classified as humid subtropical with long hot summers and short mild winters (Richter et al., 1983). Mean annual precipitation is about 1350 mm with July and August as the wettest months (28% of total) and April and November as the driest months (10% of total). Meteorological data for daily air temperature (maximum and minimum) and precipitation have been collected since 1976 at two locations inside the watershed and since 1946 at the weather station located at Santee Experimental Forest which is about 10 km from the watershed (Sun et al., 2000). Stream flow gauge that consisted of a compound V-notch and a flat concrete weir with a recording well was installed on the watershed in 1968. However, only a five-year (1976-80; 1990-91) period of complete mean daily flow data were reported by Sun et al. (2000). Automatic data loggers at these stations were installed only in 1996.

Model Description

DRAINMOD (Skaggs, 1978) simulates the hydrology of poorly drained, high water table soils on an hour-by-hour, day-by-day basis for long periods of climatological record (e.g. 40 years). The model predicts the effects of drainage and associated water management practices on water table depths, the soil water regime and crop yields using water balance for a soil profile between two parallel ditches. It has been used to analyze the hydrology of certain types of wetlands and to determine whether the wetland hydrologic criterion is satisfied for drained or partially drained sites. The model is also used to determine the hydraulic capacity of systems for land treatment of wastewater. The specific objectives of DRAINMOD are to simulate the performance of water table management systems and to simulate lateral and deep seepage from the field.

The basic model components are precipitation (main driving variable), infiltration computed using Green-Ampt equation, runoff as surface drainage (only after the average depth of surface depression storage is satisfied), subsurface drainage into drain tubes or ditches (by Hooghoudt's equation), evapotranspiration (ET) as a function of daily potential ET (PET) and soil water properties, soil water distribution, and rooting depth. Controlled drainage and subirrigation as water management practices can be simulated. In the last 20 years, the model's capability has been extended to predict the effects of drainage and water management practices on the hydrology and water quality of agricultural and forested lands both on field and watershed scale.

The main input variables are hourly precipitation, daily maximum and minimum air temperatures for estimating PET using Thornthwaite method, if weather data is not available for their better estimates. The model parameters include ditch spacing and depth, soil hydraulic properties (such as saturated hydraulic conductivity, soil moisture retention data, drainable porosity, upward flux, and infiltration parameters), depth to the restrictive soil layer, average surface storage, effective rooting depth, and initial water table depth. The model output parameters are daily infiltration, ET, water table depth, drainage, runoff, and total water loss.

Although DRAINLOB (McCarthy et al., 1992; Amatya and Skaggs, 2001), a forestry version of DRAINMOD modified for dry and wet canopy evaporation for ET and subsurface drainage flow rates computed with more accurate Boussinesq method, is available for application on pine forest with wider ditch spacing or no ditch case, in this study we tested only a simpler version of standard DRAINMOD that does not require additional data on tree physiological parameters. This study used the latest 5.1 version of DRAINMOD that combines the original DRAINMOD hydrology model with DRAINMOD-N (nitrogen sub-model) and DRAINMOD-S (salinity sub-model) into a Windows based program with graphical user interfaces for managing input and output data. The interface also facilitates analyses of the effect of drainage system design on subsurface drainage, surface runoff, crop yield, and nitrogen loss in surface and subsurface drainage by automatically editing drainage design parameters (e.g. drain spacing & drain depth) over a specified range, simulating the different designs and graphically displaying the results. More details can be found at the WEB site *http://www.bae.ncsu.edu/soil_water/drainmod/*.

