HYDROLOGIC AND WATER QUALITY EFFECTS OF THINNING LOBLOLLY PINE

J. M. Grace III, R. W. Skaggs, G. M. Chescheir

ABSTRACT. *Forest operations such as harvesting, thinning, and site preparation can affect the hydrologic behavior of watersheds on poorly drained soils. The influence of these operations conducted on organic soil sites can be more pronounced than on mineral soil sites due to the differences in bulk density and soil moisture relationships that exist between mineral and organic soils. This article reports the results of a study to evaluate the effect of thinning on the hydrology and water quality of an artificially drained pine plantation watershed on organic soils in eastern North Carolina. Outflow, water table depth, and water quality were monitored over a 3-year study period from paired 40 ha and 16 ha 15-year-old loblolly pine (*Pinus taeda *L.) plantations located in Washington County near Plymouth, North Carolina. Thinning increased daily outflow and peak flow rates based on a paired-watershed study design. Mean daily outflow doubled and peak flow rates increased 40% on the thinned watershed in relation to the control. Treatment effects were also observed on nutrient loads following the thinning operation. Phosphorous, TKN, and TSS loads increased following thinning, while nitrate-nitrogen loads decreased following thinning. These differences in hydrologic behavior are primarily attributed to the reduction in evapotranspiration that resulted from thinning.*

Keywords. *Drainage, Forest outflow, Organic soils, Peak flow,* Pinus taeda *L., Thinning, Water quality, Water table depth.*

Forest operations such as water management, site preparation, thinning, and harvesting are necessary elements in the management of pine plantation forest resources. Since the early 1900s, improved drainage has been a common water management strategy to increase productivity of poorly drained coastal forestlands in the southeastern U.S. Improved drainage is accomplished with a network of ditches or canals that lower the water table depth below the rooting zone of crops, thereby decreasing plant water stresses caused by excessive soil water. Drained pine plantations account for as much as one million hectares in the Coastal Plain Region of the U.S. (McCarthy and Skaggs, 1992). The influence of field operations in drained pine plantations can be quite different from that in their undrained counterparts due to differences in water table depth and soil water contents. Similarly, the hydrology of these drained lands is different from upland watersheds due to the relatively flat topography and fluctuating water table. Poorly drained soils typically have higher water tables and, in the case of organic surface soils, greater saturated water contents than upland mineral soils (Grace et al., 2006). However, most of our current knowledge of the effect of management operations on water quantity and quality is based on research conducted on upland systems. Impacts of thinning and harvesting on forest water yield (outflow) characteristics in artificially drained organic soils have not been extensively studied.

McCarthy et al. (1991, 1992) conducted simulation studies on the effects of thinning on the hydrology of drained loblolly pine (*Pinus taeda* L.) plantations on mineral soils in Carteret County, North Carolina. The investigators reported nearly a two-fold increase in predicted outflow following thinning operations. The investigators attributed increases in outflow to a 50% reduction in leaf area index (LAI), which effectively reduced ET and canopy interception.

In the flatwood pine landscape of the Lower Coastal Plain in Florida, Riekerk (1983) concluded that silvicultural practices had relatively little effect on water quality when compared to upland forest. However, forest management operations have been reported to affect annual and seasonal outflow characteristics from drained forest watersheds. Increases in forest outflow, nutrient concentrations, and suspended sediments can result from forest management activities (Amatya et al., 2000; Binkley and Brown, 1993; Chescheir et al., 2003; Lebo and Herrmann, 1998; Richardson and McCarthy, 1994; Shepard, 1994; Walbridge and Lockaby, 1994).

Increases in outflow and nutrient concentrations require special attention on poorly drained coastal watersheds due to their connectivity to sensitive receiving streams and estuaries. Therefore, the impact of forest management activities, such as thinning, on the hydrologic behavior of poorly drained coastal watersheds has received increased attention in recent years. Sustainability issues surround the cumulative effects of hydrologic and water quality changes resulting from tree removal on downstream systems. For instance,

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The authors are **Johnny McFero Grace, III, ASABE Member Engineer,** Research Engineer, U.S. Forest Service, Southern Research Station, Auburn University, Auburn, Alabama; **R. Wayne Skaggs, ASABE Fellow,** William Neal Reynolds Professor and Distinguished University Professor, and **George M. Chescheir, ASABE Member Engineer,** Research Assistant Professor, Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, North Carolina. **Corresponding author:** Johnny McFero Grace III, U.S. Forest Service, G. W. Andrews Forestry Sciences Laboratory, 520 Devall Dr., Auburn University, Auburn, AL 36849; phone: 334-826-8700; fax: 334-821-0037; e-mail: jmgrace@fs.fed.us.

nonpoint-source inputs of nutrients are identified as a source of potential problems for streams and estuaries. There is a gap in our current understanding of the effect of thinning operations on forest outflow quantity and quality in drained coastal forests. Information to quantify the impact of thinning operations on organic soil watersheds is also lacking. The study described here investigated the effect of thinning on water quality and quantity from a drained, organic soil forested watershed in North Carolina. The objective of this study was to evaluate the effects of thinning on outflow, water table response, and water quality from a drained pine plantation watershed with organic surface soils.

Materials and Methods

Site Description

The study site is part of a large watershed project (~10,000 ha) located at approximately 35° 50′ N latitude and 76° 40′ W longitude in Washington County near Plymouth, North Carolina, on the Lower Coastal Plain (fig. 1). The artificially drained 15-year-old loblolly pine plantation used in this study is owned and managed by Weyerhaeuser Company. The watershed is drained by parallel lateral ditches of 0.9 to 1.3 m depth spaced 100 m apart. The watershed is surrounded on three sides by various-age loblolly pine plantations and by a mature hardwood stand on the fourth side. In 1999, the study watershed was divided into 40 and 16 ha subwatersheds by blocking collector canals with earthen plugs. The larger 40 ha watershed served as the treatment watershed and the 16 ha watershed served as the control watershed, hereafter referred to as WS5 and WS2, respectively (fig. 2).

