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GROUND-WATER-TABLE RISE AFTER FOREST HARVESTING ON CYPRESS-PINE FLATWOODS IN FLORIDA

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Abstract: Forest removal represents one of the large-scale ecosystem disturbances that concern water quality degradation, species composition change, and wildlife habitat alteration along the Florida coast. We conducted a five-year study with the objective to address effects of two forest management scenarios on the water regimes of cypress-pine flatwoods ecosystems in the lower coastal plain. Three experimental blocks (16–21 ha) were used in this study, with one representing control (C), one wetlands-harvest-only (W), and one wetlands + uplands harvest (ALL). Within the center of each block, a representative cypress wetland and its surrounding pine upland were extensively instrumented to quantify the changes of each hydrologic variable induced by tree removal. Water levels in cypress wetlands in both treatment areas were significantly elevated about 32–41 cm on average, and outflow doubled in the five-month dry period immediately following the tree harvesting. The ground-water table in the upland was also raised by about 29 cm on average due to ALL, but it was not affected significantly during the entire post-treatment period by W. During wet periods, the treatment effects for both wetlands and uplands were not significant. Causes for spatial and temporal variability of hydrologic responses to forest harvesting are speculated to be 1) total evapotranspiration does not change significantly in flatwoods after tree removal during wet seasons; 2) specific yield of the flatwoods soils is variable in time and space; and 3) lateral water movement from uplands to wetlands. From this study, we conclude that harvesting both uplands and wetlands causes greater response than harvesting wetlands only. The impacts lasted for more than two years but were most pronounced only in the dry periods. Temporal and spatial variations of each hydrologic component should be considered in evaluating the hydrologic impact of forest management on the flatwoods landscape.

Key Words: forest hydrology, harvesting, ground-water table, pine flatwoods, wetlands

INTRODUCTION

Although waters drained from forested watersheds are of higher quality than those draining agricultural and urban areas (Binkley and Brown 1993), there are increasing concerns about the ecological consequences (e.g., impacts on hydrology, productivity, biodiversity) of forestry activities on intensively managed plantations (Shepard et al. 1993). A world-wide review on this issue suggested that forest removal increases total stream runoff due to reduced evapotranspiration (Bosch and Hewlett 1982). However, most of this information was drawn from upland watershed studies, and few data are available about the forest hydrology in the lowlands and wetlands of the coastal regions (Riekerk 1989). It is not clear how management of forested wetlands will affect on-site wetland water regimes and downstream hydrology. Due to flat topography, hydrology in the coastal regions of the southeastern U.S. is usually characterized by low peak flow rate with long duration, and precipitation and evapotranspiration are the major input and output in the water balance, respectively (Capece et al. 1987, Sun et al. 1995, Amatya et al. 1997). Forested watersheds are storage-based hydrologic systems where surface runoff occurs mainly when the soil profile is saturated and the ground-water table reaches the land surface. This phenomenon is most pronounced in the coastal plain, where the landscape is extremely flat and the surficial aquifer is close to the land surface. Since water table determines water status in both the saturated and unsaturated soil zones, it controls lowlands hydrology by dictating the timing and amount of runoff. Therefore, it is the most important variable in evaluating hydrologic impacts of forest management. Hydroperiod or water level in wetlands is the most important determinant of wetlands ecosystem structure and function (Entry et al. 1995). However, hydrology has been identified as the least studied area in wetlands science (Mitch and Gosselink 1986).

Pine flatwoods in the southeastern U.S. are important for timber production, wildlife habitat, groundwater recharge, and many other uses, since they consist of both cypress wetlands and pine upland ecosystems (Brandt and Ewel 1989). Most pine plantations have been intensively managed on a rotation of approximately twenty years. Clear-cutting followed by planting of seedlings is the most common regeneration method for this forest type. One 20-year study at the Bradford Forest in north-central Florida showed that the water table rose significantly during harvest, and treatment effect was greatest when the water tables were low (Riekerk 1989). This effect began to diminish by the tenth year after treatment. This observation corroborated a computer simulation with a distributed forest hydrologic model (Sun et al. 1998). Clear-cutting of birch and pine stands with 100 m^3/ha timber removal on drained peatlands in Finland caused a 40-cm increase in water table (Heikuranen 1967). Tree removal from fine-grained mineral soil wetlands caused an increase in water table and water yield (Trousdell and Hoover 1955). In contrast, Verry (1997) suggests that cutting trees may not necessarily raise water table and significantly increase streamflow volume since evapotranspration is near potential in all cases. One study on ecological responses of oligotrophic floodplain forest to harvest in southern Alabama resulted in the unexpected finding that water tables were statistically significantly lowered by clear-cutting (Lockaby et al. 1994). Dube et al. (1995) observed both water-table increases and decreases on clear-cut forested wetlands of fens where the magnitude of forest management impact varied in time and space.

In response to the uncertainty of impacts of management practices on forested wetlands, a series of multi-disciplinary research programs was initiated, covering different wetlands types in 10 states of the U.S. (Shepard et al. 1993). Early reports were summarized by Lockaby et al. (1997). The present five-year study is part of this effort, with the objective to document and eventually model the hydrologic effects of different forest harvesting strategies on a Florida flatwoods landscape (Cownover et al. 1995, Sun 1995).

METHODS

The study site is located 15 km northeast of Gainesville, Alachua County in north central Florida, USA (Figure 1). Plio-Pleistocene terrace deposits and the Hawthorne Formation dominate the geology. Slopes ranged from 0 to 1.6%. Impermeable blue-green clays (> 4 m thick) below the top organic and sandy soil layers (2–3 m thick) separate the shallow ground water from the underlying artesian secondary aquifer consisting of various materials. Approximately 35% of the 42-ha research site was in cypress swamps, with wetland sizes ranging from a few square meters to more than 5 ha, while the remaining upland areas were in mature slash pine (*Pinus elliottii* Engelm.) plantations. The average annual temperature was 21°C, with a mean monthly low of 14°C in January and high of 27°C in July. Average annual rainfall was about 1330 mm, with dry periods during the spring and the fall. Monthly rainfall patterns over the experimental years were somewhat drier in the summer but wetter in the fall (October) than a 15-year long-term average (Table 1). The 29-year-old upland plantations were fifth-row thinned in 1986 to a stem density of 500 stems/ha. Pond cypress (*Taxodium ascendens* Brongn.) dominated wetlands, along with slash pine and swamp tupelo *(Nyssa sylvatica var. biflora* Sarg.). The dominant canopy tree in uplands was slash pine, with an understory of saw palmetto (*Serenoa repens* Small) and gallberry (*Ilex glabra* Gray) shrubs. A 50 × 50 meter grid system was overlaid on the entire 42-ha experimental area, and each grid point was marked and labeled with a steel post and related to a reference coordinate (0, 0) set by an arbitrary elevation of 30.480 m above mean sea level (Crownover et al. 1995). The actual topographic elevation of the study site was about 47 m above mean sea level.

