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Influence of Thinning Operations on the Hydrology of a Drained Coastal Plantation Watershed

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Abstract. *Forest management activities such as harvesting, thinning, and site preparation can affect the hydrologic behavior of watersheds on poorly drained soils. The effects of thinning on hydrology are presented for an artificially drained pine plantation paired watershed in eastern North Carolina. Outflow and water table depths were monitored over a 3-year study period from paired 40- and 16-ha 15-year old loblolly pine (Pinus taeda L.) plantations located in Washington County near Plymouth, North Carolina. Thinning increased daily outflow, peak flow rates, and had no significant impact on water table depths. Mean daily outflow doubled and peak flow rates increased 40 percent on the* *thinned watershed in relation to the control. These differences in hydrologic behavior are primarily attributed to the thinning operation which resulted in reduced evapotranspiration.*

Keywords. *Pinus taeda L.*, thinning, forest outflow, water table depth, peak flow.

Introduction

Forest operations are a necessary element in the management of forest resources for ecological, economic, and social viability. Forest operations, as with any human intervention to natural systems, can impact ecological processes and future conditions. In the past 25 years, increased concern has arisen regarding the potential impacts of forest operations on the environment, specifically hydrology and water quality. It is this increased sensitivity to water quality impacts of forest operations that has been a part of the demands for sustainable forest management.

Implementing ecologically acceptable techniques and technologies in forest operations is dependent on a sufficient understanding of physical and biological processes in forested lands. Most of the research on the effects of forest management on forested watershed outflow has been conducted on upland sites. However, pine plantations that have been drained account for as much as 1 million hectares in the coastal plain region of the United States (McCarthy and Skaggs 1992). Drainage to improve productivity and trafficability is a common form of water management in poorly drained coastal forestland in the southern U.S.

An intensive study was established to evaluate effects of alternative forest management activities and to develop models to describe the hydrology was conducted on 75-ha (sub-divided into three 25-ha watersheds) drained loblolly pine (*Pinus taeda L.*) plantation in Carteret County, North Carolina (McCarthy et al. 1991; McCarthy and Skaggs 1992; Amatya et al. 1996, 1998, 2000). The watersheds were relatively flat, having shallow water table mineral soils with open ditch drains 1.4-m deep and spaced 100-m apart. Management practices of bedding, fertilization, controlled drainage, and thinning were evaluated on the three drained pine plantations. McCarthy and others (1991, 1992) conducted modeling studies of the effects of thinning on the hydrology of these watersheds. The investigators reported nearly a two-fold increase in drainage losses following thinning operations. The investigators attributed increases in outflows to a 50 percent reduction in leaf area index (LAI) which effectively reduced ET and canopy interception. Drainage water concentrations of NH_4-N, NO_2-N, NO_3-N, TKN, PO_4-P, TP, pH, BOD, fecal coliform, turbidity, and TSS, at several sampling locations were compared to determine water quality effects of management practices. Concentrations of NH_4-N, BOD, turbidity, fecal coliform, PO_4-P, TSS, and pH at the watershed outlets were similar to concentrations at other sampling locations. Drainage water in ditches was diluted by the water draining from plantations and was improved from an environmental standpoint.

While there are only a few studies of hydraulic and water quality impacts of thinning reported in the literature, a number of studies have been conducted to quantify effects of other operations on pine plantations, namely harvesting. Riekerk (1983) investigated the impact of silviculture on runoff and water quality on poorly drained sandy flatwood soils of the Lower Coastal Plain in Florida. Two management regimes were investigated after a clear-cut harvest; minimum and maximum practices. The minimum practices consisted of two successive drum chops, bedding, and planting. Maximum practices included stump removal, burn, windrow, harrow, bedding, and planting. The minimum and maximum practices increased annual runoff yields by 210 and 130 mm/yr, respectively, compared to the undisturbed control (70 mm/yr). Runoff yields were not significantly different ($\alpha = 0.10$) from control levels by the second treatment year.

Clearcutting and site preparation effects on forest water from lowland slash pine (*Pinus elliottii*) forests on poorly drained soils of the Lower Coastal Plain in north Florida were investigated in a 3 ½ -year study (Swindel et al. 1982, 1983a, 1983b). Three watersheds were established on a flatwoods landscape by building up existing roads and constructing new roads to form artificial dikes. Management practices for each of the three watersheds were: 1) clear-cut harvest with labor-intensive methods, 2) clear-cut harvest and site preparation with mechanized equipment, and 3) control. Both management practices significantly increased water yield from the delineated watersheds, with the magnitude proportional to the intensity of the management practice. Monthly yield increases occurred following harvest and site preparation for the labor intensive management practice, but yields returned to normal within the first year following completion of practices. Water yield increased on the mechanized-harvest watershed immediately after the prescription and was much greater than the less intensive practices. The effect of the mechanized harvest on water yield was still observed during the second year.

Accomplishing the goal of managing the forest resource for multiple uses will first require a better understanding of the impacts of thinning management activities on drained forest watersheds. This paper presents results of the effect of thinning on water table response and outflow characteristics on an artificially drained organic watershed in eastern North Carolina.

Methodology

Site Description

The study site is part of a large watershed project (~10,000 ha) located at approximately 35° North latitude and 76° West longitude in Washington County near Plymouth, North Carolina on the Lower Coastal Plain (Figure 1). An artificially drained 15-year-old loblolly pine plantation on a 56-ha experimental watershed in this study is owned and managed by Weyerhaeuser Company (referred to as the original watershed). The site is poorly drained and nearly flat, with a shallow water table under natural conditions. The watershed is isolated into an individual forest block by a network of roads and a series of drainage ditches. The watershed is drained by parallel lateral ditches of 0.9 to 1.3-m depth spaced 100-m apart. The watershed is surrounded by various age loblolly pine plantations on three sides and a mature natural (hardwood) stand on the other.

In 1999, the original study watershed was divided into 40- and 16-ha sub-watersheds using an earthen plug in the collector canals. The larger 40-ha watershed (WS5) served as the treatment watershed and the 16-ha watershed (WS2) served as the control watershed (Figure 2). The soils in the study watersheds are organic consisting of primarily the Belhaven series (SCS 1981). The total porosity is greater than 0.75 cm^3/cm^3 and organic matter content greater than 80 percent in the top 60 cm of the soil profile.