Soil properties of the profile by horizon (O_a, A, B, and C) were characterized by taking replicate soil cores for each layer from three randomly located soil pits within each subwatershed (Grace, 2004). Soil water characteristics, saturated hydraulic conductivity, drainable porosity, and bulk density were determined by laboratory analysis of collected soil cores. The soils in the study watersheds are organic consisting primarily of the Belhaven series (SCS, 1981). The soil surface layer (60 cm in depth) has a total porosity greater than 0.75 cm^3/cm^3 and organic matter content greater than 80%.

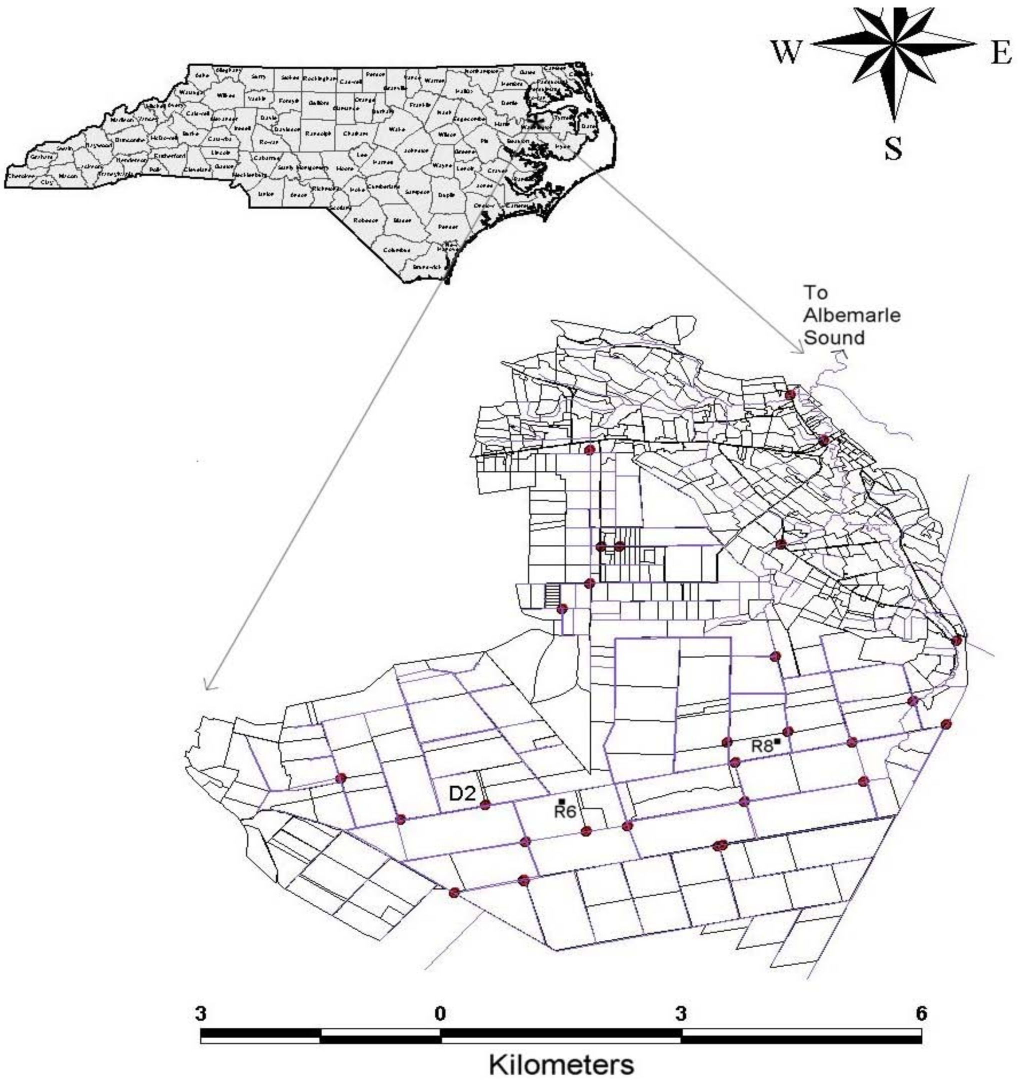

Figure 1. Large watershed containing the original plantation watershed D2 (which was divided into WS2 and WS5), canal network, and weather stations (R6 and R8).

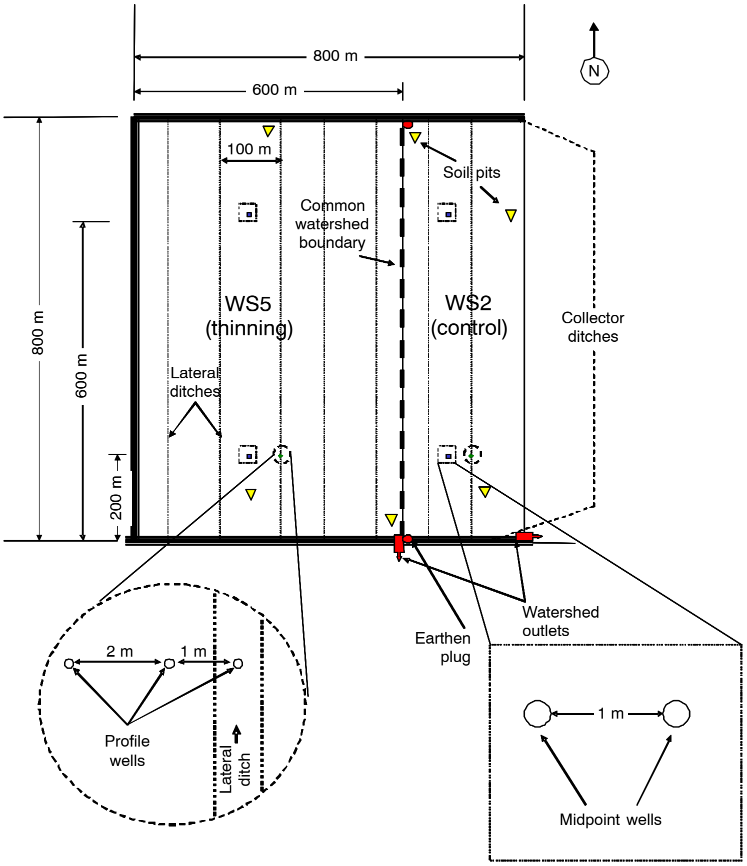

Figure 2. Paired watershed design with typical locations of water table wells, soil pits, and watershed outlets.