Three blocks, NW block, SW block, and SE block, were used for two-level treatment experiments representing clear-cutting wetlands only (W), Control (C), and clear-cutting both wetlands and uplands (ALL), respectively (Figures 1 and 2). For the NW block, cypress wetlands were harvested, with pine uplands untouched, but for the SE block, both wetlands and uplands were harvested. Within each block, a representative cypress wetland-upland system was selected and instrumented extensively to quantify each hydrologic component (Figure 2). The water table levels in cypress wetlands and pine uplands were recorded on weekly charts on Stevens F type recorders installed in

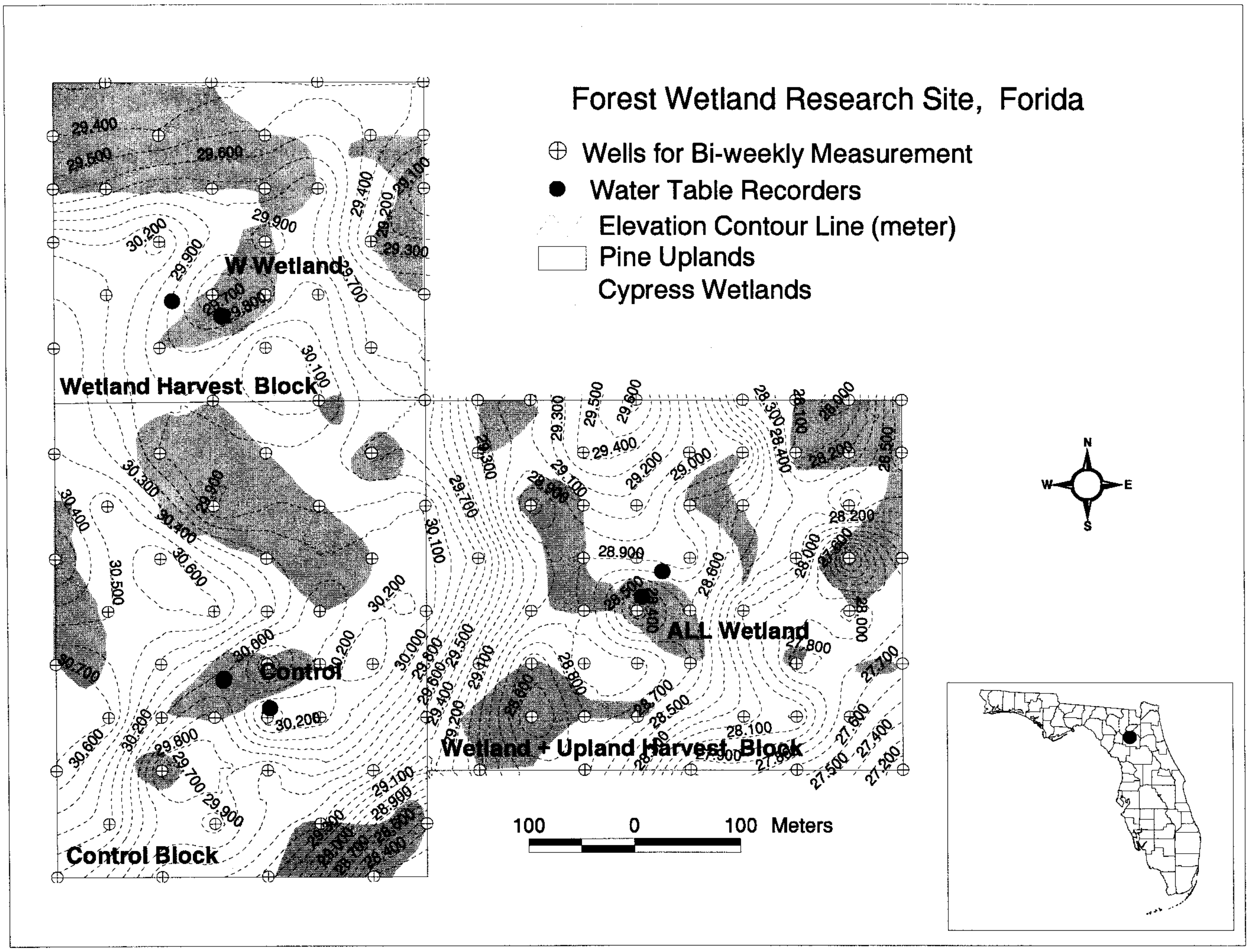

Figure 1. Experiment design and instrumentation at the wetland research site.

the center of wetlands and in the uplands 50 m from wetland margins. Surface runoff into or out of each wetland was monitored by V-shaped recording flumes adjoining sheet metal boundary wings to concentrate flow pathways (Figure 2). Spatial water flow was calculated by Darcy's method with data from 12 to 21 shallow wells radiating from the wetlands to the surrounding uplands. Detailed experimental design, pretreatment data analysis, and simulation may be found in Crownover et al. (1995) and Sun (1995). A water balance for the C wetland during the pretreatment period was reported in Sun et al. (1995).

Table 1. Seasonal distribution of precipitation (mm) at the research site.

	Season				
	Winter (Jan–Mar)	Spring (Apr–Jun	Summer (Jul–Sep)	Fall (Oct–Dec)	Annual Total
1992	341	473	466	273	1553
1993	342	224	223	315	1104
1994	327	290	407	283	1307
1995	202	378	421	214	1215
1996	347	240	420	283	1290
Long-term Average	273	344	506	262	1385

Baseline data for developing statistical relationships between C and W, and between C and ALL, were collected from January 1, 1992 to May 31, 1994. Harvesting operations on the two treatment blocks started on April 5 and finished by May 31, 1994. Post-treatment data in this paper covers the period from mid-May 1994 to December 1996. The differences between measured water-table levels for the treatments and those predicted by the regression models developed from pre-treatment data represent the effects of forest removal on hydrology.