Model parametrization

Bradford watershed: Daily streamflow and climate data from this watershed have been previously published (Sun et al., 1998a; 1998b). We also contacted the State Climatology Office of Florida to obtain relevant weather data from the closest station at Gainesville for cross verification. Daily rainfall data from 1978 to 1992 and daily temperature data from 1978 to 1995 were obtained and processed in the DRAINMOD format. Hourly data were extrapolated from daily rain data from 1978 to 1992 for conducting DRAINMOD simulations. Daily maximum and minimum temperatures were used to compute PET using Thornthwaite method (Thornthwaite, 1948) built in the model. Monthly factors developed for West Palm Beach, Florida conditions (Smajstrla et al., 1984) were used on this watershed to adjust the estimated monthly PET, which are generally underestimated during the winter and overestimated during the summer (Amatya et al., 1998). Dominant soil types at the site were described as Surrency loamy sand in the middle depressions (with an average of 15 cm depth assumed) followed by Mascotte and Palham fine sand (Sun et al., 1998a). Soil water retention data and saturated hydraulic conductivity data were based on past study by Guo (1989). A uniform hydraulic conductivity was assumed throughout the profile. The soil water retention data for the forth layer from 0.80 m to 2 m was assumed the same as in the third layer. The soil water retention curve data and hydraulic conductivity data for each layer were processed using a utility program available in DRAINMOD to obtain input data for the soil properties. Depth to the impervious layer was estimated as 2 m based on data from Mansell et al. (2000). A constant rooting depth of 40 cm was assumed for the pine flatwoods. All input parameters used in DRAINMOD simulations for this watershed are shown in Table 1.

Table 1. DRAINMOD input parameters used for Bradford and Santee Watersheds.

Input parameters	Bradford watershed	Santee (WS80) watershed
Major soil type	Surrency loamy sand, Mascotte fine sand	Wahee loam as Roanoke loam
Drainage ditch depth, cm	30	40
Ditch spacing, m	500	800
Average surface storage, cm	15	4
Depth to restrictive layer, m	2.0	1.5
Saturation water content	0.36	0.47
Wilting point	0.10	0.10
Effective rooting depth, cm	40	30
Saturated hydraulic conductivity depth, cm/cm hr^{-1}	200/3.6	20/25 150/10
Drainage coefficient, cm day^{-1}	25	50

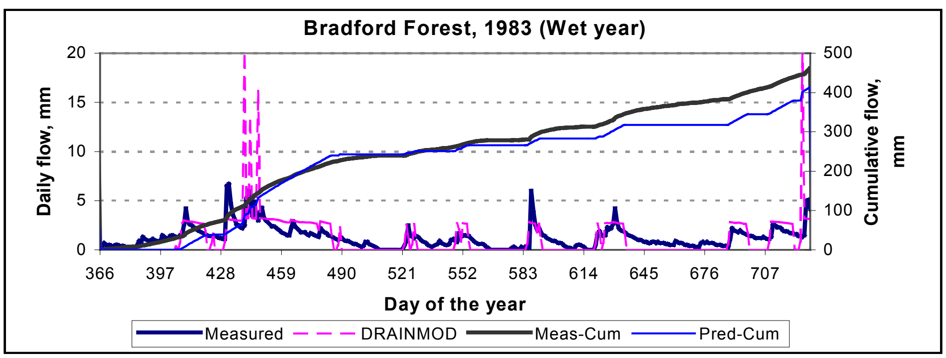
Santee watershed: Precipitation data measured at automatic tipping bucket rain gauge of the weather station (Met-25) within the watershed WS80 at Santee forest was used to obtain hourly data in DRAINMOD format for the study period 1997 to 1999. Maximum and minimum air temperatures from the weather station at Santee Forest Headquarter were input into the model. Data for the missing periods were obtained from other stations nearby the watershed (Gartner and Burke, 2001). Thornthwaite method (Thornthwaite, 1948) with monthly factors developed for West Palm Beach, Florida conditions was used to estimate PET on this watershed also, as no other regional factors was available. Field measured data on soil hydraulic properties were not available for the watershed. So estimates were based on methods suggested by Amatya et al. (2001), starting with Soil Conservation Service Soil Survey Report (SCS, 1980) for Burkeley