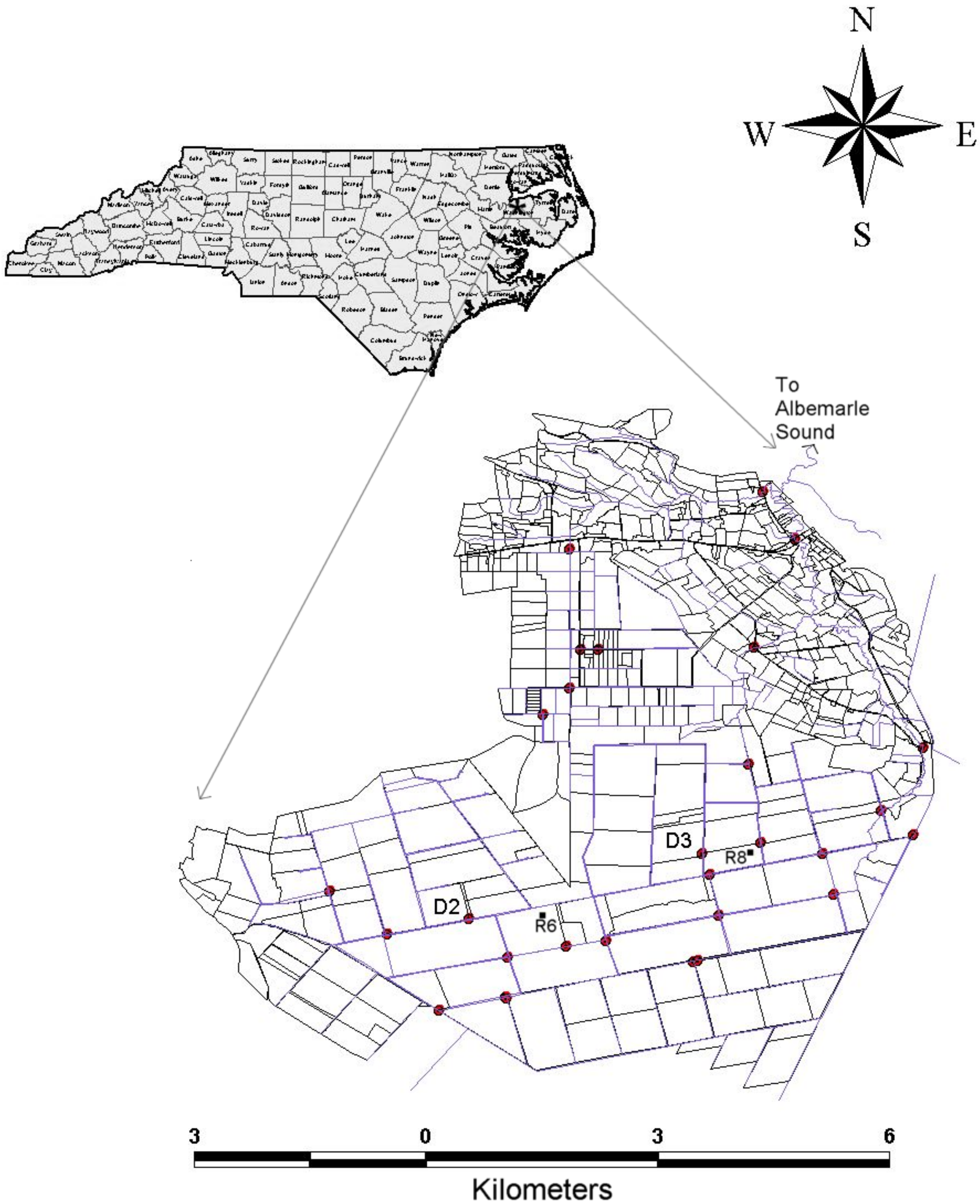

Figure 1. Diagram of watershed including the two original study watersheds.

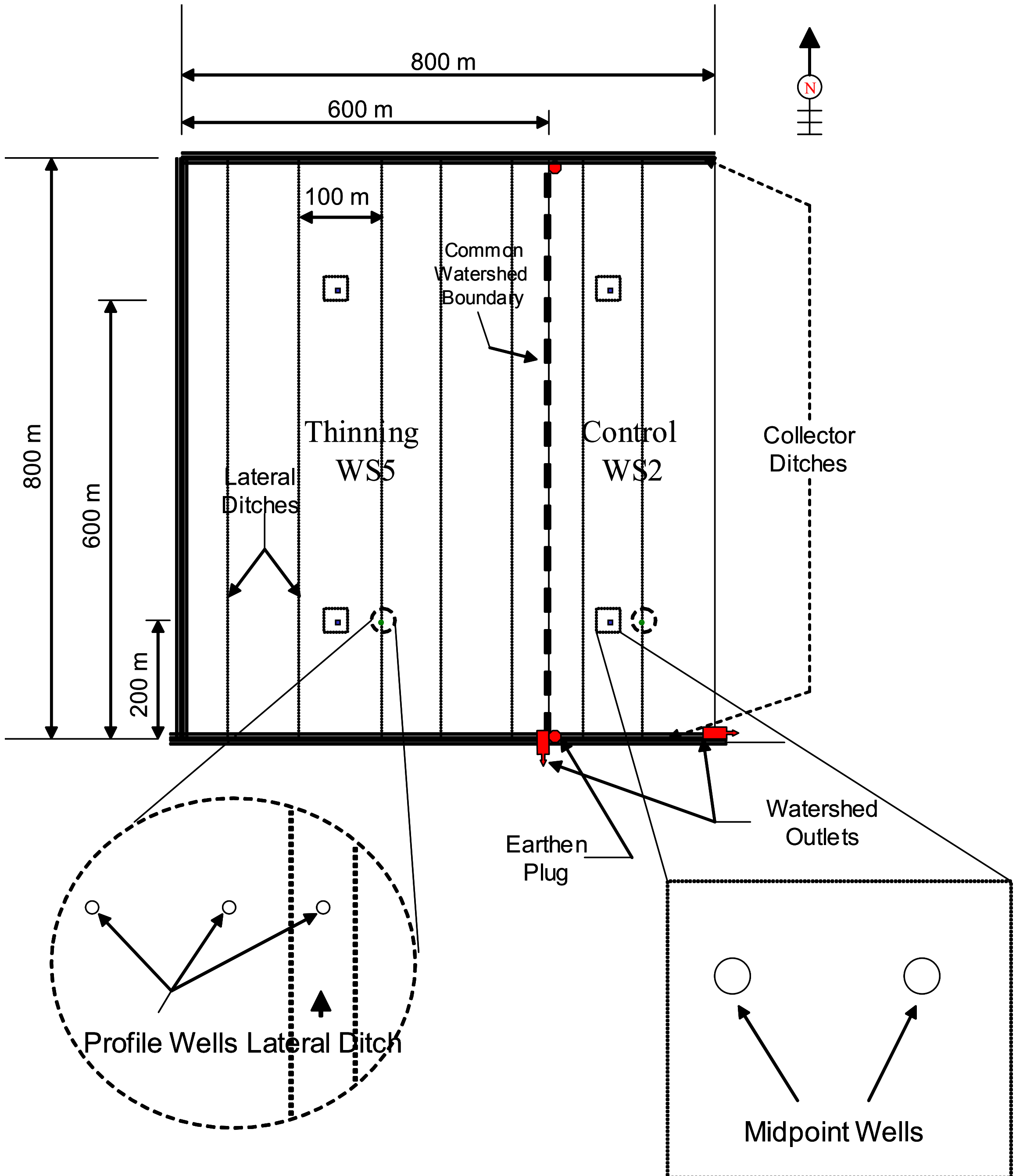

Figure 2. Paired watershed design with typical locations of water table wells and watershed outlets.

