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MODELING THE HYDROLOGIC IMPACTS OF FOREST HARVESTING ON FLORIDA FLATWOODS[1]

Ge Sun, Hans Riekerk, and Nicholas B. Comerford[2]

ABSTRACT: The great temporal and spatial variability of pine flatwoods hydrology suggests traditional short-term field methods may not be effective in evaluating the hydrologic effects of forest management. The FLATWOODS model was developed, calibrated and validated specifically for the cypress wetland-pine upland landscape. The model was applied to two typical flatwoods sites in north central Florida. Three harvesting treatments (Wetland Harvesting, Wetland + Upland Harvesting, and Control) under three typical climatic conditions (dry, wet, and normal precipitation years) were simulated to study the potential first-year effects of common forest harvesting activities on flatwoods. Long-term (15 years) simulation was conducted to evaluate the hydrologic impacts at different stages of stand rotation. This simulation study concludes that forest harvesting has substantial effects on hydrology during dry periods and clear cutting of both wetlands and uplands has greater influence on the water regimes than partial harvesting. Compared to hilly regions, forest harvesting in the Florida coastal plains has less impact on water yield.
(KEY TERMS: forest hydrology; Florida; hydrologic impacts; pine flatwoods; modeling; wetlands.)

INTRODUCTION

Environmental concerns about forest management practices in coastal areas include effects on water quality, wetland hydrologic functions, resultant influences on wildlife habitat, and long-term cumulative impacts on soil productivity (Riekerk *et al.*, 1989). Although the effects of forest management on upland watershed hydrology are well studied (Bosch and Hewlett, 1982; Swank and Crossley, 1988), little information is available for the lowland 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 process (Lovejoy *et al.*, 1997). Compared to experimental methods, a simulation model may provide following advantages: (1) extrapolate/export research results to unguaged areas; (2) explore the details of hydrologic processes within a watershed; (3) predict potential impacts of various management scenarios; and (4) is an effective tool for data synthesis. However, most of the available hydrologic models developed for hilly regions are not applicable to Florida's coastal conditions (Heatwole *et al.*, 1987; Capece, 1994; Sun, 1995). Moreover, models developed for agricultural watersheds in lowlands often need significant modification before they can be applied to forests (Thomas, 1989; McCarthy *et al.*, 1992).

The Florida flatwoods landscape is a mosaic of cypress wetlands and forest uplands; therefore, the hydrology of flatwoods is inherently complex (Figure 1). Main features are: (1) the slight spatial changes in topographic elevation causing substantial 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 further complicates the interactions between surface water and ground water. We developed a new distributed forest hydrologic model, FLATWOODS, and validated it with field data (Sun *et al.*, 1996; Sun *et al.*, 1998). This model was used to study the hydrologic processes of wetland/upland systems and provided

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[2]Respectively, Research Associate, North Carolina State University/USDA Forest Service, 1509 Varsity Dr., Raleigh, North Carolina 27606; Associate Professor (retired), School of Forest Resources and Conservation, University of Florida, Gainesville, Florida 32611; and Professor, Department of Soil and Water Science, 2169 McCarty Hall, University of Florida, Gainesville, Florida 32611 (E-Mail/Sun: gesun@unity.ncsu.edu).

