Hydrologic Modeling of a Drained Pine Plantation on Poorly Drained Soils

Devendra Man Amatya and Richard Wayne Skaggs

ABSTRACT. Three experimental watersheds in eastern North Carolina have been continuously monitored since 1988 to study long-term hydrology of loblolly pine (*Pinus taeda* L.) forests on poorly drained soils. This study was conducted to test the forestry version of an agricultural hydrology model DRAINMOD with 10 yr (1988–1997) of data collected at one of these watersheds under conventional (open ditch) drainage. The model, which is based on hourly water balance for the land between parallel drainage ditches, simulates interception, evapotranspiration (ET) as the sum of canopy transpiration and soil evaporation, drainage, and surface runoff. Results showed that model predictions of daily water table elevations and flow rates on an average annual basis were within 0.15 m and 0.61 mm, respectively, compared to the measured data. Relative errors on drainage outflow varied from –18% to 23%, with an average of 0.4%. Errors in measured flow rates during weir submergence, missing rainfall and weather data, and uncertainty in estimates of stomatal conductance contributed to the differences between model predictions and field observations. It was concluded that the model is a reliable tool for assessing hydrologic impacts of silvicultural and water management treatments, as well as climate changes, on these pine stands. For. Sci. 47(1):103–114.

Key Words: Loblolly pine, DRAINMOD, drainage, water table depth, and evapotranspiration.

A vast area of lands on poorly drained soils in southeastern coastal plains of the contiguous United States are being intensively managed with pine forests for maximum timber production. Forest management on these lands includes previously dug ditches to lower water table depths for improving both trafficability and soil water conditions. In recent years, there has been a concern about water quality degradation in the rivers and estuaries that receive fresh water from these drained forests. In that context, the hydrology and water balance of three 25 ha experimental watersheds on drained loblolly pine (*Pinus taeda* L.) forests at Carteret County in eastern North Carolina were investigated by McCarthy et al. (1991) and Amatya et al. (1996). Similarly, Amatya et al. (1998a) reported the effects of controlled drainage on water quality using a paired watershed approach on the same forests. These results were based on 2 to 4 yr of continuous monitoring. While continuous monitoring provides data for quantifying hydrologic and nutrient balances and more, it is not usually possible on a long-term basis.

One of the objectives of this and other long-term studies is to make data available for developing and testing simulation models. DRAINMOD (Skaggs 1978) is a field scale water management model that has found wide application for

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predicting hydrologic effects of land management practices on flat, poorly drained agricultural watersheds.

McCarthy (1990) modified DRAINMOD by adding new algorithms for interception, subsurface drainage, and wet and dry canopy evaporation to make it applicable for drained pine forests. The modified field scale model, DRAINLOB, was tested with a 22 month period of data (1988–1989) collected at the same three experimental forested watersheds (McCarthy et al. 1992) mentioned earlier. McCarthy and Skaggs (1992) applied this model to simulate the hydrologic water balance of the pine forests with different water management practices for both thinned and unthinned regimes. The new algorithms from DRAINLOB for pine forests were later added to FLD&STRM (Konyha and Skaggs 1992), a watershed scale model with a ditch and stream routing component for drained agricultural lands, to develop and evaluate a watershed scale forest hydrologic model, DRAINWAT (Amatya et al. 1997). When successfully developed and tested, these models can be used to evaluate alternative combinations of silvicultural and water management practices for enhancing productivity and reducing negative environmental impacts.

Recent studies in hydrologic modeling have shown that calibration or testing of rainfall-runoff models with data from a year or two may not be adequate to describe some processes (Yapo et al. 1996). This is particularly true if the observed data are collected during years that are either extremely wet or dry. In such cases, the calibrated parameters of the model may not capture some important processes and may overemphasize others. Yapo et al. (1996) concluded that approximately 8 yr of data are required to obtain calibrations that are relatively insensitive to the period selected. Therefore, in this study, DRAINLOB, the field scale model that was developed as a tool for evaluation of effects of forest management practices, is applied to predict daily hydrology of a drained pine forest under conventional drainage using 10 yr (1988–1997) of data collected at the site. The stomatal conductance function developed by McCarthy (1990) was modified using the long-term data in this modeling study. The main objective of this article is to test the model's ability to predict the daily water table elevations and drainage outflows for this watershed for the variations in weather conditions that occurred over the 10 yr observation period.

Methods

Site Description and Measurements

Field measurements were conducted on the Carteret 7 research site, which is located on a loblolly pine plantation owned and managed by Weyerhaeuser Company in Carteret County, North Carolina (Figure 1). The research site consists of three artificially drained experimental watersheds, each about 25 ha in size. Topography of the site is flat, and soils have shallow water tables. The soil is a hydric series, Deloss fine sandy loam (fine-loamy mixed, Thermic Typic Umbraquult). Results analyzed here were obtained from the control watershed (D1), which was managed in conventional drainage mode throughout the 10 yr period. The watershed is drained by four 1.4 to 1.8 m deep lateral ditches spaced 100 m apart (Figure 1).

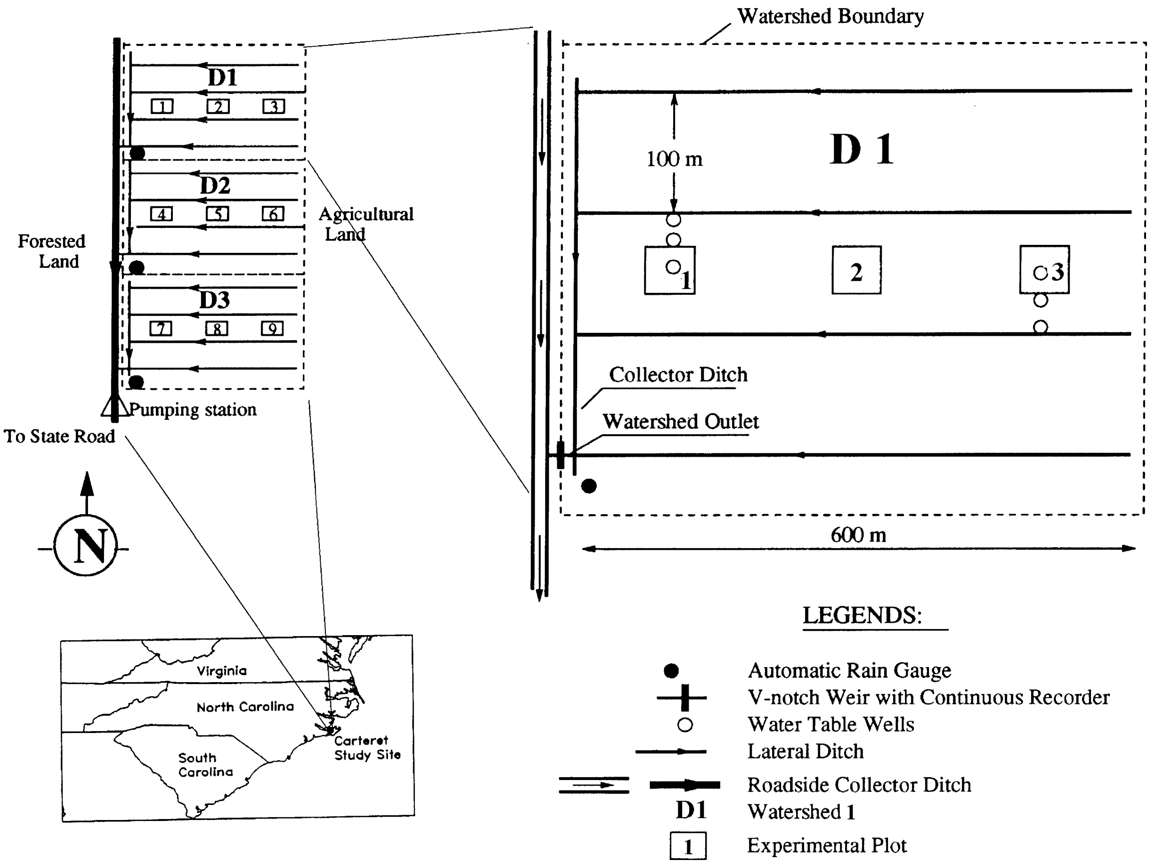

Figure 1. Location map of the study site (left) and schematic diagram of study watershed (right) at Carteret County, North Carolina.

