Hydrologic and Water Quality Effects of Harvesting and Regeneration of a Drained Pine Forest

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Abstract

Data on precipitation, weather, water tables, outflows, and nutrient concentrations from two paired watersheds (D1 - control and D2 - treatment) on a pine forest in Coastal North Carolina were measured during 1988-90 calibration period to characterize the pre-treatment hydrology and water quality. Similarly, measured data from 1995 (D2 harvested) to 2004 (seven years after planting in 1997) were then used for evaluating the effects of harvesting and regeneration (D2) using a paired watershed approach. Annual rainfall varied widely during the study period with 2388 mm in a very wet year (2003) to as low as 851 mm in a very dry year (2001). Harvesting resulted in substantial increases of as much as 20 cm in the average water table and 91 mm in outflow from D2 compared to the control (D1) in the first six months after harvest. The increase in water table was mainly attributed to decrease in ET losses as a result of reduced canopy. The water table increase declined substantially after 1998 (trees two years old), except during some dry summer months. However, by 2002 (trees five years old), the difference in water tables between the regenerated and control watersheds was reversed, consistent with the pre-treatment levels. The increase in measured annual outflows on D2 varied from 260 mm in a wet year 1996 (first year after harvest) to 56 mm in a near normal year 1999 (two years after planting). Peak flow rates from the harvested watershed for a summer event after harvest were nearly seven-fold higher than the control. The monthly and annual data indicated that the outflows on the harvested watershed returned to base line levels by 2003, nearly six years after planting. Although both the nutrient concentrations and loadings (except for total P) on D2 were substantially elevated after harvesting, they were only short-lived (< 3 years). The measured NO_3-N, TKN, and TP loadings on the harvested watershed varied from 0.01 – 4.5 kg ha^{-1}, 0.18 – 4.7 kg ha^{-1}, and 0 – 0.4 kg ha^{-1}, respectively. The minimum loadings occurred in the driest year 2001 (rain= 850 mm, outflow = 51 mm). Harvesting also increased sediment levels, but for only three years.

KEYWORDS. Water table, outflows, evapotranspiration, nutrient concentrations and loadings, paired watershed approach.

Introduction

Hydrologic and water quality impacts of sustainable forest management practices on receiving water bodies are important environmental issues. Timber harvests in the South are expected to increase over the next 20 years, which implies that impacts to forested wetlands will also increase (SOFRA, 2002). Land use pressures and environmental set asides tend to decrease the industrial forest base, leading to more areas of more intensive silvicultural practices including access, drainage, harvesting, site preparation, bedding, fertilization, herbicides and artificial regeneration. Studies have recently documented impacts on soil properties, hydrology and water quality as a result of harvesting and subsequent regeneration of pine forests in the poorly drained lowlands of Atlantic Coastal Plain (Brown et al., 2005; Grace et al., 2003; Xu et al., 2002; Sun et al., 2001;

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Blanton et al., 1998; Lebo and Herrmann, 1998; Amatya et al., 1997; Ursic, 1991; Riekerk, 1989; Swindel et al., 1983; 1982). These studies show that removing the forest canopy reduces evapotranspiration (ET), increasing the water yield from a forested site until the canopy is regenerated, and results in elevated ground water tables, increased peak flows, and higher outflows, increasing nutrient and sediment movement. Shepard (1994) reviewed results of effects of silvicultural practices on water quality from nine wetland forest sites and found that harvesting timber raised nutrient concentrations, with concentrations decreasing to "natural" levels after one to four years. However, there have been only limited long-term studies documenting effects of harvesting and regeneration of drained pine plantations on the hydrology and water quality.

A long-term forest hydrology and water management study has been continuing since 1988 at three experimental drained pine forests at Carteret County, North Carolina to quantify the potential impacts of both silvicultural and water management practices on hydrology and water quality. Continuous hydrologic monitoring on these watersheds has provided a database for quantifying the water and nutrient budgets and evaluating impacts of management practices using a paired watershed approach (McCarthy et al., 1991; Amatya et al., 1996; 1998; 2000; 2003). Blanton et al. (1998) studied the changes in soil hydraulic properties including the hydrology of one of the three drained forested watersheds at Carteret County site during harvest and early regeneration periods. The authors reported that harvesting operations including site preparation reduced drainable porosity in the top 60 cm of the profile by approximately 50%, resulting in a significant change in storm outflow hydrographs. The main objective of this study is to evaluate the hydrologic and water quality effects of harvesting and regeneration of a pine forest. A paired watershed approach was used to determine effects of harvesting. This paper presents the results based on ten years (1995-2005) of measured data since one of the watersheds was harvested in July 1995 and 2.3 years (1988-90) data from the calibration period.

METHODS

Site Description:

The study site (Figure 1) is located at approximately 34° 48' N latitude and 76° 42' W longitude in Carteret County, North Carolina, and is owned and managed by Weyerhaeuser Company. 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). Each watershed is drained by four 1.4 to 1.8 m deep parallel lateral ditches spaced 100 m apart (Fig. 1). Data on hydrology, soil and vegetation parameters were collected from three experimental plots (each about 0.13 ha in area) in each watershed (Fig. 1).

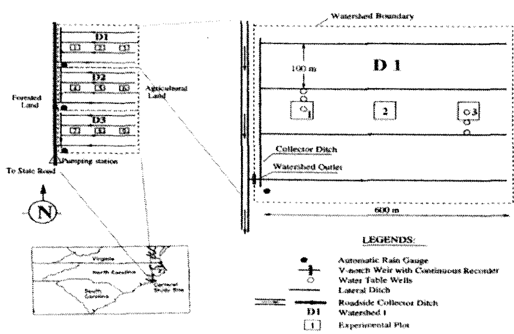

Figure 1. Location map and layout of experimental watersheds (D1 – control and D2 – treatment with plantation for regeneration) at Carteret County, North Carolina.

Two methods of water sampling (composite using Automatic water samplers ISCO-2700 and grab sampling) have been used since late 1989. For composite sampling during an event, 250 mL of water was collected every two hours; four consecutive samples were composited making three samples per day. All samples were frozen and taken to the soil-chemistry laboratory of the Soil Science Department at North Carolina State University in Raleigh, NC. Grab samples were collected weekly during the flow events of the study period. Water samples were analyzed for NO_3+NO_2-N (identified as just NO_3-N in this paper), NH_4-N, total Kjeldahl nitrogen (TKN), total phosphorus (TP), and total suspended solids (TSS). Details of procedures of sample analysis in the laboratory have been documented by Amatya et al. (1998; 2003).