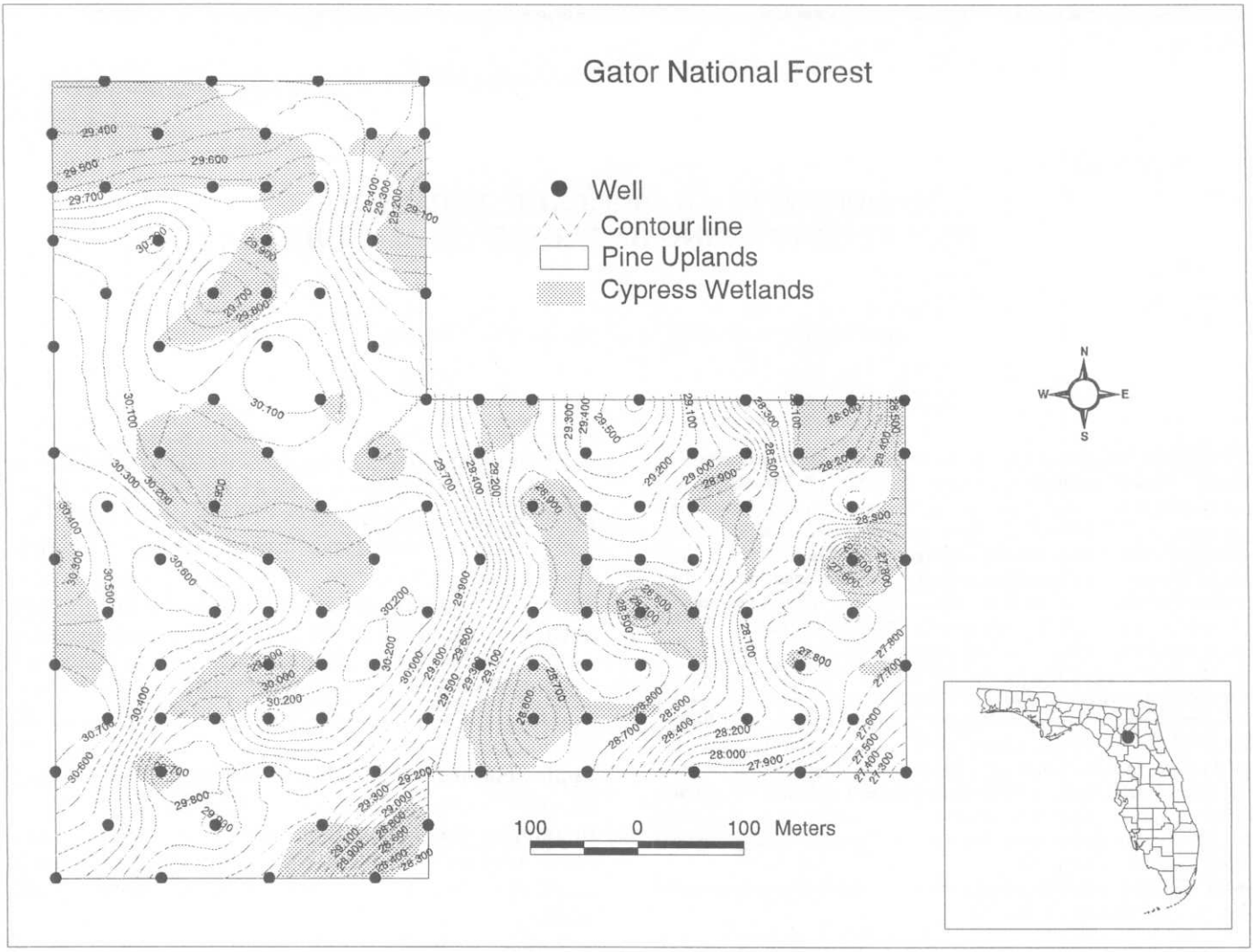


Figure 1. One Research Site on a Typical Pine Flatwoods Landscape Showing the Spatial Relations of Wetlands and Uplands.

a tool to evaluate the hydrologic impact of forest harvesting specifically for this landscape. This paper presents 13 hypothetical model simulation scenarios and discusses the implications of the results for forest management.

MODEL DESCRIPTION

FLATWOODS Model Structure

The FLATWOODS model uses a distributed approach to simulate water movement in a heterogeneous watershed. The model imposes a grid over the entire wetland-upland system to divide the landscape into different rectangular cells (Figure 2). The physical properties of each cell are assumed to be nonuniform both laterally and vertically. Each cell becomes a modeling unit that holds different mathematical equations describing the hydrological cycle within each element (Figure 3). Integration of the hydrological components of all the cells gives the hydrologic behaviors of the entire watershed.

Hydrologic Components

The FLATWOODS 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 (Figure 2). The model simulates the hydrologic processes on a daily time step. The core of the model is the