Total rainfall was collected with an automatic tipping bucket rain gauge backed up by a manual gauge in an open area on the western side of the watershed. Air temperature, relative humidity, wind speed, and net radiation were collected on an hourly basis at a weather station located approximately 800 m west of the site. The weather station was moved to the adjacent harvested watershed (D2) in September 1997. An adjustable height 120^o V-notched weir, located at the outlet of the watershed, allowed measurement of drainage outflow by continuously recording water levels upstream of the weir. The weir level at the outlet was set at different elevations until March 1990. From March 1990 it was permanently set at about 1 m below average ground surface to allow free drainage from the soil profile. A pump was installed on the main outlet of the watershed (Figure 1) in 1991 to prevent weir submergence during larger events.

Data on soil, hydrology, and vegetation parameters were collected on three rectangular plots (Figure 1). Water table elevations were measured by continuous recorders in wells in two plots midway between the field ditches. Daily water table elevation for the watershed was calculated as average of the two midpoint wells. Water table elevations in four other transect wells across the watershed were measured periodically to determine the water table shape between the midpoint and the ditch.

The detailed history of the loblolly pine stand planted in 1974 and commercially thinned in October 1988 was given by Amatya et al. (1996, 2000). Leaf Area Index (LAI) from 1988 until early 1993 was estimated from litterfall collected at the site on a monthly basis. Starting in 1994, LAI of the stand was assumed to be the same as in 1993 because the canopy was closed and we assumed that it did not change after five growing seasons following thinning (McCarthy 1990, McCarthy and Skaggs 1992). Stomatal conductance of pine needles was measured approximately every 3 to 4 wk from April 1988 through April 1992, and with lesser frequency after that until April 1994, with a porometer (LI-2000, LiCor Inc., Lincoln, NE). The measurements were done between early morning to the early afternoon. The reader is referred to McCarthy et al. (1991) and Amatya et al. (1996) for a detailed description of the site and methods for measuring stomatal conductance.

Model Description

DRAINLOB (McCarthy 1990, McCarthy et al. 1992) is a version of DRAINMOD (Skaggs 1978), which was modified for forested watersheds. The modifications were made in components for subsurface drainage, interception, and ET. DRAINMOD simulates the response of the water table and soil water regime between the ditches to different combinations of surface and subsurface water management practices. The model computes the surface and subsurface water balance based on the water table position midway between parallel ditches.

For the modified forestry version, DRAINLOB, McCarthy and Skaggs (1991) developed a simplified model for predicting drainage rates under the changing boundary conditions characteristic of forested watersheds drained by widely spaced parallel ditches. The drainage rate was computed using a "table lookup" procedure that uses tabulated results of numerical solutions to the nonlinear Boussinesq equations (McCarthy et al. 1992). Input to the table (the independent variable) is average water table depth between the midpoint and the ditch. The distance between the midpoint and the ditch was discretized into 50 equal segments in the solutions to the Boussinesq equation, to capture average water table depth and shape. By doing so, the drainage flux due to the entire range of water table positions including transitions from ponded water conditions to an elliptic water table profile, bank storage, and lag time effects were addressed.

The volume of forest canopy interception loss was calculated by the method of Rutter et al. (1972) described by McCarthy et al. (1992) and Amatya et al. (1996). Evaporative losses due to rainfall interception are first allowed to occur based on the potential wet canopy evaporation rate calculated by the Penman-Monteith (P-M) method (Rutter et al. 1972) with zero canopy resistance. When the canopy storage becomes dry, then dry canopy transpiration is allowed to occur.

ET was defined as the sum of dry canopy transpiration and soil evaporation. The hourly potential transpiration is calculated by the Penman-Monteith (P-M) method using a stomatal conductance (g_S) function in the model along with measured LAI and weather variables (McCarthy et al., 1992; Amatya et al., 1996). In this study, the g_S function is an hourly regression model built on measured stomatal conductance of the randomly selected pine needles from the same trees in each of the six plots of three watersheds and hourly weather parameters (Flewelling 1992). Weather parameters such as temperature, net radiation, and vapor pressure deficit were measured at the weather station 800 m from the watershed at the same time. This empirical relationship includes a seasonal parameter to reflect the seasonal variation, but not the root zone soil water content. The prediction function for hourly stomatal conductance is plotted with the measured data in Figure 2 for a 6 yr (1988–1994) period. Measured data showed some seasonal variation with the peak rates occurring during June–July and the lowest values during De-

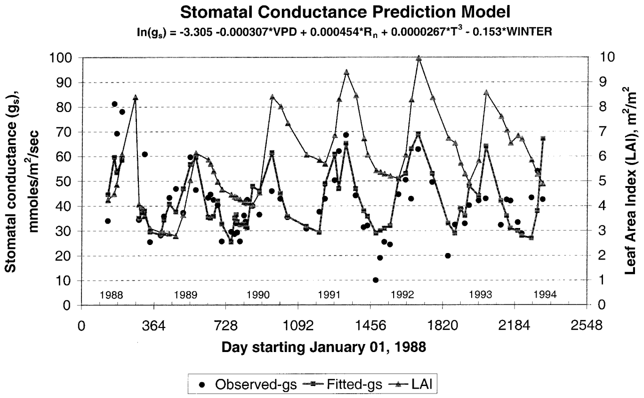

Figure 2. Measured stomatal conductance data (solid dots), fitted regression data (solid line with markers) and leaf area index (LAI, thin line with markers) of the loblolly pine stand. In the stomatal conductance (g_s) prediction model: VPD = vapor pressure deficit (kPa), R_n = net radiation (W/m^2), T = air temperature (°C), and WINTER = 1 for November to April and = 0 for May to October.

cember–January. The measured values were highest during the summer of 1988 just prior to thinning of the stand in October 1988, after which it declined until 1990. The lower peak values in the summer of 1993 may, however, be due to the stress in root zone causing stomatal closure when the soil moisture was limiting due to a long period with a little or no rainfall (Amatya et al. 1996). The same study found less than expected transpirational losses for nonlimiting soil water conditions using the same functional relationship in the P-M ET model.