Treatment and Thinning System Characteristics

WS5 received a 40-ha fifth row thinning with selection treatment (days 93-115) in April 2001 and the remaining 16-ha (WS2) served as the un-thinned control. The thinning operation was accomplished with a Tigercat 720 feller buncher, two Timberjack 460 grapple skidders, and a Prentice 384 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 170 m^2/ha to 320 trees per hectare and basal area of 51 m^2/ha.

Study Measurements

In 1995, the original watershed was outfitted with a 120^o V-notch weir located in a riser barrel structure draining the watershed. In 1999, an additional 120^o V-notch weir was installed at a 113-cm depth on the treatment watershed. Upstream and downstream stages were recorded at five-minute intervals using submerged probe pressure transducers and a data logger in conjunction with Stevens recorders (Figure 3). Backup measurements of upstream and downstream stages were recorded using ultrasonic water level sensors and data loggers.

Water table depths were continuously measured with submerged pressure transducers at replicate midpoint wells and three profile wells (Figure 2). Midpoint wells were located at the midpoint between two successive lateral ditches for each watershed. Profile wells were located on opposite sides of the watersheds at 0, 1, and 3-m from two lateral ditches within each watershed. Hourly water table depths were recorded throughout the study period by data loggers located at each of the well stations.

Figure 3. Typical flow station setup with stormwater sampler house, upstream stage recorder (left) and downstream stage recorder (right).

Outflow was monitored from the plantation watersheds during a calibration period from November 1999 to April 2001 and a treatment period from May 2001 to December 2002. Eleven events were observed during the calibration and an additional seventeen events were observed during the treatment period. Precipitation was measured with tipping bucket rain sensors in combination with data loggers located within ½ km of the paired watersheds (Figure 1).

Data Analysis Methods

Watershed daily outflow was determined using instantaneous stage measurements upstream and downstream of the outlet weir. Rainfall patterns and outflow from both watersheds followed a definite seasonal pattern, where, the majority of events occurred during the wet season (December – April). Each rainfall event during the study period was associated with an outflow event and/or water table recharge occurrence. However, 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 on 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, peak outflow, and total number of event flow days.

Forest outflow characteristics and water table responses were evaluated to determine the effect of management practices. A paired watershed approach was used to perform statistical analyses to determine the effect of treatments on forest outflow and water table depth by methods defined by USEPA (1993; 1997) and Loftis and others (2001). The underlying models for the paired watershed approach are given by (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 the calibration period intercept and slope, B_2 and B_3 the adjustments to the intercept and slope for the treatment period, and ε is the independent noise term. In the paired watershed approach, a significant difference in slopes or intercepts of regression relationships between calibration and treatment periods indicate treatment effects on the response variable. Water table depth was substituted for outflow variables in the equations given above for analysis of water table depth effects of treatments. Differences in watershed areas in analysis were adjusted by analyzing on a drainage per unit area basis.

Storm event outflow data from the paired watershed design was analyzed using SAS (1991) PROC REG procedures to develop regression relationships for each watershed for daily and peak outflow during calibration and treatment periods. Water table depths during the calibration and treatment periods were also analyzed using SAS (1991) PROC REG to develop relationships for the two periods. The resulting slopes and intercepts from regression relationships were analyzed using SAS (1991) GLM procedures. The null hypothesis is that there is no difference in the regression relationships for outflow and water table depths from the treatment and control 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. During 2001, annual outflow was less than 10 percent of 2000 outflow for both the WS2 (control) and WS5 (treatment) watersheds. This difference in annual outflow is primarily due to the difference in precipitation for the two years and differences in weir depths during the primary flow season. Precipitation during 2001 was 35 percent less than the previous year which represents abnormally dry conditions at the site. Annual outflow from WS5 during 2000 was also elevated in comparison to WS2, because the weir for WS5 was set 28 cm lower than WS2 during the period from day 1 to 166. These weir settings during the 2000 flow season should have resulted in greater outflow from WS5 compared to WS2 because less water table recharge was required to result in outflow.

Table 1. Annual outflow and precipitation summary for WS2 (control) and WS5 (treatment) watersheds during the study period.

Description	Flow Year		
	2000	2001	2002
WS2 (Control)			
Weir Setting*, cm	85	85	85
Average ground elevation, m	5.44	5.44	5.44
Outflow, mm	292	20	206
Precipitation, mm	1160	756	1378
WS5 (Treatment)			
Weir Setting*, cm	113 / 85†	85	85
Average ground elevation, m	5.64	5.64	5.64
Outflow, mm	340	31	326
Precipitation, mm	1160	756	1378

*Weir setting depth below average ground surface elevation.

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

WS5 event drainage outflow was slightly greater than WS2 outflow during the primary flow season of 2000 (through day 150) (Figure 4), and 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 (day 166), WS2 event outflow was greater than WS5 until thinning, which took place in April 2000. The 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. During this calibration period, WS2 peak outflows were 35 percent greater than WS5 peak outflows. The outflow pattern shifted between the two 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 (Figures 5 & 6). Specifically, WS5 produced outflow during five events between days 158 and 183 (2001), days 60 and 85 (2002), days 260 and 264 (2002), and days 286-290 (2002) that were not observed from WS2 (Figures 5 and 6). The thinned watershed, WS5, also produced outflow 24 days earlier during 2002 than did the control (WS2) watershed. Greater ET from the control in the summer and fall of 2001 apparently caused the water table to be deeper (Figure 8) and the watershed drier than the thinned site. Thus more recharge was required to raise the water table on WS2 and initiate outflow in comparison with WS5. Peak daily outflows from WS5 were on average 40 percent greater than WS2 peak outflows.