County, South Carolina map (1:20,000 scale) to identify dominant soil series in the watershed. Wahee loam soil series which is classified as Clayey, mixed, thermic, Aeric Ochraquults (SCS, 1980) was found to be the dominant soil followed by Bethera loam, Meggett loam , and Craven loam. Wahee soils are nearly level, deep and somewhat poorly drained formed in clayey sediment. Based on the classification, the nearest match of this soil series with published data was with poorly drained Roanoke soil, classified as Clayey, mixed, thermic, Typic Ochraquults (SCS, 1981). So all soil hydraulic properties published for Roanoke soil (Amatya et al., 2001) were used in the model. Average values of saturated hydraulic conductivity based on past measurements at the site were used for lower depths. A higher value was assumed for the top 20 cm of the forest soil layer. A rooting depth of 30 cm was used as an estimate for this forest dominated by pine hardwoods on shallow depressions. A shallow depressional storage of 4 cm and a large ditch spacing of 800 m were assumed to characterize this flat bottomland hardwood forest drained by a first order stream (Skaggs et al., 1991). All other input parameters used in the model are presented in Table 1.

Results and Discussion

Bradford watershed

DRAINMOD predicted daily and cumulative flow data are compared with measured data from Bradford forest watershed (Sun et al., 1998a) for a wet year 1983 and a normal year 1984 with dry summer-fall in Figure 4. Similarly, results for a normal year (1985) with dry winter-spring and a very dry year 1989 are given in Figure 5.



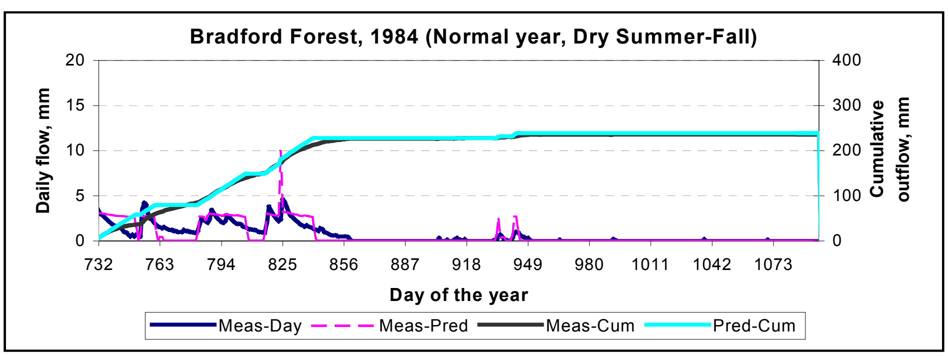


Figure 4. Measured and DRAINMOD predicted daily and cumulative outflows for Bradford watershed for a wet (1983) year (top) and a normal year with dry summer and fall (1984) (bottom).

