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MODELING THE FOREST HYDROLOGY OF WETLAND-UPLAND ECOSYSTEMS IN FLORIDA[1]

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ABSTRACT: Few hydrological models are applicable to pine flatwoods which are a mosaic of pine plantations and cypress swamps. Unique features of this system include ephemeral sheet flow, shallow dynamic ground water table, high rainfall and evapotranspiration, and high infiltration rates. A FLATWOODS model has been developed specifically for the cypress wetland-pine upland landscape by integrating a 2-D ground water model, a Variable-Source-Area (VAS)-based surface flow model, an evapotranspiration (ET) model, and an unsaturated water flow model. The FLATWOODS model utilizes a distributed approach by dividing the entire simulation domain into regular cells. It has the capability to continuously simulate the daily values of ground water table depth, ET, and soil moisture content distributions in a watershed. The model has been calibrated and validated with a 15-year runoff and a four-year ground water table data set from two different pine flatwoods research watersheds in northern Florida. This model may be used for predicting hydrologic impacts of different forest management practices in the coastal regions.
(KEY TERMS: forest hydrology; Florida; ground water hydrology; pine flatwoods; modeling; wetlands.)

INTRODUCTION

The southeastern United States has always been a center for soft wood timber production due to its ideal climatic and soil water conditions for tree growth (Sabine, 1994). More than one million acres in the coastal area are classified as pine flatwoods (Cubbage and Flather, 1993). Important values of this ecosystem include timber production, wildlife habitat, and groundwater recharge (Brandt and Ewel, 1989). As human population and wood demands continue to rise in the southeastern United States, forestry activities on pine flatwoods have become increasingly intensified (Riekerk and Korhnak, 1984). Environmental concerns about forest management practices in the coastal areas include impacts on water quality, wetland hydrologic functions, resultant influences on wildlife habitat, and long-term cumulative impacts on soil productivity. Although the effects of forest management on upland watershed hydrology have been well studied in the past century (Bosch and Hewlett, 1982; Swank and Crossley, 1988), little information is available for the low-land and forested wetland landscape (Riekerk, 1989; Shepard *et al.*, 1993).

Hydrologic computer simulation models are becoming essential tools for scientists as well as land managers in the decision making processes (Lovejoy *et al.*, 1997). Although the building procedures and components of existing hydrologic simulation models are similar, one model may be very different from another in its capability and applicability. For example, most of the available hydrologic models developed for hilly regions are not applicable to Florida's coastal conditions (Heatwole *et al.*, 1987; Capece, 1994). Also, models developed for agricultural watersheds often need significant modification before they can be applied to forests (Thomas, 1989; McCarthy *et al.*, 1992). Several efforts have been made in modeling flatwoods hydrology. Heatwole *et al.* (1987) modified the CREAMS model (Knisel, 1980) into CREAMS-WT to better represent the storage-based flatwoods hydrologic system of agricultural watersheds in southern Florida. Based on the agricultural drainage model DRAINMOD (Skaggs, 1984), a forest hydrology version DRAINLOB was developed to model water management effects on the hydrology of loblolly pine plantation in North Carolina (McCarthy *et al.*, 1992). The DRAINMOD model was also modified to a new model, Field

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Hydrologic And Nutrient Transport Model (FHANTM), to simulate the hydrology and phosphorus movement on flatwoods fields (Tremwel and Campbell, 1992; Campbell *et al.,* 1995). Limited success was found in directly applying an upland event-based forest hydrological model (VSAS2) (Bernier, 1982) to a pine flatwoods watershed (Guo, 1989). It was suggested that the flat topography and large cypress wetland storage significantly reduced stormflow under most situations. Hydrologic cycles are included in most of the forest ecological models for slash pine plantations, but water movement processes are not physically and explicitly modeled (Golkin and Ewel, 1985; Ewel and Gholz, 1991).

In recent years, there has been a tendency to develop more physically based distributed models (Beven, 1989; Jensen and Mantoglou, 1992; Bathurst and O'Connell, 1992; Wigmosta, 1991) and couple hydrologic processes with biological processes (Al-Soufi, 1987; Band *et al.,* 1993; Wigmosta *et al.,* 1994). This development has been driven by the need for comprehensive large-scale (e.g., basin, global) ecosystem studies, in which the hydrology is one of the most important components (Swank *et al.,* 1994; Pierce *et al.,* 1987), and has been accelerated by the increase of computation power. The advance of Geographic Information Systems (GIS) technologies makes it possible to develop large-scale databases and interpret complex model outputs (Maidment, 1993).

The Florida flatwoods landscape is a mosaic of cypress wetlands and forest uplands; therefore the hydrology of flatwoods is inherently heterogenous and complex (Figure 1). Examples are: (1) the slight spatial changes in topographic elevation causing significant changes in the water regime, and (2) obstructive soil layering because of the spodic and argillic horizons in the soil profile. The heterogeneous vegetation cover of wetlands and uplands and associated phenology may further complicate the interactions between surface water and ground water. Due to the complex geologic formation of flatwoods, the preferential water pathways under different management conditions of this system have not been well documented or understood. A new distributed flatwoods forest hydrologic model is needed to study the hydrologic processes of wetland/upland systems and provide a tool to evaluate the hydrologic impact of forest harvesting, specifically for this landscape. The South Florida Water Management District has proposed a conceptual integrated hydrologic model for Dade County in southern Florida. This area is characterized by flat topography, sandy soils, a shallow ground water table, and well developed canal systems (Yan and Smith, 1994). Unfortunately, the model has not been implemented for the intended use in regional water supply planning. Based on MODFLOW (McDonald and Harbaugh, 1984) and BROOK (Federer and Lash, 1978), the COASTAL model was developed for modeling large coastal basins (Sun, 1985). Distributed structure and major hydrologic components of this model fit the pine flatwoods hydrologic system, but several algorithms have to be rewritten to model forested landscape. Advantages and disadvantages of the COASTAL model have been discussed in detail in Sun (1995).

Based on its basic structure, a new forest hydrological model, FLATWOODS, was developed and validated for pine flatwoods to: (1) predict spatial and temporal hydrologic effects of forest management practices; (2) account for hydrologic heterogeneity and continuity of wetland/upland ecosystems and environmental variables; and (3) provide a tool for forest water management and hydrologic research. This paper describes model development procedures and presents model calibration and validation results.

MODEL DEVELOPMENT

Structure

Recognizing the heterogeneity of the flatwoods landscape, the model imposes a grid over the entire wetland-upland system to discretize the heterogeneous watershed into different, but homogeneous rectangular cells (Figure 2). The physical properties of each cell are assumed to be uniform laterally for each soil layer, but non-uniform vertically in different soil layers. Each cell becomes a modeling unit that holds mathematical equations describing the physical properties. In practice, spatial data for forest lands are rarely available at high resolution with the exception of some readily available parameters such as surface elevation, vegetation and soil types (wetlands vs. uplands), etc.