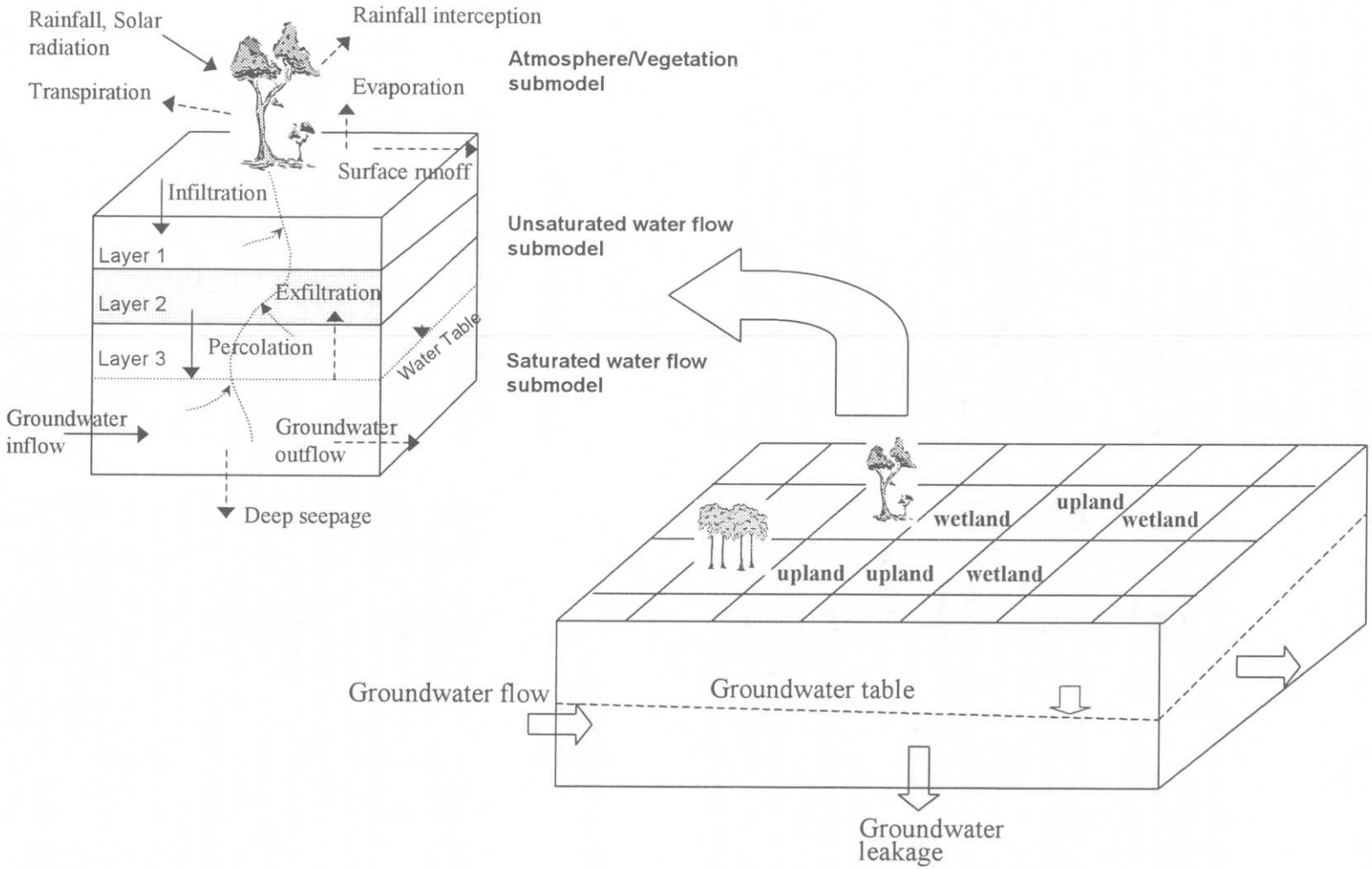


Figure 2. The FLATWOODS Model Showing the Grid System and Modeling Units of Pine Uplands and Cypress Wetlands.

ground water flow submodel that links various hydrologic processes in both lateral and vertical directions. Mathematical formulation may be found in Sun *et al.* (1998) and Sun (1995).

Model Input and Output

Like any other distributed models, FLATWOODS requires more input parameters than lumped models. Major inputs required include: (1) climatic data (daily, rainfall, average air temperature), (2) soil parameters (soil moisture release curves, specific yield, soil depth etc.); (3) vegetation parameters (Leaf Area Index dynamics for each dominant species, canopy interception parameters, and root density distributions); and (4) watershed characteristics (surface elevation, parameters for surface water flow models). Initial and boundary conditions (e.g., ground water table depth and soil moisture) are also required.

The FLATWOODS model has the capability to simulate daily dynamics of the ground water tables, evapotranspiration, and soil moisture content for each grid cell. Therefore, it can be used to predict the temporal and spatial distribution of ground water under various forest management scenarios. Daily runoff at the watershed outlet is another important model output.

MODEL APPLICATIONS

Research Sites

Two research sites, Gator National Forest (GNF) (Figure 1) and Bradford Forest (Figure 3) in north-central Florida, were selected for model application to evaluate the potential hydrologic impact of common forest harvesting practices. Both sites are on typical pine flatwoods of the lower coastal plain geographic region. The GNF site has been monitored since 1992 to study the hydrologic interactions between cypress wetlands, slash pine uplands, and hydrologic influences of forest regeneration (Crownover *et al.*, 1995; Sun *et al.*, 1995a, 1995b). Extensive ground water table, evapotranspiration and runoff data for pre-treatment and post-treatment periods have been accumulated for FLATWOODS model development and validation (Sun *et al.*, 1996, 1998). The forest watershed hydrology study at the Bradford Forest site was the most complete in the southern coastal plain regions of the United States. Long-term (15-year) precipitation and runoff data from this site have been used in testing the FLATWOODS model.

Model Application Schemes

Clear cutting is the most common method for pine stand regeneration in Florida. Traditionally, cypress trees are left uncut due to their low timber values. However, recent demands on cypress uses and recognition of wetland values have imposed great pressure on this marginal land (Brandt and Ewel, 1989). Alteration of wetland hydrology due to tree removal has been regarded as the main cause of wetland ecosystem degradation. Forest ecosystems are dynamic, and hydrologic responses change as the biomass accumulates under different climatic regimes. Harvesting impacts on wetland hydrology are expected to be most significant in the first year after disturbance and to diminish in subsequent years (Wang, 1996). However, long-term field experiments are rare and few studies have documented this change pattern. Field studies suggest that the hydrology of flatwoods varies dramatically from year to year (Riekerk, 1989; Sun *et al.*, 1995a, 1995b).

Three forest harvesting methods and three climatic conditions were included in the simulation design to compare the first year impacts of forest management (Table 1). Long term responses of flatwoods hydrology to clear cutting were simulated using the Bradford Forest data.

RESULTS AND DISCUSSION

Gator National Forest Site – First-Year Responses

Normal Year. The year of 1986 had a typical rainfall pattern for Alachua County, Florida, showing high rainfall in the winter and summer but a drought period in the spring and the late fall (Figure 4a). The simulation results demonstrated that the ground water tables had a significant rise for all three treatments during the summer and fall months. Clear cutting both cypress ponds and pine uplands resulted in the most pronounced effects on ground water tables as well as runoff. Harvesting pine uplands only (Treatment 2) caused a maximum water table increase of 51.7 cm in June, but no significant increase of runoff for most of the time in 1986. The higher increase in water levels and runoff caused by Treatment 1 compared to Treatment 2 suggested that flatwoods hydrology was more sensitive to wetlands disturbance than uplands in this landscape. Harvesting of the wetlands may have increased the extent of saturated depression areas and thus caused more runoff than harvesting uplands only. The uplands had less water storage capacity, but under normal weather