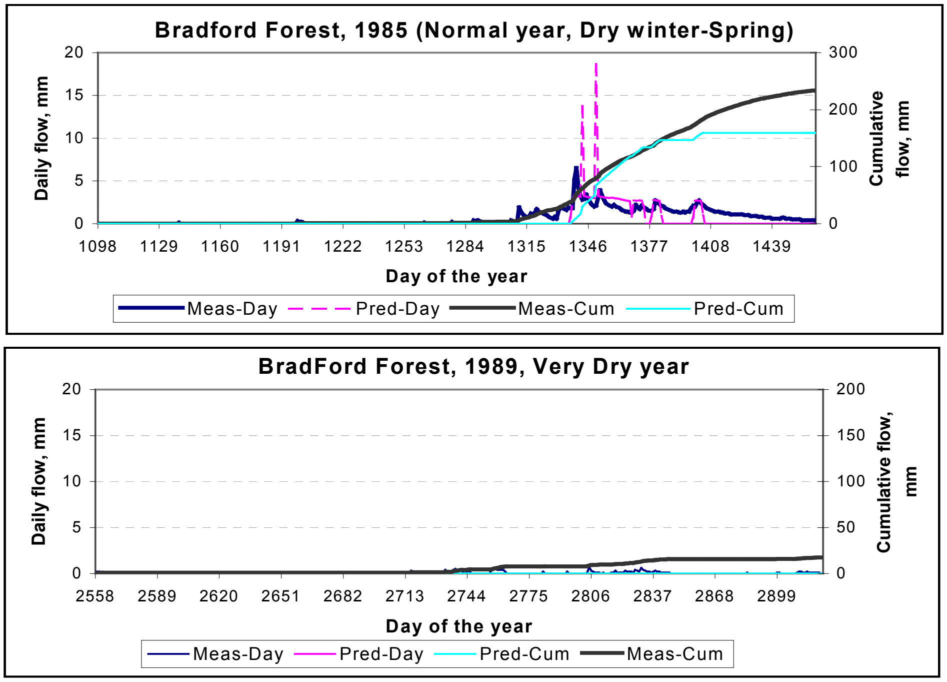


Figure 5. Measured and DRAINMOD predicted daily and cumulative outflows for Bradford watershed for a normal year (1985) with dry winter and spring (top) and a very dry year (1989) (bottom).

With only minimal field calibration of input parameters, DRAINMOD flow predictions on this natural pine flat woods with non-pattern drainage are in good agreement for all weather patterns (Figures 4 and 5). In general, the model accurately predicted almost all drainage events of 1984 and 1985 (Figure 4) including the zero flows for a long dry summer-fall period of 1984 (Figure 4, bottom). One exception was the failure of the model to predict the small events at the beginning of the year 1983 (Figure 4, top), possibly due to drier antecedent conditions. The model poorly predicted the recession part of almost all events. The model tended to overpredict the large peak flow rates in the spring period possibly due to errors in estimate of surface storage parameter or even PET. On a cumulative basis, the prediction was very good for the wet year 1983 with 1628 mm of annual rainfall and for the normal year (1984) with dry summer-fall (annual rainfall = 1204 mm) (Figure 4).

In the year 1985 with dry winter-spring period (Figure 5, top), the model did not respond to rainfall events until about a month after the watershed response, and again did not predict the recession part well as in 1984. As a result, DRAINMOD underpredicted cumulative flow by about 33 % in this year (1985) with annual rainfall of 1281 mm. One of the reasons is possibly due to errors in modeling ET. It also completely failed to predict an outflow of about 17 mm, which amounted to insignificant (about 2 %) part of the total rainfall (only 810 mm) for the whole year. These underpredictions during very dry period, possibly with deeper water table depths (no data to show), may be either due to over-predictions in ET and/or potential errors in soil hydraulic properties. In this study, the model predicts ET based on PET estimated by temperature based Thornthwaite method, which has a tendency to overestimate PET during hot summer months (Amatya et al., 1998).

Sun et al., (1998a) fully calibrated and validated the FLATWOODS model specifically developed for this cypress wetland-pine upland landscape by integrating a 2-D ground water model, an ET model, and an unsaturated water flow model with the same 15-year runoff data. This model required more parameters including the Leaf Area Index and others. The model predicted hydrology including daily outflows with sufficient accuracy. As with DRAINMOD, FLATWOODS also overpredicted most of the peak flows, but the size of overprediction was less than that with DRAINMOD for given years. In the very dry year 1989, however, FLATWOODS was able to predict the small flow rates in the summer, which DRAINMOD barely did.

Considering the limited time and efforts spent in model calibration with available input data from past studies, we believe these results are satisfactory and that they indicate a strong potential of application of DRAINMOD based models for flat poorly drained pine flatwood watersheds with non-pattern drainage systems. Based on our analysis, we also believe that more accurate simulation results may be obtained by calibrating effective surface storage parameter that drives the surface runoff, the dominant flow component in this system. . In this preliminary modeling attempt we used only temperature based Thornthwaite method for PET estimate, which is the other significant parameter, affecting ET (Amatya et al., 1998), except during the winter. This is because in these flat poorly drained natural forests, most of the water removed from the soil profile is lost via ET (Skaggs et al., 1991; Sun et al., 1998a). DRAINMOD predicted flows with a surface flow routing developed by Konyha and Skaggs (1992) and applied by Chescheir et al. (1994) for a natural wetland may further correct the errors in predicting recession part of the events. Furthermore, hourly precipitation instead of extrapolated daily values and use of DRAINLOB with interception component may also enhance the daily predictions.