Hydrologic Components and Governing Equations

The model consists of four major submodels to simulate the full hydrologic cycle including: (1) evapotranspiration, (2) unsaturated water flow, (3) ground water flow, and (4) surface flow (Figures 2 and 3). The model simulates the hydrologic processes on a daily time step. Computer codes were written in one program in FORTRAN language, which integrates all four submodels. The flow chart describes the relationships among the submodels (Figure 3).

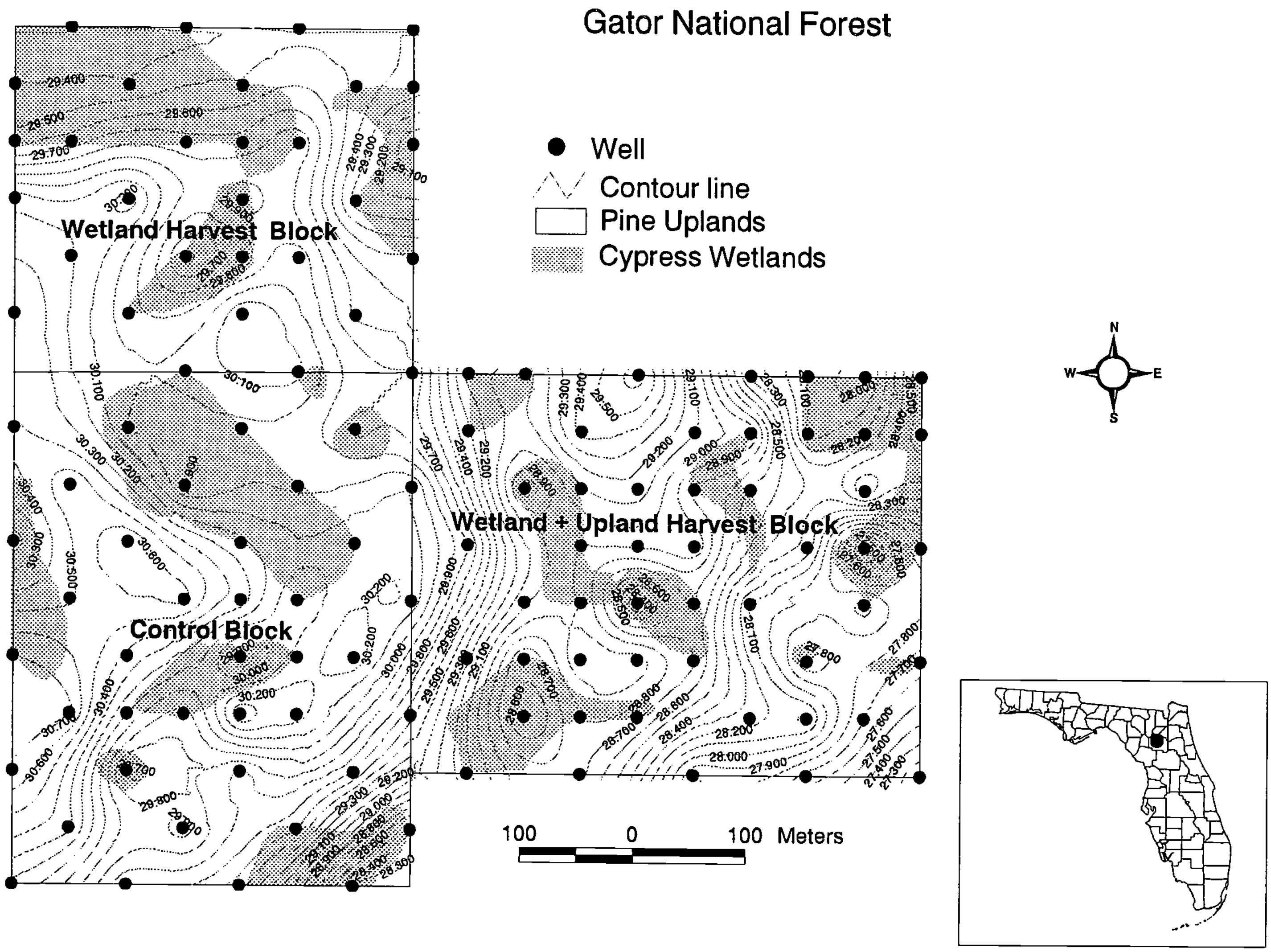

Figure 1. One Research Site on a Typical Pine Flatwoods Landscape Showing the Spatial Relations of Wetlands and Uplands.

Evapotranspiration

Evapotranspiration (ET) is the most important component of pine flatwoods water balance (Ewel and Smith, 1992; Sun *et al.,* 1995). Driving forces for the hydrologic system are climatic variables including rainfall and air temperature (evapotranspiration). The daily rainfall and temperature data as model inputs of climatic variables are available from actual field recordings or the local weather station. The ET submodel has three components including a rainfall interception component (I_p) by forest canopies, evaporation from soil/water surfaces, and transpiration through plant stomata. The rainfall interception depends on daily rainfall, leaf area index (LAI) and available canopy interception storage or dryness of the forest canopy.

Rainfall interception is modeled using an empirical equation:

$$I_p = a + b \times P \quad (1)$$

where I_p = rainfall interception (mm/day); P = gross daily rainfall (mm/day); and a and b = coefficients fitted from throughfall measurements.

The maximum interception or canopy storage capacity C_{max} in mm was introduced to make the empirical model (Equation 2) more realistic. Canopy storage capacity was determined by assuming that canopy saturation was approximated by a 1.0 mm thick water film over the foliage surfaces:

$$C_s = 1.0 \times LAI \quad (2)$$

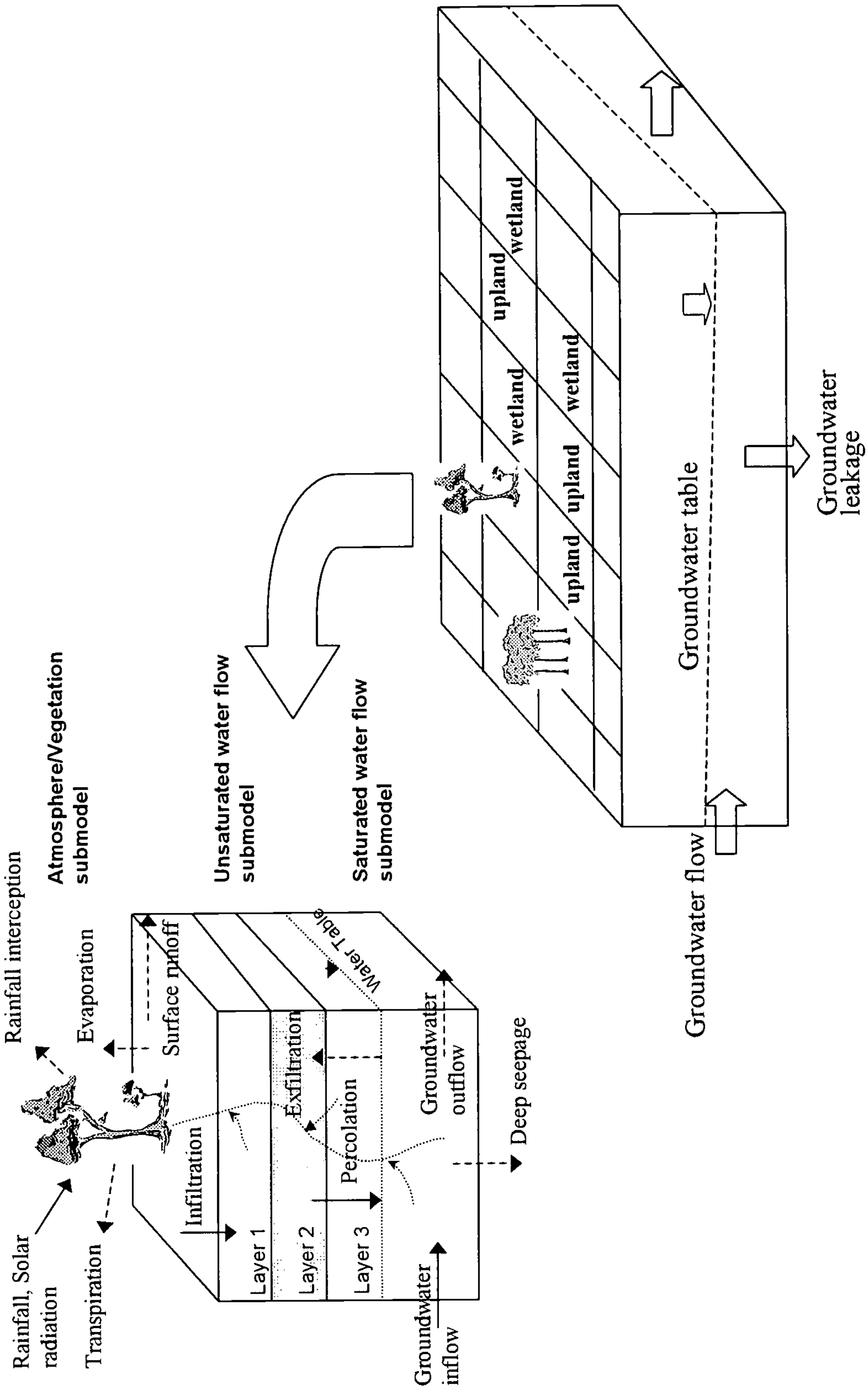

Figure 2. Structure of the FLATWOODS Model Showing the Grid System and Model Components.

Then, available canopy storage for rainfall interception (ASIN) is calculated as:

$$ASIN = C_s + PET - SIN$$

where SIN = water stored on the forest canopy the day before the simulation date (mm); PET = potential evapotranspiration (PET) is estimated by Hamon's method (Hamon, 1963; Federer and Lash, 1978).

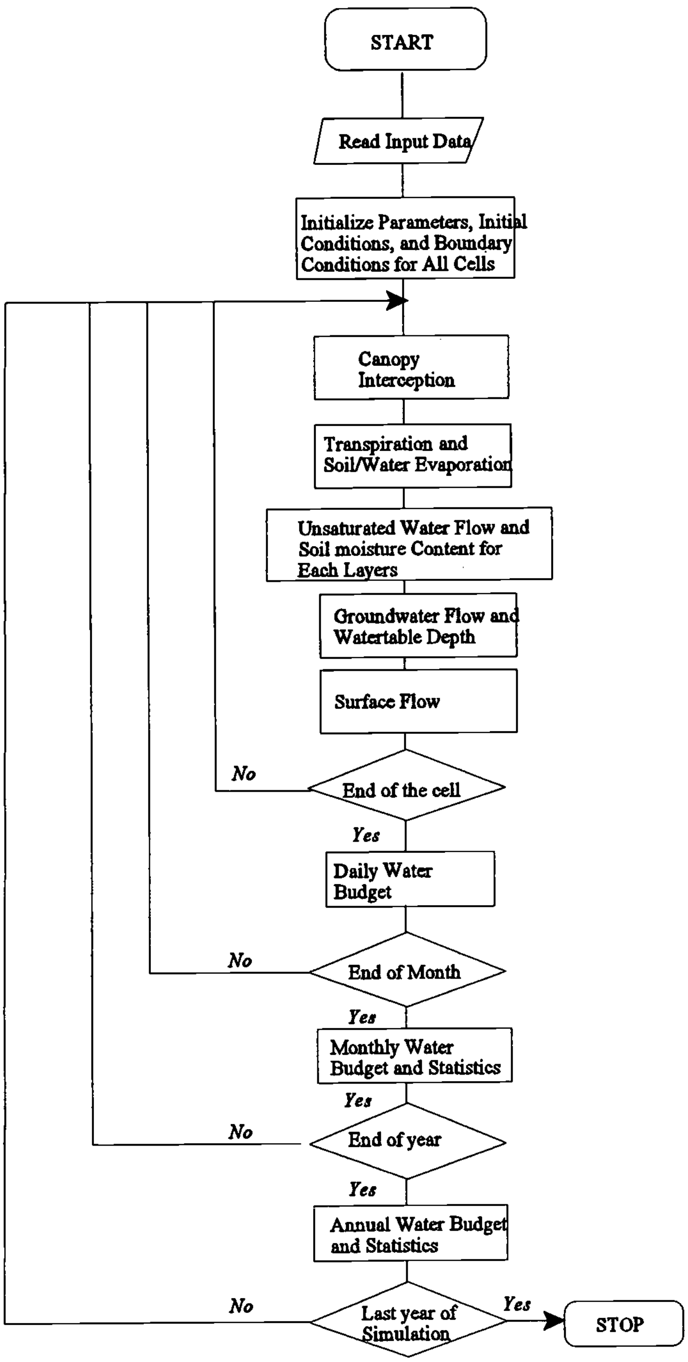

Figure 3. FLATWOODS Model Flow Chart Showing the Relationships Between the Submodels.

A PET correction coefficient of 1.3 was found to be appropriate for the Florida climatic conditions as compared 1.0 used for Hubbard Brook, New Hampshire and 1.2 for Coweeta, North Carolina (Federer and Lash, 1978).