Study design and treatments:

A paired watershed approach (EPA, 1993; Brown et al., 2005; Swank et al., 2001; Stednick, 1996) was used to assess the comparability of hydrologic characteristics of these watersheds during the 1988-90 pre-treatment calibration period (McCarthy et al., 1991; Amatya et al., 1996). In this study, watershed D1 with a 21-year old (in 1995) mature pine forest was the control and watershed D2, harvested in July 1995 at stand age of 21 years was the treatment watershed. Site preparation and bedding occurred on D2 in October 1996 followed by planting for regeneration in February 1997. Ten years of hydrologic data have been collected both on the control watershed (D1) and treatment watershed (D2) since harvesting in July 1995. In the remainder of the text, the period July 1995 to December 1997 will be referred to as "harvesting" and the period from 1998 to 2004 will be referred to as "regeneration". The study period encompasses years one to seven in the growth cycle on the treatment watershed (D2) while the stand age of the trees on the control watershed D1 was 23 to 30 years.

Evaluation methods:

Average measured daily water table elevations on two wells on each watershed were used for comparisons. The effects of harvesting and regeneration on hydrology were evaluated using both graphical and statistical comparisons of (a) measured daily water table elevations, (b) annual and monthly drainage outflows, and (c) daily and hourly hydrographs between the control (D1) and treatment (D2) watersheds (Amatya et al., 2004). Data on monthly difference between the water table elevations from the control (D1) and treatment (D2) watersheds for the 10-year treatment period was graphically plotted with that of the calibration period to determine the return of baseline conditions. The same analysis including annual plot was conducted for outflows.

In order to assess the actual effects of harvesting and regeneration on the annual hydrology and water quality during the treatment period, the characteristic differences observed in the annual outflows and concentrations between the two watersheds during the pre-treatment period were taken into account by Amatya et al. (1998; 2000). Calculated ratio (0.96) of the measured annual outflow of the treatment watershed (D2) and the control (D1) for the calibration period (1988-90) was used with measured ratio from the control watershed D1 for the treatment years to predict the expected annual outflows from the treatment watershed D2. Similarly, water quality effects were evaluated by comparing annual mean concentrations to the annual expected concentrations for each of the years of harvesting and regeneration using (D2:D1) ratios of 0.645, 0.679, 1.25, and 1.356 for NO_3-N, TKN, TP, and sediment, respectively. Comparisons were also made between measured and expected annual nutrient loadings for the treatment watershed (D2).

RESULTS AND DISCUSSION

Rainfall

Annual data on measured rainfall, outflow and runoff coefficients, and potential evapotranspiration (PET) for the 1988-90 calibration and 1995-2004 harvesting and regeneration periods are presented in Table 1. Rainfall in 1990 covers only from January 01 to March 20 (end of the calibration) and rainfall for 1995 covers only from July (since harvesting) to December. In cases where all gauges failed or had missing data, data from the third watershed (D3) or the weather station were also used. The study period covered a wide range of variation in annual rainfall. The rainfall of 2330 mm (on D1) in year 2003 with Hurricane Isabelle was the highest of the 17-years (1988-2004) of record at this site. The lowest annual rainfall of around 850 mm was recorded in 2001, the driest year of the 17-year period.

Table 1. Measured annual rainfall, outflow, runoff ratios for two watersheds, and Penman-Monteith potential evapotranspiration (PET) for the 1988-90 calibration and 1995-04 harvesting and regeneration periods.

Year	Annual Rainfall D1 mm	Annual Rainfall D2 mm	Annual Outflow D1 mm	Annual Outflow D2 mm	Runoff Ratios D1	Runoff Ratios D2	Expected Outflow on D2, mm	% Change in D2 Outflow	Annual P-M PET mm
1988	1235	1208	173	166	0.14	0.14			1041
1989	1876	1829	658	642	0.35	0.35			945
1990	163	159	101	87	0.62	0.55			1031
1995	728	685	96	183	0.13	0.27	92	-98.5	849
1996	1646	1556	704	936	0.43	0.60	676	-38.4	877
1997	1382	1305	397	588	0.29	0.45	381	-54.2	1075
1998	1658	1617	771	838	0.47	0.52	740	-13.2	1007
1999	1362	1401	614	646	0.45	0.46	590	-9.6	1072
2000	1718	1786	857	792	0.50	0.44	823	3.7	1023
2001	852	851	45	51	0.05	0.06	43	-17.7	1024
2002	1718	1776	426	430	0.25	0.24	409	-5.2	919
2003	2331	2388	1399	1459	0.60	0.61	1343	-8.6	1097
2004	1313	1370	389	372	0.30	0.27	374	0.5	1060

Annual rainfall amounts were similar in 2000 and 2002, 1996 and 1998, and 1999 and 2004. Average annual rainfall measured was 3.4% lower on watershed D2 than on D1 from 1988 to 2000. After the new gauges were installed at the end of 2000, the trend was slightly reversed with the D1 average 2.8% lower than D2 (Table 1). Years 1989, 1996, 1998, 1999, 2002, and 2003 had higher than normal rainfall (Amatya et al., 2004). Year 1998 had a wet spring and summer followed by dry fall-winter continuing until the summer of 1999 when the Hurricane Dennis and Floyd brought large amounts of rain.

Water Table Elevations (WTE)

Calibration Period (1988-90)

Daily water table elevations measured on both the watersheds D1 and D2 (14 to 16 years old trees) during the pre-treatment calibration period (1988-90) are presented elsewhere (Amatya et al., 2000). Water tables on both the watersheds responded almost identically during this period, with D1 only slightly higher than D2, as expected because of the small difference in rainfall. Water table reached the ground surface during the wet events of winter as well as during Hurricane Hugo in September 1989. The dry summer in 1988 resulted in water table below 1 m elevation. The annual average daily difference in WTE between D1 and D2 varied from 4 to 5.5 cm with an average of 5 cm. There was a very good correlation ($R^2 = 0.99$) between the daily water tables with a slope of 0.98 ($p < 0.0001$).