Santee watershed (WS 80)

DRAINMOD simulation was conducted for a three-year (1997-99) period although a good flow data set for model comparison existed for only two-year (1997-98) period. Predicted daily and cumulative outflows for 1997-98 period are shown in Figure 6. Thornthwaite method with daily maximum and minimum temperatures was used in the model for computing daily PET.

Results show that the model was able to predict almost all drainage events including the zero outflows during the dry summer-fall period of 1998. However, the model failed to predict small events after day 70 (late March) including a large one (>20 mm day^{-1}) on day 121 (May 01) of 1997, resulting in a total underprediction of outflow by about 190 mm in 1997. Similarly, the model underpredicted the magnitude of some wet winter events in 1998. The largest peak outflow rates of the *La Nina event* in early February in 1998 were significantly underestimated. The model also predicted faster recession of flow rates compared to the measured data. As a result, the model predicted 2-year outflow of about 1020 mm was underestimated by about 32% compared to 1510 mm of measured outflow. The model accurately predicted all zero flow events of the summer-fall period in 1998, except for a small outflow as a response to Hurricane Bonnie in mid-August. Most of the large peak flow rates were predicted a day or two earlier.

Overall, given the minimal calibration of the model with field data, the model's predictions of daily outflows were considered satisfactory. The discrepancies observed were basically of four kinds: overprediction of some peak flow rates, earlier time to peak, quicker flow recession, and underprediction mostly during the spring-summer periods. One important reason for the first three discrepancies is most likely due to flow routing effects that DRAINMOD, as a field scale model, does not take into account. The model assumes that the predicted outflow (subsurface plus surface runoff) from the field arrives instantaneously (within 1 hour) to the outlet. Although this headwater watershed is of the first order only, there is a clear concentrated flow path as a stream draining about 206 ha area at the outlet, which is relatively larger in size to have some potential effects of flow routing. Furthermore, surface water on these low gradient natural sites moves slowly through longer path allowing a longer recession of flows. Amatya et al. (2000) suggested that a field size of as large as 160 ha may be assumed for simulating hydrology using DRAINMOD on the lower coastal watersheds, when a unit hydrograph method suggested by Konyha and Skaggs (1992) is used to route the overland and/or ditch flow routing within the field to the outlet. By doing so, the larger instantaneous peak flow rates may be delivered to the outlet in successive time intervals with a longer recession time.