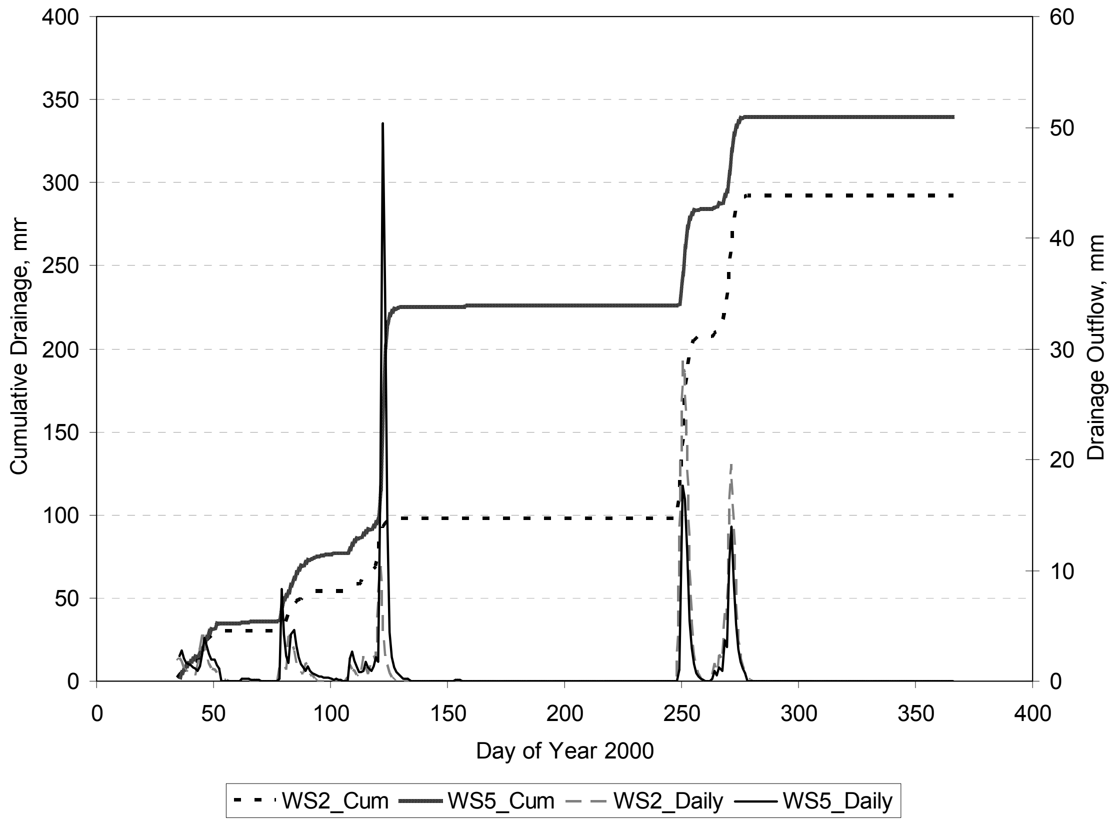

Figure 4. Observed outflow for the WS2 (control) and the WS5 (treatment) watersheds during 2000.

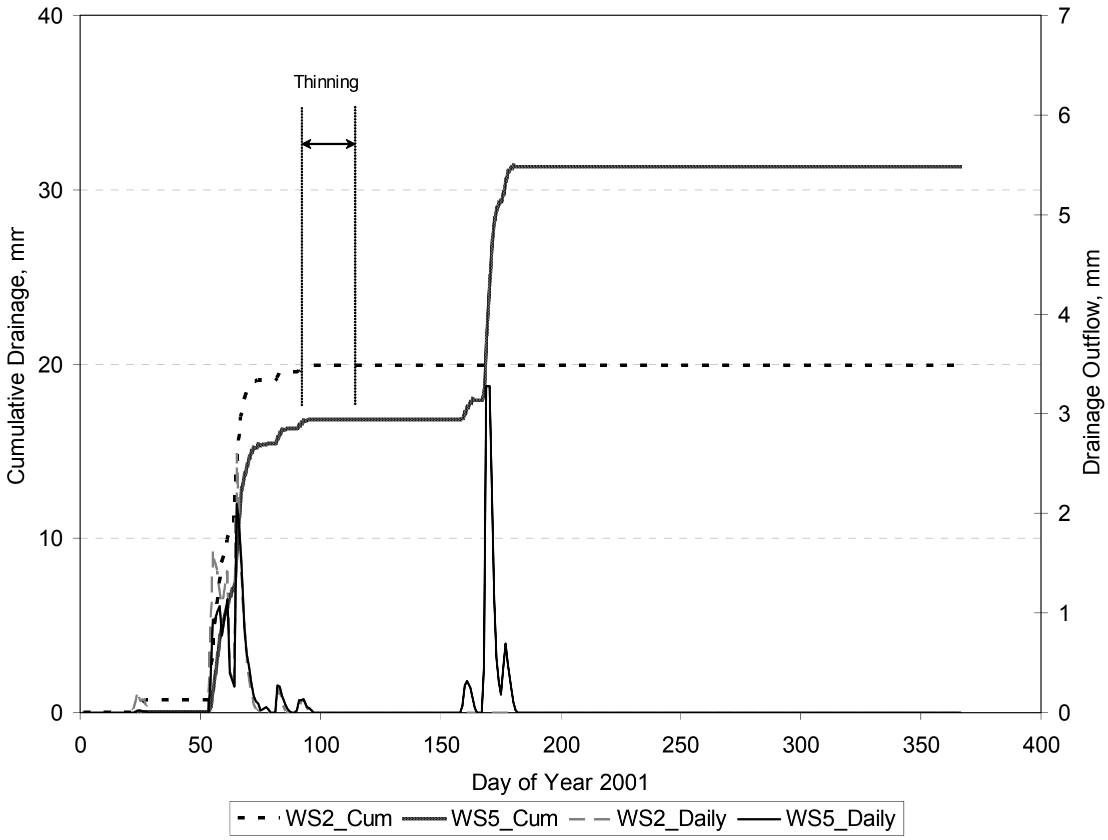

Figure 5. Observed outflow for the WS2 (control) and the WS5 (treatment) watersheds during 2001.