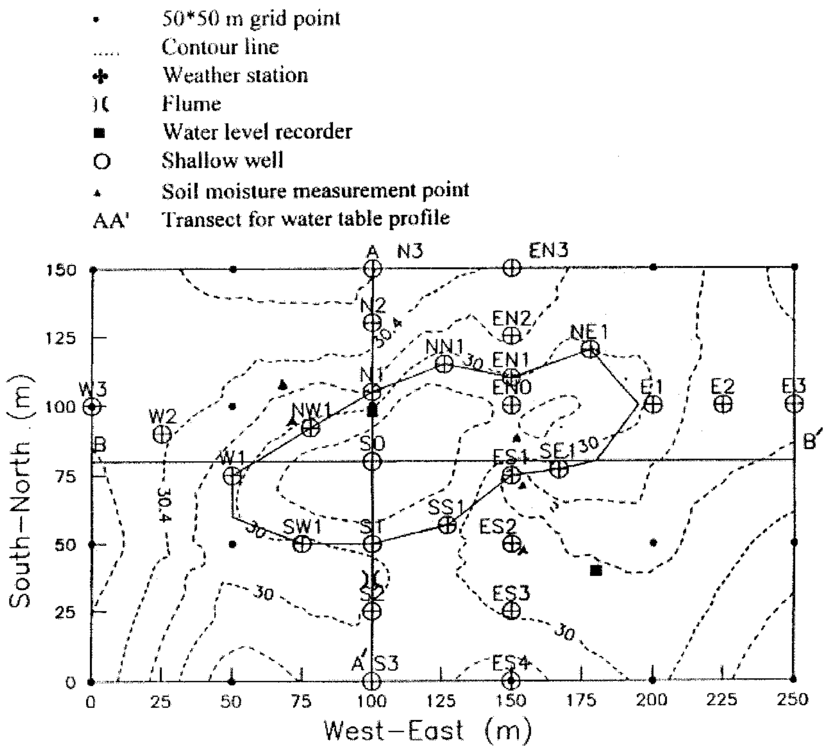

Figure 2. Instrumentation at the C wetland.

RESULTS

Seasonal and Spatial Water-Table Dynamics

During the pre-treatment period, the years 1992 and 1993 had distinct rainfall patterns (Table 1). As a result, the water table in 1992 showed a different pattern from that in 1993 for all the wetlands (Figure 3). Compared to a normal year, 1992 had a surplus annual rainfall of 168 mm, while 1993 had a deficit of 281 mm (Table 1). The water levels were above ground surface in over 10 months in 1992, compared to only 6 months in winter 1993 (November to April). Year 1993 was the driest during the 5-year experimental period. The wells in wetlands and uplands were dry during the summer months from May to September. The two years with distinct hydrologic regimes were useful for developing regression models for prediction purposes. The relationships between water-table elevations of the control wetland (C) and the W wetland or the ALL wetland were established by non-linear regression analysis using these two years' daily water-level data (Table 2). Similar regression models were also developed for other wells that were located throughout the two wetland-upland systems and were measured manually on a biweekly basis during 1993–1994. Only pairs (control vs. treatment) with correlation coefficient (R) values greater than 0.9 were selected for prediction during the post-treatment period. These well networks were used to detect any spatial differences between wetland and upland in response to forest harvesting.

Annual total rainfall in 1994 was close to average, but there was a dry spring, causing the water-table depth in the control C wetland to be more than 50 cm (Table 1). Although 1995 had low annual total rainfall, a significant portion of it was in the spring and summer, resulting in wet conditions. All the wetlands, including the control wetland (C), had surface water in 1995 (Figure 3). Similar to 1993, 1996 had low rainfall input in the winter and spring; therefore, the water table fell below the pond bottom (i.e., soil surface) in the Control wetland (C) and more than 120 cm below upland soil surface in those seasons (Figures 3 and 4).

One centimeter of rainfall or evapotranspiration may cause one centimeter of water-table rise or drop in ponded wetlands but may cause a 10-cm water-table change assuming a specific yield (i.e., drainable porosity) of 0.1 for upland soils. As a result, upland ground-water tables fluctuated more dramatically as compared to wetlands (Figures 3 and 4). The greater fluctuation of water table in uplands may also be caused by subsurface drainage immediately following storm events. During wet seasons when the ground-water tables were close to soil surfaces, water might move quickly from high elevation points to lower points or local depressions.

Two cross-sections of the water-table distributions in C wetland suggest that ground-water tables have a