Estimates of transpiration using the P-M method have been found to be highly sensitive to the estimates of g_s parameter, with the next most sensitive parameter being LAI (Beven 1979, Amatya 1993). Therefore, accurate estimates of both g_s and LAI are important in estimating dry transpiration in the P-M method. LAI data measured at the study site (Figure 2) were comparable to the published data for similar other stands (Vose and Allen 1988). The stomatal conductance values in Figure 2 are, however, generally smaller than values observed for an 11- to 13-year-old upland loblolly pine plantation in the sandhills of North Carolina (Lavanier 1998). The prediction function also underpredicted large peak values and overpredicted smaller ones. A short-term detailed study conducted at the site (Flewelling 1994) revealed that the stomatal conductance of the current year's cohort (new needles) was found to be as much as 1.5 times larger than that of the last year's cohort (old needles). Similar conclusions on stomatal response to the age of pine needles with generally higher values for juvenile (new) ones compared to the mature were made by Murthy et al. (1997).

Studies have shown that the g_s has a large diurnal as well as seasonal variation (especially for dry days) with its maximum occurring between early morning to mid-day (Lavanier 1998, Murthy et al. 1997, Lindroth 1985). These diurnal variations were not taken into consideration during the near 6-yr (1988–1993) measurements at this study site. Lavanier (1998) also showed a decrease in g_s with increasing LAI or nutrition. Under the same environmental conditions, stomatal conductance for trees on thinned stands may be higher than that for trees with closed canopies due to availability of more soil water in the former. Other studies (Lindroth 1985, Whitehead and Kelliher 1991, Oren et al. 1998) have also shown a strong dependence of stomatal conductance on vapor pressure deficit (VPD) and soil moisture. Lavanier (1998) showed stomatal conductance declines linearly with increasing VPD. Soil moisture, however, did not begin to restrict g_s until volumetric soil moisture fell below 70% available. The VPD data measured at a weather station distant from our pine stands, however, did not show a well-defined relationship with stomatal conductance, which was measured mostly in the morning (Figure 3). These studies clearly indicate that stomatal conductance is affected by many environmental factors. Because of the uncertainties associated with both the measured data and those factors, the g_s computed by the regression model was chosen as the only calibration parameter to test the model's capability in predicting daily water table depths and drainage outflow rates in this study.

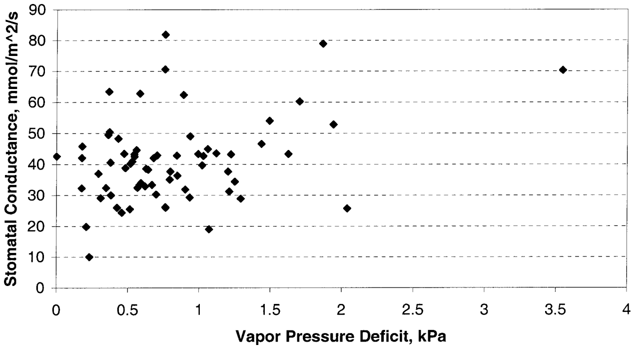

Figure 3. Plot of measured stomatal conductance and vapor pressure deficit.

For periods when wet canopy evaporation is zero, the model, as in DRAINMOD, allows the transpiration losses to occur at the potential rate as long as the upward soil water flux can satisfy the potential demand. When the upward flux becomes smaller than the potential rate, the deficit is then supplied by soil water from the root zone. This creates a dry zone, which subsequently increases in depth as ET continues. When the dry zone depth becomes equal to the rooting depth, transpiration is limited by soil water conditions and is set equal to the upward flux.

Soil evaporation in McCarthy et al.'s (1992) study was calculated as a decreasing exponent of LAI times potential ET (Thornthwaite method) as suggested by McKenna and Nutter (1984). Because of the minimal understory vegetation at the site, it has not been separately considered in the model. Detailed procedures for modeling the components of soil drainage, interception, and evapotranspiration for the experimental watersheds have been explained elsewhere (McCarthy 1990, McCarthy et al. 1992, Amatya 1993).

Determination of Model Input Parameters

Weather.–Hourly weather data on air temperature, relative humidity, wind speed, vapor pressure deficit, and net radiation collected at the weather station located 800 m west of the site were used for estimating potential wet and dry canopy evaporation with the P-M method. Data from this station were used until September 1997, after which data from the new weather station at the adjacent watershed were used. Weather data prior to 1993 were reported by Amatya et al. (1996). Whenever the weather station was down after 1992, data were synthesized using the average values with data from the same periods in previous years. Continuous breakpoint rainfall measured at the watershed itself was processed to use as an hourly format in the model. Data were verified using backup data from the adjacent manual gauge whenever possible and available. Missing rainfall data were supplemented by data from the adjacent watersheds located 400 to 800 m to the south. When all gauges were inoperable, data from Cozier Tract site located 6.5 km to the north were used. Although the continuous simulations were conducted with these data, the model prediction results from the periods when weather station was down for more than a month and/or rainfall had to be extrapolated from a distant gauge at Cozier Tract were not included for model testing using comparisons with observed data.

Drainage Design and Topographic Parameters.–Model inputs for ditch spacing, depth, and average effective surface storage were measured at the site and were the same as those used by McCarthy et al. (1992) and are given in Table 1. Daily weir elevations at the ditch outlet were also measured directly. The weir depth was 0.96 m below the average ground surface. A measured average ground surface elevation of 2.67 m above mean sea level was used to calculate water table depth at the midpoint wells in the watershed.

Soil Hydraulic Properties.–Soil hydraulic properties including the soil water characteristics, saturated hydraulic conductivity (K_s), drainable porosity, upward flux, and wilting point as measured or estimated by McCarthy et al. (1992) were used as inputs to the model (Table 1). A uniform and constant K_s value of 3.9 m day^{-1} was used for the whole soil profile.

Vegetation Parameters.–Monthly leaf area index (LAI) for the site estimated by using measured litter fall data were interpolated to obtain daily values for the model. Measured LAI data are shown in Figure 2 for the period 1988 through the beginning of 1994. Stomatal conductance on an hourly basis was estimated with the regression model built by using hourly weather variables, but modified with a calibration factor for the reasons discussed earlier. A factor of two was used for the period 1988 through 1994 when the tree canopy completely closed. From 1995 on, the factor was reduced to 1.4, assuming a full-grown canopy in the tree stand. Rooting depth was assumed to be constant for each year and varied according to the function derived by Baldwin (1987) for thinned and unthinned loblolly pine plantations of stand ages from 0 to 60 yr as reported by McCarthy et al. (1992) and McCarthy and Skaggs (1992). Canopy storage capacity was estimated as a function of the LAI (McCarthy et al. 1992) using the method of Spittlehouse and Black (1981). Canopy cover was estimated as a linear function similar to LAI with peak values during July–August and was based on the assumption that by the year 1993 the canopy was full with 87% coverage (McCarthy and Skaggs 1992). Canopy coverage of 50% was assumed for the thinned condition (McCarthy et al. 1992). A constant aerodynamic resistance parameter of 5.9 sec m^{-1} was used for the pine stand throughout the 10 yr study period.

Model Testing

Testing/validation of rainfall-runoff models is generally performed by comparing only measured and predicted outflows. A good model testing/validation procedure, however, should include checks of the goodness-of-fit not only of stream flow, but also other simulated fluxes and storages (Ambroise et al. 1995). In this model, in addition to measured daily drainage outflows at the outlet, measured water table elevations were also used to test the model's capability to simulate the daily hydrology. The model predicts average water table depth, which was compared to the average of water table depths or elevations measured at the midpoint and the ditch. This model's outputs allow for both the identification of proper input parameters and verification of internal consistency of the model structure in predicting subsurface drainage rates, surface runoff and ET.