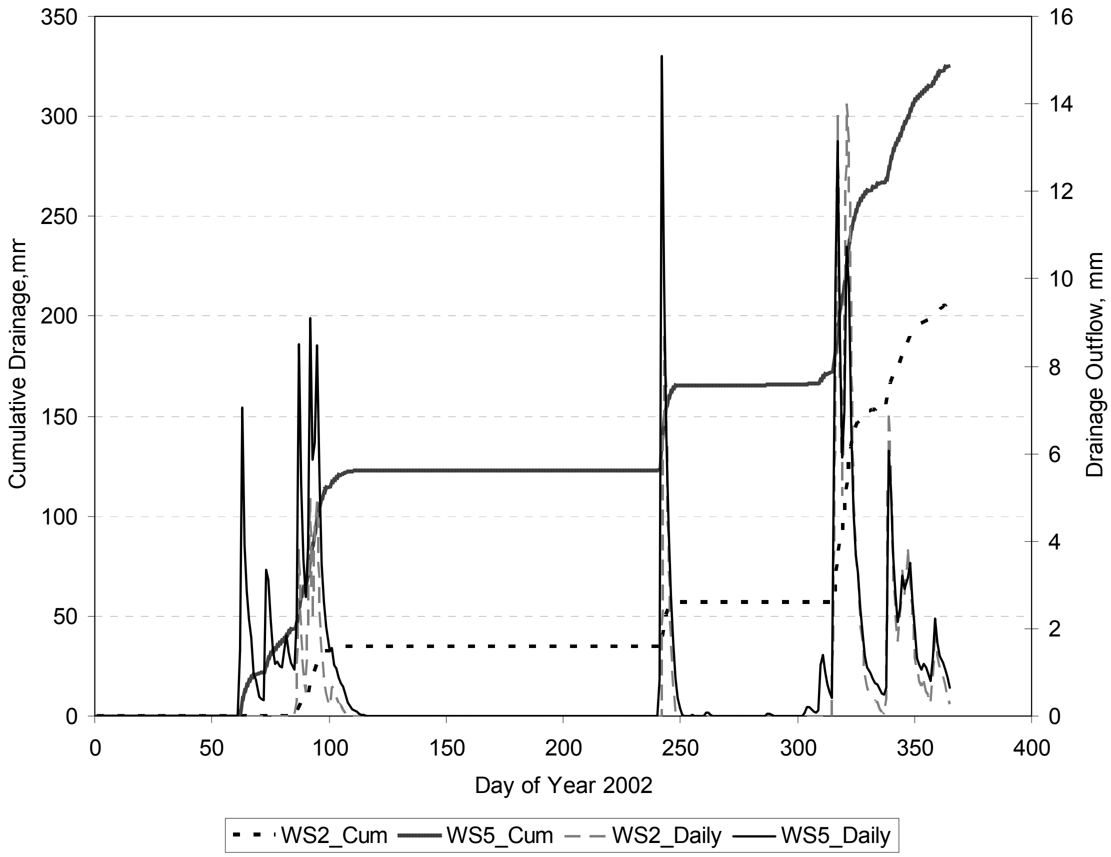

Figure 6. Observed outflow for the WS2 (control) and the WS5 (treatment) watersheds during 2002.

Water table depths on the plantation watersheds appeared to be affected by treatment in the same way as outflow. The water table on watershed WS5 was shallower than WS2 for all but a few periods during the three years (Figures 7-9). This was true even during the beginning of 2000 when the weir setting on WS5 was 28 cm lower than for WS2. The shallower water table depth for WS5 prior to thinning indicates that WS2 was better drained than WS5. After thinning the difference in water tables became greater as reduced ET on the thinned watershed (WS5) caused it to stay closer to the surface and wetter than the control as discussed above. This was especially true during the dry season. For instance, on days 125 – 240 during 2001, the water table on WS2 was more than 0.60 m deeper than on D5 (Figure 8). Not only was the water table deeper on WS2, but the zone above the water table was apparently drier at the end of 2001 than on the thinned watershed. When rains started in early 2002 the water table on WS5 rose to the 60 cm depth by day 22. By comparison, the water table on the control (WS2) did not respond until day 63. During this 41-day period the water table on WS2 was more than 1.3 m deeper than on WS5 (Figure 8). The water table on WS5, characterized by quick water table rise following rain events, also appeared more responsive to rainfall events than WS2. These trends were statistically tested to detect treatment effects on the hydrology; the analysis is presented in the next section.

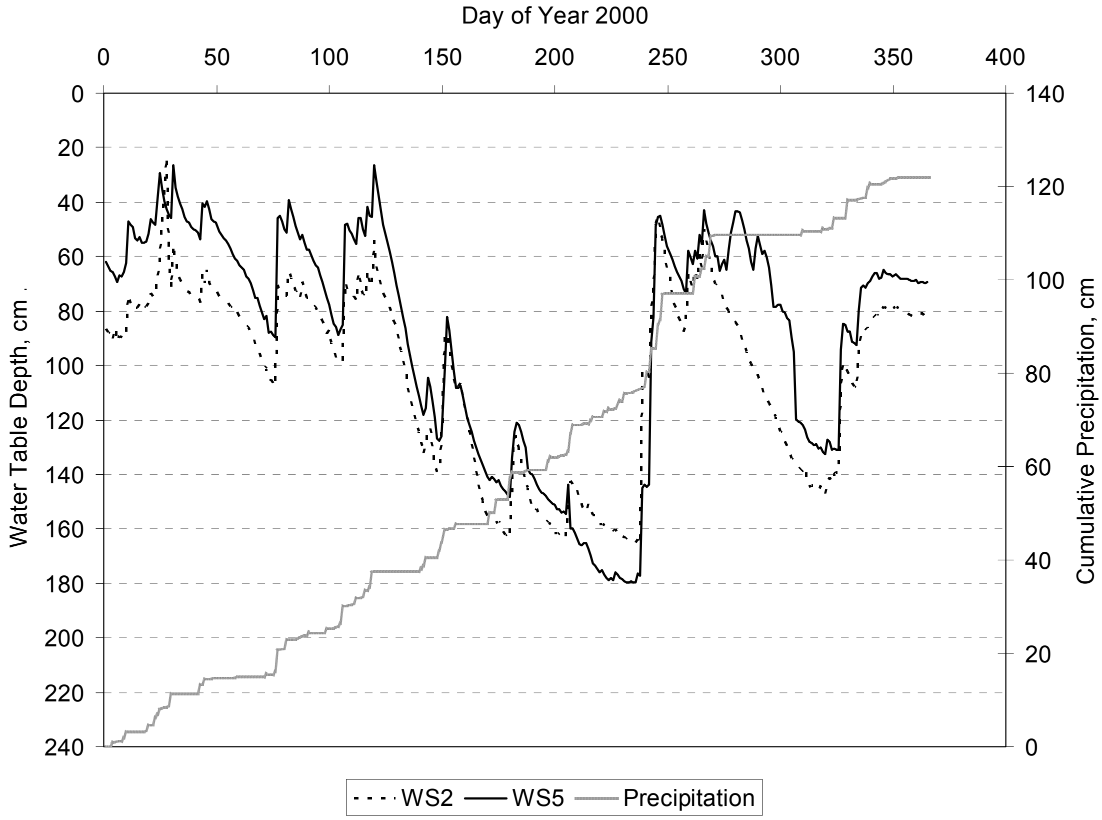

Figure 7. Daily average mid-point water table depths and precipitation for the WS2 (control) and WS5 (treatment) watersheds during 2000.