TREATMENT AND THINNING SYSTEM CHARACTERISTICS

WS5 received a fifth-row with selection thinning treatment in April 2001 (days 93 to 115). The remaining WS2 subwatershed served as the un-thinned control. In the fifth-row with selection thinning method, every fifth row is removed, creating a corridor for access, and trees are selected for removal between the corridors. The thinning operation was accomplished with a feller buncher, two grapple skidders, and a loader. The entire thinning was serviced by a deck located at the western watershed boundary. A primary skid trail, the length of the watershed (east to west), serviced intermediate skid trails between lateral ditches. The stand was thinned from an estimated 1060 trees per hectare and basal area of 39 m^2/ha to 320 trees per hectare and basal area of 12 m^2/ha.

STUDY MEASUREMENTS

In 1995, a 120° V-notch weir located in a riser barrel structure was installed at the outlet draining the original watershed. In 1999, the watershed was divided by installing an additional 120° V-notch weir at a 113 cm depth below ground level at the outlet draining the newly defined treatment watershed (WS5). Upstream and downstream stages were recorded with submerged probe pressure transducers and a data logger in conjunction with Stevens recorders. Backup measurements of stage were recorded using ultrasonic water level loggers.

Water table depths were continuously measured during a calibration period from November 1999 to April 2001 and during a treatment period from May 2001 to December 2002 with submerged pressure transducers at replicate midpoint wells and three profile wells (fig. 2). Water table wells were located at the midpoint between two successive lateral ditches for each watershed. Midpoint water table depth was determined as the average of midpoint water table depth measurements for each watershed for a given time. Profile wells were located on opposite sides of the watersheds at distances of 0, 1, and 3 m from a ditch within each watershed. Hourly water table depths were recorded throughout the study period by data loggers located at each of the well stations.

Outflow was monitored during the calibration and treatment periods for both watersheds. Storm water samplers were used to collect a composite of 500 mL subsamples taken for each millimeter of watershed outflow. At the conclusion of storm events, 500 mL grab samples were taken from the composite storm water samples following agitation. Grab samples were placed in an ice bath and transported to the laboratory for nutrient analysis. Storm water samples were analyzed for total Kjeldahl N (TKN), nitrate + nitrite-nitrogen (NO_3-N), ammonium-nitrogen (NH_4-N), total phosphorus (TP), orthophosphate (OP), total suspended solids (TSS), and pH. Analysis of TKN (macro Kjeldahl method), NO_3-N (cadmium reduction method), NH_4-N (automated phenol method), TP (persulfate digestion method followed by ascorbic acid method), and OP (ascorbic acid method) were determined using Standard Method 4500 defined by the APHA (1995). Analysis of TSS was determined through gravimetric filtration by standard methods, i.e., an unfiltered sample was filtered through a Millipore AP40 series (or Gelman type) glass fiber filter (APHA, 1995). Precipitation was measured with tipping-bucket rain sensors in combination with data loggers located within 0.5 km of the paired watersheds (fig. 1).

Data Analysis Methods

Outflow was determined using instantaneous stage measurements upstream and downstream of the outlet weir. Average nutrient concentrations (TKN, NO_3-N, NH_4-N, TP, OP, and TSS) and corresponding outflow depths for events were used to determine nutrient load from study watersheds. Rainfall events during the study period were associated with an outflow event and/or water table recharge occurrence. In some instances, outflow events were attributed to a combination of several rainfall events. In this analysis, outflow events were defined as storm events that produced distinguishable hydrographs in the watersheds. Distinguishable hydrographs were taken as hydrographs representing a minimum of 1.0 mm of drainage depth from the watershed of interest. Upon identification of outflow events, the corresponding outflow records were identified on the paired watershed and used in the analysis of daily outflow (outflows), peak flow, water table depth, and nutrient load.

A paired watershed approach was used to perform statistical analyses to determine the effect of thinning operations on forest outflow and water table depth by methods defined by USEPA (1993; 1997) and Loftis et al. (2001). The underlying model for the paired watershed approach is given by equations 1 and 2:

$$Y_1 = B_0 + B_1X_1 + \varepsilon \qquad (1)$$

$$Y_2 = (B_0 + B_2) + (B_1 + B_3)X_2 + \varepsilon \qquad (2)$$

where Y_1 and X_1 are daily outflows from the treatment and control watersheds, respectively, during the calibration period, Y_2 and X_2 are daily outflows from the treatment and control watersheds during the treatment period, B_0 and B_1 are the calibration period intercept and slope, B_2 and B_3 are the adjustments to the intercept and slope for the treatment period, and ε is the independent error term. In the paired watershed approach, a significant difference in slopes or intercepts of regression relationships between calibration and treatment periods indicates treatment effects on the response variable. Water table depth and nutrient load were substituted for outflow variables in equations 1 and 2 for analysis of water table depth and water quality effects of thinning. Differences in watershed areas in analysis were adjusted by analyzing on an outflow per unit area basis.

Storm event outflow data from the paired watershed design were analyzed using SAS (1991) PROC REG procedures to develop regression relationships for each watershed for daily outflow, peak outflow, and nutrient loads during calibration and treatment periods. Water table depths during the calibration and treatment periods were also analyzed using SAS PROC REG to develop relationships for the two periods. Analysis of variance (ANOVA) was performed on the resulting slopes and intercepts from regression relationships for 11 calibration period and 17 treatment period storm events using SAS (1991) GLM procedures. The null hypothesis is that there is no difference in the regression relationships for daily outflow, peak flow, water table depths, and nutrient loads from the watersheds during the calibration and treatment periods.