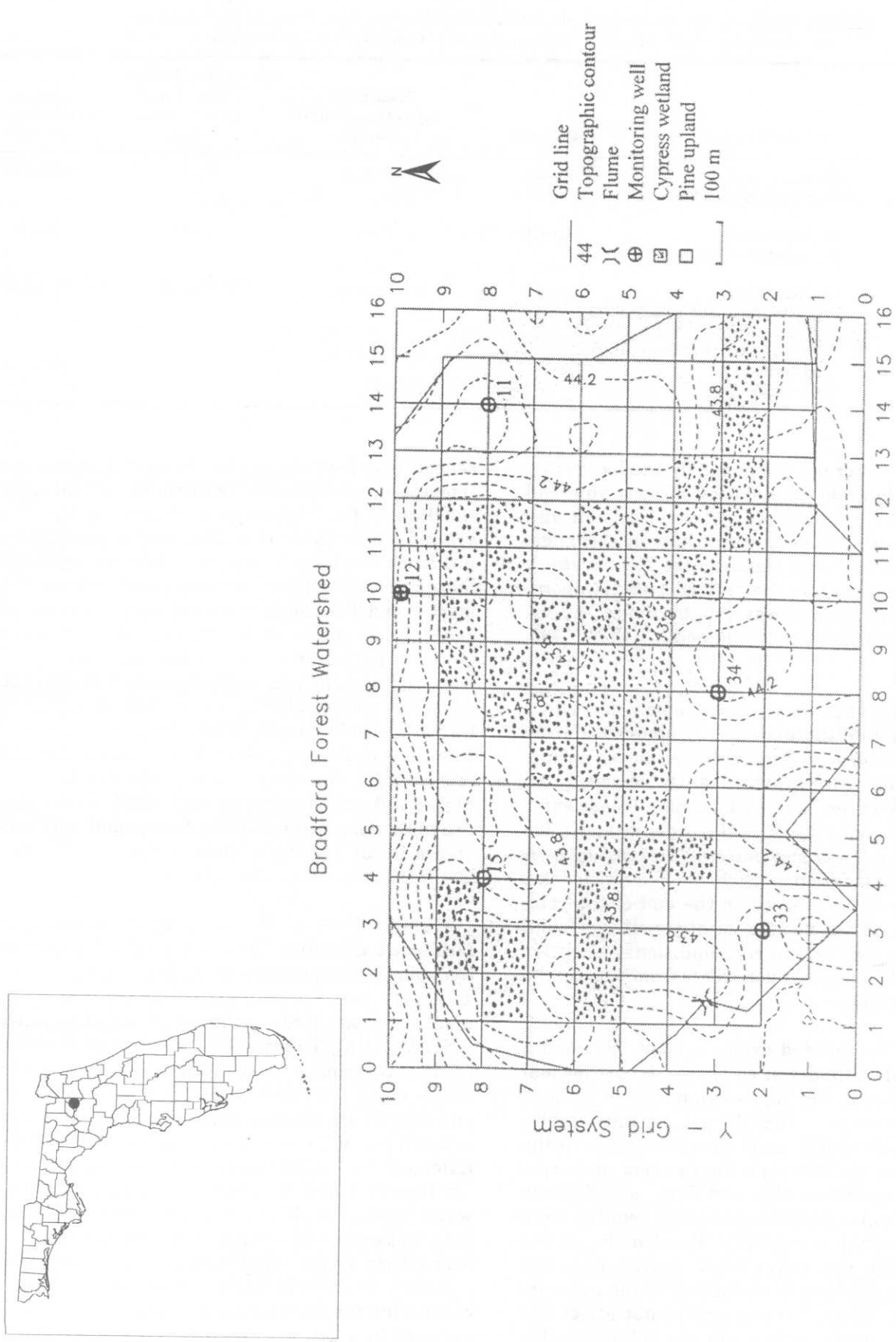


Figure 4. Control Watershed at the Bradford Forest Research Site in North Florida.

TABLE 1. Simulation Schemes to Study the Potential First-Year and Long-Term Harvesting Effects on Pine Flatwoods Hydrology at the Gator National Forest and Bradford Forest Sites.

Site	Climatic Condition	Control	Harvesting Methods		
			Treatment 1 (cypress wetlands only)	Treatment 2 (pine uplands only)	Treatment 3 (wetlands and uplands)
Gator National Forest	Normal Year (1986) Precipitation = 1329 mm	Case 1	Case 2	Case 3	Case 4
	Dry Year (1977) Precipitation = 839 mm	Case 5	Case 6	Case 7	Case 8
	Wet Year (1964) Precipitation = 1995 mm	Case 9	Case 10	Case 11	Case 12
Bradford Forest Watershed	Long Term (1978-1992)				Case 13

conditions this factor did not dominate the harvesting effects on the hydrology. Removal of both pine and cypress forests reduced plant transpiration and canopy interception substantially, but, in exchange, soil evaporation increased significantly. The net result was less water loss from the treated land. Evaporation from the sandy soils was usually limited as the water table was below the 35-cm depth (Hillel, 1980; Phillips, 1987).

Dry Year. The year 1977 was extremely dry with a 493-mm rainfall deficit that mostly occurred during the first half of the year (Figure 4b). As in the normal year, water tables were significantly raised by all treatments. However, Treatment 1 and Treatment 2 showed very similar effects on the groundwater table rise and the runoff increase patterns. Harvesting both wetlands and uplands increased runoff tremendously from the early spring season to the end of the year, but during this period no significant runoff was found from the other two treatment conditions. Negative values of runoff suggested net inflow from outside the system boundaries.