Several goodness-of-fit or model performance criteria have been recommended for evaluation and validation of hydrologic models (Legates and McCabe Jr. 1999, Coffey et al. 1999, Aitken 1973). The criteria adopted in this study include graphical comparison of measured and predicted data for daily water table elevations, daily drainage amounts and daily cumulative drainage outflow volumes, and tabular comparison of seasonal and annual drainage outflow volumes. Daily flow frequency–duration relationships were also plotted to evaluate the distributions of observed and simulated values. The following five statistics were used for quantitative evaluation of the model's overall performance:

1. Average daily difference (ADD): It is computed as an average of differences between the observed and simulated data. This parameter, also called "mean error," is used for recognizing bias of the model. Positive values indicate underprediction and negative values as overprediction.

2. Average absolute daily difference (AADD) is a measure of the average model deviation from the observed data. Unlike the ADD parameter, it prevents cancellation of errors with opposite signs when calculating the average. A value of zero indicates a perfect fit of the measured data.

3. Coefficient of Determination (R^2) measures degree of association between observed and simulated flows. A value of $R^2 = 1$ indicates the model describes all the variability of the measured data. A value of $R^2 = 0.2$ indicates the model describes only 20% of the variability.

4. Nash-Sutcliffe coefficient or coefficient of efficiency (E): This parameter is analogous to R^2, but is not identical (Legates 1999). It ranges from minus infinity to 1.0, with higher values indicating better agreement. The E parameter is an improvement over R^2 for model evaluation purposes in that it is sensitive to differences in the observed and simulated means and variances. If the model results in high R^2 values with a biased slope, then the value of E will be lower than R^2. Because of the squared differences, however, E is sensitive to extreme values, as is R^2.

5. Residual Mass Curve Coefficient (RMC) measures the association between the observed and simulated residual mass curves and is always less than unity (Aitken 1973). This statistic is thought to have an important advantage over R^2 and E in that it measures the relationship between the sequence of flows and not simply the relationship

Table 1. Measured and estimated parameters input to the model DRAINLOB.

Depth to impervious layer (cm)	300
Hydraulic Conductivity (m/day)	3.9
Drainable porosity (m/m)	~ 0.05
Saturated water content at root zone (m^3/m^3)	0.44
Water content at wilting point (m^3/m^3)	0.21
Rooting depth (cm)	variable 37–50
Ditch spacing (m)	100
Ditch depth (cm)	120
Depth to bottom of the weir (cm)	96
Surface storage (cm)	7.5

between individual flow events. If the flow sequence contains systematic errors this coefficient should indicate their presence. All statistics, except the RMC, were computed only for periods when measured data on rainfall, weather, and flow rates were available.

Results and Discussion

Rainfall and Temperature

Total annual rainfall and annual average, maximum, and minimum temperatures for 10 yr (1988–1997) are shown in Table 2. Annual rainfall is also compared with long-term (1950–1980) normal rainfall from Morehead City, NC (Epperson et al. 1987) located about 15 km southeast of the study site. The 10 yr average of 1,526 mm rainfall clearly shows that the study period was wetter than normal, as the long-term average rainfall is 1339 mm. The year with the least rainfall was 1990, while 1988, 1995, and 1997 were close to normal. The highest rainfall occurred in 1989 followed by 1996, which was dominated by tropical storms and hurricanes. The variability in rainfall among the three adjacent watersheds is evident from year to year with D1 consistently receiving the greatest amounts. The annual variations, caused mostly by the coastal tropical storms, are reflected in the seasonal rainfall (Figure 4). Seasonal rainfall patterns with the highest in July–September followed by January and March were reported by Amatya et al. (1996). February was generally the month with the least amount of rainfall (Figure 4). The warmest year was 1990 followed by 1991 and 1994. However, because of relatively high rainfall in 1991 and 1992, the total net radiation, which explains a substantial portion of ET, was less in those years than in other years. Net radiation was highest for the years 1988 and 1997, followed by 1990, 1994, and 1993. Note that some missing radiation data were extrapolated.

Water Table Elevations

Predicted and measured daily water table elevations (WTE) for the 10 yr period (1988–1997) are plotted in Figure 5. Statistics quantifying agreement between the measured and predicted values are presented in Table 3. Model predictions of daily average WTE were in very good agreement with measured data through 1993. Both the ADD values and the plots indicate slight underpredictions (positive) in 1990 to 1993 as well as overpredictions (negative) in 1988 and 1989. For these years, R^2 values ranged from 0.61 to 0.93 and average absolute daily deviation (AADD) ranged between 0.11 to 0.14 m. The fact that E values were equal or only slightly less than R^2 indicates little bias in model predictions for these years. Excluding periods when data were missing, the model yielded R^2 values from 0.91 to 0.98 with average absolute error (AADD) ranging from 0.16 m to 0.22 m in the year 1995 due to large overprediction during the events of June and early July. Despite removal of data for periods with missing weather and rainfall, the bias in the water table predictions was visible in the years 1994 to 1997 because of substantially lower E values compared to R^2. The negative ADD values in all of the last 4 yr show consistent overprediction of water table elevations. These errors were attributed to the errors in modeling ET with a calibrated stomatal conductance function.

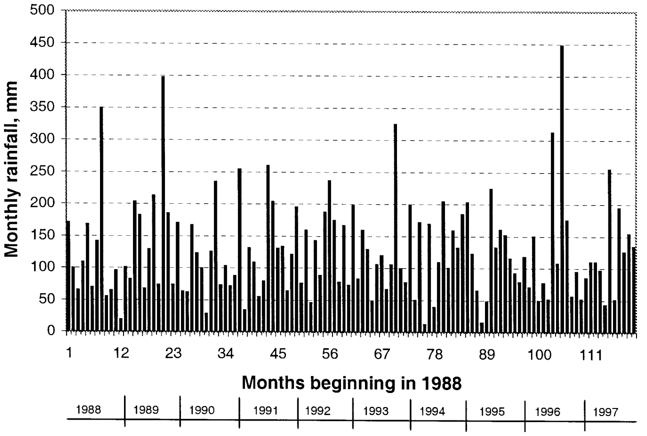

Figure 4. Measured monthly rainfall for a 10 yr (1988–1997) period at the study watershed (D1).

The model consistently overpredicted average water table elevations during peak events when water table elevation was

Table 2. Measured annual rainfall, annual average, maximum, and minimum temperatures and total net radiation at the Carteret study site. All temperatures are average of 365(6) days of the year. Net radiation in W/m^2 was converted to "mm" equivalent of water depth. D1 is the study watershed, and D2 and D3 are the other two adjacent watersheds.