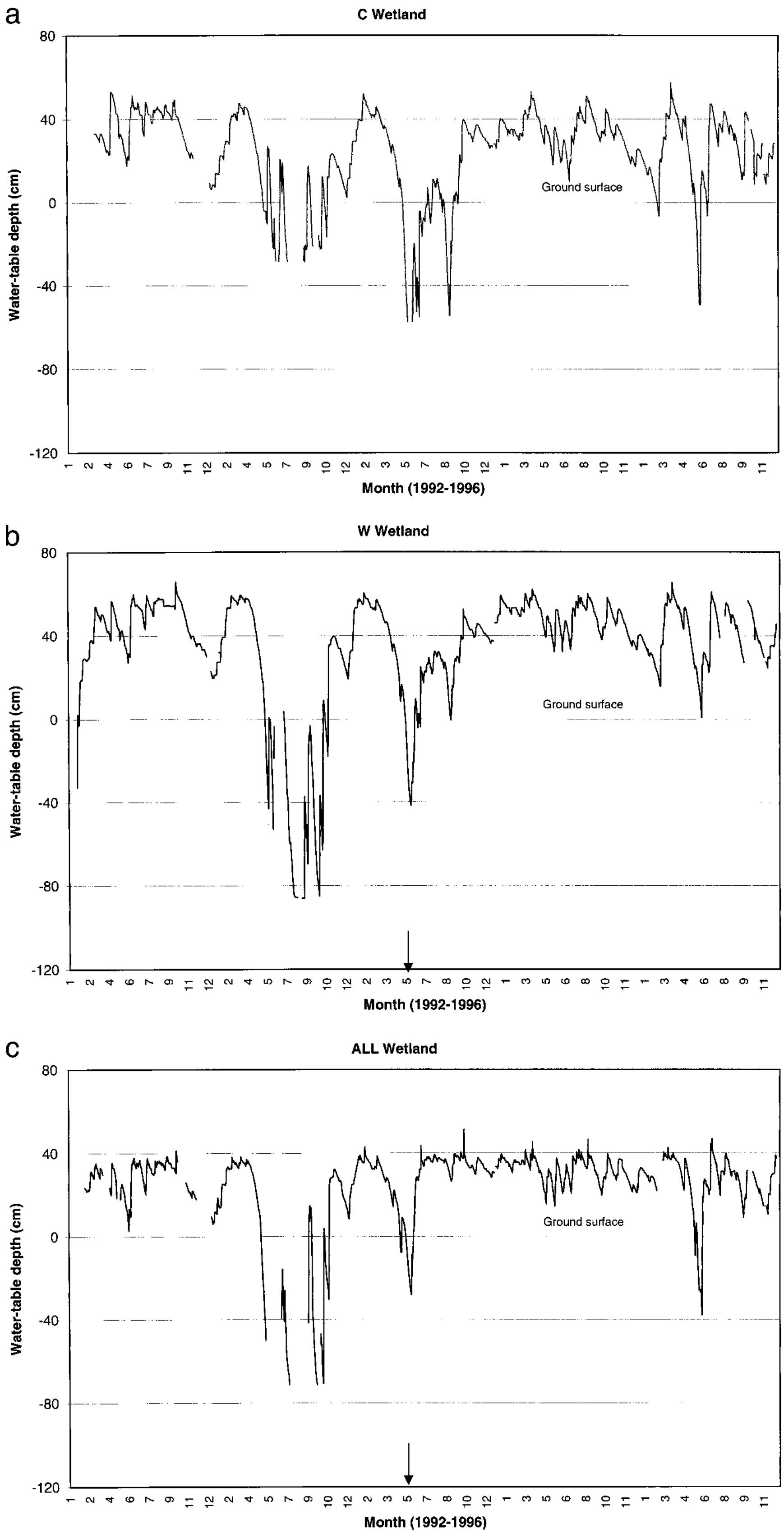

Figure 3. Daily water-level dynamics in three cypress wetlands during 1992–1996; the arrow indicates harvesting treatment completed.

Table 2. Water-level relationships between the control (C) and two treatment systems.

	Wetlands Models*	
C-W	$W_{wet} = -1.253 \times 10^3 + 84.763 \times C_{wet} - 1.400 \times C_{wet}^2$	$R^2 = 0.90$
C-ALL	$ALL_{wet} = -5.985 + 1.148 \times C_{wet}$	$R^2 = 0.75$
	Uplands Models	
C-W	$W_{up} = -5.073 + 0.583 \times C_{up}$	$R^2 = 0.82$
C-ALL	$ALL_{up} = -7.75 + 0.708 \times C_{up}$	$R^2 = 0.86$

* Variables in this table have units in meter; C_{wet}, W_{wet}, and ALL_{wet} are water-table elevations for the C, W, ALL wetlands; C_{up}, W_{up}, and ALL_{up} are water-table elevations for the C, W, ALL uplands.

rather complex shape and do not always mirror the shape of land-surface topography (Figure 5). Compared to cross section BB′, the cross section AA′ represents a relatively high topographic gradient (Figure 2 and 5). Water tables tend to follow the land-surface topography during both extremes of high and low water tables. The similarity in shape between the deepest water table (June 1993) and the ground surface suggests that the clay layer generally follows the surface topography. Because of the landscape geological control, most of the wetlands on flatwoods landscape were flow-through types (i.e., upland ground-water flows into a wetland and then flows out of it) (Crownover et al. 1995). Spatial distribution of the underlaying clay layer may play an important role in interactions between groundwater in the uplands and surface water in the wetlands.

Water-Table Responses to Treatments

The treatment activities were completed by May 31, 1994 coincident to a dry period when evapotranspiration was the highest. Water-table response was calculated as the difference between values predicted by the regression equation and those measured. Standard errors for the predicted value in the regression models are less than 15 cm, so water-table rise/drop within ±30 cm is considered non-significant. The water-table effect (i.e., water-table rise) on wetlands was most pronounced in eight months, May–October 1994 and May–Jun 1996, during the entire post-treatment period (Figure 6). These periods were extremely dry, with water tables in the control wetland and upland being well below the soil surface (Figures 3a and 4a). The water table in the W upland well, which was located 50 m from the wetland edge, was not affected by the harvesting during the entire post-treatment period (Figure 7a). During the 31-month post-treatment period, water-table elevations were the lowest from May to October 15, 1994 (Figures 3 and 4). On average, water levels were elevated by 32 cm and 41 cm for W and ALL wetlands, respectively, during the 8-month dry periods in 1994 and 1996. The ground-water table in the ALL upland was elevated by 29 cm during the same dry periods (Figure 7b). During the other 23 relatively wet months, the water tables in both wetlands and uplands were not affected significantly (< 5 cm). During those months, the water levels in wetlands were above pond bottoms and within 10–20 cm of the palmetto lines, resulting in sheet surface flows. Surface outflow occurs when the ponds are full and the water-table levels are higher than the elevation of the palmetto lines or the edges of the cypress ponds. Surface outflows from harvested wetlands were doubled during the 5-month dry period in 1994 (Riekerk et al. 1996).

From the flatwoods landscape point of view, water tables in depression wetlands showed greater response to forest removal than in the surrounding uplands (Figure 8). Differences of evapotranspiration reduction due to tree removal between a wetland and upland system were presumably small. The different harvesting effect between a wetland and an upland most likely resulted from their geomorphologic differences. In other words, because ground-water tables have a tendency to level due to forces of gravity, increased water in the upland or wetland system due to reduction of evapotranspiration may move towards local depressions, wetlands or lower elevation areas in the landscape.