Wet Year. The selected extremely wet 1964 had a surplus rainfall of 666-mm compared to the normal year of 1986. Due to the higher rainfall input in April and thus more water stored, the ground water tables did not decline so rapidly as in the normal year or the dry year (Figure 4c). Although the wet year also experienced a dry period in May and June, significantly more rainfall input in the subsequent months from July to September eventually flooded the entire watershed, with the water table approaching the ground surface (29.43 m in elevation). In the extremely wet season, forest harvesting did not affect the hydrology as significantly as in the relatively dry season (April-June). As in the previous two cases, removal of vegetation in both wetlands and uplands resulted in the highest perturbation of runoff and ground water table rise. The model predicted less influence from the two partial harvesting methods than clear cutting both wetlands and uplands. Treatment 1 and Treatment 2 showed no significant difference in their effects on ground water table and runoff. Under high water table conditions, the water loss from the system was dependent on available solar energy or potential evapotranspiration rather than transpiration by plants. When the ground water table was close to the ground surface or above the surface (e.g., ponds), the water table responded less due to higher soil porosity and specific yield. Rapid surface runoff or near-surface subsurface runoff was considered a factor causing a lower increase in the ground water table by storms during the wet seasons.

Comparison of Harvesting Methods Under Different Climatic Conditions. Simulated annual hydrologic components have been summarized in Table 2 to show the different effects of the three treatment methods under various climatic conditions. ANOVA using Tukey's Test (SAS, 1985) was performed to group the treatment methods by their effects on the variables of runoff, ground water table, and evapotranspiration using the simulation results of the three different years. In general, no significant difference ($\alpha = 0.001$) was found between the Control, Treatment 1 and Treatment 2 groups in affecting water table, runoff and ET. However, clear cutting both wetlands and uplands however showed significant effects on the runoff and ground water tables ($\alpha = 0.001$). Examining Table 2 in detail, one may conclude that the harvesting effects become more pronounced in a dry year than in a wet year. During a

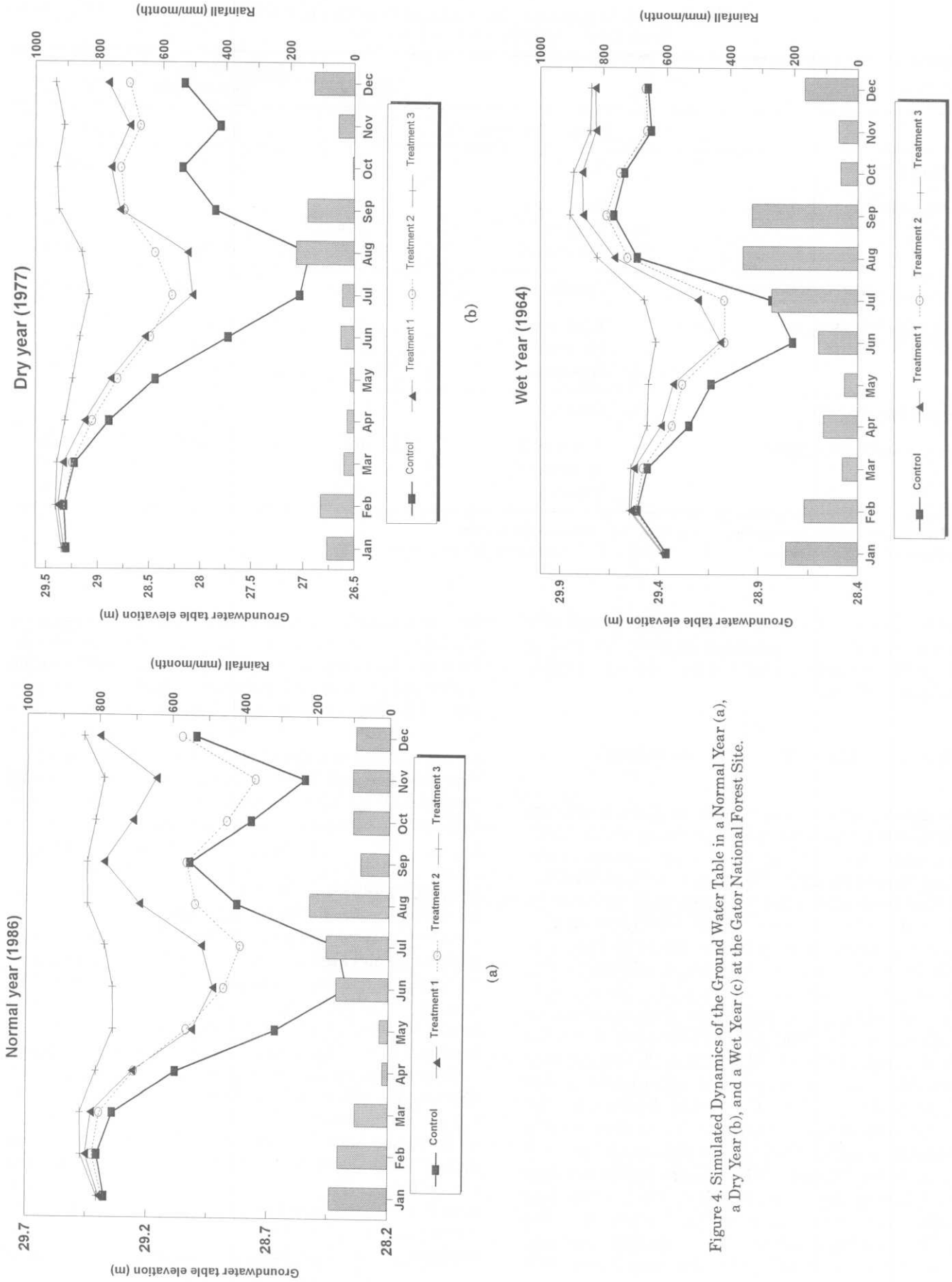


Figure 4. Simulated Dynamics of the Ground Water Table in a Normal Year (a), a Dry Year (b), and a Wet Year (c) at the Gator National Forest Site.

