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# Increased Water Yields Following Harvesting Operations on a Drained Coastal Watershed


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**Abstract.** *Forest harvesting operations have been reported to affect annual and seasonal outflow characteristics from drained forest watersheds. Increases in forest outflow, nutrient concentrations, and suspended sediments are commonly seen as a result of these forest management activities. Thus, it is important to assess the impact of forest management activities on hydrology, soils, and water quality on drained forested lands. The impact of harvesting a 23-ha mature natural (primarily hardwood) forest stand located in Washington County near Plymouth, North Carolina was evaluated using a paired watershed approach. Event outflow, event peak flow, and number of flow days were significantly increased by the harvesting operation. Mean event outflow increased from 22.6 mm on the control to 47.3 mm on the harvested, which represents a 2-fold increase. Similarly, event peak flow and number of flow days from the harvested watershed were more than 50 percent greater than*



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*observed on the control. Daily outflow and water table depths observed on the harvested watershed were similar to those from the control. Mean water table depths for the harvested and control were 68 and 97 cm during the treatment period.*

**Keywords.** Harvesting, hydrology, forest outflow, water table depth, peak flow.

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## Introduction

Increased demand for timber products in the past 25 years has resulted in management practices to increase productivity of the current forestland base. The U.S. supplies 25 percent of the world-wide demand for timber products. Forests within the southern US are some of the most productive in the world and supply 60 percent of the nation's timber products. Use of appropriate forest operations is essential to meet the ever-increasing demand for timber products. Common forest management practices on southern forests include site preparation, planting, harvesting, thinning, fertilization, and road construction and maintenance. These operations are state-of-the-art tools for management of our forest resources for ecological, economical, and social viability.

Implementing ecologically acceptable techniques and technologies in forest operations is dependent on an understanding of physical and biological processes in forested lands. Previous research in upland managed forests on Coastal Plain sites in Arkansas showed that forest outflow significantly increased following clear-cut harvesting operations (Beasley and Granillo 1988). Mean annual water yield from clear-cuts was 13 times greater than that of the undisturbed controls one year post-treatment. Selectively harvested treatments had a 5-fold increase in mean annual water yields compared to undisturbed watersheds. Results of research have also shown that any decrease in evapotranspiration by timber removal on upland forest will increase water yield (Hoover 1944; Hewlett and Hibbert 1961; Hibbert 1966, 1969; Swank et al. 1982; Troendle and Olsen 1993; Binkley and Brown 1993). There is a large body of work documenting the effects of harvesting at different intensities and site preparation on upland forest hydrology. The work reported here focuses on forested lowlands, which are poorly drained with shallow water tables under natural conditions.

There have been fewer reported studies of the effects of forest operations on water quality and yield in lowland forests than on upland forest with shallow soils and greater relief (Hollis et al. 1978; Sun et al. 2001). Gentle relief and deep soils on lowland sites reduces the amount of water movement by surface flow. Effects of silvicultural operations, the duration of which typically range from a few months to several years, on water quality are measurable, although drainage water quality rarely exceeds current criteria. Minimal water quality responses can be expected in wetland forests because most surface water in wetland systems is the result of ponding of excess rainfall rather than runoff from areas upslope (Shepard 1994). Based on his review of forest management and water quality research, Shepard (1994) concluded that properly conducted silvicultural operations present no permanent threat to the water quality functions of lowland systems.

Increases in forest outflow and water table rise have been observed following removal of timber due to reduced evapotranspiration rates (Hibbert 1966; Williams and Lipscomb 1981; Riekerk 1983; Richardson and McCarthy 1994; Dube et al. 1995; Lebo and Herrmann 1998; Sun et al. 2000). However, 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. Nutrient concentrations and suspended sediments are commonly increased as a result of forest management activities (Swindel et al. 1982, 1983a, 1983b; Askew and Williams 1986; Shepard 1994; Binkley and Brown 1993; Walbridge and Lockaby 1994; Richardson and McCarthy 1994; and Lebo and Herrman 1998; Barbe et al.

2000; Kitchens et al. 1975). Based on conclusions presented from these earlier works, it is important to assess the impact of forest operations on hydrology and water quality in poorly drained systems.