Year	Annual rainfall watersheds			Long-term average rainfall	Average temperatures			Total net radiation (mm)
	D1	D2	D3		Mean	Max	Min	
	(mm)				(°C)			
1988	1,406	1,380	1,371	1,339	15.7	21.7	10.2	1,355
1989	1,876	1,829	1,768	1,339	16.3	21.6	11.5	1,191
1990	1,236	1,192	1,109	1,339	17.4	23.4	12.0	1,236
1991	1,575	1,508	1,478	1,339	16.6	22.3	11.6	1,132
1992	1,619	1,616	1,519	1,339	16.1	22.0	11.1	1,013
1993	1,514	1,507	1,510	1,339	15.9	22.4	10.2	1,206
1994	1,528	1,414	1,420	1,339	16.3	22.5	10.8	1,236
1995	1,404	1,304	1,329	1,339	15.9	22.4	10.5	1,191
1996	1,707	1,592	1,653	1,339	15.8	21.7	10.5	1,191
1997	1,409	1,287	1,376	1,339	16.1	21.6	10.6	1,358
Average	1,526	1,463	1,453	1,339	16.2	22.2	10.9	1,211

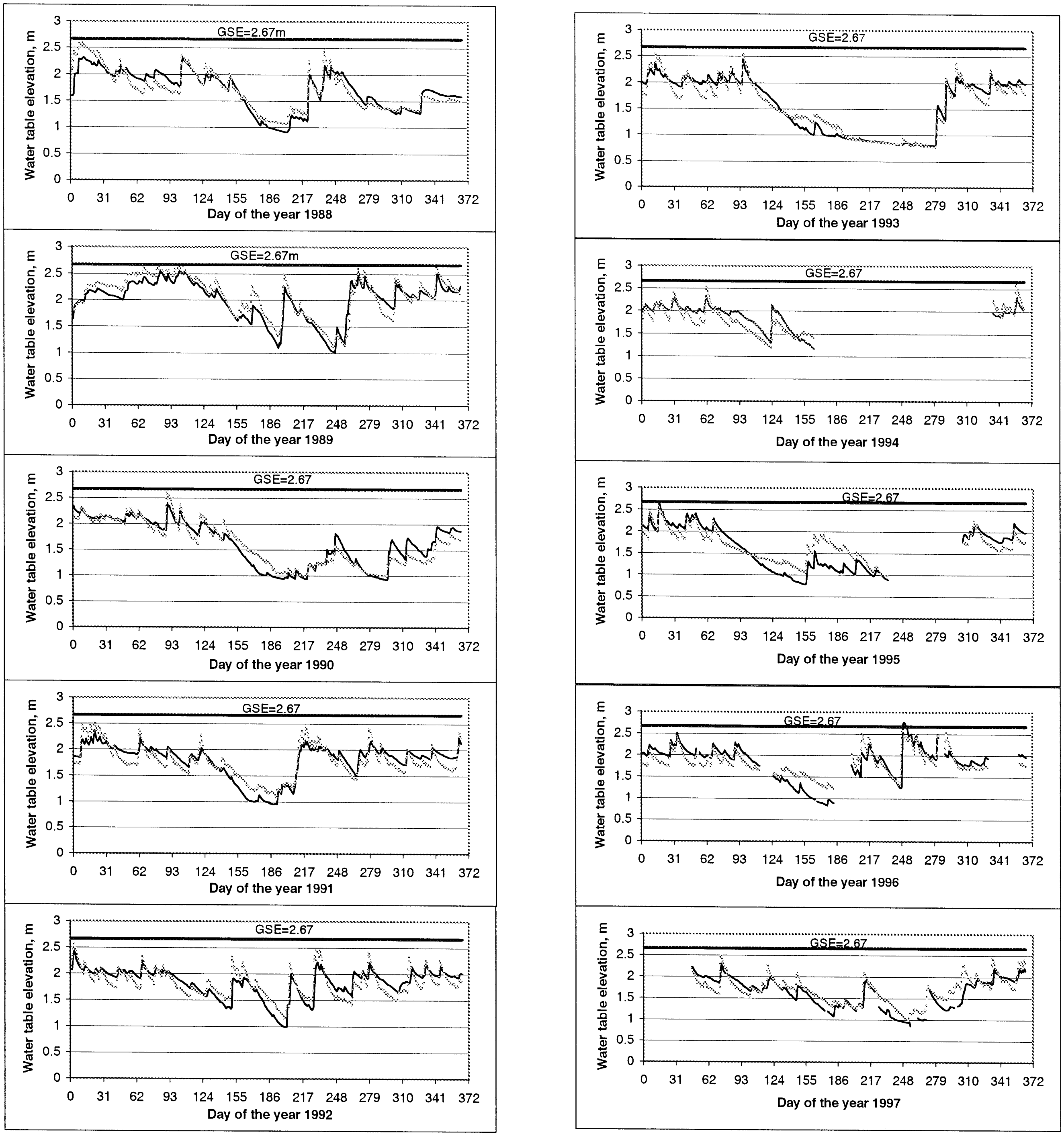

Figure 5. Measured (solid line) and model predicted (dotted line) water table elevations for a 10 yr (1988–1997) period. Broken lines indicate periods with missing water table or weather or rainfall data. GSE indicates average ground surface elevation above mean sea level (amsl).

about 2.25 m and higher. This indicates a possible discrepancy in drainable porosity around that depth. Interestingly, predicted drawdown in the range of 1–1.5 m elevation was slower than the measured data in the May–June period of all years except 1989. As a result of this, a somewhat large overestimation of water table elevations occurred in the spring and early summer of 1995. The error is not caused by errors in hydraulic conductivity because no drainage occurs for that water table elevation. Apparently the discrepancy in this period is due to errors in either drainable porosity or predicted ET.

Another possible source of discrepancies between measured and predicted water table is the method used to determine the average measured water table depth. First, there was a discrepancy between the two midpoint wells where the difference in water table elevations was as much as 0.20 m for large events. Secondly, there was some error caused by averaging only two data points (midpoint and ditch) to obtain measured average water table elevations. This error is greatest during large storm events when water table is high, as shown in Figure 6(a). It is evident that for the large events when the water table is high, the average water table eleva-

Table 3. Computed statistics for goodness-of-fit between measured and predicted daily water table elevations for watershed D1 at Carteret study site for a 10 yr (1988–1997) period. The values exclude the periods with missing weather and rainfall data in the years 1994 through 1997.

Year	AADD	ADD	R^2	E
	···············(m)···············			
1988	0.12	−0.00	0.83	0.82
1989	0.13	−0.08	0.87	0.81
1990	0.12	0.02	0.88	0.88
1991	0.14	0.01	0.77	0.76
1992	0.14	0.01	0.61	0.59
1993	0.11	0.02	0.93	0.93
1994	0.20	−0.04	0.98	0.53
1995	0.22	−0.06	0.91	0.71
1996	0.20	−0.01	0.93	0.67
1997	0.16	−0.08	0.94	0.67
1988–1997	0.15	−0.01	0.93	0.78

NOTE: AADD = Average Absolute Daily Deviation.
ADD = Average Daily Deviation.
R^2 = Coefficient of Determination.
E = Nash-Sutcliffe Coefficient (Coefficient of Efficiency).

tion, determined by taking the mean of only two data points, is somewhat lower than the average of measurements across the transect (Figure 6b). The differences were small for water table elevations lower than 2 m. Other errors are possibly associated with definition of average ground surface elevations (which was 2.67 m here) on these bedded plantations. The beds and furrows are 10 to 15 cm above and below the average ground surface, respectively. The 10 yr predictions of daily water table depths had an AADD of 0.15 m, R^2 of 0.93 and E of 0.78, respectively. Similarly, the 10 yr mean (1.75 m) and standard deviation (0.34 m) of the predicted data were also very close to the measured data with a mean of 1.74 m and standard deviation of 0.38 m. The statistics indicated that the model is able to predict the daily water table depths in the watershed within the error limits (AADD = 0.15 m with standard deviation of 0.03 m on the annual basis) due to some uncertainties in modeling ET and the measured data discussed above. This error is 30% lower than the AADD value of 0.22 m reported by McCarthy et al. (1992) for this watershed for the 22 month (1988–1989) period.