TABLE 2. Simulated Hydrologic Effects of Forest Harvesting Under Three Climatic Conditions in Pine Flatwoods.

		Climatic Conditions		
		Dry Year	Normal Year	Wet Year
	Precipitation (mm)	836	1329	1955
Runoff (mm)	Control	39	76	158
Runoff Increase*	Treatment 1	0.18	0.42	0.11
	Treatment 2	0.56	0.11	0.09
	Treatment 3	2.15	0.93	0.25
Average Ground Water Table Elevation (m)	Control	28.337	28.899	29.322
Ground Water Table Rise (cm)	Treatment 1	60	34.3	18.7
	Treatment 2	57.4	17.5	8.2
	Treatment 3	107	51.5	27.4
Evapotranspiration (mm)	Control	769	1037	1202
Evapotranspiration Reduction**	Treatment 1	0.1	0.11	0.09
	Treatment 2	0.05	0	0.05
	Treatment 3	0.24	0.19	0.08

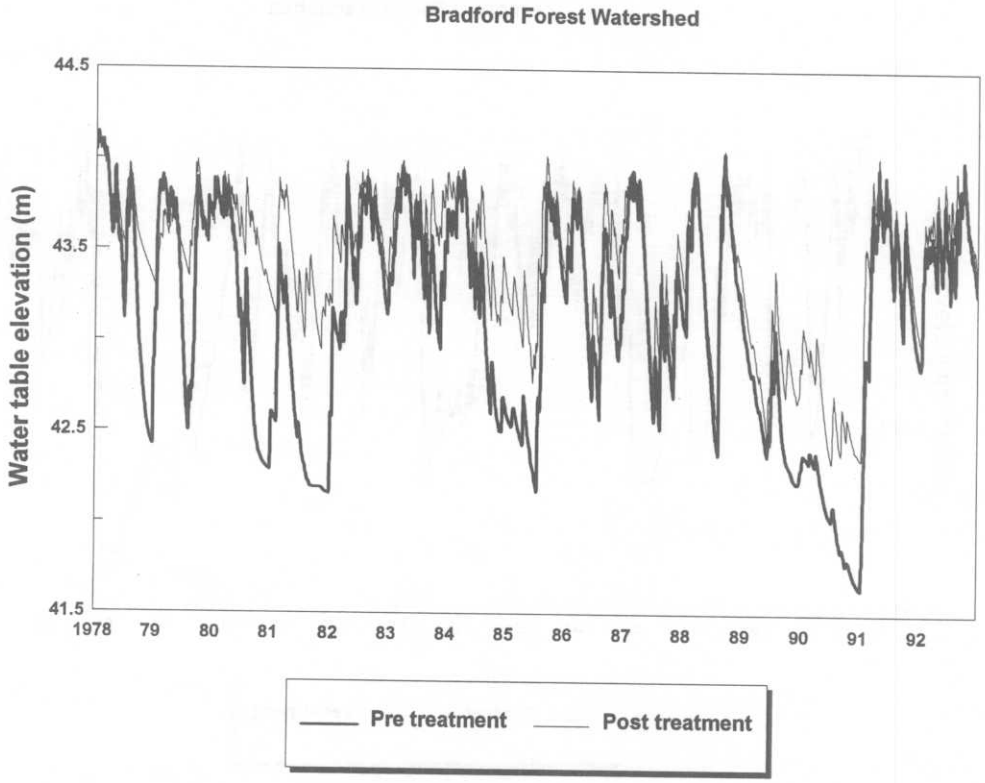
*Runoff increase = (runoff by treatment – runoff by control)/runoff by control.
**Evapotranspiration (ET) reduction = (ET by control – ET by treatment)/ET by control.

dry year, Treatment 1 and Treatment 2 apparently also caused substantial hydrologic impacts, increasing runoff by 18-56 percent and the ground water table level by about 60 cm.

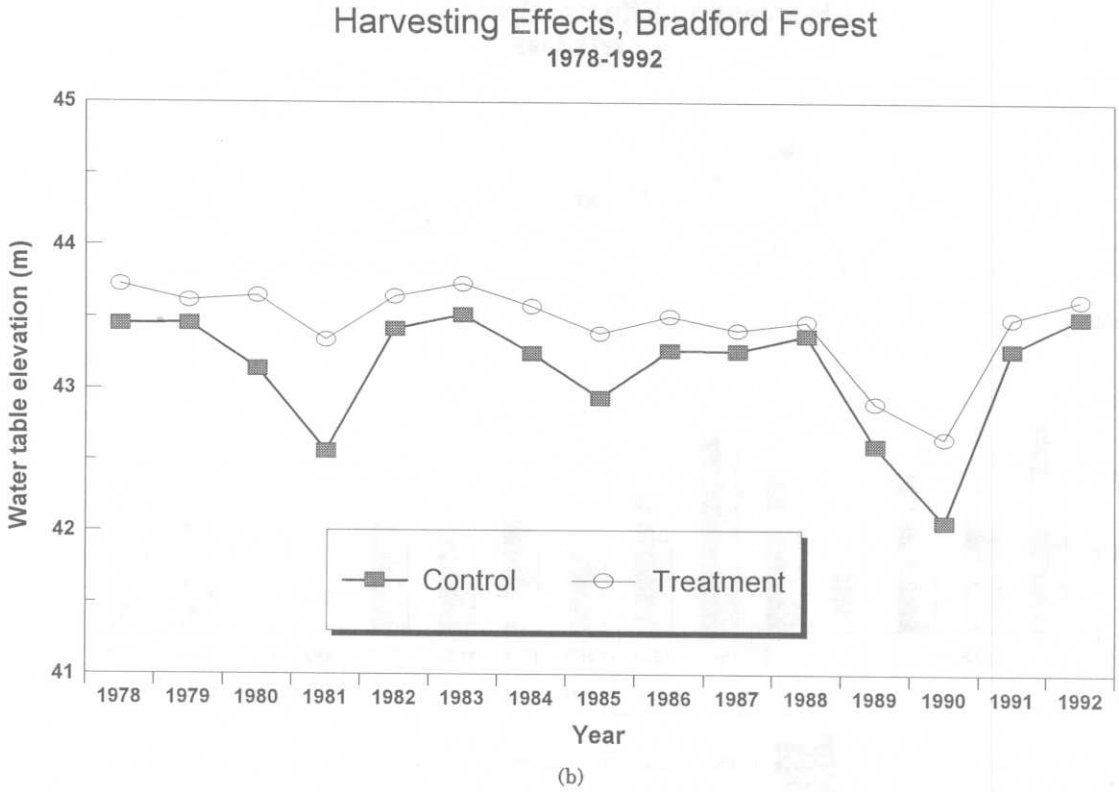
Bradford Forest Watershed – Long-Term Study