$ASIN = C_s$	If PET > SIN
$I_p = a + b \times P$	If I_p < ASIN
I_p = ASIN	If I_p > ASIN
$I_p = 0$	If ASIN = 0

Throughfall (T_p), $T_p = P - I_p$, represents rainfall that passes through all vegetation layers and becomes available for infiltration into the ground. Variation of the leaf area index (LAI) of cypress wetlands and slash pine plantations as a function of Julian day (t) were derived from measurements (Liu, 1996). For the slash pine forest at the Gator National Forest site (GNF),

$$LAI(t) = 2.25 + 0.25 \times \sin\left(\frac{2\pi}{365}t + 1.1\pi\right) \quad (3)$$

For mature slash pine plantations, a maximum LAI and transpiration rate were assumed (Gholz *et al.*, 1991):

$$MLAI(t) = 5.0 + 0.83 \times \sin\left(\frac{2\pi}{365}t + \pi\right) \quad (4)$$

For the cypress wetlands at the research site (Liu, 1996):

$LAI(t) = 1.2$	If $t < 60$
$LAI(t) = 1.2 + (3.93 - 1.20)/(121 - 61)\,t = 1.2 + 0.0455\,t$	If $60 < t < 121$
$LAI(t) = 1.5 + 4.4 \times \sin\left(\frac{1.1\pi}{365}t + 1.9\pi\right)$	If $t >= 121$

Cypress forests at the sites of the present study were assumed to be in the mature stage with the maximum leaf area index.

Evaporation of intercepted water on forest canopies has first demand on PET. Residual potential evapotranspiration (RET) is the difference between PET and intercepted water evaporation from plant surfaces. Actual evaporation (AE) from soil/water surfaces is dependent on atmospheric demand, soil water conditions, and is affected by forest canopy shading. Actual transpiration (AT), which involves physical and physiological processes, is the most difficult component to model. In the FLATWOODS model, AT extracted from each of the soil layers is a function of possible realized transpiration (PRT), soil water conditions, and root density. The concept of PRT is defined as the maximum transpiration that a crop can have for a certain atmospheric condition and LAI. PRT is a function of the residual potential evapotranspiration (RET), and stage of plant development indicated by LAI and root density.

Solar energy is first consumed by evaporation of the rain water intercepted on the forest canopy before reaching the ground. Residual potential evapotranspiration (RPET) has been defined as the difference between PET and SIN. Evaporation from the soil surface is also reduced by forest canopy shading (McCarthy *et al.*, 1992). Field data suggest that evaporation from a floating pan under the cypress wetland canopies of the study area was only about 30 percent of the standard pan evaporation (Liu, 1996).

$$PE = RPET \times \exp[-KE1 \times LAI(t)] \quad (5)$$

where PE = potential evaporation (mm/day); RPET = residual potential evapotranspiration (mm/day) = PET - SIN; LAI(t) = leaf area index on Julian day t; and KE1 = soil evaporation reduction coefficient.

Actual evaporation (AE) is modeled as a function of water table depth (WDEP) in two phases:

Phase 1: Atmosphere Dependent
$AE = PE$ If WDEP < 35 cm

Phase 2: Water Table Dependent
$AE = PE \times KEC \times [(100-h)/(100-35)]^{KE2}$
If 35 cm < WDEP < 100 cm

Phase 3: No Evaporation
$AE = 0$ If WDEP > 100 cm

where KEC and KE2 are parameters.

The assumption was made that transpiration will not be limited as long as the soil moisture content is higher than the field capacity, and plant roots of both cypress and slash pine plantations do not stop extracting water when under inundation (Fisher and Stone, 1990). Potential transpiration (PT) is the difference between RPET and AE, representing the maximum available energy for plant transpiration.

$$PRT = PT \times \frac{LAI(t)}{MLAI(t)} \times \frac{TRD}{MTRD} \quad (6)$$

where PRT = potential realized transpiration as explained in the previous section (mm/day); TRD = root density of the entire soil profile of the modeled forest (m/m2); and MTRD = root density when the forest reaches an age with maximum transpiration capacity (m/m2).

The actual transpiration (AT_i) from each of the three layers depends on PRT, root density, and the soil moisture content of each layer:

$$AT = \Sigma AT_i \qquad i = 1, 2, 3$$

$$AT_i = WEIGHT(i) \times PRT \times F_i$$

$$WEIGHT(i) = RD_i/TRD$$

where RD_i = root density of the layer i (m/m2); $WEIGHT_i$ = weighing factor that distributes the total transpiration among the soil layers according to the root density distribution; and

$$F_i = 1.0 \qquad \text{If } \theta_i >= \theta_{i,f},$$

$$F_i = 1 - \left(\frac{\theta_{i,f} - \theta_i}{\theta_{i,f}\theta_{t,w}}\right)^{\frac{CT}{PRT}} \qquad \text{If } \theta_i < \theta_{i,f}$$

where F_i = coefficient to reflect the effects of soil moisture content, ranging from 0-1; CT = empirical parameter; θ_i = soil moisture content in layer i; $\theta_{i,f}$ = soil moisture content at field capacity in layer i; and $\theta_{i,w}$ = soil moisture content at the wilting point in the layer i.

Unsaturated Water Flow

Due to the high infiltration rate of sandy soils, rainfall that is not intercepted by forest canopies infiltrates rapidly into the soils without much overland flow. A maximum of three unsaturated soil layers have been used to simulate subsurface unsaturated water flow. The first layer (0-40 cm) represents the A horizon where most plant roots reside. The second layer (40-65 cm) represents the spodic horizon (B_h) where soil properties (soil porosity and saturated hydraulic conductivity) are distinct from the top layer. The third layer ranges from the 65-cm depth to the water table. The thickness of each layer varies throughout the simulation depending on the water table depth. For example, if the water table comes to the soil surface, the whole soil profile is saturated and the number of unsaturated soil layers becomes zero; if the water table depth is greater than 40 cm but less than 65 cm, two unsaturated soil layers are stipulated with the first layer as 0-40 cm and the second as 40 cm to the water table level. Drainage representing downward unsaturated water flow from an upper layer to a lower layer is estimated by Darcy's equation assuming unit total potential gradient. Upward water flux represents water flow from a lower layer to an upper layer, driven by the water potential gradients induced by ET. This component is calculated in direct proportion to the ET flux in the layer. While evaporation from the soil surface takes place only from the first layer, plant roots extract water from all three unsaturated layers and the saturated zone. Soil moisture content in each layer is calculated by the water balance for each time step. For some areas, such as wetlands, the soil profile may be fully saturated during part or all of the year. Percolation from the bottom of the third layer of the unsaturated zone becomes the input (source) to the underlying saturated subsystem.

Water flow in the unsaturated zone is essentially vertical due to the low topographical gradient of flatwoods. Lateral unsaturated hydraulic gradients may increase at the pond margin areas, where surface water/ground water interactions take place.