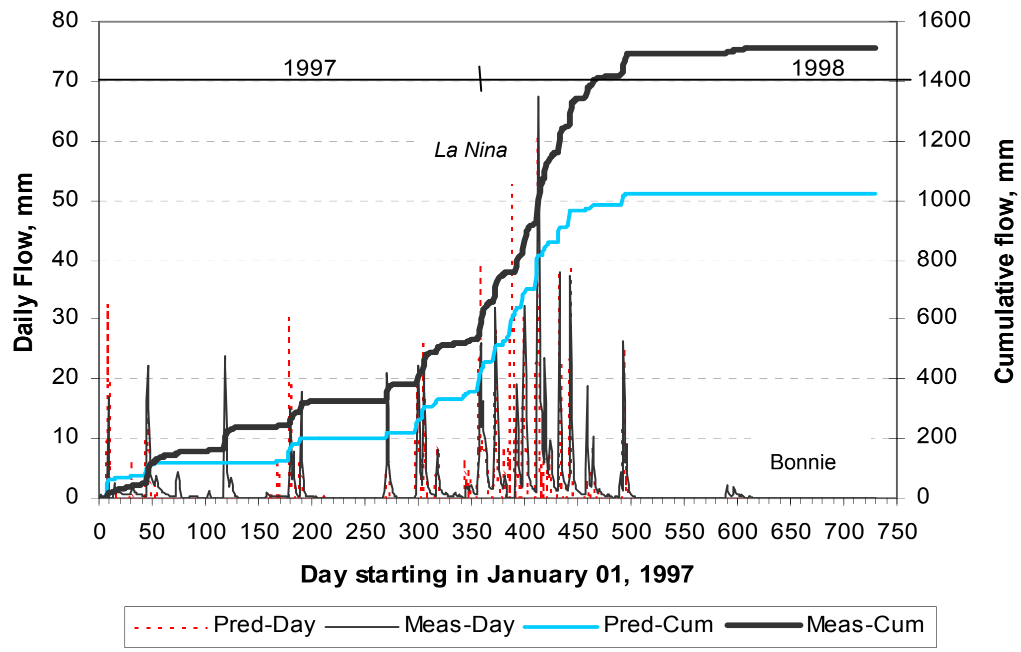


Figure 6. Measured and predicted daily and cumulative outflows for the years 1997 and 1998 at Santee watershed (WS 80), SC (using daily PET for 1997-99).

One of the reasons for underprediction of the flow rates in the winter of 1998, especially for the very wet *La Nina* event (February), was likely due to the potential errors in measured flow data, when water table in the watershed was above the surface many more times than in 1997 (Figure 7), and runoff from adjacent areas may have contributed to the outflow. In fact, both of these years with annual rainfall higher than 1418 mm were relatively wetter compared to long-term value of 1350 mm for the region. Accordingly, the annual outflows were computed as 652 mm and 858 mm with runoff coefficients of 45% and 60% for 1997 and 1998, respectively. These coefficients were higher than the maximum value of 50% with a long-term average of only 25-

30% reported by Sun et al. (2000) for this watershed. Therefore, the coefficient of 60% estimated for 1998 may be a possible indication of error in drainage area during some large events. The effects of PET in this winter period were assumed to be minimal because of low evaporative demands.

Surface storage is another parameter in the model that affects the surface runoff causing peak flow rates. Almost all flow rates that were predicted in both the years were when the water table was at the surface and storage was exceeded. However, an intensive calibration of surface storage parameter was not carried out in this study.

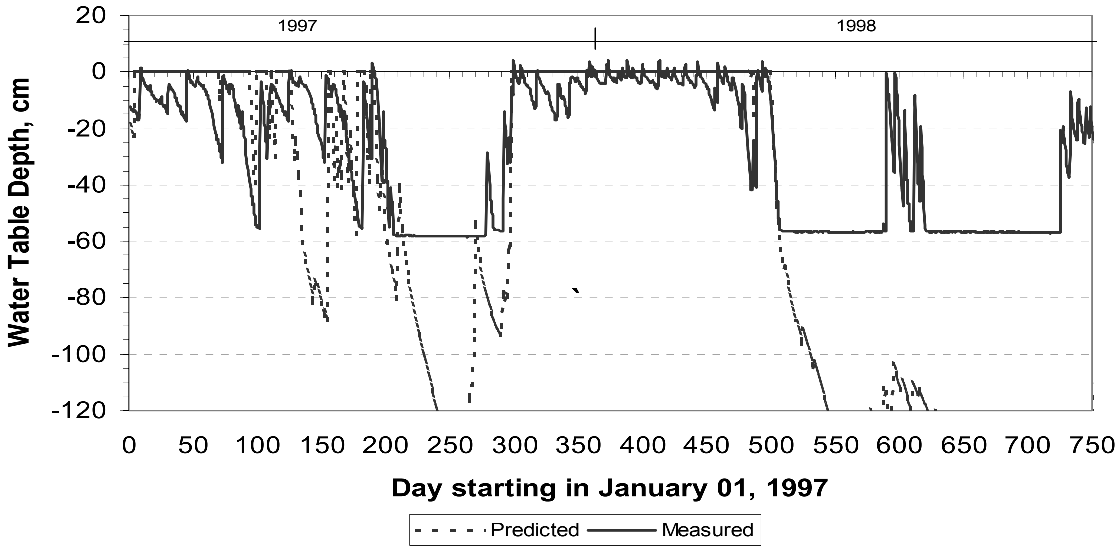


Figure 7. Measured (12-hourly, solid line) and predicted daily (dotted line) water table depths for a shallow well located inside the Santee watershed (WS 80).