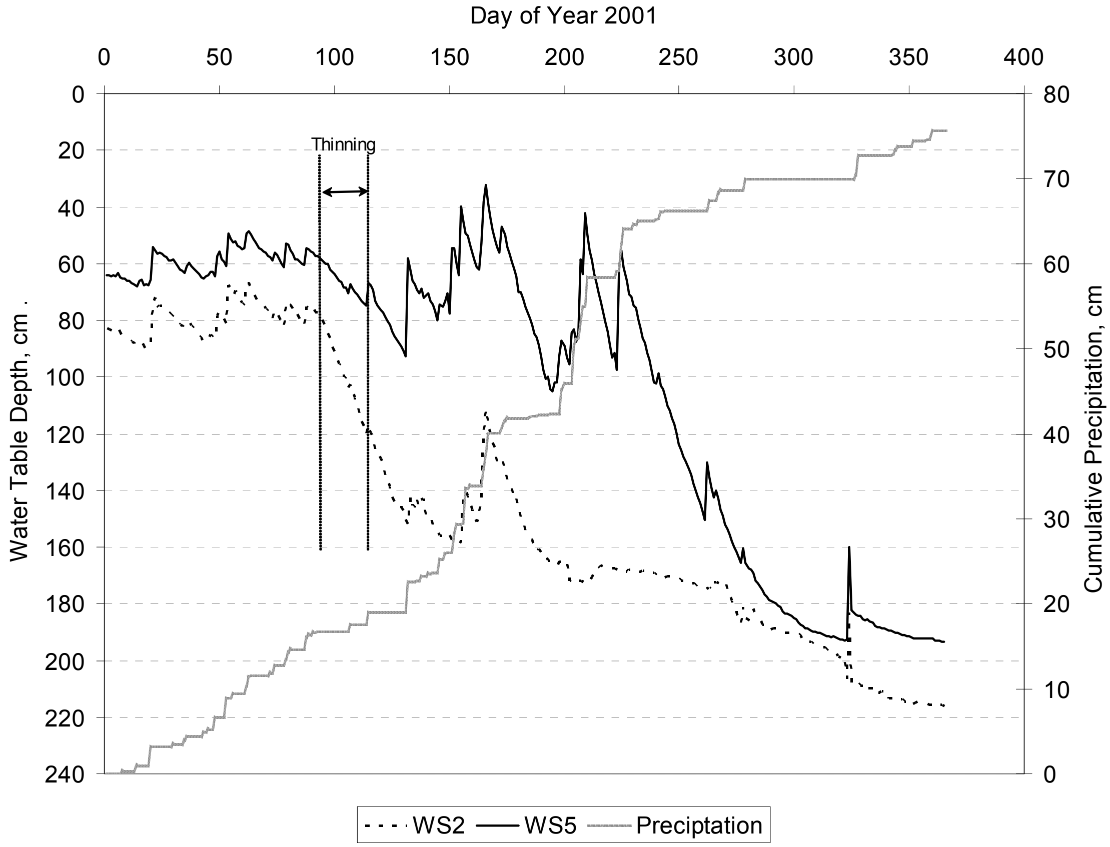

Figure 8. Daily average mid-point water table depths and precipitation for the WS2 (control) and WS5 (treatment) watersheds during 2001.

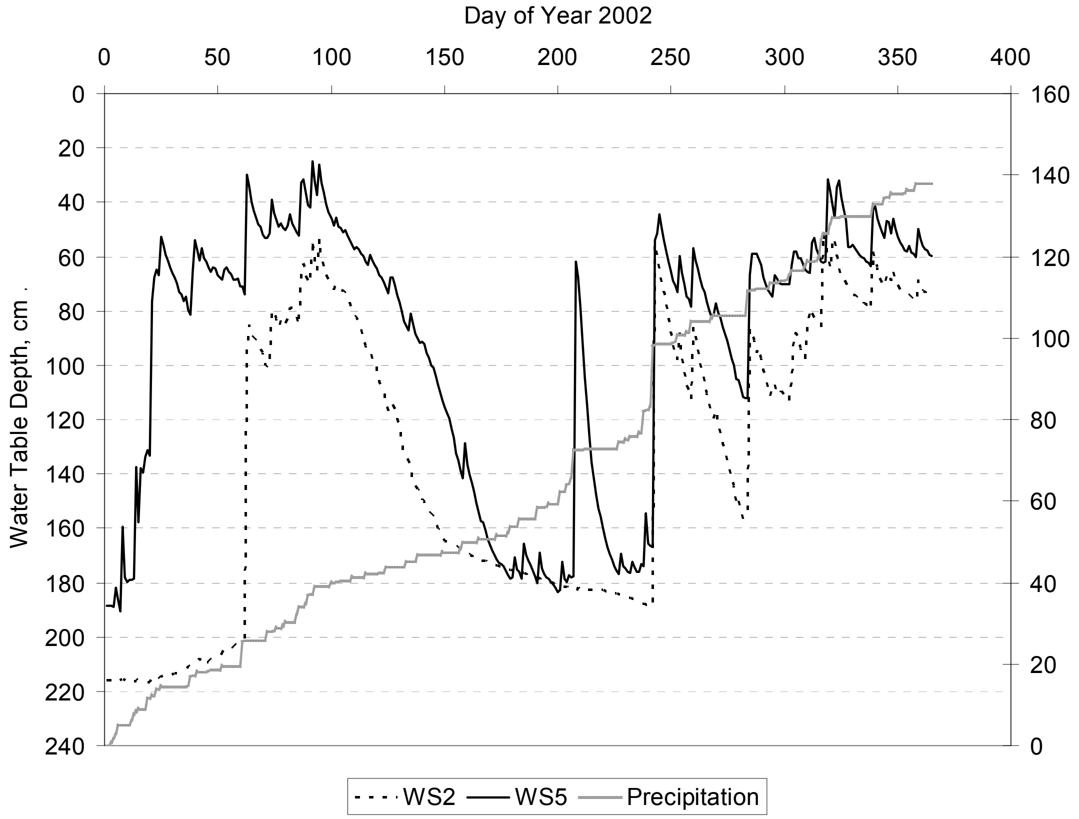

Figure 9. Daily average mid-point water table depths and precipitation for the WS2 (control) and WS5 (treatment) watersheds during 2002.

Regression Analysis

Flow was observed a total of 83 and 76 days for WS2 and WS5 watersheds during the calibration period, respectively. During the treatment period, flow was observed from WS2 on 113 days, as compared to 170 days on WS5. A total of 28 outflow events were identified on the plantation watersheds over the three year (2000-2002) observation period. Eleven of these events occurred during the calibration period and the remaining 17 events were 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 (Figures 10 & 11). Daily outflows during the calibration period were highly correlated between the watersheds with a 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 relationships developed between the watersheds were significant at $p<0.0001$. Slope of the calibration regression relationships for daily outflow and peak flow was also significantly different from zero ($p<0.0001$); however, the intercepts of the regression relationships were not significant ($p=0.24$ and 0.23, respectively) based on this analysis.