This paper documents results of a field research project in eastern North Carolina with the objective of quantifying the hydrologic impacts of forest operations on artificially drained watersheds. The impact of harvesting on forest outflow from a mature natural (primarily hardwood) stand on poorly drained organic soils was evaluated using a paired watershed approach. The effect of harvesting on water table rise was also evaluated by analyzing water table depths from a harvested and a paired control watershed.

## Methodology

### *Site Description*

The study sites are part of a large watershed study (~10,000 ha) located at approximately 35$^{o}$ N latitude and 76$^{o}$ W longitude in Washington County near Plymouth, North Carolina (Figure 1). The experimental watersheds are located on land owned and managed by Weyerhaeuser Company. In its natural condition the site was poorly drained and nearly flat, with a shallow water table before improved drainage. In 1995, a 120$^{o}$ V-notch weir was installed in a riser barrel structure on the outlet of an artificially drained 44-ha mature natural (primarily hardwood) watershed. The watershed was bisected in 1999 to create independent 23- and 21-ha sub-watersheds. The 23-ha sub-watershed drained to the original outlet and was called WS3. In December 1999, the outlet of the 21-ha sub-watershed (WS6) was outfitted with a 120$^{o}$ V-notch weir set at a depth of 90-cm below average ground surface. After monitoring flow for the subsequent flow season, the weir setting at the outlet of WS3 was raised from 120-cm to 90-cm below average ground surface. Both watersheds were drained by lateral ditches 1-1.2-m deep spaced approximately 100-m apart. The laterals drain to 2-m deep collector canals along the roadside. The site is bound on the south and west by natural forests and on the north and east by plantation pine. The two watersheds are isolated as an individual forest block by a network of roads and drainage ditches.