Results and Discussion

Annual outflow and precipitation for the plantation watersheds during the three study years (2000-2002) are presented in table 1, with the exclusion of four brief periods of weir submergence. Periods of weir submergence were observed during days 119-124, 248-254, and 269-271 in 2000 and during days 317-325 in 2002. The canal drainage system was overwhelmed during these submergence periods, which resulted in downstream stages rising above the invert of the weirs throughout the system. Outflow estimations during these periods of submergence raised concerns about errors inherent in submerged weir equations. Submerged conditions existed for a total of 13 days for WS2 and 10 days for WS5. Submerged periods during the 3-year study period were excluded from the analysis and comparisons of outflows and nutrient loads due to possible errors from overestimation of outflow.

Annual precipitation depths during 2000 and 2002 were similar to the long-term average annual precipitation of 1280 mm (1951-2001) for Plymouth, North Carolina. Precipitation during 2001 was only 760 mm, making it one of the driest years on record for this location. Prior to 2001, the driest year on record was 1970, with an annual precipitation totaling 907 mm. Observed precipitation for 2001 was 35% less than for 2000 and 45% less than observed precipitation for 2002.

Figure 3 presents cumulative and daily outflow, water table depth, and cumulative precipitation for WS2 and WS5 for each of the three study years (2000-2002). WS5 event drainage outflow was slightly greater than WS2 outflow during the primary flow season of 2000 (fig. 3). This coincided with the period when the WS5 weir setting was 28 cm deeper than the WS2 weir. After the WS5 weir was set at 85 cm to match the WS2 weir setting (in June 2000), WS2 event outflow was greater than WS5 until thinning, which took place in April 2001. This period between raising the WS5 weir to match the WS2 setting and completion of the thinning operation on day 115 in 2001 was used as the calibration period in this experiment. Cumulative drainage during the calibration period was 77 mm for WS2 and 60 mm for WS5. The outflow pattern shifted between the two

Table 1. Weir settings, elevation, annual outflow, and precipitation summary for WS2 (control) and WS5 (treatment) watersheds during the study period.

	Flow Year		
Description	2000[a]	2001	2002[b]
WS2 (control)			
Weir setting[c] (cm)	85	85	85
Average ground elevation (m)	5.44	5.44	5.44
Outflow (mm)	144	20	168
Precipitation (mm)	1160	756	1378
WS5 (treatment)			
Weir setting[c] (cm)	113 / 85[d]	85	85
Average ground elevation (m)	5.64	5.64	5.64
Outflow (mm)	151	31	326
Precipitation (mm)	1160	756	1378

[a] Outflow for days 119-124, 248-254, and 269-271 excluded due to weir submergence.

[b] Outflow for days 317-325 excluded due to weir submergence.

[c] Weir setting depth below average ground surface elevation.

[d] Weir setting raised to 85 cm below average ground surface during the summer of 2000 (day 166).

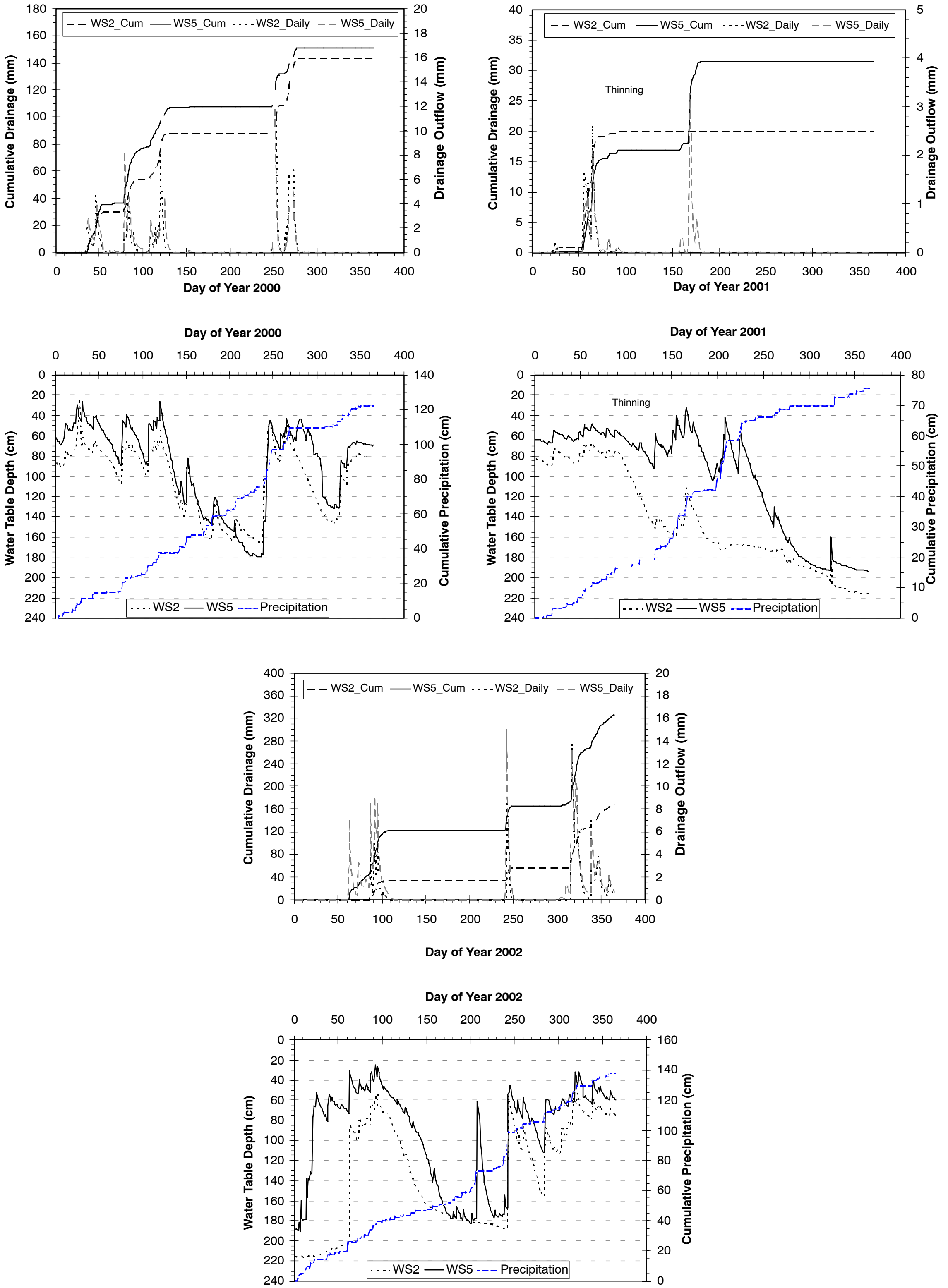

Figure 3. Observed outflow, water table depth, and precipitation for the WS2 (control) and the WS5 (treatment) watersheds during each study year (2000-2002).