Harvesting/Planting Treatment Period (1995-97)

Data in Table 2 shows the measured average water table elevations (WTE) on the two watersheds (D1 and D2) and their differences on the annual and semi-annual basis for 1995 to 2004. Data from January to June in 1995 represent conditions just prior to harvest. The trees were 21 years old during that period. The trees on D2 were harvested during the period of June 28 to July 03. D1 WTE was about 4 cm higher (on average) than D2 for January - July, consistent with the calibration period. As expected, soon after the first rainfall events in early July of 1995, watershed D2 had much higher water table elevations than the control watershed (D1). The largest difference was as high as 66 cm on Day 223 of 1995 as a result of a rain event of 38 mm. The next largest was a 58 cm rise as a result of 51 mm rain on Day 203 (not shown). The average WTE on D2 was 20.3 cm higher than D1 from July to December of 1995 (Table 2). These increases are consistent with the observations of Grace et al. (2003) for a harvested mature hardwood forest in eastern North Carolina but larger than the observations of Sun et al. (2000) for Florida cypress-pine flatwoods. The average difference in water tables decreased from 13.3 cm in the first-half of 1996 to 6.1 cm in first-half of 1997. This small difference in 1997 was due to the wet days in the winter and early spring when ET demands were low and difference in vegetation may not have a big effect on soil moisture. The higher water table on harvested watershed (D2) compared to the control (D1) was most pronounced (22.3 cm) during later half of 1997 when water table elevations were generally low. This was probably due to reduced ET rates from the harvested watershed, which only had emergent vegetation, compared to the control with a mature pine stand (see Sampson et al., this proceeding). This was also true for the wet periods of summer and fall affected by tropical storms and by Hurricane Fran in 1996 (7.5 cm). Because of relatively dry year in 1997, the annual average difference was 14.6 cm compared to 10.7 cm for 1996 (Table 2). This is consistent with results by Xu et al. (2002).

Table 2. Statistics of half-yearly and annual water table elevations on D1 and D2 for 1995-2004. Difference is D1-D2, with negative values representing higher WTE on watershed D2.

Watershed	Average Water Table Elevation	Average Deviation in Water Table Elevation between D1 and	Average Water Table Elevation	Average Deviation in Water Table Elevation between D1 and	Average Water Table Elevation	Average Deviation in Water Table Elevation between D1 and
	m	cm	m	cm	m	cm
	January 01-December 31, 1995		January 01-June 30, 1995		July 1-December 31, 1995	
D1	1.65	--	1.65	--	1.64	--
D2	1.72	-7.43 (-66)	1.61	3.75	1.84	-20.3
	January 01-December 31, 1996		January 01-June 30, 1996		June 30-December 31, 1996	
D1	1.84	--	1.75	--	1.95	--
D2	1.95	-10.7 (-41)	1.88	-13.3	2.04	-7.50
	January 01-December 31, 1997		January 01-June 30, 1997		July 1-December 31, 1997	
D1	1.64	--	1.84	--	1.47	--
D2	1.79	-14.6 (-57)	1.90	-6.07	1.70	-22.3
	January 01-December 31, 1998		January 01-June 30, 1998		June 30-December 31, 1998	
D1	1.98	--	2.06	--	1.70	--
D2	2.01	-2.98 (-50)	2.07	-0.67	1.81	-10.50
	January 01-December 31, 1999		January 01-June 30, 1999		July 1-December 31, 1999	
D1	1.85	--	1.83	--	1.88	--
D2	1.87	-2.15 (-36)	1.87	-3.82	1.88	0.20
	January 01-December 31, 2000		January 01-July 03, 2000		July 04-December 31, 2000	
D1	1.91		1.91		1.91	
D2	1.92	0.83	1.92	-0.68	1.92	3.10
	m	cm	m	cm	m	cm
	January 01-December 31, 2001		January 01-June 30, 2001		July 1-December 31, 2001	
D1	1.22	--	1.66	--	0.84	--
D2	1.27	-4.0	1.72	-6.9	0.86	-2.0
	January 01-December 31, 2002		January 01-July 03, 2002		July 04-December 31, 2002	
D1	1.66	--	1.4	--	1.92	--
D2	1.61	1.4	1.42	-2.0	1.84	5.0
	January 01-December 31, 2003		January 01-June 6, 2003		June 6-December 31, 2003	
D1	2.16	--	2.22	--	2.11	
D2	2.11	5.0	2.18	4.1	2.05	5.8
	January 01-December 31, 2004		January 01-June 28, 2004		June 29-December 31, 2004	
D1	1.72	--	1.87	--	1.59	--
D2	1.69	4.2	1.81	5.9	1.57	2.6

Regeneration Treatment Period (1998-04)

Data in Table 2 show the average difference in water table elevations between two watersheds (D1-D2) for semi-annual and annual periods for the 1998 to 2004 regeneration period. Based on the limited data, the watershed D2 still had somewhat higher water tables (2.01 m) compared to the control (1.98 m), especially during the summer. As a result the average difference in WTE in the second-half of 1998 was 10.5 cm compared to only 0.7 cm in the first-half. The smaller difference in the first-half was expected because of lower PET during the very wet winter and spring months. Similar high water level response was observed for both watersheds during the event of Hurricane Bonnie in August 1998. The difference in water table elevations between the watershed D2 and the control (D1) continued to decrease until the first half of 1999 when planted trees entered the 3rd year after planting. The difference was reversed with higher elevations (by only 0.20 cm on average) on the control D1 than the treatment (D2). The annual average deviation was still higher on the treatment by about 2.2 cm. However, the slightly higher (0.8 cm) elevation on the control (D1) than the treatment in 2000 may be insignificant. This was shown by the data for 2001 when the water table elevations on the regenerated watershed were still higher by 6.9 and 2 cm in the first and second-half of 2001, respectively, with an annual average of 4 cm. This year was the driest of the 10-year treatment period with an annual rainfall of only 845 mm

(Table 1). The decreasing trend in difference in WTE between D1 and D2 continued until the first-half of 2002 (Table 2) after which the trend was reversed with 5 cm on average higher water table elevation on the control watershed (D1) than the regenerated (D2). This positive trend continued all the way though the end of 2004, for which the computed annual average difference in WTE between the control and regenerated was 4.2 cm indicating the return of WTEs to original baseline levels. This required five years after planting in 1997.

A plot of the monthly average difference in WTE between the treatment and control (Fig. 2) shows that the WTE on the treatment watershed was higher than D1 until August 2001 after which the trend is reversed. This may be possibly due to the increased ET loss on the regenerated watershed (D2) due to increased LAI (Sampson et al et al., this proceedings poster). Data in Figure 2 also support the earlier arguments that the difference in WTE between two watersheds increases during the dry summer months. Dry periods caused deeper water tables in late 2001 and early 2002. Even the months of January and February 2002 had large differences between D2 and D1 (Fig. 2). This phenomenon is explained by higher ET from the control watershed with matures trees (deeper rooting depths) compared to young trees (shallower roots) on the treatment watershed.