Most of the other flow underpredictions were due to potential errors in predicting ET as affected by both the PET and soil hydraulic properties, which affect predicted water table depth. For example, the model completely failed to predict all events from day 60 to 130 (March to mid-May) in 1997, although the water table was near or at the surface. This was most likely due to the increased evaporation from ponded surface causing lower predicted surface storage that might have prevented runoff. When the predicted data were analyzed, a large ET as much as 104 mm equaling PET (Table 2) in March 1997 was predicted as a result of unusually high mean temperature (17.7 ^{0}C) observed in that month (Table 2). Same was true for February also. To examine these effects in detail, a constant daily PET for each month derived as an average from monthly PET for the 1997-99 period was used to simulate the daily hydrology. The predicted daily outflows for the same 1997-98 period are shown in Figure 8. As expected, with the reduced daily PET averaged for the months from three years, the model even over-predicted some peak flow rates that were not predicted in earlier simulation for the same days 60 to 130 in 1997 (Figure 6). With these new values of PET, the model now failed to predict the event of day 268 (September 25) in 1997, possibly because of increased 3-year average PET for the earlier months in July and August, compared to 1997. But on 2-year basis, the error in total predicted outflow reduced from 32 to 25% (Figure 8). Similar phenomenon was observed in August of 1998, when the model failed to predict Hurricane Bonnie related small outflows. As expected, even though the model responded to this event, the predicted water table depths were much deeper compared to measured data (Figure 7). As a result of these drier antecedent conditions compared to measured data, the model significantly underestimated the outflow rates in early 1999 (not shown). The PET factors derived from Florida as well as use of soil hydraulic properties for Roanoke soil instead of Wahee soil at the site may have also introduced errors.

Table 2. Mean monthly air temperatures at Santee weather station for the study period (1997-99) compared with 30-yr (1971-00) average from Charleston Airport Station, SC. Calculated total monthly adjusted PET based on Thornthwaite method are also shown together with adjustment factors from Florida watershed.

Month	30yr Average Temperature deg C	Mean monthly temperatures 1997 deg C	1998 deg C	1999 deg C	Monthly Adjust. factors	Total adjusted monthlyPET 1997 mm	1998 mm	1999 mm
1	9.61	10.2	12	11.7	1.66	34.7	43.4	43.5
2	10.7	12.7	12	11.8	1.93	60.2	52.4	55.4
3	14.2	17.7	13.6	12.1	1.69	104.8	67.3	51.4
4	18.2	17.5	18.1	20	1.46	95.4	101.5	125.4
5	22.6	20.5	23.8	21.5	1.09	103.6	139.3	112.8
6	25.9	24.3	28	24.8	0.83	113.7	151.0	117.2
7	27.4	27.8	29	28.5	0.78	137.3	149.3	144.2
8	26.9	26.1	27.5	28.8	0.76	112.1	123.9	136.5
9	24.6	25.6	25.5	23.6	0.76	99.4	98.8	85.1
10	19.3	19.2	20.3	19.2	0.95	65.9	73.8	65.8
11	14.3	12.9	16.5	15.7	1.25	36.6	58.4	54.3
12	10.4	10.1	13.1	10.2	1.57	28.2	49.7	29.4
Average	18.7	18.7	20.0	19.0	1.2			
Total						991.8	1108.6	1020.8