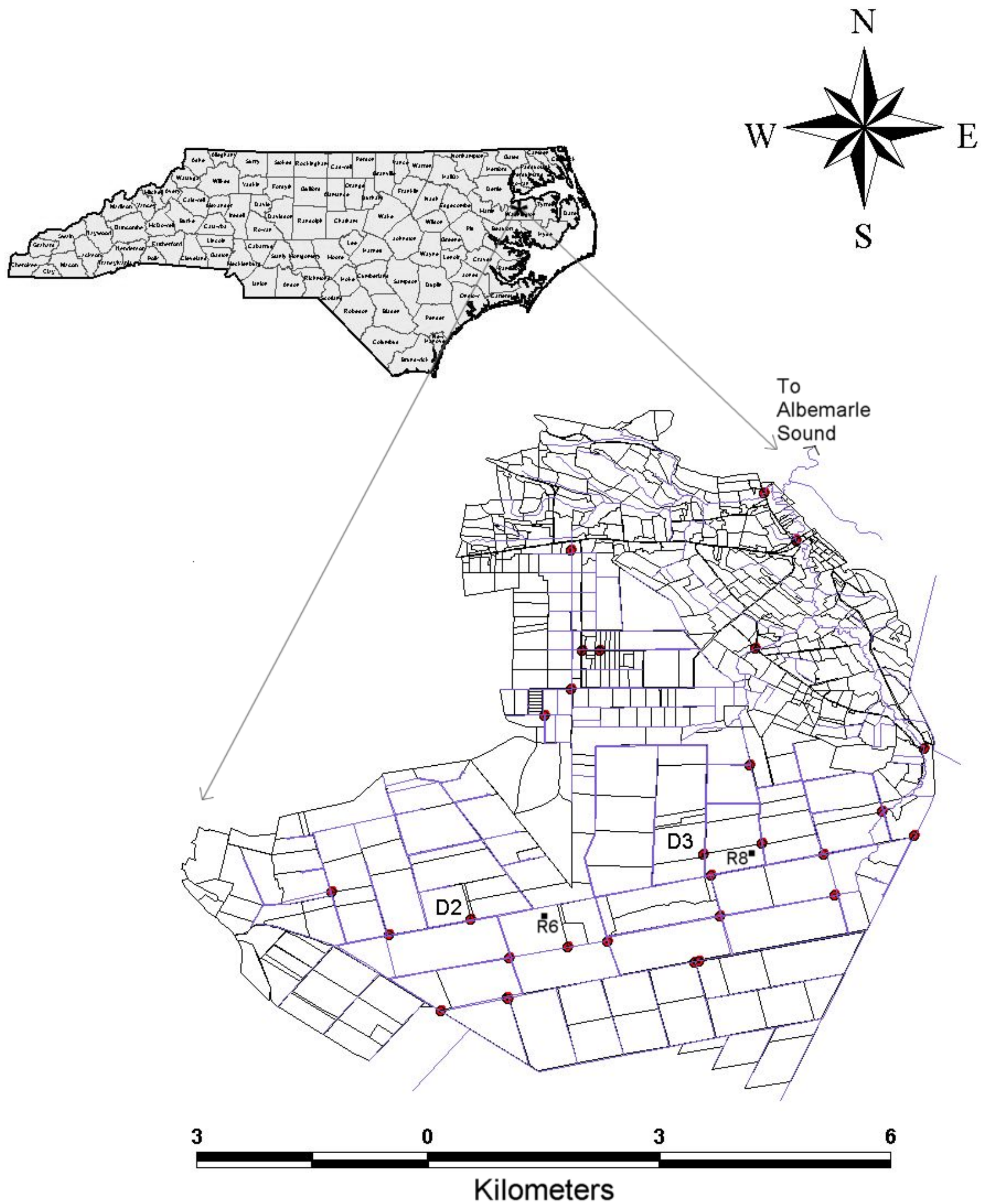


**Figure 1. Location of Parker Tract study watershed near Plymouth, NC.**

The soils in the study watersheds are classified as Belhaven series (SCS 1981) with a thick organic surface layer extending to a mineral interface at a depth of 60 cm. The organic surface layer on both watersheds has a total porosity exceeding 0.75 $cm^3/cm^3$ and organic matter content greater than 80 percent. Soil properties, hydraulic conductivity, soil water characteristics, and bulk density were determined based on soil core samples taken from soil pits on both areas.

### *Treatment and Study Measurements*

WS3 received a 23-ha clearcut harvest treatment in June 2001 (days 159-178) and the remaining 21-ha (WS6) served as the un-harvested control. Felling was accomplished with a Tigercat 860 tracked feller buncher. Skidding was conducted with two Timberjack 660 grapple skidders with dual tires, a Tigercat 860S tracked shovel loader and a Tigercat 640 rubber tired clambunk skidder. Approximately half of the timber was skidded to each of the two decks located on each side of the harvested area (on the east and west watershed boundaries). The volume of timber removed from the WS3 site was 6800 tons, hardwood accounted for 5800 tons of that total.

Stream water levels upstream and downstream of the weir were recorded at five-minute intervals using submerged pressure transducers and a data logger in conjunction with Stevens chart recorders (Figure 2). Secondary measurements of upstream and downstream stage were recorded using ultrasonic water level sensors and a data logger. Outflow rates were continuously measured from both watersheds during a calibration period from December 1999 to mid-June 2001 and a treatment period from mid-June 2001 to October 2002. Precipitation was measured with a tipping bucket rain sensor in combination with a data logger (R8) located within ½ km of the paired watersheds (Figure 1).

**Figure 2. Typical flow station setup with stormwater sampler house, upstream stage recorder, and downstream stage recorder.**

Water table depths were measured hourly with submerged pressure transducers connected to data loggers at replicate midpoint wells and three profile wells along a transect from the midpoint to the drainage ditch (Figure 3). Midpoint wells were located midway between two successive lateral ditches for each watershed. Profile wells were located between laterals on opposite sides of the watersheds at 0, 1, and 3-m from a lateral ditch within each watershed.