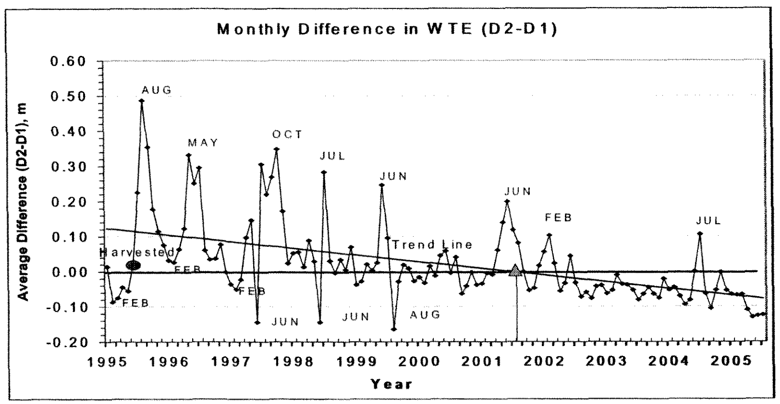

Figure 2. Monthly average difference in water table elevations measured on the treatment (D2) and control (D1) watersheds during the 1995-05 harvesting and regeneration treatment period.

The effects of harvesting and regeneration were also examined using the computed regression slopes between the two watersheds since 1995. The slope of 0.98 between D2 and D1 calculated for the first-half of 1995 prior to harvesting was consistent with the slope of 1988-90 calibration period. Immediately after harvesting for the second-half of 1995 the slope increased to 1.12 indicating an increase in D2 WTE. The slope declined to as low as 0.99 by the year 2000, but this value may be questionable because of missing data in that year. Due to increased WTE on D2 in the very dry year in 2001, the slope increased back to 1.03, which immediately dropped to 0.99 by 2002 and stayed 0.98 both in 2003 and 2004 as the one obtained for the calibration period (Amatya et al., 2000). This further supports the earlier argument that the water table elevations on watershed D2 have returned to base line conditions, at least by 2002 which is seven years after harvesting and five years after planting for regeneration.

Daily Drainage Outflows

Calibration Period (1988-90)

Calibration relationships between outflow volumes and peak flow rates for storm events for the control (D1) and treatment (D2) watersheds were reported earlier by Amatya et al. (2000) when both the watersheds were under same hydrologic treatment. The authors found a high correlation between the outflow volumes ($R^2 = 0.96$) and peak rates ($R^2 = 0.97$). The regression relationships for both the daily and monthly outflows for the same period were also strong ($R^2 = 0.98$). However, only the slope (0.98) was significant and not the intercept (-0.02). The relationships show that both the watersheds have similar hydrologic responses during the calibration period.

Harvesting/Planting Treatment Period (1995-97)

Measured hourly outflow rates for a 1996 winter storm event (Days 5-37) and a summer event (Days 210-226) are shown in Figure 3. These events followed harvest in July 1995. As expected, flow rates on the harvested watershed (D2) were higher compared to the control for both winter and summer events. However, the increase was much higher during the summer than in the winter period when the ET demands are lower and the difference in vegetation would not be expected to have a big effect on antecedent soil water conditions. In the summer event, the absence of trees on D2 would logically cause ET to be substantially less on the treatment watershed (D2) compared to the control (D1). As a result water table was higher on the harvested watershed resulting in increased drainage rates (Table 2). Increase in water table elevation on the harvested watershed (D2) may have also been partially due to reduced porosity in the surface soil layer (Blanton et al., 1998; Skaggs et al., this proceedings). These effects were visible with the treatment watershed already yielding flows at the beginning of the summer event (Days 184) when the control was still dry (not shown). Due to the higher water table on the harvested watershed, the peak drainage rate on Day 212 was seven times higher than that on the control. Grace et al. (2003) recently reported more than 50% increase in peak outflow rates from a harvested mature natural hardwood forest in coastal North Carolina. As the water table on both watersheds came closer to the surface, the difference in peak flow rates was also reduced on Day 217. Throughout the end of 1997, daily peak flow rates and outflow volumes continued to increase on the harvested watershed (D2) compared to the control on the mature pine forest (D1), consistent with Grace et al (2003) study.

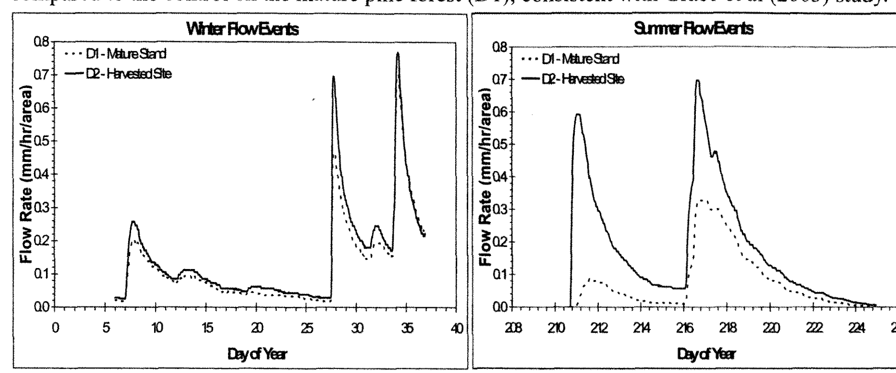

Figure 3. Measured hourly drainage rates from the control matured stand (D1) and the harvested (D2) watersheds for a winter (January-February) and a summer (July-August) events of 1996.

There was little difference in daily outflows between two watersheds, however, during the wet summer event of Hurricane Fran, which raised the water table to similar elevations on both the watersheds. The higher ET rates on the mature forest (D1) soon after Fran brought water table down to the extent that there was no outflow on this watershed as a result of Hurricane Josephene on Day 282 when the harvested watershed yielded peak daily outflow of 23 mm (not shown). Daily flow duration data (not shown) from the harvested watershed indicated consistent higher outflows occurring 63% of time compared to only 48% of time in the control. For example, a flow rate of 15 mm/day was exceeded 1.6% of time (in 2.5 years) on the harvested compared to only 1.1% of time on the control.