Drainage Outflows

Predicted and measured daily drainage rates and cumulative flows for each of the 10 yr of the study period are shown in Figure 7. Data for periods when weather and rainfall data were missing (as mentioned earlier in 1994 to 1997) have been excluded for both the graphical comparison and the computation of goodness-of-fit statistics (Table 4). The plots show that the model predicted nearly all measured drainage events. There were overpredictions in 7 out of 10 yr, as shown by the negative average daily difference (ADD) parameters. But the remaining 3 yr (1993, 1994, and 1995) had somewhat larger underpredictions as indicated by positive ADD values (Table 4) and by the graphical plots (Figure 7). Computed ADD value for 1997 was negative (i.e., overprediction) due to overpredictions of some summer-fall events. Most of the large deviations in daily differences (AADD) were in the years of 1989, 1991, 1992, 1994, and 1996. All these years had also large numbers of drainage events with high peak flow rates (Table 2 and Figure 4). With the exception of 1997, the AADD values (Table 4) were less than 0.47 mm/day for all of the relatively dry years (1988, 1990, 1993, and 1995). This was due to the fact there were many days with zero-flows both in measured and predicted data. Furthermore, there were fewer days with submerged flow events, which usually resulted in higher discrepancies. The large discrepancy in March and April of 1989 were due to weir submergence, which caused relatively large uncertainties in flow measurements, as reported by Amatya et al. (1998b). Large underpredictions of flows in early January 1990 were also due to submergence of the weir. A pump installed in the outlet ditch downstream prevented submergence after January 1991 except for a few periods when power went out during hurricane Fran (Day 248–250) in 1996.

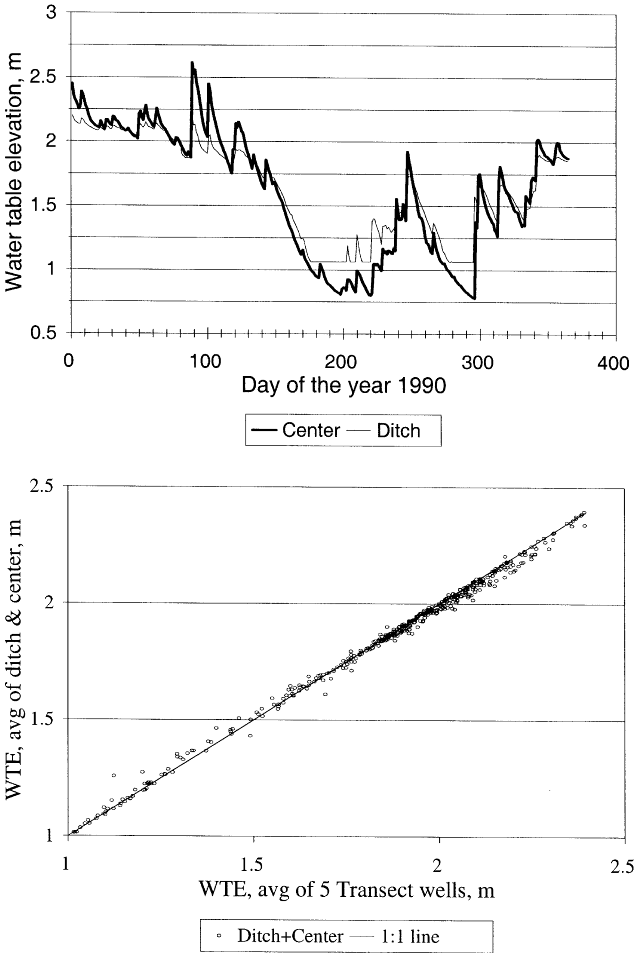

Figure 6. (a) Measured water table elevations amsl at the midpoint (thick line) in the watershed and at the ditch outlet (thin line) for the year 1990; (b) Measured water table elevation as an average of midpoint and ditch (blank circle), and average of five transect wells (straight line).

An assumption of a constant aerodynamic resistance in the interception submodel may have also resulted in overprediction of canopy evaporation (Amatya et al. 1996) and underprediction of subsurface outflow. Errors may have also occurred in estimates of stomatal conductance, due to the use of the same factors as in the previous years. The sensitivity of predicted wet canopy evaporation and ET to stomatal conductance, aerodynamic resistance, and LAI has been