This simulation was designed to show the long-term hydrologic response following forest stand development after clear cutting the mature forests at the Bradford Forest in 1978. Because the FLATWOODS model had been calibrated and validated using measured data under forested conditions (Sun *et al.*, 1998), it was advantageous to use the same data sets of 1978-1992 to study the hydrologic effects due to harvesting. The leaf area index (LAI), as the only biomass accumulation indicator, was assumed to reach 60 percent and 100 percent of the maximum for a mature stand at the age of five and 15, respectively. Simulated ground water table elevations under untreated and treated conditions are depicted in Figure 5. These two graphs show that forest clear cutting significantly raised ground water table levels by 20-80 cm on an annual average. The most drastic increase occurred during dry years in 1981, 1984, 1989, and 1990 when the ground water tables were down in the deepest soil layers, which had lower specific yield and porosity. Measured runoff under the control condition (no harvesting), simulated runoff under the treatment condition (assuming the harvest was completed by January 1, 1978), and simulated evapotranspiration under the control and treatment conditions are presented in Figure 6. Runoff substantially increased during the first six years 1978-1984 by an average of 200 mm after the treatment was imposed in 1978. The dry year of 1981 showed a maximum runoff increase of 12 times during the 15-year simulation. However, because there was little runoff, the harvesting activities would have little impact downstream. Unlike the dry year of 1981, the two continuous dry years of 1989 and 1990 had no significant runoff increase due to the increased transpiration by recovered vegetation. The ground water tables in 1989 and 1990 were elevated substantially but not high enough to cause the runoff to increase. The significant reduction of evapotranspiration loss of 100-300 mm after the forest removal apparently contributed to the increasing in runoff and ground water table elevation.

A comprehensive survey of effects of vegetation changes on water yield and evapotranspiration for 94 catchment experiments around the world was reported by Bosch and Hewlett (1982). They concluded that reductions in pine forest cover increased water yield about 40 mm per 10 percent reduction in cover. They also found that water yield changes after clear cutting were positively related to the precipitation of the treatment year. The increase of water yield after clear

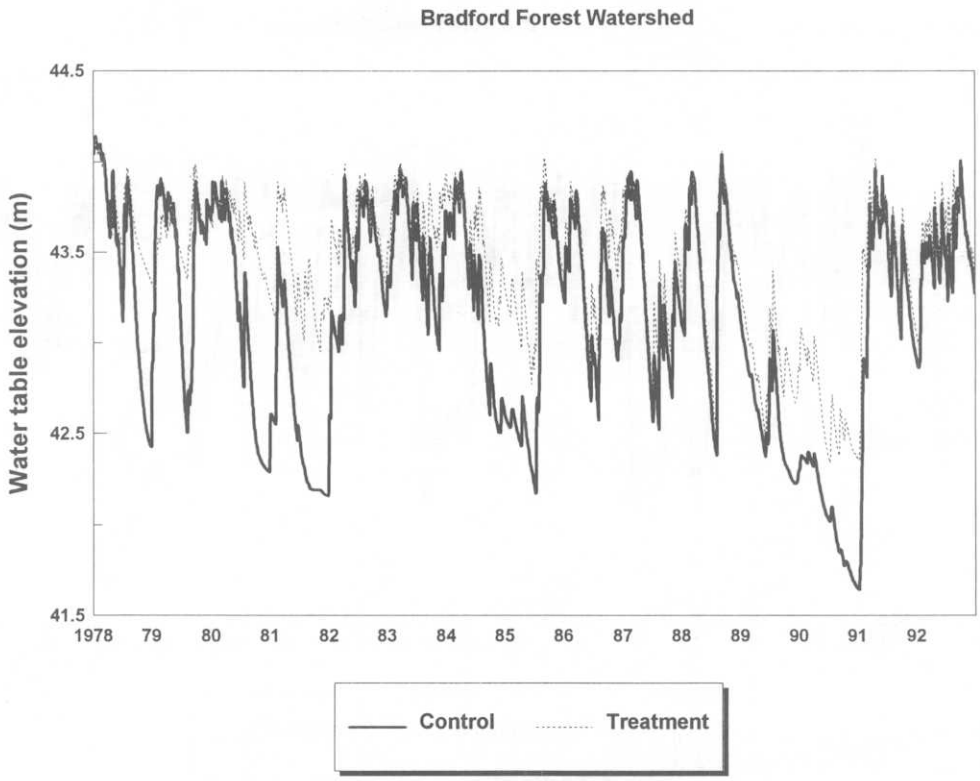


(a)



(b)

Figure 5. Simulated Long-Term Effects of Clear Cutting on Daily Ground Water Table Dynamics (a) and Annual Average (b) During a 15-Year Stand Rotation. The treatment is assumed to be completed on January 1, 1978.