Regeneration Treatment Period (1998 – 2004)

The winter and early spring of 1998 was very wet (545 mm rain by April) resulting in high water table elevations (Table 2) and large drainage events. As a result, there was not much difference in water table elevations on two watersheds (Fig. 2). The reason for some of the daily flows in

January 1998 measured higher on the control (D1) than the treatment was not clear. Soon after Hurricane Bonnie on Day 239 in 1998, there was a long period without any flows until near the end of the year when the regenerated watershed responded sooner than the control. Daily flows, especially the peak flow rates, from the regenerated watershed continued to be higher than the control during most of the periods in 1999 (not shown), which had a long period with substantially low rain until the end of August with Hurricane Dennis bringing the deep water table to the surface at 2.75 m. Two other hurricanes, Floyd on September 15 and Irene on October 10, also resulted in large event outflows on both the watersheds. By year 2000, the daily outflows from both watersheds behaved similarly, except for the peak flow rates, which were slightly higher for the regenerated (D2) watershed. This year was also much wetter than the average resulting in higher drainage outflows (Table 1). The flow duration for the 1998-00 regeneration period (data not shown) showed that daily flows on the treatment watershed were nearly equal to flows from the control watershed about 98% of time. Flows on the treatment exceeded those from the control only about 2% of the time.

One of the storm events in 2003 exceeded 50 mm day^{-1} as a result of 176 mm of rain with a maximum intensity of 33 mm hr^{-1} brought by Hurricane Isabelle on September 18 (not shown). On the other extreme, all daily outflows were lower than 5 mm for the driest year, 2001, with an annual rainfall of only 850 mm (Table 1). No flows occurred from either watershed after mid-April (Day 100) 2001 until mid-March 2002 due to dry conditions as shown by the deeper water table depths (Figure 2). Although the daily drainage outflows from the treatment watershed closely followed the control, the peak flow rates on the treatment were consistently higher for most storm events. Otherwise, the measured daily outflows for treatment watershed D2 were closely associated ($R^2 > 0.92$) with that from the control (D1) for all years. An exception was 2003 when there was uncertainty in the flow data due to submergence of the outlet weirs. By the period 2001-2004 frequency of occurrence of daily flows on the treatment watershed (D2) (not shown) was very similar to that of the calibration period (Amatya et al., 1996). Daily flows on the treatment watershed exceeded that of the control for only 0.75% of the time for that period.

So in general, the difference in daily flow rates between the treatment watershed (D2) and the control (D1) tended to decrease from the year 2000 to 2004 (not shown). This is also evident from the slope for the 1988-90 calibration period plotted together with each of the slopes from the treatment years (Amatya et al., 2004). The results of SAS (1994) GLM procedure for significance test indicated no difference ($\alpha = 0.05$) in slopes in daily flows between the calibration and treatment periods by the year 2003, but there was a difference ($\alpha = 0.05$) in 2004. This difference was already opposite with higher slope of D1 compared to the treatment, indicating more water loss from the 7-year old young stand. This indicates that unlike the water table depths, the daily flow regime on treatment watershed (D2) returned to base line conditions a year later than the water table depths.

Monthly Drainage Outflows

Difference between monthly outflows measured on the treatment watershed (D2) and the control (D1) is shown in Figure 4 from June 1995, the month of harvesting, to the end of June 2005. Apparently, immediately after harvesting the flow increased to 36 mm in September 1995. The highest increase of 104 mm in monthly outflow occurred in August 1998 when there was a long dry period. This was a result of heavy rain of about 292 mm brought by Hurricane Bonnie in last two days in August that brought the water table high to near the surface and resulted in earlier and larger outflows from the harvested watershed than the control. Data shows that by late 1999 outflows from the planted watershed were lower than the control for most of the time until the beginning of 2003 when the trend was again reversed with increased outflows from D2. However, the flows for some wet months in 2003 and 2004 were complicated by weir submergence. The fitted trend line indicates that the flow on the regenerated watershed (D2) was smaller than the control after mid-2003, which is consistent with the calibration period.

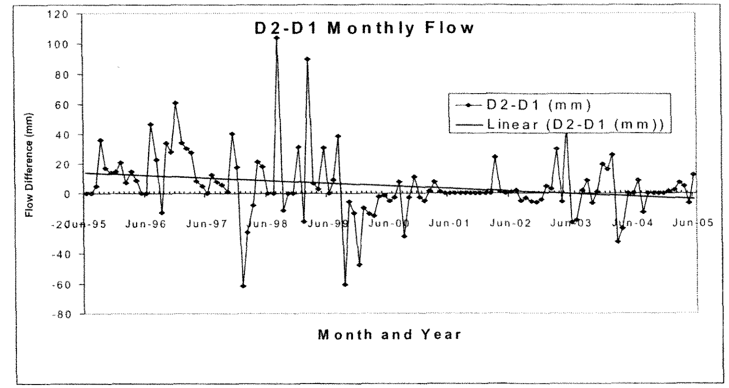

Figure 4. Difference in monthly outflows between the treatment watershed (D2) and the control (D1) for the harvesting, site preparation, planting and regeneration period (1995 to 2005).

Annual Drainage Outflows

The outflows varied widely from as low as 51 mm in a dry year (2001) to as high as 1459 mm in a very wet year (2003) (Table 1). The outflow in later half of 1995 immediately after harvesting doubled (183 mm) the computed value (92 mm) for what would have expected without harvest. This was primarily due to substantial drop in ET caused by complete loss of canopy and vegetation. The increases in outflow from D2 in 1996 (site preparation/bedding) and 1997 (planted) were 260 mm and 207 mm, respectively. This difference decreased to only 56 mm by the year 1999 when the trees were 2 years old. Although the outflow in 2000 was already lower by 31 mm than the expected, the trend continued to be opposite from 2001 to 2003. However, the increase of 116 mm of outflow from D2 again in the wettest year of 2003 (when planted trees were six years old) with 2388 mm of rainfall (on D2) (Table 1) was questionable due to frequent weir submergence. Otherwise, the increases observed in 2001 (8 mm) and 2002 (21 mm) may be within the limits of errors of the outflow measurements. By the year 2004 the increase was reversed with higher outflow from the control watershed than the watershed under regeneration. The effects of discrepancies in annual rainfall on expected outflows were assumed to be small and were not taken into account.

The annual average daily difference in outflow between the treatment watershed (D2) and the control (D1) for the 2.3-year (1988-90) calibration period, the harvesting period (1995-97), and regeneration period from 1998 to 2004 are presented in Figure 5. As the plot indicates the average daily difference was larger in first three years (1995-97) after harvest, which then decreased to a very small amount (0.01 mm) by 2002, except for the year 2000 with a pattern opposite to that of the calibration period. By year 2004 the observed difference was again similar to the calibration period. This annual analysis also supports the conclusion that the outflows came back to base line levels around in 2003 or soon thereafter.