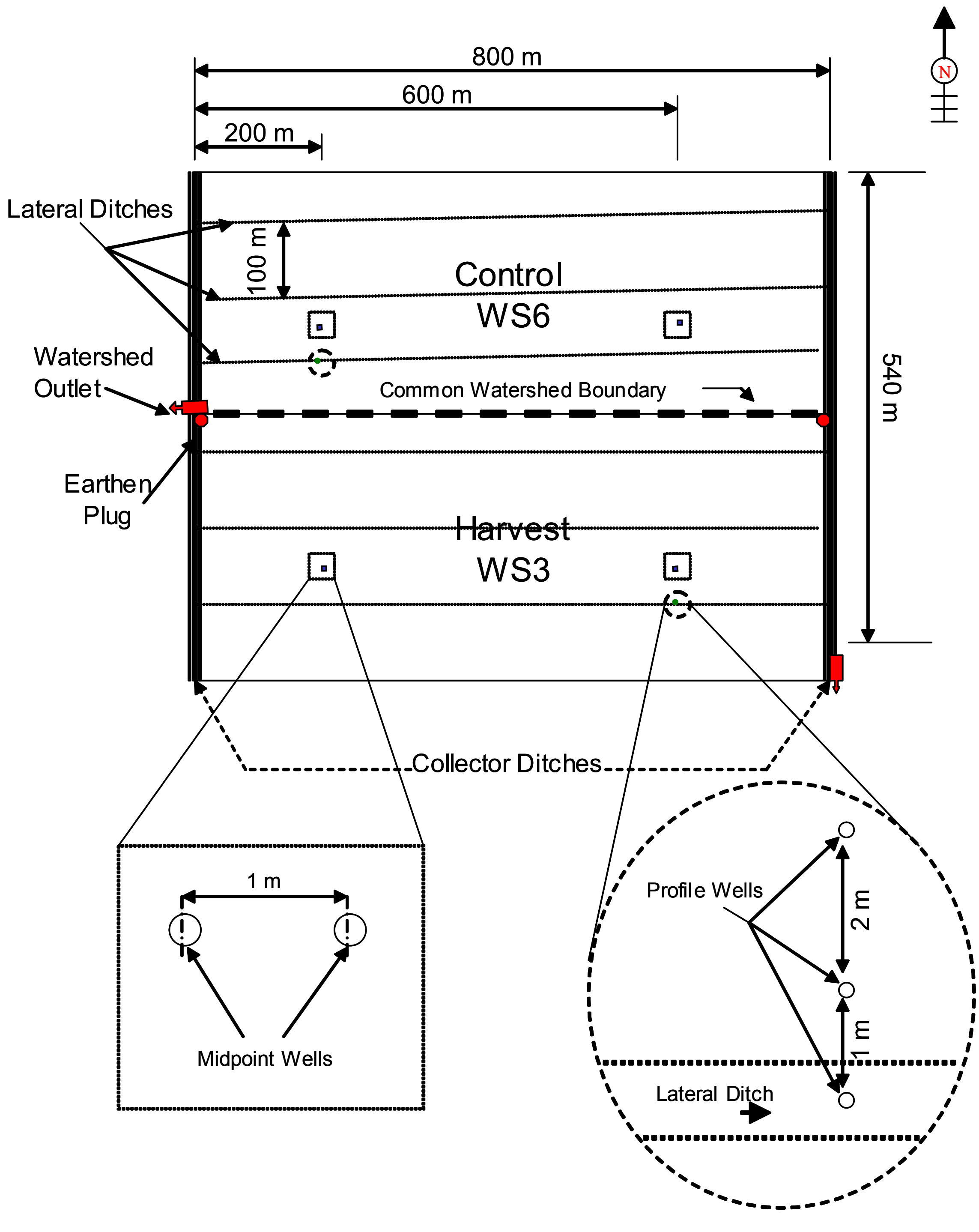


**Figure 3. Schematic diagram of the study watersheds with locations of midpoint and profile wells.**

### *Data Analysis Methods*

Watershed daily outflow was determined based on instantaneous stage measurements upstream of the outlet weir. Outflow from both watersheds followed a seasonal pattern, that is, the majority of events occurred during the wet season (December – May). Each outflow event during the study period was associated with a rainfall event. 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 which 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 on watersheds, corresponding outflow record was identified on the paired watershed and used in the analysis of event outflow, event peak flow, daily outflow, daily peak flow, and total number of event flow days.

Forest outflow characteristics and water table responses were evaluated to determine the effect of management practices. Event outflow, event peak flow, and number of event flow days were analyzed using SAS (1991) GLM procedures for differences in watersheds. Duncan Multiple Range Tests were used to separate mean values for response variables. A paired watershed approach was used to perform statistical analysis to determine the effect of treatments on daily 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 $\varepsilon$ 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.