watersheds following the thinning operation. That is, event drainage outflow in 2001 following the thinning operation as well as during 2002 was greater for WS5 than for WS2 (fig. 3). The thinned watershed (WS5) also produced outflow 24 days earlier during 2002 than did the control (WS2) watershed. Greater ET from the control (WS2) in the summer and fall of 2001 apparently caused the water table to be deeper and the watershed to be drier than the thinned WS5 site (fig. 3). Thus, more recharge was required to raise the water table on WS2 and initiate outflow in comparison with WS5. These trends were

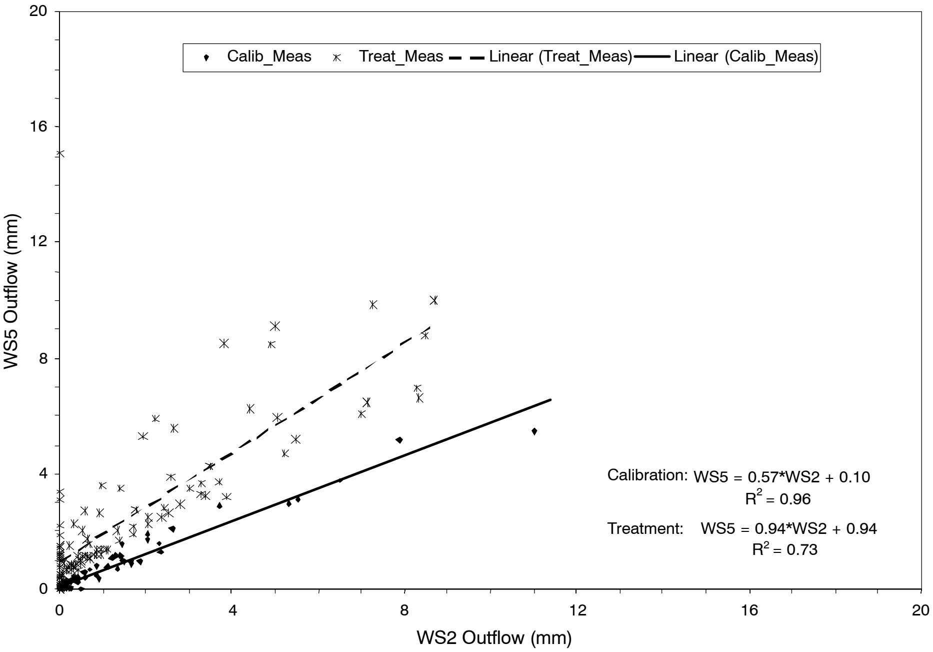

Figure 4. Regression relationships for measured daily outflow of the WS2 (control) and WS5 (treatment) watersheds during the calibration and treatment periods.

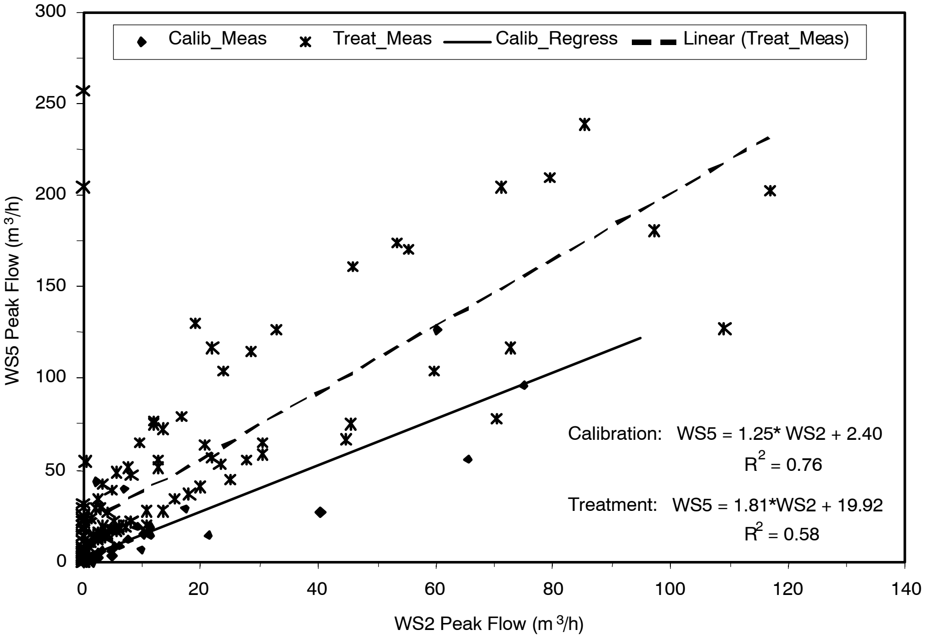

Figure 5. Regression relationships for measured peak flow of the WS2 (control) and WS5 (treatment) watersheds during the calibration and treatment periods.

statistically tested to detect treatment effects on the hydrology; the analysis is presented in the next section.

REGRESSION ANALYSIS

During the calibration period, flow was observed a total of 76 and 70 days for the WS2 and WS5 watersheds, respectively. During the treatment period, flow was observed from WS2 on 107 days, as compared to 170 days for WS5. A total of 28 outflow events were identified on the plantation watersheds over the 3-year (2000-2002) observation period. Eleven of these events occurred during the calibration period, and the remaining 17 events occurred during the treatment period. Daily outflows and peak flow for each event were used in the development of regression relationships for the watersheds. Regression relationships were developed by regressing outflows from the treatment (WS5) watershed versus outflows from the control (WS2) watershed for both the calibration and treatment periods (figs. 4 and 5). Daily outflows during the calibration period were highly correlated between the watersheds, with an R^2 value of 0.96 (table 2). WS5 peak flow showed a moderate correlation with WS2 peak flow during the calibration period. The daily outflow and peak flow calibration regression relationships developed between the watersheds were significant at $p < 0.0001$.