Our results of increase in outflow soon after harvest clearly support the annual yield increase of over 250 mm, when all vegetation was removed, reported by Stednick (1996) for the eastern coastal plain hydrologic region. However, these increases are somewhat larger than those reported by Grace et al. (2003) and Lebo and Herrman (1998) for North Carolina coastal Plain, but smaller than those reported for short leaf pine and hardwood in the Mississippi Upper Coastal Plain (Grace, 2005). Although the pine trees planted in 1997 on the treatment watershed (D2) are about 8-9 m tall compared to the mature 25-26 m tall forest on the control (D1), the difference in water table elevations between the treatment and control seemed to close by 2003. This seemed to hold true for the drainage outflow as well. These data also indicate that the ET losses from these young pine trees may have been similar to that from the control by 2004, for which the measured LAI of 5.4 m^2 m^{-2} for the regenerated pine stand was close to 6.0 m^2 m^{-2} for the control. Most of the other studies on pine plantations and pine flatwoods (Xu et al., 2002; Lebo and Herrmann; 1998; Shepard,1994; Swindel et al., 1982) reported the hydrology returning back to base line levels within one to four years. Our results on this drained pine plantation site show longer periods than these reported data and are consistent with the study by Sun et al. (2000) for harvesting on cypress-pine flatwoods in Florida. These results also support the findings of Brown et al. (2005) who reported that depending on the changes in soil water storage and the transpiration-vegetation age characteristics of the new vegetation type, it takes longer than five years for a new hydrologic equilibrium to be established. However, factors such as deviations in rainfall between the watersheds and data extrapolation for some periods which had outlet weir submergence and instrument malfunction during this 10-year study may have somewhat affected these results.

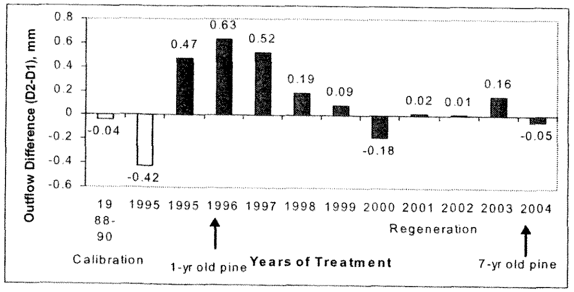

Figure 5. Difference of measured annual average daily outflows between the treatment (D2) and the control (D1) watersheds for the 1988-90 calibration period, the first-half of 1995, and 1995-2004.

Nutrients and Sediment:

Measured NO_3-N concentrations in water draining from watershed (D2) harvested in late June 1995 increased in later-half of 1995 (0.65 mg L^{-1}) and 1996 (0.51 mg L^{-1}) compared to 0.29 mg L^{-1} in 1995 and 0.33 mg L^{-1} in 1996 for the control (D1). These values were greater than 3.5 and 2 times than the expected values without harvesting of 0.19 mg L^{-1} in 1995 and 0.21 mg L^{-1} in 1996, respectively. However, by 1997 the measured value of 0.18 mg L^{-1} was already lower than the expected value of 0.33 mg L^{-1}. This decrease continued to be as low as 0.01 mg L^{-1} in 1999. The highest NO_3-N concentration of 1.63 mg L^{-1} occurred during the second drainage event after the harvesting. Similarly, TKN concentration of the harvested watershed also increased (0.39 mg L^{-1}) soon after harvesting in 1995 compared to the expected (0.24 mg L^{-1}). The highest TKN concentration of 1.11 mg L^{-1} was observed during the first event in August 1995 soon after the harvest. Only a slight increase of TKN persisted in 1996 and leveled off in 1997. However, there was about 50% increase (0.66 mg L^{-1}) again in 1998 compared to the expected value of 0.44 mg L^{-1}. This was perhaps due to a long dry period when organic N was accumulating from May to August, and was then flushed by a very large storm event during Hurricane Bonnie. The concentration in 1999 was the same as expected. The TP concentration increased by only 0.01 mg L^{-1} in 1995 after harvesting, but the increase was almost twofold (0.08 mg L^{-1}) in 1996 and 1997 compared to the expected (0.04 mg L^{-1}). Sediment concentration did not increase in later half of 1995 after the harvest. But both 1996 (5.4 mg L^{-1}) and 1997 (8.8 mg L^{-1}) yielded increased concentrations compared to the expected (4.92 mg L^{-1} in 1995 and 4.79 mg L^{-1}). By 1998 and 1999 the measured concentrations were again much lower than the expected.

Measured annual average NO_3-N concentrations from the third year (2000) after planting on watershed D2 were much lower than that on the control (D1) as well as expected values for D2 for all four years (2000-03) indicating no more effects of the treatment. The four-year average value of (0.05 ± 0.06) mg L^{-1} observed on D2 was also within the ranges of values published for other harvested drained pine forests in the same region (Lebo and Herrmann, 1998).

Measurement for TKN and sediment were not available in 2003. There was a decreasing trend in TKN concentrations with the expected values lower than the measured from 2000 to 2002 as the pine trees on watershed D2 grew. This may be due to decrease in organic nitrogen (TKN - NH_4), as under-story emerging vegetation continued to decrease with the growth of pine trees. However, the expected value in 2001 with a long dry summer and fall was somewhat greater than the measured perhaps due to very little nitrification caused by low flows. Annual TP concentration (0.03 ± 0.01) mg L^{-1} for the four-year period was almost the same as the expected value and less than half of those found by Lebo and Herrmann study. It was similar to that obtained in the calibration period (Amatya et al., 1998). Sediment concentrations were lower than their expected values and the observed on control watershed (D1). They were also lower than those reported by Lebo and Herrmann (1998). The lower 4-year average sediment concentration (8.2 ± 7.8) mg L^{-1} on treatment watershed (D2) compared to (19.8 ± 6.9) mg L^{-1} on the control (D1) was opposite of what was found during the calibration period. The reasons(s) for the trend of increasing sediment on watershed D1 since 1998 (Amatya et al., 2003) were not clear.

The fact that the nutrient and sediment concentrations came back to base line levels in nearly three years after harvest is consistent with other studies (Shepard, 1994; Lebo and Herrmann, 1998). Although TKN concentrations showed similar trends to NO_3-N, they tended to increase after a long dry period. The mean annual nutrient concentrations were below the calibration values and also the data by Chescheir et al. (2003). These concentrations are also well below the values for agricultural lands in the region (Amatya et al., 1998).