DISCUSSION

Factors affecting the response of water-table change to forest harvesting can be identified by mathematical analysis. Hydrologic impacts of forest harvest practices essentially were caused by altering the water cycles on a stand-, watershed- or landscape-scale through vegetation and soil disturbance. Effects of forest harvesting can be best explained by examining the affected hydrologic variables in the water-balance equations as described in the following mathematical forms.

$$\Delta S = P + S_i + G_i - I_c - G_o - E - T \qquad (1)$$

where,

- ΔS = water storage change in the wetland;
- P = precipitation measured above tree canopy;
- S_i = surface inflow from outside of the system (wetland or upland);
- G_i = ground-water inflow from outside of the system (wetland or upland);
- I_c = canopy interception (wetland or upland);
- S_o = surface outflow from the system (wetland or upland);

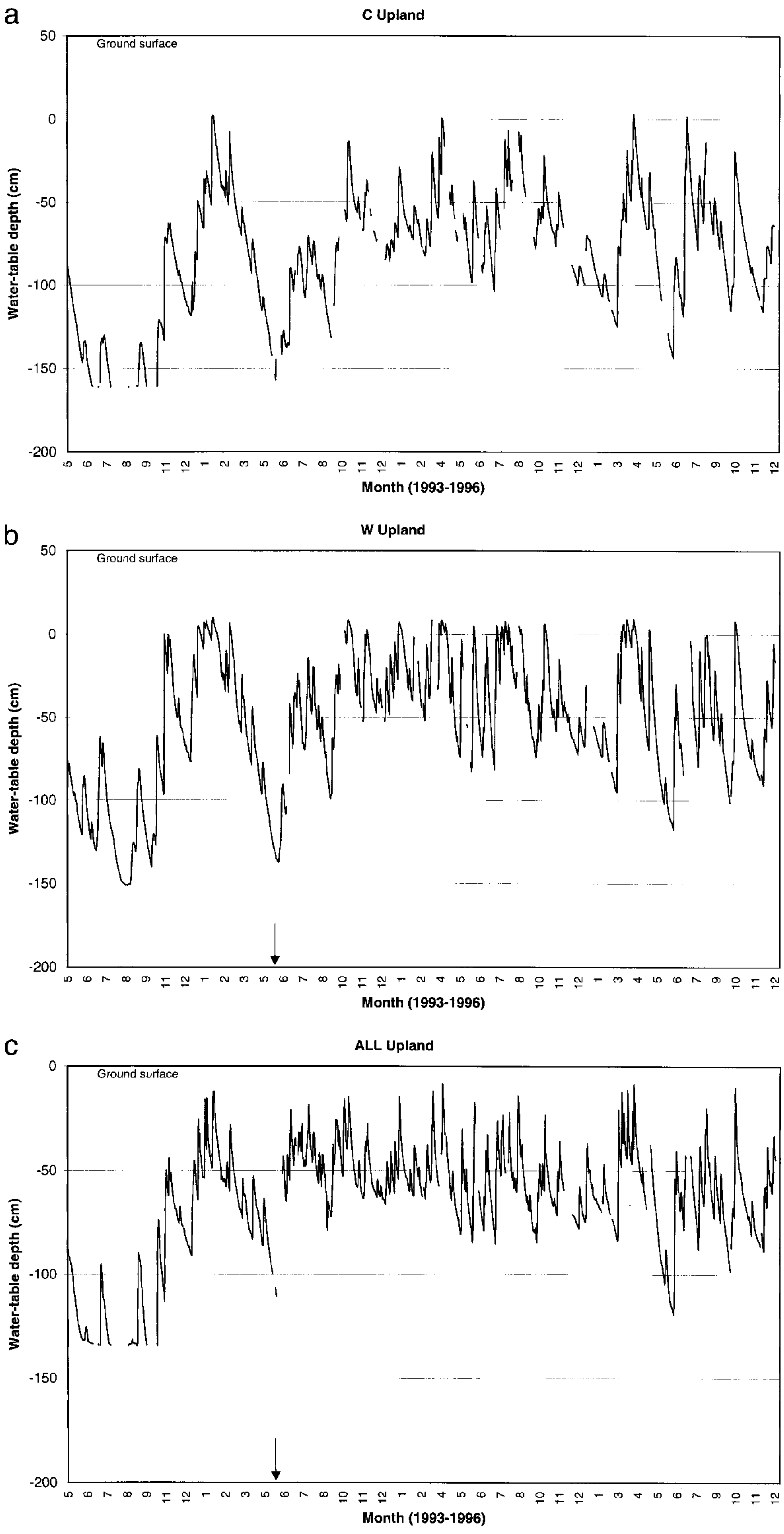

Figure 4. Daily water-level dynamics in three pine uplands during 1993–1996; the arrow indicates harvesting treatment completed.