Table 2. Outflow and water table depth (WTD) regression relationships between WS5 and WS2 watersheds for calibration and treatment periods.

Period	Regression Equation	*N*	Regression R^2	Regression F-value[a]	P-Value Slope	P-Value Intercept
Calibration	WS5_Flow = 0.57 × WS2_Flow + 0.10	70	0.96	722*	<0.0001	0.027
	WS5_Peak = 1.25 × WS2 + 2.40	69	0.76	277*	<0.0001	0.14
	WS5_WTD = 1.18 × WS2_WTD − 46.1	294	0.86	1220*	<0.0001	<0.0001
Treatment	WS5_Flow = 0.94 × WS2_Flow + 0.94	107	0.73	2140*	<0.0001	<0.0001
	WS5_Peak = 1.81 × WS2 + 19.9	107	0.58	1160*	<0.0001	<0.0001
	WS5_WTD = 0.78 × WS2_WTD − 13.4	418	0.55	1421*	<0.0001	<0.0001

[a] * indicates significance of the regression model for the given period at the <0.0001 level.

Regression analysis showed a moderate correlation between WS5 and WS2 daily outflows during the treatment period, as evidenced by an R^2 of 0.73 (table 2). The regression model to predict outflow from WS5 based on WS2 outflow was highly significant at $p < 0.0001$. Both the slope and intercept of the regression relationship were significant at $p < 0.0001$. The highly significant regression relationships between outflows from the study watersheds for both calibration and treatment periods suggest that the paired watershed approach could be used to test for treatment effects on outflow parameters in this investigation.

Water table depths were grouped by period for regression analysis to test for a regression relationship between WS2 and WS5. Twelve months of water table depth data were recorded during the calibration period, and an additional 20 months were recorded for the treatment period. A highly significant ($p < 0.0001$) regression relationship was developed between the watersheds for the calibration and treatment periods (fig. 6). The calibration period regression ($R^2 = 0.86$) indicates that WS5 and WS2 water table depths were highly correlated; however, correlation between WS5 and WS2 water table depths during the treatment period was low, with an $R^2 = 0.55$.

Regression relationships were developed for 11 outflow events during the calibration period and 17 outflow events during the treatment period. Slopes for calibration and treatment periods were detected by ANOVA as significantly different (table 3), indicating a treatment effect on daily outflow. Daily outflow had a mean slope during the treatment period of 1.39, which was twice the calibration period slope of 0.58. Daily outflows from WS5 doubled during the treatment period in relation to daily outflows from the control watershed. Intercepts of the daily outflow regression relationships during the treatment period were also greater than during the calibration period. Peak flow regression intercepts of 2.10 and 17.9 m^3/h for the calibration and treatment periods were also significantly different (table 3). Similar to daily outflow results, peak flow rates increased more than two-fold on WS5 following thinning in relation to WS2. The removal of trees decreased ET from WS5, which resulted in a wetter soil profile. In contrast, the increased number of trees on WS2 dried out the soil profile, which increased storage and resulted in less outflow from rainfall events. The observed increases in the water yield following thinning are consistent with the findings of other researchers (McCarthy

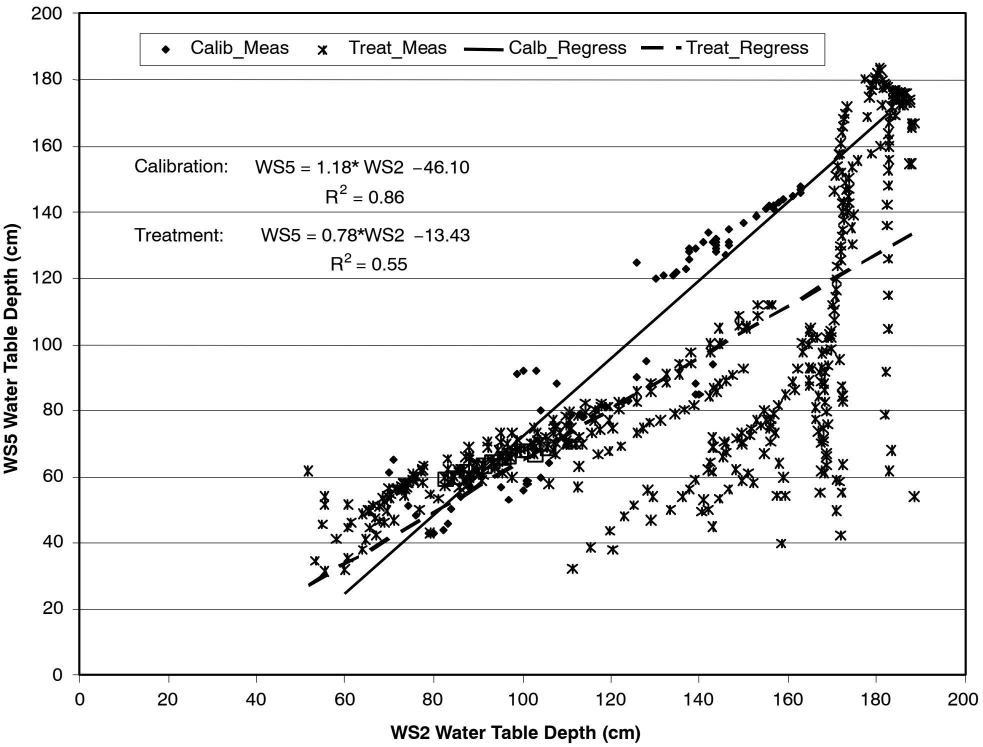

Figure 6. Regression relationships for measured water table depths of the WS2 (control) and WS5 (treatment) watersheds during the calibration and treatment periods.

Table 3. Regression slopes and intercepts for WS5 and WS2 watersheds during the calibration and treatment periods.