Comparison of the measured and expected watershed nutrient and sediment loadings for the post-harvesting, planting, and regeneration periods (1995-2004) is presented in Figure 6. Clearly, harvesting in early July 1995 increased both the nutrient (except for total P) and sediment loadings from the treatment watershed as shown by the higher measured loading compared to the expected. The increase in NO_3-N loading in 1996 was more than three-fold (4.5 kg/ha) (due to both increased outflow and concentration) compared to only 1.4 kg/ha expected (Fig.6). This was also larger than that measured for the calibration period. However, starting in 1997 like the concentration, the measured annual NO_3-N loading continued to be lower than both the expected and the base line levels through 2004. The very high rate of expected loading in 2000 was a combined result of high concentration (2 mg L^{-1}) and outflow that occurred in late July on the control watershed. This data indicates that harvesting a drained pine plantation has only a short-term effect on nitrate levels in its drainage outflow.

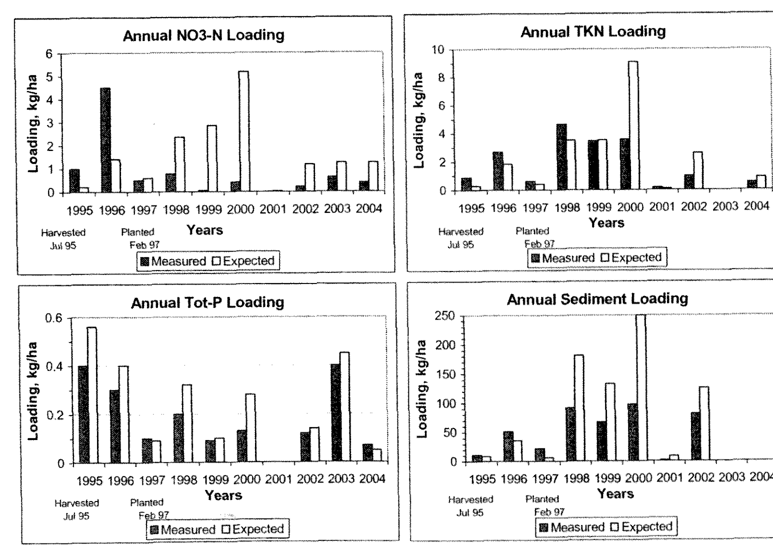

Figure 6. Measured and expected annual nutrient and sediment loadings for the treatment watershed (D2) for ten treatment years since the harvest in July 1995.

TKN loading increased about threefold (0.9 kg/ha) compared to the expected (0.29 kg/ha) soon after harvest in 1995 (Fig. 6). This increase persisted until 1998 after which it continued to decrease through 2004, except for the year 2001 with the lowest rainfall and outflow (Table 1). However, the measured loadings (> 3.6 kg/ha) from 1998 to 2000 were higher than those observed during the calibration period (Amatya et al., 1998). It may be speculated that by 2002 the 5-year old trees may have dominated the understory vegetation reducing the organic N contents in the soil litter. Measured annual total P loading was lower than the expected in all years since harvest, except for the years 1997, 2000, and 2004, which had some increase. This indicates that harvesting did not seem to have effect on total P loading. Increase in sediment loading was observed from 1995 to 1997 only, after which the measured loading was substantially lower than the expected. This was due to increasing trend of sediment concentration in the control watershed starting in1998. Sediment loadings have increased dramatically on both watersheds compared to the calibration period (Amatya et al, 1998) mainly due to increases in concentrations.

Annual loadings of both the total P and total N (NO_3-N + TKN) even after harvesting were within the published values for forested lands in eastern North Carolina (Chescheir et al., 2003). Although all nutrients loadings were lower than the expected by three years after planting on the harvested watershed, measured TP loadings on both the control and treatment were found to be higher than those observed during the calibration period (0.12 kg $ha^{-1}yr^{-1}$) (Amatya et al., 1998). NO_3-N loadings measured on D2 in 1996 (4.5 kg $ha^{-1}yr^{-1}$) soon after harvest and on the control in 2000 (8.0 kg $ha^{-1}yr^{-1}$) were higher than the average (3.4 kg $ha^{-1}yr^{-1}$) measured for the calibration period. TKN loading on the control (D1) exceeded the calibration period value of (4.9 kg $ha^{-1}yr^{-1}$) only once in 2000 (13.4 kg $ha^{-1}yr^{-1}$) due to both increased outflow (Table 1) and concentration.

Conclusions

This study period (1995-2004) recorded both the highest (2330 mm in 2003) and lowest (850 mm in 2001) annual rainfall of the 17-years (1988-2004) of record at this site. Harvesting raised the average daily water table elevation by as much as 22 cm compared to the control for a six-month period in the second year after harvest. The effects of harvesting on increased water table elevations persisted for five years after planting returning back to base line conditions by the sixth year. Water table elevation on this site was clearly dependent upon rainfall and ET as shown by the water table as deep as 1.8 m in the driest year 2001 to nearly zero (water table at the surface during wet year (2003).

Harvesting resulted in substantial increases in both the daily drainage rates and outflow volumes up to at least four years after which the increase declined. The first half-year increase in outflow in 1995 was as much as 91 mm followed by 260 mm in the wet year 1996. The peak drainage rate was seven-fold higher than the control for a summer event in 1996. The increase in outflow (> 50 mm) lasted for only four years after harvest. The effects were higher during the dry summer periods than the wet winter. Annual drainage outflows were affected by large storage created by deeper water tables during years with lower rainfall such as 2001 and 2002. Outflows on the treatment watershed (planted for regeneration) came back to baseline conditions by the end of six years after planting which is a longer recovery period than reported in the literature.

Both the nutrient and sediment concentrations and loadings (except for total P) measured on the treatment watershed were increased substantially soon after the harvest. However, the NO_3-N levels on the treatment watershed went back to base line levels within two years after harvest in 1997 when the trees were planted. Measured TKN levels were lower than the expected by 1999, two years after planting. Harvesting did not increase total P levels of the drainage water. Harvesting did affect sediment levels up to three years only, although the concentrations on both the control and treatment watersheds tended to be elevated compared to the calibration period. Results indicated that harvesting effects on water quality lasted for only about three years only.