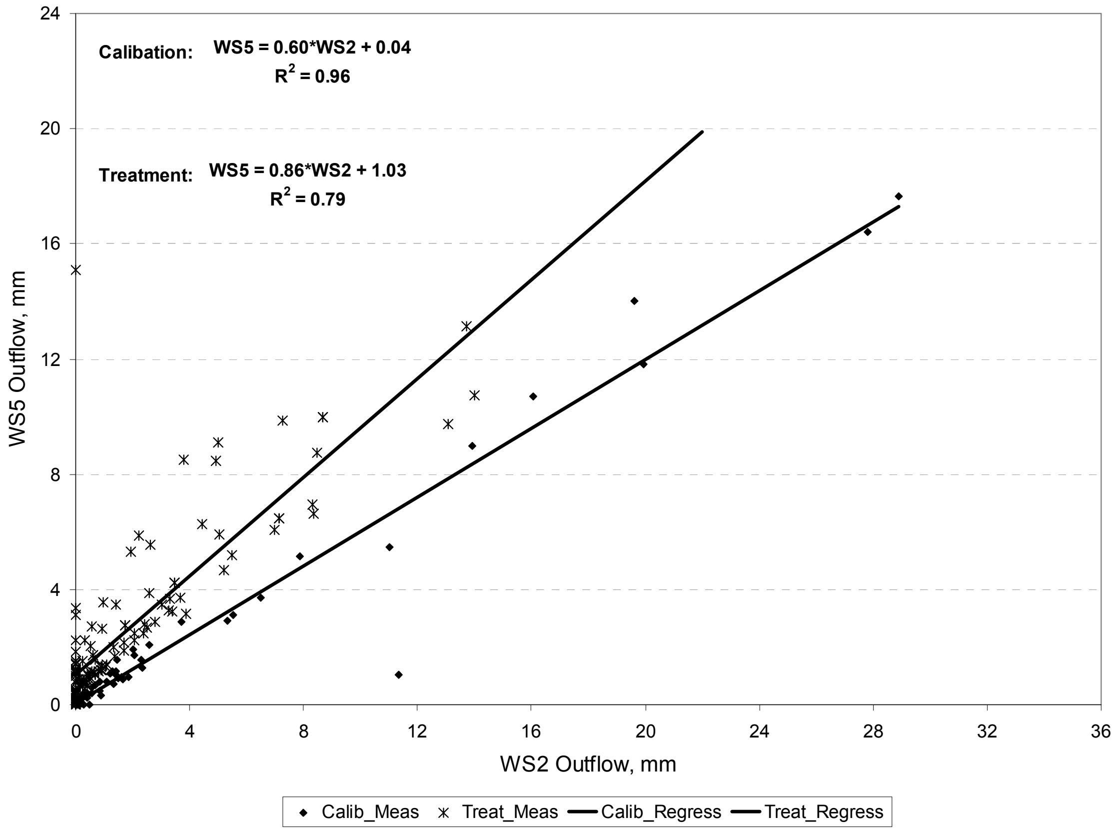

Figure 10. Measured outflows and regression relationships for the WS2 (control) and WS5 (treatment) watersheds during the calibration and treatment periods.

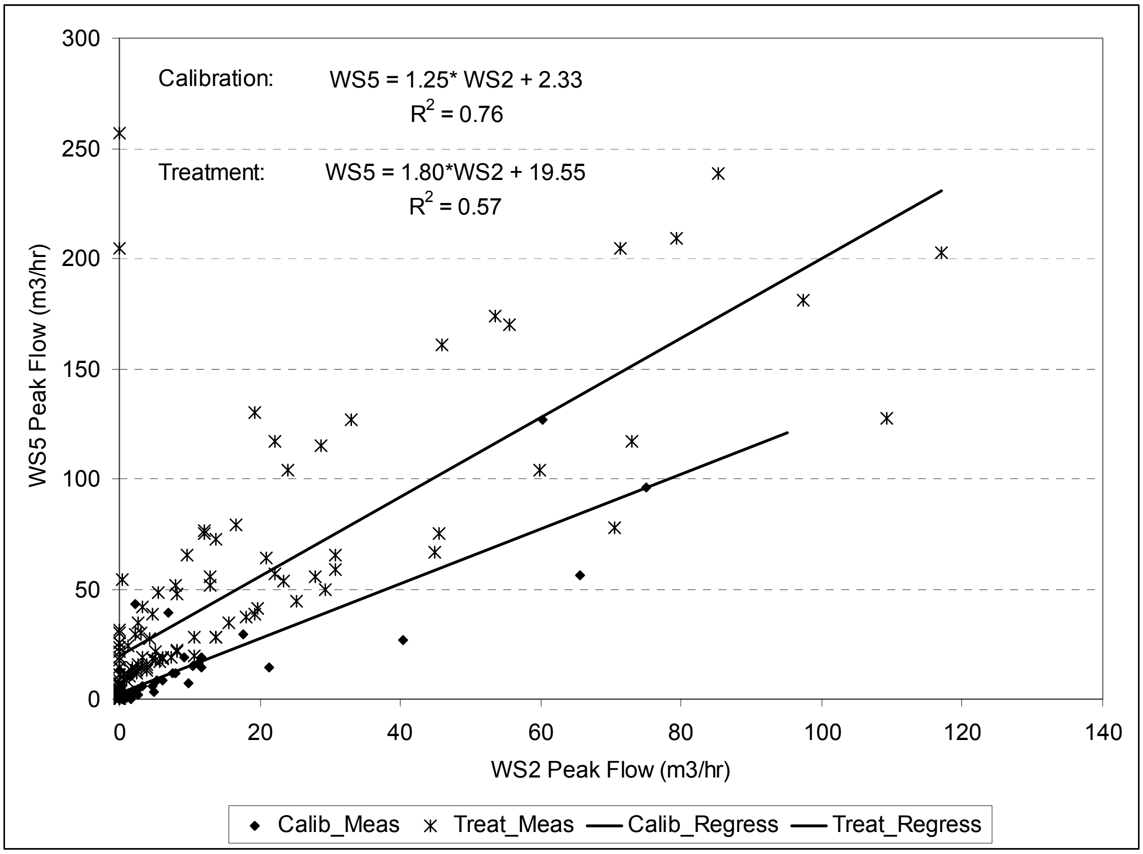

Figure 11. Measured peak flow and regression relationships for the WS2 (control) and WS5 (treatment) watersheds during the calibration and treatment periods.

Regression analysis showed a moderate correlation between WS5 and WS2 daily outflows during the treatment period, as evident by a R^2 of 0.79 (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 outflow from the study watersheds for both calibration and treatment periods suggest that the paired watershed approach can be used to test for treatment effects on outflow parameters in this investigation.

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

Period	Regression Equation	Regression R^2	Regression F-value	P-Value Slope	P-Value Intercept
Calibration					
	WS5_Flow = 0.60*WS2_Flow + 0.04	0.96	6330†	<0.0001	0.24
	WS5_Peak = 1.25*WS2 + 2.33	0.76	147†	<0.0001	0.23
	WS5_WTD = 1.18*WS2_WTD – 46.10	0.86	1220†	<0.0001	<0.0001
Treatment					
	WS5_Flow = 0.86*WS2_Flow + 1.03	0.79	2270†	<0.0001	<0.0001
	WS5_Peak = 1.80*WS2 + 19.55	0.57	162†	<0.0001	<0.0001
	WS5_WTD = 0.78*WS2_WTD – 13.43	0.55	1421†	<0.0001	<0.0001

† Indicates significance of the regression model for the given period at the <0.0001 level.

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 twenty months recorded for the treatment period. A highly significant ($p<0.0001$) regression relationship was developed between the watersheds for the calibration and treatment periods (Figure 12). 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 lower with a correlation coefficient of 0.74 (R^2 = 0.55). Water table depth regression slopes of 1.18 and 0.78 for the calibration and treatment periods, respectively, were significant in the regression analysis ($p<0.0001$). In addition, regression intercepts of -46.10 and -13.43 for the calibration and treatment periods were also significant.