Daily outflow data from the paired watershed design was analyzed using SAS (1991) PROC REG procedures to develop regression relationships for each watershed for daily outflow and daily peak flow 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. The resulting slopes and intercepts from regression relationships were analyzed using SAS 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

WS3 and WS6 had outflows of 96 and 33 mm following the raising of the WS3 weir during the 2000 observation period (days 267-366) (Figure 4). Annual outflows from WS3 were 273 and 602 mm for years 2001 and 2002, respectively (Table 1). WS6 annual outflows were 33, 214, and 419 mm, which were 66, 22, and 30 percent less than WS3 annual outflows for 2000, 2001, and 2002, respectively.

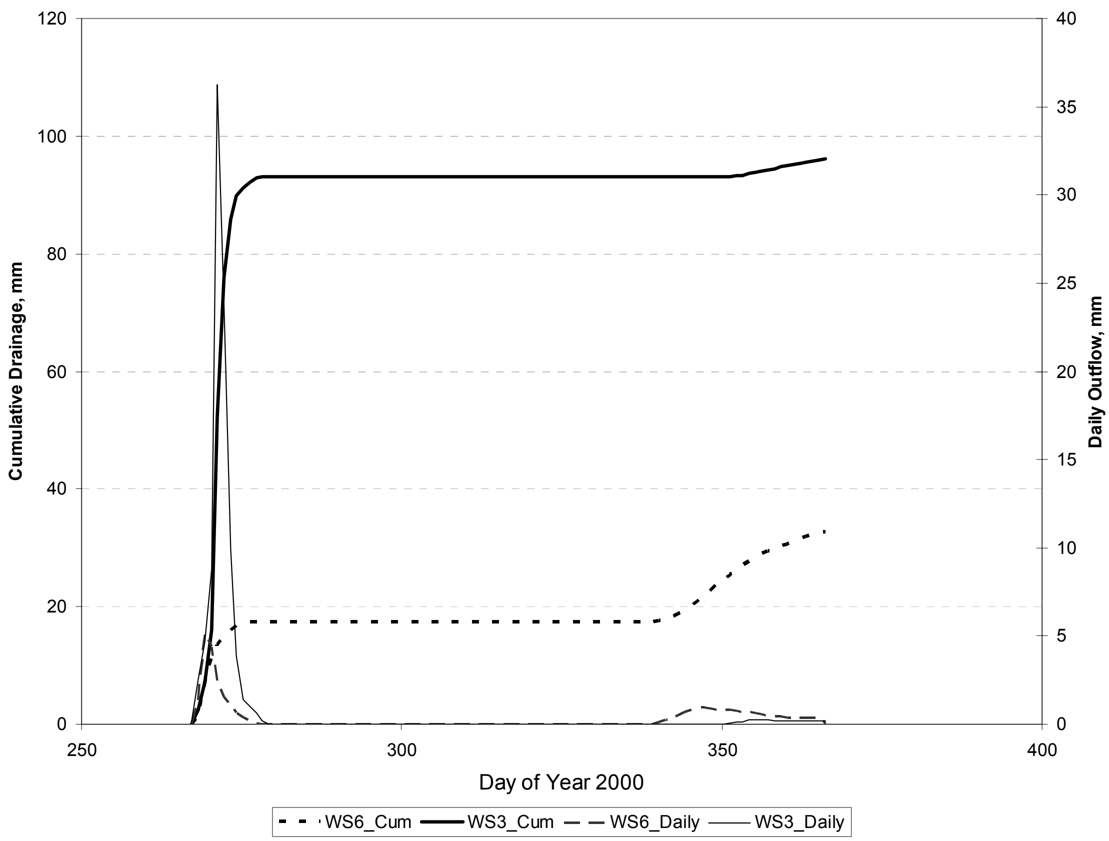


**Figure 4. Observed outflow for the WS6 (control) and the WS3 (treatment) watersheds during 2000.**

Annual precipitation during 2000 and 2002 was similar to the long-term average precipitation (1951-2001) for Plymouth, NC. Precipitation during 2001 was only 60 percent of the long-term average annual precipitation making it one of the driest years of record. Prior to 2001 the driest year since 1950 was 1970 when annual precipitation was 907 mm. Observed precipitation for 2001 was 38 percent less than for 2000 and 45 percent less than observed precipitation for 2002. In addition, monthly precipitation during 2001 was less than the long-term average monthly precipitation for all except two months during the year (June and July) (Table 2).