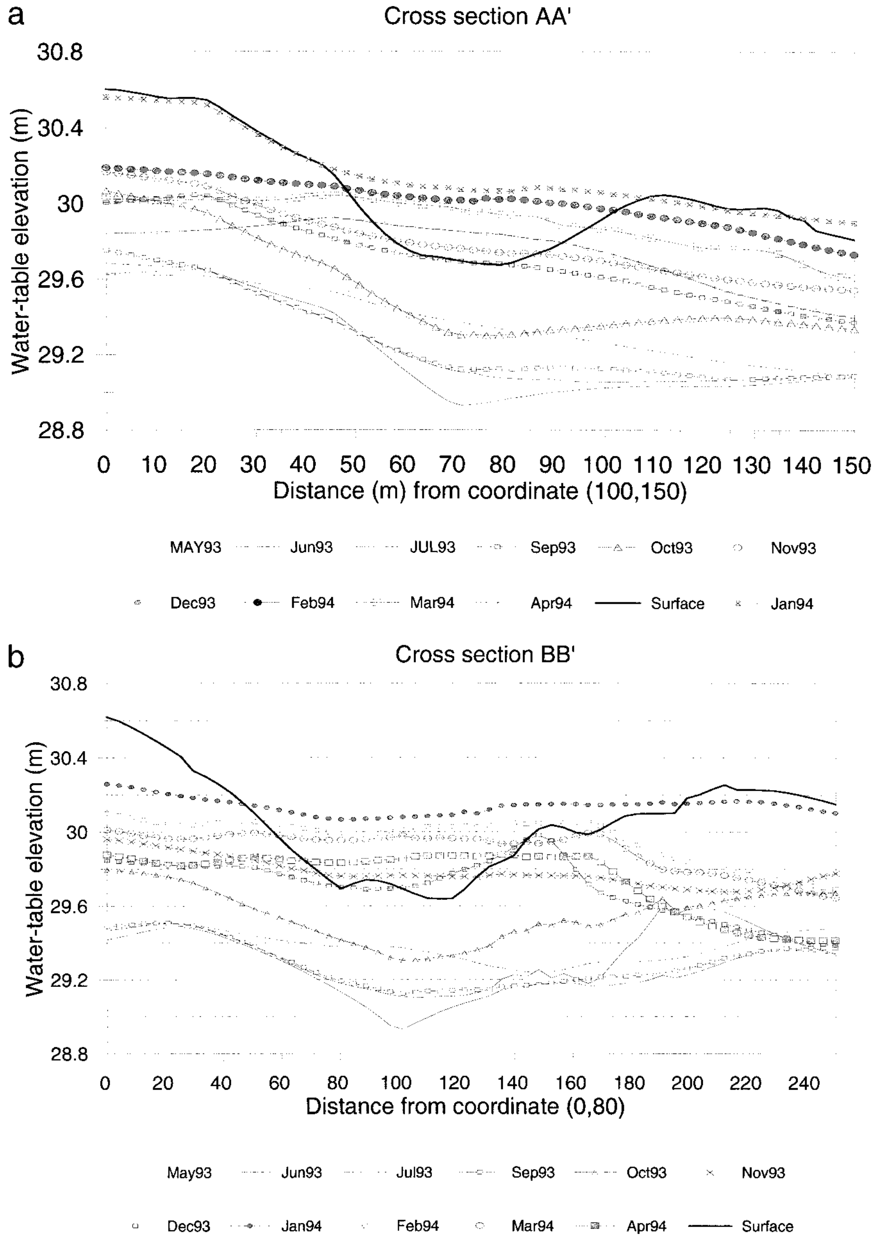

Figure 5. Water-table profiles for the cross section AA′ (a) and BB′ (b) in the C wetland showing the spatial and seasonal dynamics of water levels in each month during May 1993–April 1994. The Jun93 line, similar to the clay layer, represents the lowest water-table profile during the study period.

G_o = ground-water outflow from the system (wetland or upland);
E = evaporation from the soil or water surface; and
T = plant transpiration.

The following equation is derived to evaluate the effects of harvest activities on ΔS

$$\Delta S_{eff} = \Delta Inflow_{eff} - \Delta Outflow_{eff} - \Delta ET_{eff} \quad (2)$$

where,

ΔS_{eff} = water storage effect due to forest harvest. In this equation, the change of a variable = the value of post-harvest − the value of pre-harvest;
$\Delta Inflow_{eff}$ = $(Si_{post} + Gi_{post}) - (Si_{pre} + Gi_{pre})$;
$\Delta Outflow_{eff}$ = $(So_{post} + Go_{post}) - (So_{pre} + Go_{pre})$; and
ΔET_{eff} = $(E_{post} + T_{post} + Ic_{post}) - (E_{pre} + T_{pre} + Ic_{pre})$.

To describe the effect of harvest on ground-water table, substituting ΔS_{eff} with $\Delta h_{eff} \times S_y$ then,

$$\Delta h_{eff} = \frac{(\Delta Inflow_{eff} - \Delta Outflow_{eff} - \Delta ET_{eff})}{S_y} \quad (3)$$

where,

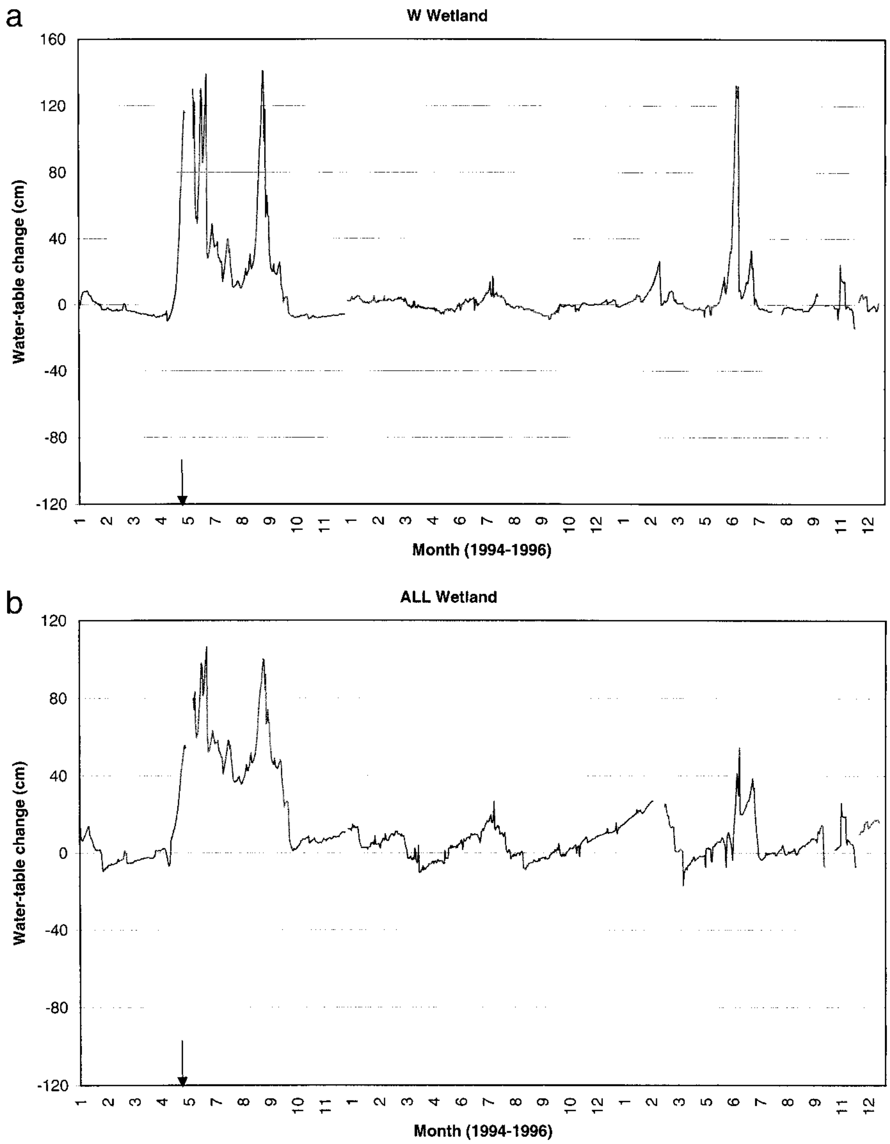

Figure 6. Water-table change (predicted water level by the regression model − measured water level) for the W wetland (a) and ALL wetland (b); the arrow indicates harvesting treatment completed.