Parameter		Calibration Mean	Treatment Mean[a]
Daily outflow (mm)	Regression slope	0.58	1.39*
	Regression intercept	0.07	0.73*
Peak flow (m^3/h)	Regression slope	1.06	2.99
	Regression intercept	2.10	17.9*
Water table depth (cm)	Regression slope	0.79	0.83
	Regression intercept	−1.79	−21.8

[a] * indicates a significant difference during the treatment period at the 0.05 level.

Table 4. Total phosphorus load (TP and OP), nitrogen load (NH_4-N, NO_3-N, and TKN), and sediment load (TSS) in kg/ha from WS2 and WS5 for the calibration and treatment periods.

	Total Nutrient Load (kg/ha)					
	TP	OP	NH_4-N	NO_3-N	TKN	TSS
Calibration period						
WS2	0.02	0.01	0.14	0.70	1.49	13.1
WS5	0.02	0.02	0.19	2.05	1.72	21.9
Treatment period						
WS2	0.03	0.01	0.12	4.84	3.68	63.4
WS5	0.04	0.03	0.22	4.97	5.79	101.6

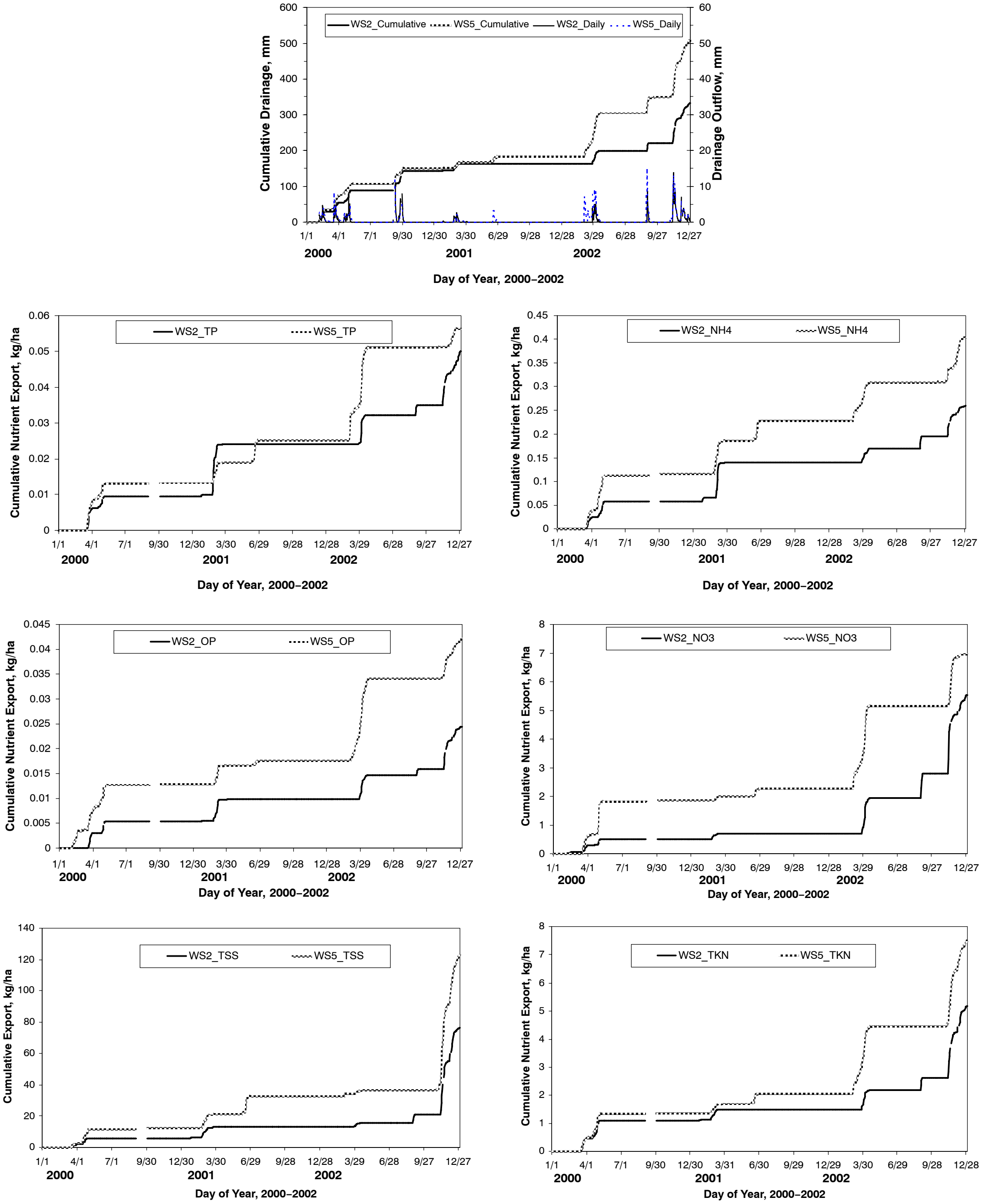

Figure 7. Cumulative phosphorus load (TP and OP), nitrogen load (NH_4-N, NO_3-N, and TKN), and sediment load (TSS) in kg/ha presented along with daily and cumulative outflow (in mm) from WS2 and WS5 for the 3-year study period (2000-2002).

and Skaggs, 1992; Richardson and McCarthy, 1994; Williams and Lipscomb, 1981).

Water table depth regression relationships were developed for storm events in both study periods (table 3). The regression slope of 0.83 for the treatment period was not significantly different from the calibration period slope of 0.79 (p = 0.75, F = 0.11). The difference between the intercepts for the calibration and treatment periods was not statistically significant (p = 0.19, F = 1.93). An analysis of the mechanisms affecting water table depth, and of observed water table responses in both treatment and control watersheds, indicates that thinning had an effect on water table depth during the periods of high ET, i.e., late spring and summer. However, there appears to be negligible effect during wet periods when PET is low, as would be expected, and a treatment effect on water table cannot be detected using the regression relationships between the calibration and treatment periods in the paired watershed approach.