The procedure for soil moisture routing and unsaturated water flow is based on the soil water balance:

$$\theta_i^{t+1} = \theta_i^t + \left(D_{i-1}^t - E_i^t - T_i^t - D_i^t\right) \times \Delta t \tag{7}$$

where θ_i^{t+1} = unknown water content expressed in the layer i, day t+1 (cm); θ_i^t = known water content at the layer i, day t (cm); D_{i-1}^t = drainage rate at the layer i-1, day t; if layer i is the top layer, D_{i-1}^t = infiltration (cm/day); D_i^t = drainage rate at layer i, day t (cm/day); E_i^t = if the layer i is the first layer, it represents the evaporation rate from layer 1 – otherwise, it is the upward flux from the layer i to i-1 due to water potential differences between the two layers (cm/day); T_i^t = transpiration rate from the layer i (cm/day); and Δt = time step (one day).

The expression for the drainage rate (D_i) may be derived from Darcy's Law (Equation 8), where h is the matric potential uniquely related to the water content θ:

$$q = -K(h)\frac{\partial H}{\partial z} = -K(h)\left(\frac{\partial h}{\partial z} + 1\right) = -K(h) \tag{8}$$

Assuming the water matric potential is uniform for each layer, then $\partial h/\partial z = 0$. The drainage rate or percolation rate can then be approximated as unsaturated hydraulic conductivity K(h). The flux of q can also be approximated by K(h) corrected by a coefficient of 1.5. By combining the relationship of k(h)~h and the relationship between S_e, θ, and h that are developed by Van Genuchten (1980), a new equation that relates soil moisture content and percolation rate [D(θ)] was derived as in Equation (9).

$$D(\theta) = K(\theta) = K_s S_e^{1/2}\left[1 - S_e\left(S_e^{-1/m} - 1\right)^m\right]^2 \tag{9}$$

where S_e = effective degree of water saturation (%); K_s = saturated hydraulic conductivity (cm/day); m = 1-1/n, where n is a constant determined by fitting the soil moisture release curve; and = volumetric soil moisture content (%).

The upward flux, E_i^t or exfiltration rate in layer i is controlled by the evaporation at the soil surface and the transpiration from the layer i and those above it. In the present model, E_i^t is modeled by:

$$E_i^t = CET \times T_i^t \tag{10}$$

where CET = model input parameter; and T_i^t = transpiration from the layer i.

Ground Water Flow

The base of the unsaturated zone becomes the upper boundary of the saturated zone. The bottom of the saturated zone is the restricting clay layer about 2 m from the soil surface. Below this flow-restricting clay layer with hydraulic conductivity < 10^{-3} m/day, which may be discontinuous in extent, often lies another intermediate aquifer composed of sands and sandy loams. Vertical flow (leakage) through the bottom of the saturated zone is estimated using an empirical function. Within the saturated zone, water moves horizontally from one cell to the surrounding four cells governed by a 2-D groundwater flow model with Dupuit assumptions (Bras, 1990). The two important parameters in the groundwater flow equation (Equation 11), specific yield and hydraulic conductivity, are not constant but vary depending on the position of the water table in the soil profile. A water source for the submodel is water percolation from the unsaturated zone. A sink of the ground water flow model includes ET extracted from the aquifer, exfiltration (upward flux) from the saturated zone to the unsaturated zone and/or surface flow from those cells where the water table is above a critical elevation, and deep seepage from the bottom of the saturated zone.

The 2-D model for ground water flow in an unconfined aquifer was adopted to represent the saturated flow system and constitutes the core of the FLATWOODS model.

$$\frac{\partial\left(K_x h \frac{\partial h}{\partial X}\right)}{\partial X} + \frac{\partial\left(K_y h \frac{\partial h}{\partial Y}\right)}{\partial Y} - W = S_y \frac{\partial h}{\partial t} \qquad (11)$$

where K_x, K_y = hydraulic conductivity along the horizontal X axis and Y axis, calculated as the average of the aquifer thickness and varying with water table elevation (m/day); h = hydraulic head (m); W = water flux representing sources (e.g., drainage from unsaturated layers) and sinks (e.g., ET, surface runoff, deep seepage)(m^3/day); t = time (day); and S_y = specific yield of the aquifer – it is not a constant, but varies with water table elevation.

To solve the above equation, boundary conditions and initial conditions must be first specified. For a closed system, such as a watershed, the boundary conditions at watershed ridges can be set as a no-flow boundary. For a plot without lateral physical boundaries, a constant gradient boundary may be appropriate, especially for flat homogeneous terrain. Initial conditions included spatial distributions of the soil moisture content and corresponding hydraulic head for each cell. The initial soil moisture content was automatically estimated by a generalized relationship between the water table depth and the soil moisture content of the unsaturated layers (Sun, 1995).

Since Equation (11) is only applicable to the ground water flow in porous media, problems may arise when it is applied in the wetland-upland landscape under certain circumstances.

Case 1: Surface Water - Ground Water Interaction. This case can be found at the margins of a cypress pond when the area of a grid cell used in the model is smaller than a certain specific wetland/pond area. Under this condition, Darcy's law still holds for water flow between adjacent cells. However, the specific yield of the cell in the wetland may be set to 1.0.

Case 2: Surface Water - Surface Water Interaction. This case applies to the situations when the sizes of two adjacent grid cells are smaller than a certain wetland/pond area. In this case, the surface flow dominates the entire pond system and the ground water flow model is not valid. However, an approximation is justified by setting S_y = 1.0 and Ks = 50 m/day (Walters and Bengtsson, 1994).

Surface Flow

Surface flow may occur from a grid cell under extreme wet conditions when the soil profile is saturated and the water table elevation is higher than the specified critical elevation. This situation happened in both wetlands and uplands areas of the study sites. The critical elevation is defined as the surface elevation above which overland flow occurs. For uplands, it was the topographical elevation. For cells in cypress ponds, the critical elevation was the minimum elevation of the palmetto line at the flow outlet. Palmetto line indicates an abrupt vegetation change from palmetto to cypress at the edge of a cypress wetland. The total daily runoff from the watershed was first simulated as a function of the average water table level, then runoff leaving a specific flooded cell is modeled as a function of the total saturated area in the entire watershed and the water table elevation of that cell.

Based on the Variable Source Area Concept (Hewlett and Hibbert, 1965), the surface runoff leaving a flooded cell is modeled proportionally to the total saturated area of the entire watershed. The total daily runoff from the watershed was first simulated as a function of the average water table level, then distributed proportionally to each cell that had overland flow.

$$S_f(t) = K1 \times \exp\,[h(t) - K3\,]^{K2} \qquad \text{If } h(t) \geq CWT$$

$$S_f(t) = K1 \times [h(t) - K3]/[CWT - K3] \qquad \text{If } K3 < h(t) < CWT$$

$$S_f(t) = 0 \qquad \text{Otherwise}$$

where $S_f(t)$ = daily total surface runoff from the entire watershed (mm/day); K1, K2 = parameters calibrated by measured data; h(t) = average water table elevation (m); CWT = critical water table elevation (m) = Average Topographical Elevation of the watershed - Critical Soil Depth = ATOPO - CSD; CSD = the soil depth above which the runoff occurs at the outlet of the watershed (m); and K3 = the water table elevation below which no runoff occurs from the entire watershed (m).