Δh_{eff} = water-table effect due to forest harvest. It is positive in most cases;

S_y = effective specific yield of the soils; $S_y = 1$ when the water table is above the soil surface. Its value may vary from 0.05 to 0.25 depending on the soil moisture content and soil porosity in the unsaturated zone. The surface soil layer has larger S_y, while the deep and moist soil layers have smaller S_y.

Equation 3 suggests that the ground-water table effects of a wetland or upland are controlled by and related to four components: inflow and outflow changes, evapotranspiration ($ET = E + T + I_C$) change, and specific yield. All four variables are functions of water table levels.

Two observed scenarios at the research site are explained using Equation 3.

Case 1: $\Delta h_{eff} > 0$; Ground-water table is elevated by forest harvests.

This is the expected case. As presented previously, this scenario was most pronounced in the dry period during the summer of 1994 and May–June 1996 when the water tables in wetlands and uplands were low. The following reasons may explain this case. 1) S_y was low since the water tables in the control plots were well below the ground surface. The low water tables were mainly caused by low rainfall inputs but also by high ET outputs. 2) ΔET_{eff} was negative but high in absolute value. This appeared to be true during May–October 1994 when the trees were harvested and understories

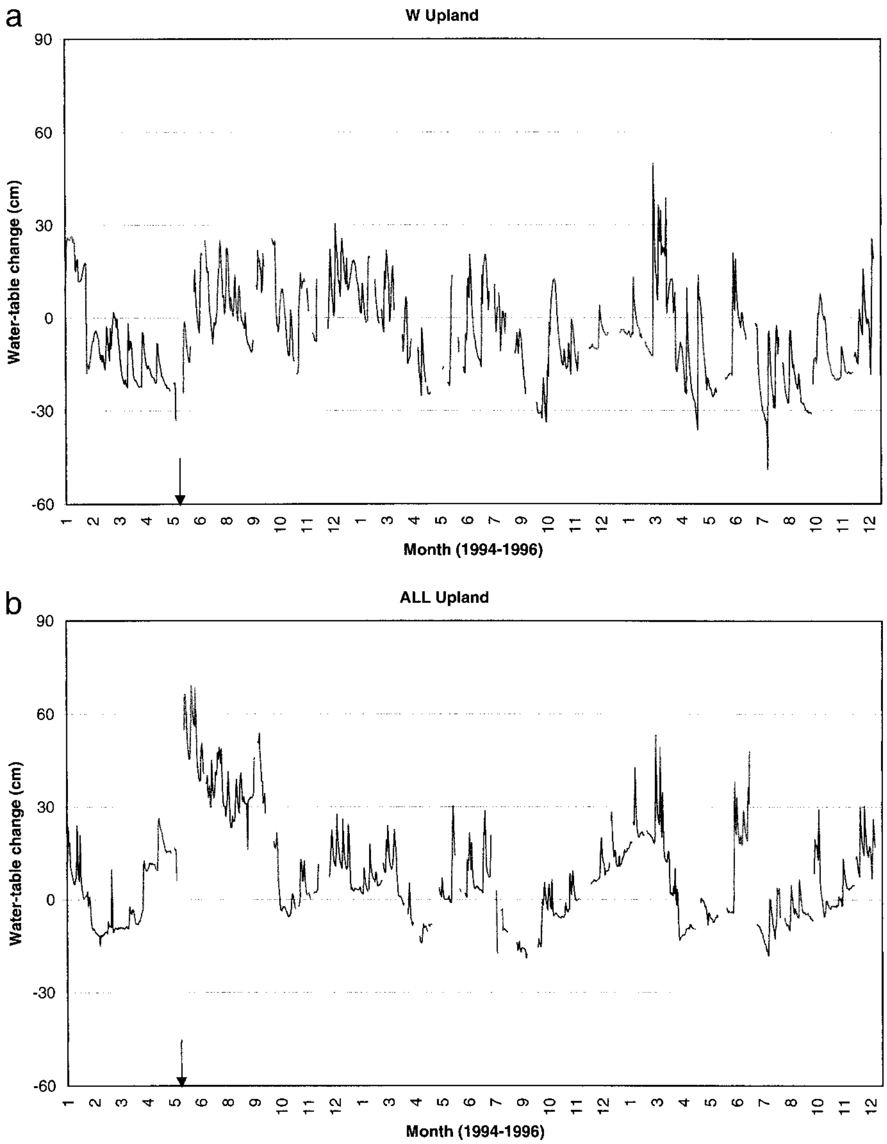

Figure 7. Water-table change (predicted water-table elevation by the regression model − measured elevation) for the W upland (only wetland harvest) (a) and ALL (wetland + upland harvest) upland (b); the arrow indicates harvesting treatment completed.

had not recovered. Unfortunately, there have been no direct measurements quantifying ΔET_{eff}. For the flatwoods landscape in a subtropical climate, a small ΔET_{eff} is expected under high water-table conditions when E plus T dominate water loss at its potential. However, when the water table is deep, ΔET_{eff} could be large since T dominates the total water loss for this case. 3) In order to allow this case ($\Delta h_{eff} > 0$) to occur, the net flow component of $\Delta Inflow_{eff} - \Delta Outflow_{eff}$ must be either positive or having a small negative value. In other words, the net flow (surface plus ground water) for the post-treatment period must be greater than or equal to the pre-treatment period. Field measurements from individual wetlands showed that outflow increased as much as 50% from the pre-treatment period during the dry period in 1994 (Riekerk et al. 1996). This increase diminished in the winter of 1994 and the entire year 1995 when the water table was high. Although a complete water balance was available for this study, we observed that water-table effect (rise) was coupled with increase in runoff from wetlands.

Case 2: $\Delta h_{eff} \leq 0$; No effect on ground-water table; this scenario occurred from Oct. 1994 to Dec. 1996, except for June 1996.