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References

1. Amatya, D.M., R.W. Skaggs, J.W. Gilliam and J. E. Nettles. 2004. Effects of Regeneration on Hydrology and Water Quality of a Managed Pine Forest. Paper No. 04-2217, St. Joseph, Mich.: *ASAE.*
2. Amatya, D.M., R.W. Skaggs, J.W. Gilliam, and J.E. Hughes. 2003. Effects of an Orifice and a Weir on the Hydrology and Water Quality of a Drained Forested Watershed. *South. J. Appl. For.*, 27(2): 130-142.
3. Amatya, D.M., J.D. Gregory, and R.W. Skaggs. 2000. Effects of Controlled Drainage on the Storm Event Hydrology in a Loblolly Pine Plantation. *J. of the Amer. Water Resou. Assoc.* 36(1):175-190.
4. Amatya, D.M., J.W. Gilliam, R.W. Skaggs, M. Lebo, and R.G. Campbell. 1998. Effects of Controlled Drainage on Forest Water Quality. *J. of Environ. Quality* 27:923-935(1998).
5. Amatya, D.M., R.W. Skaggs, J.D. Gregory, and R.B. herrmann. 1997. Hydrology of a Forested Pocosin Watershed. *J. of American Water Resources Association.*, 33(3):535-546.
6. Amatya, D.M., R.W. Skaggs and J.D. Gregory. 1996. Effects of Controlled Drainage on the Hydrology of a Drained Pine Plantation in the North Carolina Coastal Plains. *J. of Hydrology*, 181(1996), 211-232.
7. Blanton, C.D., R.W. Skaggs, D.M. Amatya, and G.M. Chescheir. 1998. Soil Hydraulic Property Variations during Harvest and Regeneration of Drained Coastal Pine Plantations. Paper no. 982147, St. Joseph, Mich.: *ASAE.*
8. Brown, A.E., L. Zhang, T.A. McMohan, A.W. Western, and R.A. Vertessy. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *J. of Hydrology 310(2005):28-61.*
9. Chescheir, G.M., M.E. Lebo, D.M. Amatya, J. Hughes, J.W. Gilliam, R.W. Skaggs, and R.B. Herrmann. 2003. Hydrology and Water Quality of Forested Lands in Eastern North Carolina. Research Bulletin 320, North Carolina Agricultural Research Service, Raleigh, NC, 79 p.
10. EPA. 1993. Paired Watershed Design. Report No. 841-F-93-009, *United States Environmental Protection Agency*, Office of Water, Washington, D.C. 20460, 8 p.
11. Grace III, J.M. 2005. Forest Operations and Water Quality in the South. Forest Operations and Water Quality in the South. *Trans. of the ASAE*, 48(2):871-880.
12. Grace III, J.M., R.W. Skaggs., H.R. Malcom, G.M. Chescheir, and D,K. Kassel. 2003. Increased Water Yields Following Harvesting Operations on a Drained Coastal Watershed. ASAE Paper No. 032039, St. Joseph, Mich.: *ASAE.*
13. Lebo, M.E. and R.B. Herrmann. 1998. Harvest Impacts on Forest Outflow in Coastal North Carolina. a*J. of Environ. Quality*, 27:1382-1395 (1998).
14. McCarthy, E.J., R.W. Skaggs, and P. Farnum. 1991. Experimental determination of the hydrologic components of a drained forest watershed. *Trans. Amer. Soc. Agr. Eng.*, 34(5):2031-2039.
15. Riekerk, H. 1989. Influence of Silvicultural Practices on the Hydrology of Pine Flatwoods in Florida. *Water Resources Research*, 25(4):713-719.
16. Sampson, D.A., D.M. Amatya, C.D. Blanton, and R.W. Skaggs. 2006. The influence of emergent vegetation on LAI dominance during early stand development of drained loblolly

pine plantations. In: Abstract, *Proc. of the ASABE/Weyerhaeuser Int'l Conf. on Hydrology and Management of Forested Wetlands*, ed. Williams et al., April 8-12, 2006, New Bern, NC (in Press).

17. SAS 1994. SAS/STAT User's Guide. Volumes 1 & 2, 4th Ed., Vs 6, SAS Institute Inc., Cary, NC.

18. Shepard, J.P. 1994. Effects of Forest Management on Surface Water Quality in Wetland Forests. *Wetlands*, 14:18-26.

19. Skaggs, R.W., D.M. Amatya, G.M. Chescheir, C.D. Blanton, and J.W. Gilliam. 2006. Effect of Drainage and Management Practices on Hydrology of Pine Plantation. In: *Proc. of the ASABE/Weyerhaeuser Int'l Conf. on Hydrology and Management of Forested Wetlands*, ed. Williams et al., April 8-12, 2006, New Bern, NC (in Press).

20. SOFRA 2002. *Southern Forest Resource Assessment.* D.N. Wear and J.G. Greis (eds.), USDA Forest Service, Southern Research Station, Asheville, NC, September 2002.

21. Stednick, J.D. 1996. Monitoring the effects of timber harvest on annual water yield. *J. of Hydrology*, 176(1996): 79-95.

22. Sun, G., S.G. McNulty, J.P. Shepard, D.M. Amatya, H. Riekerk, N.B. Comerford, R.W. Skaggs, and L. Swift, Jr. 2001. Effects of Timber Management on Hydrology of Wetland Forests in the Southern United States. *Forest Ecology and Management*, 143(2001):227-236.

23. Sun, G., H. Riekerk, and L.V. Kornhak. 2000. Ground-Water Table Rise after Forest Harvesting on Cypress-Pine Flatwoods in Florida. *Wetlands*, 20(1):101-112.

24. Swank, W.T., J.M. Vose, and K.J. Elliott. 2001. Long-Term Hydrologic and Water Quality Responses Following Commercial Clearcutting of Mixed Hardwoods on a Southern Appalachian Catchment. *Forest Ecology and Management*, 143(2001):163-178.

25. Swindel, B.F., C.J. Lassiter, and H. Riekerk. 1982. Effects of Clearcutting and Site Preparation on Water Yields from Slash Pine Forests. For. Ecol. & Managem. 4:101-113.

26. Swindel, B.F., C.J. Lassiter, and H. Riekerk. 1983. Effects of Different Harvesting and Site Preparation Operations on the Peak Flows of Streams in *Pinus Elliotti* Flatwoods Forests. For. Ecol. & Managem. 5:77-86.

27. Ursic, S.J. 1991. Hydrologic Effects of Clearcutting and Stripcutting Loblolly Pine in the Coastal Plain. *Water Resources Bulletin*, 27(6):925-937.

28. Xu, Y.J., J.A. Burger, W.M. Aust, S.C. Patterson, M. Miwa, and D.P. Preston. 2002. Changes in Surface Water Table Depth and Soil Physical Properties after Harvest and Establishment of Loblolly Pine (*Pinus taeda* L.) in Atlantic Coastal Plain Wetlands of South Carolina. *Soil & Tillage Research*, 63(2002):109-121.