Surface runoff from each flooded cell, a sink term in Equation (11), was modeled by:

$$SC_i\,(t) = S_f(t) \times A_i/TSA \qquad (12)$$

where A_i = the surface area of the cell (m^2); and TSA(t) = total saturated area (variable source area) (m^2).

The deep seepage component, one of the sink terms in Equation (11), is defined as the water that leaks from the bottom of the water table aquifer to the lower and sometimes artesian aquifer. The deep seepage loss was assumed to follow a power function of the thickness of the surficial aquifer:

$$DS(t) = K_d \times [h(t) - BOT]^2 \qquad (13)$$

where K_d = a model parameter; and BOT = bottom elevation of the surficial aquifer of a cell (m).

MODEL INPUTS AND OUTPUTS

Compared to lumped models, distributed models like FLATWOODS require detailed spatial information about a watershed. Such information is generally acquired through GIS. There are 10 input files required to run the FLATWOODS model and it generates two output files. Detailed information regarding model input requirements and outputs are listed in Table 1 and Table 2, respectively.

MODEL CALIBRATION AND VALIDATION

The FLATWOODS model was calibrated and validated with hydrologic data collected from the GNF (Figure 1) and the Bradford Forest study sites (Figure 4). Detailed information about experimental installation and measurement data from the two sites have been documented in Sun (1995). A combination of statistical and graphical methods was employed to quantify differences between simulated and measured variable series. The Pearson Correlation Coefficient and the objective function (index of disagreement) were used to evaluate the model performance and obtain optimum parameters. Soil parameters such as

TABLE 1. A List of Inputs Required to Run the FLATWOODS Model.

Model Inputs	Variables/Parameters
Climatic Data	– Daily rainfall – Daily average air temperature – Latitude of the study site – Correction factor for calculating potential evapotranspiration by Hamon's method – Empirical function for rainfall interception
Watershed Configuration	– Grid size, width and length, and area – Land use type (cypress wetlands, pine upland, harvested wetland, and harvested upland – Topographical elevation and bottom elevation of each cell; the critical elevation of each cell – Boundary condition identifiers 0 = no flow 1 = variable hydraulic head -1 = constant gradient boundary
Soil Parameters	– Soil moisture characteristic curves by Van Genuchten's method – Saturated hydraulic conductivity of each soil layer in each cell; – Specific yield of each soil layer in each cell – Relation between soil moisture content and water table level for different soil layers – Empirical parameters used in the ET submodels – Empirical parameters used to calculate surface runoff and deep seepage
Vegetation Parameters	– Leaf area index functions for each forest type and their change with time – Root density for each forest type in each soil layer (m m^{-2})
Initial Conditions	– Hydraulic head (water table elevation) in each cell throughout the watershed at the beginning of a simulation.

TABLE 2. A List of Outputs From the FLATWOODS Model.

– Daily water table elevation in each grid cell and its average over the entire watershed

– Daily rainfall interception, evaporation, and transpiration from each cell

– Daily total surface runoff and groundwater flow across the boundaries from the entire watershed

– Daily water drainage (percolation) from the unsaturated zone to the saturated zone

– Daily soil water storage in each soil layer

– Daily deep seepage from the surficial aquifer to the underlying second aquifer

– Statistical analysis on model performance

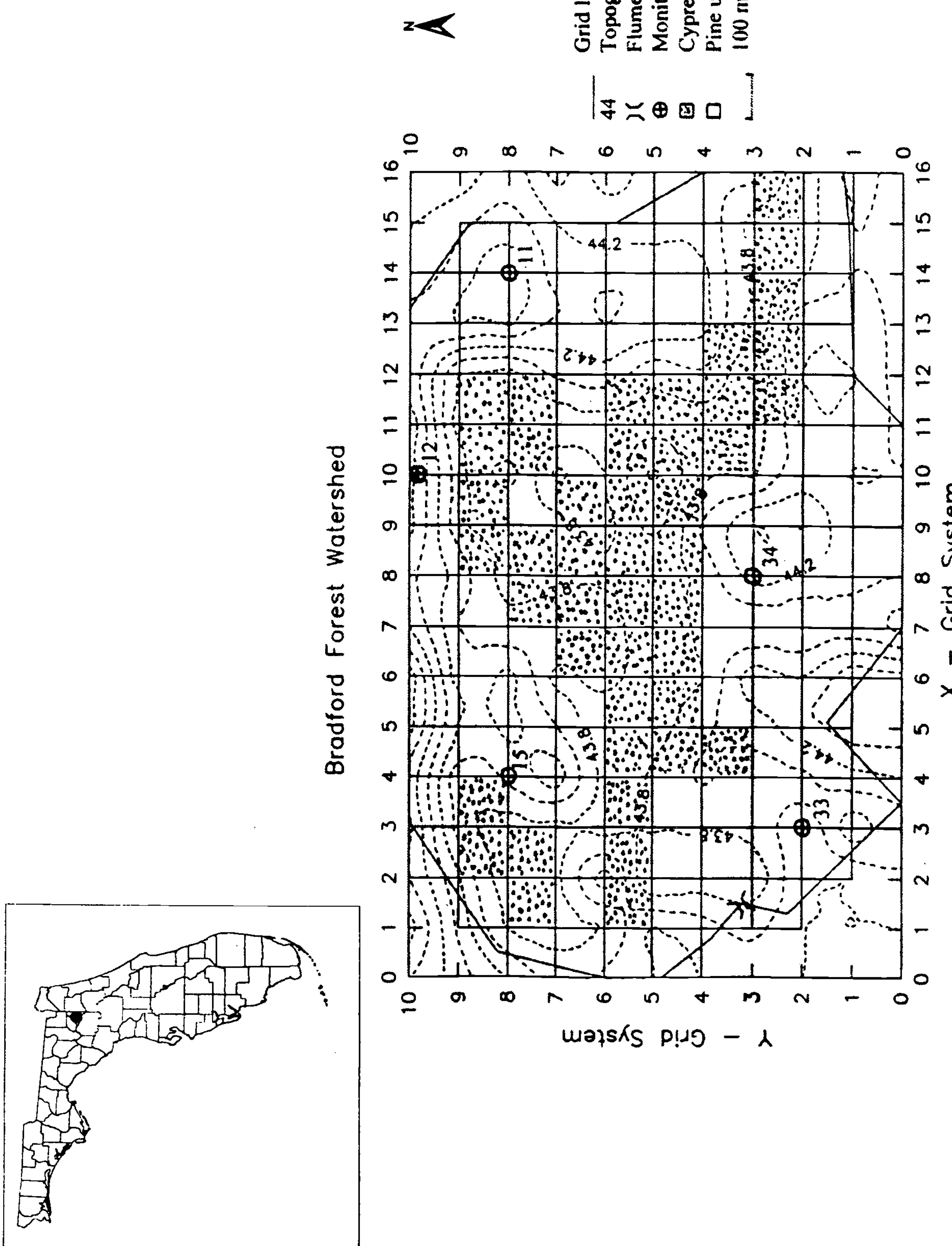

Figure 4. Control Watershed at the Bradford Forest Research Site in Northern Florida.

specific yield (S_y) and coefficients for evapotranspiration are the major calibrated parameters.