This case occurred most of the time during the 31-month post-treatment period. The following reasons may explain this case. 1) S_y has a large value (Maximum = 1) when the water table is close to the soil surface. 2) $\Delta ET_{eff} \approx 0$ when the water table is close to the soil surface and available energy may be consumed

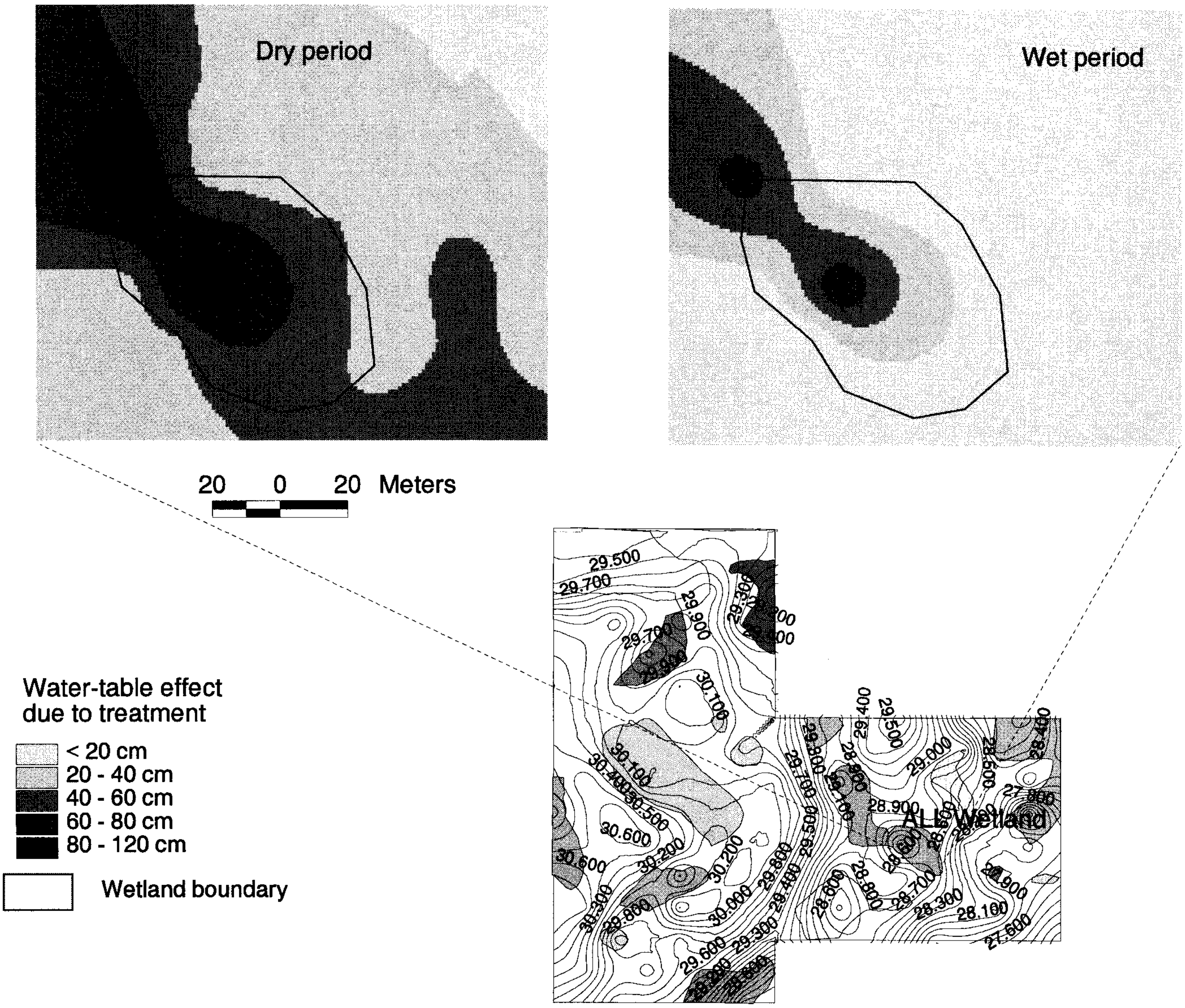

Figure 8. Spatial display of water-table effects showing that clear-cutting (ALL) resulted in a greater magnitude in a dry (July 1994) month than in a wet month (November 1994). The wetland boundary is indicated by the palmetto line, a vegetation shift from upland species (palmetto) to wetland species (cypress). Wetland plus upland harvesting was completed at the end of May 1994.

fully by ET during both pre- and post-treatments. Thus, harvesting had little influence on the total water loss due to ET. 3) Net flow, $\Delta Inflow_{eff} - \Delta Outflow_{eff,}$ had small values as evidenced by field measurements during high water-table conditions, approximately 80% of the post-treatment period (Riekerk et al. 1996).

CONCLUSIONS

This study corroborated other similar forested wetland hydrology studies in finding that tree removal will reduce ET and causing forest soils to become wetter (Williams and Lipscomb 1981, Preston 1996). However, several distinct hydrologic characteristics of pine flatwoods were observed. Forest clear-cutting in wetlands and uplands caused significant water-table rise mostly during dry periods when the water-table levels were low ($\pm$10 cm from wetland ground surface or > 50 cm from the upland ground surface). Wetland tree harvest did not affect the water-table level in upland areas about 50 m from the cypress wetland margin. This result suggested that hydrologic effects from cypress removal were relatively localized and water-table rise in a wetland could not cause a reversal of flow from a wetland to the surrounding upland. Wetland hydroperiods were not altered in the harvested areas in wet periods, mostly during the fall and winter months from November to April under normal climatic conditions in north central Florida. Water-table responses, however, were still significant for dry periods in the second year after clear-cutting. This study and similar studies (Riekerk 1989; Sun et al. 1998) suggest that tree removal from cypress wetlands may have longer term effects compared to other forested wetlands such as floodplain bottomlands where water-table effects were diminished at the second growing season (Wang 1996). On flatwoods landscapes, cypress wetlands representing local depressions showed greater impact than their surrounding uplands. The main cause is the fact that wetlands are local depressions receiving net ground-water inflow from surrounding uplands during wet period (i.e., both upland and wetland water table levels are high). Cypress wetlands were 'isolated' during dry periods when the water tables were low, normally during the spring and summer months. This study suggests that evaluating effects of forest harvesting on flatwoods hydrology, a ground-water- and ET- dominated 'storage-based' system, must consider short-term (e.g., seasonal) climatic variability. There is a research need to quantify ET changes in harvested sites to fully understand the mechanisms of hydrologic recovery processes. Although this paper could not provide data to fully explain the processes of water-table response to forest management, the mathematical analysis offers a rigorous guide for future study.

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