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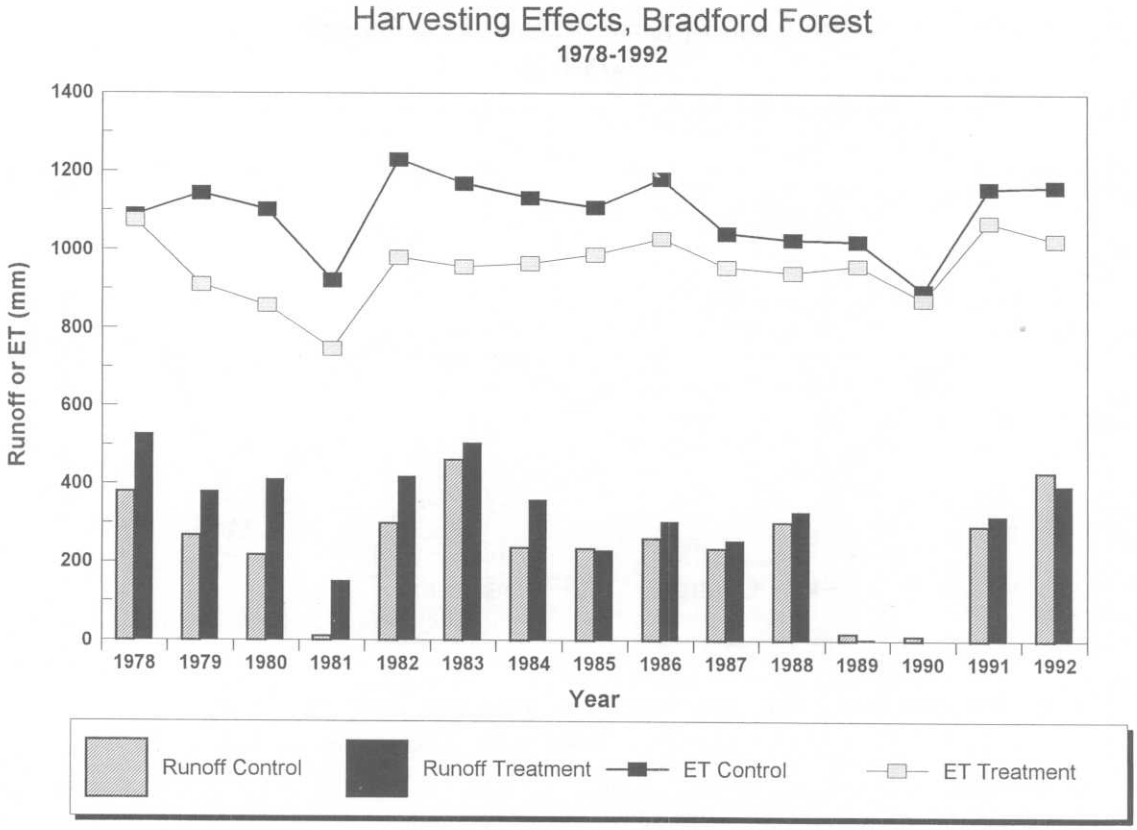

(b)

Figure 6. Simulated Long-Term Effects of Clear Cutting on Daily Runoff (a) and Annual Average Runoff and Evapotranspiration (b) During a 15-Year Stand Rotation. The treatment is assumed to be completed on January 1, 1978.

cutting varied from 100 mm to 600 mm in the zone with annual precipitation of 1200 - 1400 mm, which is the approximate amount of rainfall for this study. Based on our simulation study, it appears that clear cutting of pine forests on flatwoods causes an increase of runoff in the low range compared to that in other regions. However, due to the flat topography of pine flatwoods ecosystems, the changes in water storage and ground water table are expected to be more pronounced than those of other systems.

Riekerk (1989) studied the hydrologic influences of two silvicultural practices (high site disturbance and low site disturbance) by a paired watershed experimental method (regression method) at the Bradford Forest. It was found that the increase of runoff from the high-disturbance watershed dropped from 150 percent in the first year to 60 percent of predicted in the sixth year of post treatment, implying the hydrology of this watershed would return to pre-harvesting conditions in the eleventh year. However, the water table returned to normal about eight years after treatment. This simulation study corroborated these conclusions, showing the strength and promise of the FLATWOODS model for forest water management.

CONCLUSIONS

This study suggests that pine flatwoods are storage based hydrologic systems where the ground water table dictates the surface runoff. The shallow ground water levels are controlled by both the precipitation input and the evapotranspiration output. Clear cut harvesting reduced total water loss by evapotranspiration, therefore significantly elevating ground water tables and runoff from pine flatwoods during dry periods. Partial harvesting has less potential influence on watershed hydrology than the clear cut method. Runoff increases become insignificant around the tenth year after forest regeneration while the ground water table effects are somewhat prolonged. Forest management practices and associated harvesting disturbances have many impacts, such as forest vegetation composition, soil physical properties, and even drainage patterns. Mathematical models must consider all these factors to be useful for practical applications by land managers.

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