Gator National Forest (GNF) Site

More than 130 shallow wells were installed at the GNF site and the water table levels in each well were measured bi-weekly from 1992 to 1995 (Crownover *et al.*, 1995). Harvesting treatments were imposed from April 5 to May 31, 1994. Therefore, two years of pre-harvest and one year of post-harvest data are available for model testing. The arithmetic average of all water table elevations from each measurement was used for the model calibration. The model was calibrated with water table data for the wet year of 1992 and a dry year 1993, which had a 170 mm surplus and 230 mm deficit of rainfall compared to normal years (rainfall =1330 mm), respectively. Satisfactory results were obtained for those two years (Figure 5a). During May-October of 1993, 6-93 percent of the observation wells were dry due to extremely low rainfall. Using both a dry and a wet year for the model calibration enhanced the generality of the model for future prediction. Model validation with data from January 1, 1994, to May 31, 1994, during the pretreatment period also showed good model performance (Figure 5a). The Pearson Correlation Coefficient was 0.91 and 0.96 for the calibration period and the validation period, respectively.

Harvesting in May 1994 was followed by double bedding activities in the fall of 1994. The southeast block was totally clear cut, including both cypress wetlands and uplands, but only the wetlands were clear cut in the northwest block of the research area. The harvested upland areas in the southeast block were planted with slash pine seedlings in January of 1995 and the cypress wetlands was left for natural regeneration. Apparently, the most significant effect of the forest harvesting on model parameters was the reduction of LAI. This was assumed to be reduced to 0.5 for harvested wetlands and 0.1 for uplands under clear-cut conditions. Soil structure of the first layer also might have been altered due to compaction by the mechanical operations, but the change was difficult to parameterize quantitatively and thus was neglected. Under these assumptions, the model was calibrated and validated with post-treatment data collected during June 1, 1994-May 31, 1995 (Figure 5b). The Pearson Correlation Coefficient was 0.88 and 0.82 for model calibration and verification periods, respectively.

Bradford Forest Watershed

The Control Watershed at the Bradford Forest in Bradford County, Florida has been monitored since 1978 as one of the most comprehensive efforts of forest hydrological studies in the southeastern United States (Pratt, 1979; Riekerk, 1989). Spatial water table distribution data were not available for this study. Instead, a long-term data series of runoff at the watershed outlet was used for model calibration and validation. The FLATWOODS model was calibrated with five years runoff data (1978-1982) on a year by year basis (Sun, 1995). Several water table data sets from individual wells were used as a guide for calibrating the average water table elevation across the watershed. The year 1978 was a wet year (1453 mm rainfall) while the year 1981 was a very dry year (916 mm rainfall). The model was validated with runoff data from 1983 to 1992 using the same parameters for the five-year calibration (Figure 6). The model did not predict the pike flows very accurately in wet years (1983 and 1992) with low Pearson Coefficient of 0.61 and 0.62, respectively. Two reasons have been hypothesized: (1) the boundary and outlet ditches in this artificially created watershed may generate higher peak flows during the wet seasons, especially in extreme years (Iritz *et al.*, 1994); and (2) the FLATWOODS model used a single runoff-water table level relationship independent of time to predict runoff, and no cell-by-cell surface flow routing procedures. However, the assumption made in the runoff-groundwater table relationship proved effective since the model fitted the low flow reasonably well during the two-year drought period of 1989-1990. Using more physically based models such as manning's equation and unit hydrograph, or incorporating daily rainfall in the water table-runoff relations may improve model performance for stormflow events.

SUMMARY AND CONCLUSIONS

Based on the existing COASTAL model, a new distributed forest hydrologic model, FLATWOODS, was developed. The FLATWOODS model was specifically designed to simulate the hydrologic processes in forested wetland-upland systems, where saturated and unsaturated soil zones coexist and the surface water and subsurface water interact. Vertically, the model divided a flatwoods hydrologic system into three connected subsystems: an ET subsystem, an unsaturated water flow subsystem, and a ground water flow subsystem. Laterally, the model divides the entire watershed into small rectangular cells