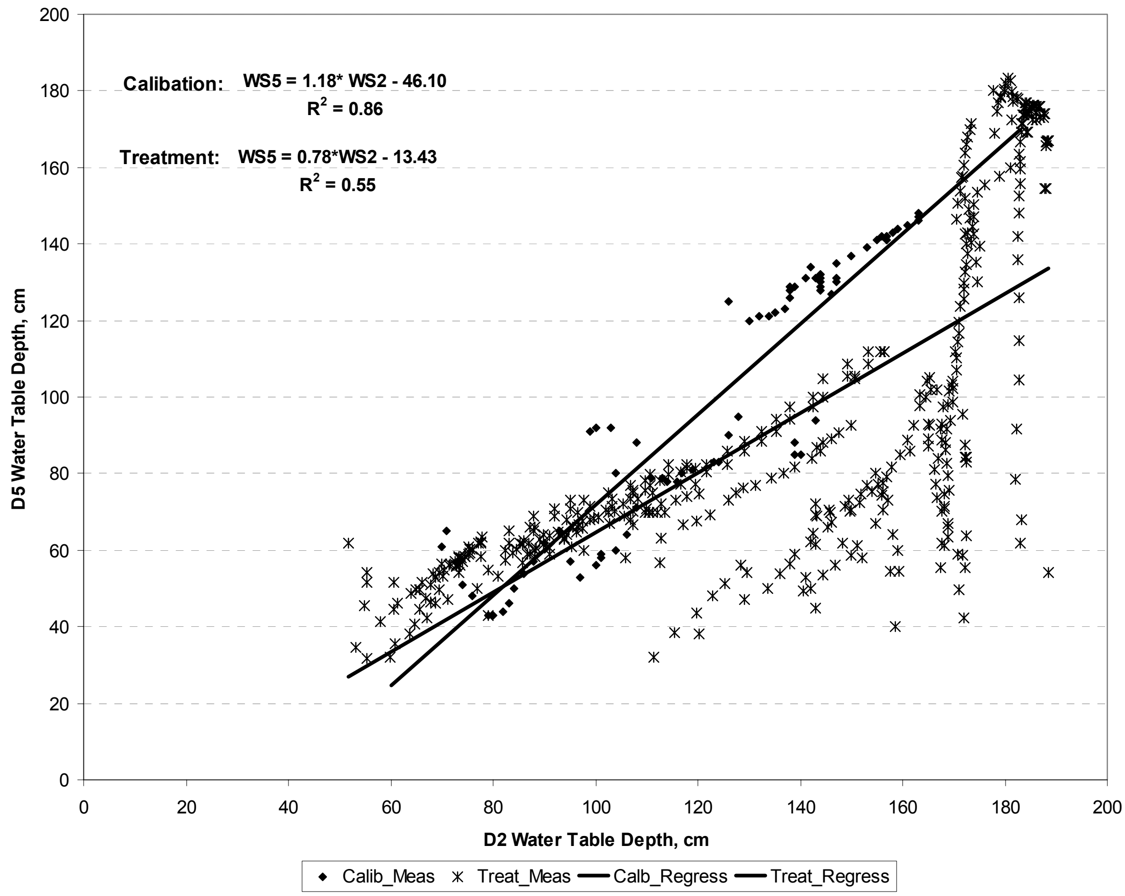

Figure 12. Measured water table depths and regression relationships for the WS2 (control) and WS5 (treatment) watersheds during the calibration and treatment periods.

Regression relationships were developed for eleven outflow events during the calibration period and seventeen outflow events during the treatment period. SAS GLM procedures were used to test for differences between the calibration and treatment periods in slopes and intercepts of daily outflow regression relationships. Slopes for calibration and treatment periods were detected by ANOVA as significant (Table 3) indicating treatment effect on daily outflow. Daily outflow had a mean slope during the treatment period of 1.38 which was twice the calibration period slope of 0.68. Daily outflows from WS5 doubled during the treatment period in relation 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. This significant increase in the water yield from treatment watersheds is typical following thinning operations (McCarthy and Skaggs 1992; Richardson and McCarthy 1994; Williams and Lipscomb 1981).

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

Parameter		Calibration Mean	Treatment Mean
Daily outflow, mm†			
	Regression Slope	0.68b	1.38a
	Regression Intercept	-0.01b	0.76a
Peak flow, m^3/hr†			
	Regression Slope	1.06a	2.99a
	Regression Intercept	2.10b	17.9a
Water table depth, cm†			
	Regression Slope	0.79a	0.83a
	Regression Intercept	-1.79a	-21.8a

†Mean values in rows with the same letter for parameters were not statistically different at $\alpha = 0.05$ using Duncan Multiple Range Test.

Mean peak flow regression intercepts of 2.10 and 17.9 m^3/hr for the calibration and treatment periods were significantly different (Table 3). Similar to daily outflow results, this difference indicated treatment effects on peak flow between periods. Peak flow rates increased 40 percent on WS5 following thinning in relation to WS2. For instance, during the calibration period a peak flow rate of 60 m^3/hr for WS2 corresponded to 80 m^3/hr for WS5. However, the same 60 m^3/hr peak flow rate for WS2 corresponds to130 m^3/hr during the treatment period. This increase is attributed to the thinning operation on WS5 which resulted in increased outflow response. 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.

Water table depth regression relationships were developed for storm events in both study periods (Table 3). The mean slope of 0.83 for the treatment period was statistically similar to the calibration period slope of 0.79 (p=0.75, F=0.11). The treatment period mean intercept was also statistically similar to that of the calibration period (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, appear to indicate that thinning had a substantial effect on water table depth during the periods of high ET. However, there appears to be negligible effect during wet periods when PET is low 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.

Summary and Conclusions

Paired watersheds were used to evaluate the impact of thinning a 40-ha 15-year old loblolly pine plantation. The investigation was conducted on organic soil sites with organic matter content greater than 80 percent in eastern North Carolina. The effects of thinning on daily outflow, peak flow and water table depths were evaluated over a calibration period from December 1999 to April 2001 and a treatment period from May 2001 to December 2002. Outflow and water table depths were first tested for correlations and then tested for treatment effects using the paired watershed approach.

Regression analysis for daily outflow from the paired plantation watersheds revealed a significant relationship between WS2 and WS5 outflow. WS2 daily outflow had predictive power in predicting WS5 outflow for both calibration and treatment periods, indicated by a p-value of <0.0001. Mean daily outflow more than doubled on WS5 following the thinning operation in comparison to the outflow response from WS2. Peak outflows were 40 percent greater on the thinned watershed than on the control. For example, WS2 outflow of 1.0 mm/day corresponded to a WS5 outflow of 0.6 mm/day during the calibration period; whereas the same 1.0 mm/day WS2 outflow corresponded to 1.9 mm/day for WS5 during the treatment period. Regression analysis of water table depths during the calibration and treatment periods detected significant regression relationships between the WS2 and WS5 watersheds. While thinning appeared to reduce water table depth during and following periods of high ET, no significant treatment effects on water table depths were detected using the paired watershed approach.

Acknowledgements

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