WATER QUALITY

Nutrient loads per watershed area (kg/ha) were determined as a product of daily outflow and nutrient concentrations for watersheds during each period. Table 4 presents total nutrient loads for each study period for all nutrient constituents considered. Figure 7 presents cumulative phosphorus load (TP and OP), nitrogen load (NH_4-N, NO_3-N, and TKN), and sediment load (TSS) in kg/ha along with daily outflow in mm for each watershed.

The presence of thinning treatment effects on nutrient loads draining from the study watershed was evaluated using the paired watershed approach. Nutrient loads were determined for each of the 28 outflow events observed during the study period (11 calibration events and 17 treatment events). The analysis performed was similar to the analysis of outflow and water table depths discussed earlier in this article. Mean nutrient load for WS5 was regressed with mean nutrient load for the WS2 watershed for each of the aforementioned nutrients (table 5) using SAS PROC REG procedures. Regression slopes and intercepts for nutrient constituents were tested using SAS GLM procedures for differences.

TP regression slopes and intercepts were significantly greater during the treatment period than during the calibration period (p = 0.048). TP load increased during the treatment period in comparison to the calibration period for WS5. In addition, a significant treatment effect also existed in OP loads from the watersheds, indicated by differences in the intercepts (p = 0.003) between the two periods. Similar to the TP results, OP load significantly increased on the WS5 watershed following the thinning operation in relation to WS2 OP. These differences in phosphorus load can likely be attributed to differences in outflows following thinning; however, phosphorus loads from the thinned watershed are less than the values reported for agricultural lands in eastern North Carolina (Evans et al., 1995; Chescheir et al., 2003).

Table 5. Regression slopes and intercepts for nutrient load from WS5 and WS2 watersheds during the calibration and treatment periods.

	Parameter	Calibration Mean	Treatment Mean	P value[a]
TP	Regression slope	0.650	1.15	0.048*
	Regression intercept	0.007	0.137	0.048*
OP	Regression slope	0.946	0.671	0.375
	Regression intercept	−0.003	0.072	0.003*
NH_4−N	Regression slope	0.802	1.76	0.223
	Regression intercept	0.502	0.784	0.425
NO_3−N	Regression slope	3.02	0.45	0.026*
	Regression intercept	0.795	12.7	0.138
TKN	Regression slope	0.975	2.64	0.406
	Regression intercept	−3.33	18.7	0.013*
TSS	Regression slope	0.976	0.977	0.997
	Regression intercept	−24.4	304	0.006*

[a] * indicates a significant difference in mean values for a given constituent at the 0.05 level.

Consistent with results found for phosphorous load, treatment effects were also found with nitrate and TKN fractions of nitrogen. The nitrate load regression relationship during the calibration period was significantly different from the treatment period relationship, indicating a significant decrease in WS5 nitrate load following thinning. Similarly, the regression relationships between the calibration and treatment periods were detected as significantly different in the analysis of TKN loads. The treatment period mean regression intercept was 18.7 and significantly greater than the calibration period mean intercept of −3.33. Based on this analysis, the thinning operation resulted in increased TKN load from WS5. Conversely, the analysis found that there was no significant difference in ammonium load for the two watersheds between the calibration and treatment periods.

Sediment load increased from the treatment and control watersheds during the treatment period in comparison to the calibration period. Analysis found a significant increase (p = 0.006) in sediment load regression intercepts between WS2 and WS5 (table 5), indicating treatment effects on sediment load from WS5. Sediment load significantly increased following the thinning on the treatment watershed. While the analysis of sediment loads revealed that thinning increased sediment losses compared to the control, sediment load from these flat forested watersheds was very small. Sediment losses are normally measured in tons per hectare rather than kilograms per hectare. The losses measured here (58 kg ha^{-1} $year^{-1}$) are less than previously reported losses following harvesting (1.0 to 1.5 t ha^{-1} $year^{-1}$) from upland watersheds in the southern U.S. (Grace, 2005).

With the exception of OP, the significant increases in nutrients from the thinned forest site were observed for those nutrients that are usually bound to TSS and exported from a field by surface runoff. Surface runoff, however, is not expected from these forested sites due to high surface storage and high soil hydraulic conductivities. Although higher water tables were observed on the thinned site, the water table was never observed at or above the soil surface at this site. The more likely sources for TSS are the ditch banks and the area immediately adjacent to the ditches. These areas were probably wetter for longer periods of time at the thinned site than at the control site due to increased drainage from the thinned site. These areas are very small compared to the areas of the entire fields, and thus only a small increase in TSS and nutrients associated to TSS was observed.

CONCLUSIONS

The hydrologic impact of thinning a 40 ha 15-year-old loblolly pine plantation was evaluated using a paired watershed approach. The investigation was conducted on organic soil sites with organic matter content greater than 80% in eastern North Carolina. The effects of thinning on daily outflow, peak flow, water table depths, and nutrient load (water quality) were evaluated over a calibration period from December 1999 to April 2001 and a treatment period from May 2001 to December 2002.

Regression analysis for daily outflow, peak flow, water table depth, and nutrient load from the paired plantation watersheds revealed significant relationships between the paired watersheds. Mean daily outflow and peak flow doubled on WS5 following the thinning operation in comparison to the outflow response from WS2. Regression analysis of water table depths during the calibration and treatment periods detected significant regression relationships between the WS2 and WS5 watersheds. Thinning appeared to reduce water table depth during and following periods of high PET; however, no significant treatment effects on water table depths were detected using the paired watershed approach, since water tables on both watersheds were similarly high during wet periods with low PET.

Findings indicate that phosphorous, sediment, and TKN loads increased significantly during the treatment period following the thinning operation. However, increases in load can be primarily attributed to increases in water yield following thinning (Grace, 2004). Surprisingly, nitrate load decreased on the thinned watershed in comparison to the control during the treatment period. The treatment effects found in this water quality investigation, although significant, are not likely to adversely impact water quality downstream. The elevated nutrient constituents found here are similar to other forest operations based on a review of watershed-scale research in the southern U.S. (Grace, 2005) and less than typically observed from agricultural lands (Evans et al., 1995; Chescheir et al., 2003). However, these results indicate that addressing nonpoint source issues related to forest operations on artificially drained lands require additional research to establish the effect of these operations on water quality and evaluate of the effectiveness of BMPs in reducing impacts.

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