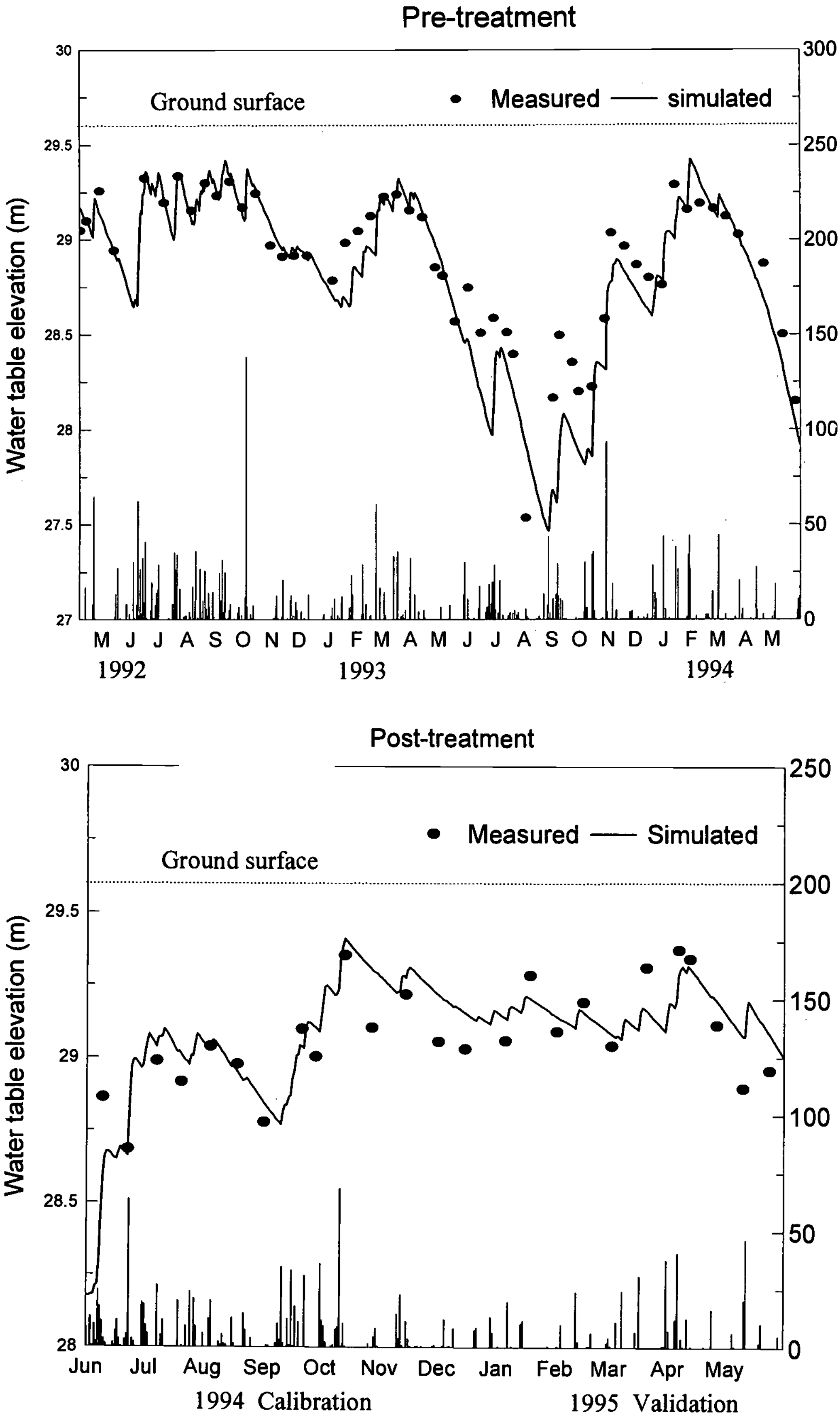

Figure 5. FLATWOODS Model Calibration and Validation During the Pre-Harvest (a) and Post-Harvest (b) Periods for the GNF Site.

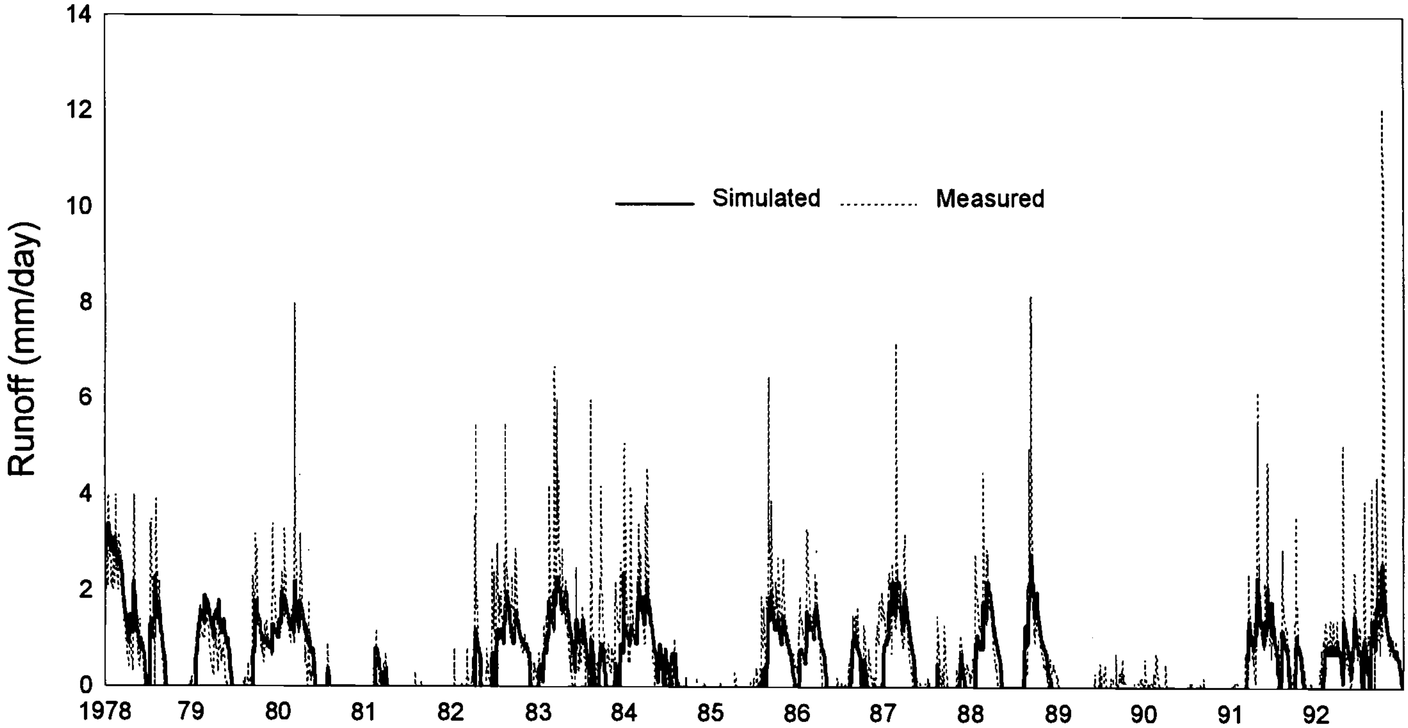

Figure 6. FLATWOODS Model Calibration (1978-1982) and Validation (1983-1992) Using 15 Years Runoff Data From the Bradford Forest Site.

which serve as the simulation units. The present model employs deterministic equations to calculate the water balances of each subsystem on a daily time step with readily available climatic data and measurable parameters. The FLATWOODS model has the capability to predict daily groundwater table levels, evapotranspiration, soil water storage in up to three layers, and total daily runoff from a watershed subject to various boundary conditions.

Model validation using both daily runoff and water table suggests the model can simulate the general hydrologic processes on flatwoods landscape with sufficient accuracy. The FLATWOODS forest hydrological simulation model provides an alternate tool to study the hydrology of pine flatwoods ecosystems. By using this model, impacts of different forest management scenarios such as various harvesting schemes may be evaluated. Also, this model can be used to simulate the dynamics of long-term wetland hydroperiod.

As any other existing watershed scale hydrological model, the predictability of the present model is heavily dependent on field testing with measured data. Empirical equations that simulate surface runoff in the model may be further validated with new research data. Predictions of spatial features are also needed to compare with measured data. Computer simulation models cannot replace the field experimentation, but they are a complementary means to achieve the same goals. Field investigations are essential for model improvements. With the help of GIS, model parameterization and interpretation of model outputs become easier tasks for distributed model such as FLATWOODS (Maidment, 1993; Sun *et al.*, 1998).

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