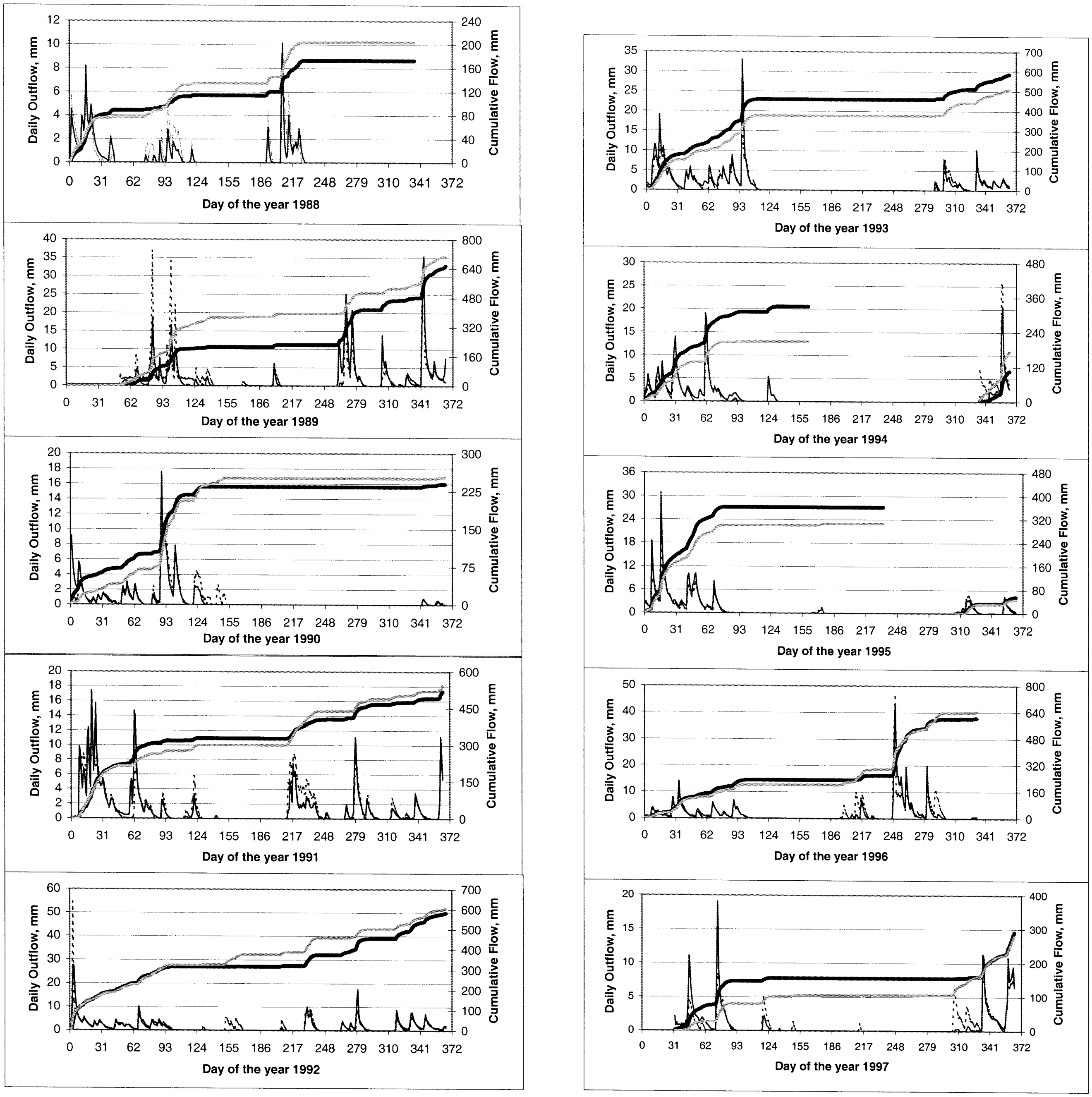

Figure 7. Measured (dark solid line) and model predicted (light solid line) daily drainage outflow rates for a 10 yr (1988–1997) period. Blank lines indicate periods with missing weather or rainfall data.

extensively reported elsewhere (Beven 1979, Amatya et al. 1996). Similarly, the high sensitivity of predicted drainage outflows by DRAINMOD to rainfall and PET has been reported by Skaggs (1978).

Peak drainage rates larger than 10 mm/day were overpredicted in some years (1989, 1992, and 1996) and underpredicted in others (1993, 1994, 1995, and 1997). This indicates no systematic errors in the model structure that predicts this variable. However, the negative values of residual mass curve coefficient (RMC) in the years 1989, 1994, and 1997 show the persistence of systematic errors. Most of the other RMC values stayed higher than 0.74 indicating near absence of systematic errors in other years. From Figure 7 it is evident that errors in 1989 mostly occurred from March to May when there were periods of weir submergence. The underestimates of peak drainage rates in early 1997 were attributed to drier antecedent conditions predicted by the model due to use of reduced amount of rainfall than it actually occurred for the missing periods in January (not shown). However, the overprediction of drainage in Day 297-333 was attributed to extrapolated rainfall from the nearby gauge when the station was intermittently down between the period Day 286–317. The underestimate in late winter and early spring of 1994 may be the result of errors in modeling ET.

Most of the peak drainage rates were the result of high subsurface drainage rates rather than direct surface runoff. The model predicted surface runoff for only one event (Hurricane Fran on Day 249 in 1996). Surface runoff is rarely

Table 4. Computed statistics for goodness-of-fit between measured and predicted daily drainage outflow rates for watershed D1 at Carteret study site for a 10 yr (1988–1997) period. All statistics except RMC exclude periods with missing weather and rainfall data in the years 1994 through 1997.

Year	AADD	ADD	R^2	E	RMC
	··········(mm)··········				
1988	0.32	–0.09	0.71	0.66	0.74
1989	1.07	–0.14	0.68	0.61	–1.29
1990	0.29	–0.04	0.77	0.76	0.83
1991	0.63	–0.06	0.72	0.71	0.80
1992	0.69	–0.06	0.65	0.54	0.78
1993	0.47	0.21	0.85	0.83	0.85
1994	1.01	0.28	0.77	0.72	–0.63
1995	0.35	0.22	0.91	0.90	0.95
1996	0.86	–0.11	0.74	0.73	0.86
1997	0.56	–0.13	0.66	0.65	–0.35
1988–1997	0.61	0.01	0.73	0.71	0.32

NOTE: AADD = Average Absolute Daily Deviation.
ADD = Average Daily Deviation.
R^2= Coefficient of Determination.
E = Nash-Sutcliffe Coefficient (Coefficient of Efficiency).
RMC = Residual Mass Curve Coefficient.

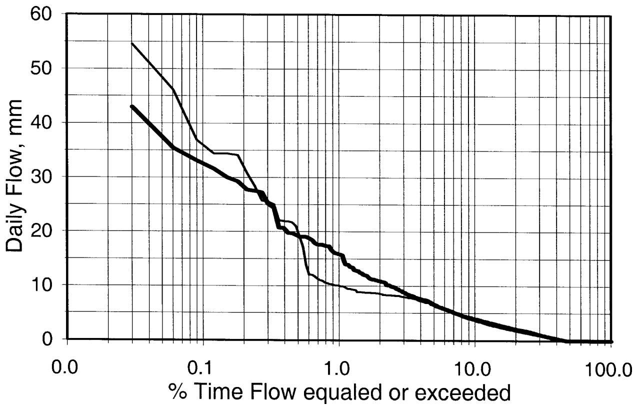

Figure 8. Measured (thick line) and predicted (thin line) daily flow frequency curves using 10 yr (1988–1997) flow data (days with missing weather or rainfall data are excluded).

predicted, because the effective surface storage is approximately 75 mm for these bedded plantations. The predictions were in much better agreement during the winter events (December to March) than during the growing season (late March to early November). The model tended to slightly overpredict some smaller events (<5 mm/day) during the growing season. This indicates that model predictions are more accurate during the winter when ET is smaller than during the growing season when errors in calculating ET have a larger impact on the water balance. The model also accurately predicted most days of zero-flow during the growing season. This indicates that the model does a better job during both wet (flow up to 8 mm/day) and dry (zero-flow) events compared to large events.

The R^2 values were greater than or equal to 0.71 for 7 of the 10 yr, and the corresponding *E* values were larger than or equal to 0.71 for 6 of the 10 yr. *E* values were close to R^2 values (1990, 1991, 1993, 1995, and 1996) when the residual mass curve coefficients (RMC) were very large (>0.80) indicating negligible systematic errors due to bias. The regression between measured and predicted daily flows for all 10 yr of data yielded an R^2 value of 0.73, indicating that the model explained 73% of the variation overall. T-tests indicated that the slope of 0.88 and intercept of 0.14 were not significantly different than 1 and 0 ($\alpha = 0.05$), which suggests a good correlation between the measured and predicted data. The predicted daily flow rates for the 10 yr period had the mean (1.37 mm/day) and standard deviation (3.0 mm/day) that were nearly the same as the mean (1.36 mm/day) and standard deviation (3.1 mm/day) of the measured data. These statistics indicate that the distributions of the measured and predicted daily flow data seem to be in good agreement. The cumulative probability distributions of measured and predicted daily flows are plotted as daily flow frequency in Figure 8. The comparison showed that the prediction of daily flow rates less than about 8 mm/day, which occurred over 96% of the time during the 10 yr period, were in very good agreement with measured data. The model accurately predicted the days with zero-flows that occurred nearly 50% of the time. However, the model underpredicted flow rates in the range of 8 to 20 mm/day that occurred 3.0% of the time. The errors for this range may be due to errors in modeling potential ET and errors in soil hydraulic properties that were assumed constant, and equal to that measured in early 1988. However, most of the overpredictions in high flow rates greater than 25 mm/day, that occurred less than 0.3% of the time, were associated with errors during the weir submergence. Amatya et al. (1998b) showed that flow rates using a weir equation for submerged flow conditions may be substantially underestimated. The 10 yr average of AADD value of 0.61 mm/day with a standard deviation of 0.27 mm/day was very close to 0.62 mm/day reported by McCarthy et al. (1992) for this watershed for the 22 month (1988–1989) period. This error is substantially lower than the value of 0.94 mm/day for a 5 yr (1988–1992) period reported by Amatya et al. (1997) for a nearby 340 ha drained forest watershed at Cozier Tract. In that watershed scale modeling study, this model was used to predict the hydrology of the individual fields. These analyses showed that the model is able to predict daily drainage rates of the study site within the error limits shown by the above computed statistics.