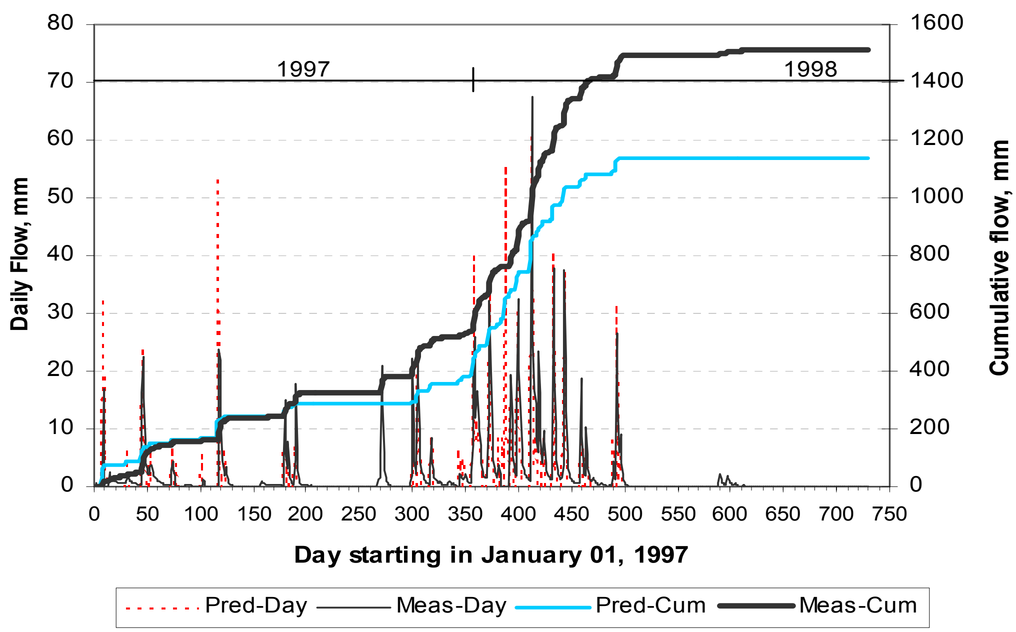


Figure 8. Measured and predicted daily and cumulative outflows for the years 1997 and 1998 at Santee watershed (WS 80), SC (using monthly average PET from 1997-99).

The predicted water table depths were at the surface for a longer period of time compared to the measured data fluctuating within 0 to15 cm most of the time (Figure 7). One possible reason for this was the errors in drainable porosity. This parameter, which was probably higher in the model, was not measured and used directly from the published data (Amatya et al., 2001). The predictions were more accurate in the winter and spring with less evaporative demands than in the summer period in both the years. The model predicted deeper water table depths than the measured data in the summer. First of all measured values stayed flat at about 58 cm depth, which was the bottom of the recording well. The larger discrepancy in the summer was clearly due to overestimate of PET as discussed earlier. Another reason is the location of the well in the watershed, which is somewhat on a higher elevation farther away from the stream. Data from a well at a lower elevation near the stream depression perhaps indicate shallower depths. The model predictions generally represent the average water table depth conditions in the watershed. Exclusion of forest interceptional loss and differences in temporal scales of the measured (twice a day) and predicted data (daily only) may also have contributed some errors. Again, given the very limited calibration, the water table depths predicted for the watershed were satisfactory.

Conclusion

DRAINMOD performed better in predicting daily and annual outflows for the years studied on Bradford pine flatwoods watershed with more field calibrated parameters than it did for Santee watershed on pine mixed with bottomland hardwoods with a less degree of calibration. This modeling work indicates a strong potential for using DRAINMOD and associated models developed in eastern North Carolina studies to describe the hydrology of poorly drained natural forested lands that do not have patterned drainage systems. Results from this study also suggest that DRAINMOD predictions of outflows on these depressional lands could be enhanced by further calibration of surface storage parameter, better estimates of PET (use of DRAINLOB to include interception component), as well as the field calibrated soil hydraulic properties. DRAINMOD with a surface flow routing component may further correct for the observed errors in magnitude and timing of flow rates as shown in a previous study. A study is underway to further test these calibration procedures in detail for these watersheds with longer period of data.

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