Predicted seasonal and annual drainage outflows were compared with measured data in Table 5. All daily data, including the periods with extrapolated weather and rainfall data, were considered to obtain the values given in Table 5. For this study site, winter season was defined as the period from November to April and summer season was defined as the period from May to October. Model predictions for the winter season were in much better agreement with measured data than were the summer predictions. Drainage was underpredicted during all the winters except in 1989 and was generally overpredicted during the summer. Besides the effects of weir submergence, some of the discrepancies in drainage outflows during the winter, when the LAI is small and ET effects are negligible, can be attributed to an assumption of a constant saturated hydraulic conductivity of 3.9 m/day for the

Table 5. Seasonal and annual measured and predicted drainage outflows for a 10 yr period (includes all data) for watershed D1 at Carteret study site, NC. Winter period (W) = November to April and Summer period (S) = May to October.

	Measured			Predicted			Relative error		
Year	W	S	A	W	S	A	W	S	A
	(mm)						(%)		
1988	94	79	173	91	113	204	3	–43	–18.0
1989	426	231	657	530	178	708	–24	23	–7.7
1990	224	16	240	208	45	253	7	–181	–5.5
1991	372	147	519	337	206	543	9	–40	–4.5
1992	445	140	585	429	178	607	4	–26	–3.5
1993	550	35	585	469	41	510	15	–15	13.0
1994	419	18	437	404	75	479	4	–312	–9.5
1995	418	39	457	346	5	351	17	87	23.1
1996	336	369	705	257	436	693	24	–18	1.8
1997	393	2	395	299	36	335	24	–1,479	15.2
Mean	368	108	476	337	131	468	8	–200	0.4
SD	120	112	164	124	121	168	13	439	12.1

NOTE: Annual outflow = Winter outflow + Summer outflow.
Relative error = (measured – predicted) / measured * 100.
SD = Standard deviation.
W = Winter, S = Summer, and A = Annual.

whole soil profile. In general, hydraulic conductivity on the top layer with litter and root mats may be higher than the bottom layer in the forest soil profile (Chescheir et al., 1995).

The relative errors were highest for the summer of 1997, followed by 1994 and 1990. However, these errors, stated on a percentage basis, should be cautiously interpreted, as they tend to be higher for smaller values. On an annual basis, the relative error varied between 1.8% for 1996 to 23.1% in 1995 with an average of 0.4% for the 10 yr period. The mean and standard deviation computed for the 10 yr period of simulated data were in very close agreement with the measured data. This indicates a strong relationship between the annual distributions of drainage outflows (Table 5). The model performance was excellent in predicting annual cumulative drainage, with an error near 15% except in 1988 and 1995. However, the timing of drainage outflows was poor in some years (1994, 1995 and 1997), indicating potential errors in rainfall input and potential ET as stated earlier. A small amount of error may result from inclusion of rainfall directly into the ditch. Average errors as much as 5% can occur in the measurement of rainfall due to this phenomenon (Whitehead and Kelliher, 1991). Other possible errors are associated with spatial variability during the summer storms, which was true especially for 1997. This is indicated by consistently lower annual rainfall (by about 4–5%) in adjacent watersheds D2 and D3 at distances of 400 m and 800 m, respectively, from the study site. Similarly, most studies have reported a possible error of 10% or more in the annual rates of ET and interception (Whitehead and Kelliher 1991). The estimation of potential ET of pine stands using weather data from a distant weather station may have further contributed to the error. Also lateral and deep seepage were not considered in the model. Amatya et al. (1996) reported a loss due to lateral seepage that amounted to about 3% of the annual rainfall for this study site.

Summary and Conclusions

A modified forestry version (DRAINLOB) of the agricultural water management and hydrology model, DRAINMOD, was tested with 10 yr (1988–1997) of data from a loblolly pine plantation on poorly drained soils in eastern North Carolina. The model simulated water table elevations with an average absolute daily deviation of 0.15 m for the 10 yr period. This was deemed to be acceptable, given the errors in some measured data and complexities in defining ground surface elevation on these bedded plantations. Other goodness-of-fit statistics such as E (coefficient of efficiency) = 0.78 and R^2 = 0.93 further support the conclusion that the model can be used to reliably predict daily water table depths on poorly drained forested watersheds.

Similarly, average absolute error of prediction of daily drainage rates for the same 10 yr period with varying seasonal and annual weather conditions were within 0.61 mm d^{-1} with a standard deviation of 0.27 mm d^{-1}. The range of R^2 value was 0.65 to 0.91 (average = 0.73) with coefficients of E ranging from 0.54 to 0.90 (average = 0.71), respectively. These statistics indicate that the model can be used for predicting daily drainage rates, and hence the seasonal and annual outflow for the site. The model overpredicted most of the summer events. On an annual basis the errors on drainage outflow varied from –18% (overprediction) to 23.1% (underprediction) with an average of 0.4%. Some of the larger differences between predicted and measured flow rates were attributed to both modeling and measurement errors. Use of the calibrated stomatal conductance function, developed using only weather data (from a distant weather station) in the Penman-Monteith ET submodel could have been a source of error in modeling ET, especially during the summer. The measurement errors were attributed not only to some extrapolated data but also to uncertainties in hydraulic conductivity and the identification of ground surface elevation at both the wells and the weir outlet.

Although the results of this study demonstrated that the model could be used for evaluating the hydrology of drained loblolly pine plantations, the following suggestions are made for further research. The stomatal conductance function used in the Penman-Monteith ET method needs further modification, refining and testing with data collected on pine stand of varying ages to enhance the reliability of modeling dry ET. The model also needs to be tested with data for controlled drainage, a water management practice that is imposed for both reducing off-site impacts and conserving water for tree growth. These studies will ensure a full testing of the model for its application on evaluation of hydrology of pine plantations under the different silvicultural and water management treatments that occur during the complete life cycle from regeneration to harvesting.

The model can not only be used for predicting water balance of drained pine plantations of all stand ages (McCarthy and Skaggs, 1992) including effects of thinning and harvesting practices, but also for assessing the seasonal hydro-periods (variation of water table depths). The model has been linked with the watershed scale models that consider the cumulative impacts of different management practices (Amatya et al., 1997) on the hydrology of a large landscape. The model has also the potential to be linked with forest productivity models for assessing water yield and timber production, and water quality and climate models for assessing the environmental impacts on poorly drained coastal plain soils.

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