Table 1. Annual outflow and precipitation summary for watersheds during the study periods.

| Description | Year | | |
|---|---|---|---|
| | 2000 | 2001 | 2002‡ |
| WS6 (Control) | | | |
| Weir Setting*, cm | 90 | 90 | 90 |
| Average ground elevation, m | 5.10 | 5.10 | 5.10 |
| Outflow, mm | 33§ | 214 | 419 |
| Precipitation, mm | 1165 | 726 | 1106 |
| | | | |
| WS3 (Harvest) | | | |
| Weir Setting*, cm | 120 / 90† | 90 | 90 |
| Average ground elevation, m | 5.20 | 5.20 | 5.20 |
| Outflow, mm | 96§ | 273 | 602 |
| Precipitation, mm | 1165 | 726 | 1106 |

*Weir setting depth below average ground surface elevation.

†Weir setting raised to 90 cm below average ground surface September 2000.

‡through October 11, 2002.

§Outflow record from September 2000 – December 2000 (days 267-366).

| | Month | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | J | F | M | A | M | J | J | A | S | O | N | D | Annual |
| Long-Term Average Precipitation | 102.5 | 95.0 | 108.7 | 80.6 | 110.1 | 117.4 | 154.2 | 154.1 | 120.5 | 79.8 | 76.4 | 78.6 | 1280.5 |
| 2000* | | | | | | | | | | | | | |
| Precipitation | 112.8 | 36.6 | 89.4 | 130.8 | 102.9 | 127.0 | 77.7 | 225.6 | 130.6 | 0.8 | 78.7 | 52.6 | 1165.4 |
| Outflow D6 | 32.7 | 91.1 | 29.3 | 21.4 | 2.7 | 0.9 | 0.0 | 0.0 | 19.2 | 0.7 | 0.0 | 15.2 | 213.1 |
| Outflow D3 | 0.0 | 19.7 | 32.8 | 47.1 | 13.3 | 2.0 | 0.1 | 0.0 | 233.5 | 3.3 | 0.0 | 3.2 | 354.9 |
| 2001 | | | | | | | | | | | | | |
| Precipitation | 44.2 | 59.9 | 65.8 | 27.2 | 50.8 | 140.5 | 166.6 | 72.9 | 32.3 | 15.0 | 29.2 | 21.3 | 725.7 |
| Outflow D6 | 37.9 | 49.6 | 98.1 | 27.3 | 0.0 | 0.0 | 0.6 | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 214.3 |
| Outflow D3 | 40.7 | 44.7 | 60.3 | 17.0 | 0.0 | 0.0 | 1.3 | 95.9 | 13.1 | 0.0 | 0.0 | 0.0 | 273.1 |
| 2002 | | | | | | | | | | | | | |
| Precipitation | 152.7 | 51.1 | 153.4 | 71.9 | 56.1 | 107.2 | 159.0 | 170.9 | 74.9 | 109.2 | 137.7 | 87.5 | 1331.6 |
| Outflow D6 | 12.4 | 67.8 | 172.6 | 104.0 | 0.0 | 0.0 | 0.0 | 9.6 | 52.1 | 0.0 | | | 418.5 |
| Outflow D3 | 99.2 | 42.5 | 90.2 | 67.0 | 31.3 | 10.0 | 86.1 | 50.8 | 121.3 | 1.8 | | | 600.2 |

**Table 2. Monthly totals for precipitation and watershed outflow during the study period (in mm).**

* September – December 2000 included in this analysis due to different weir settings before that period.

Cumulative outflow from WS6 was greater than from WS3 prior to harvest (calibration period) in 2001 (Figures 5 & 6). However, following the harvest operations there was considerable difference in outflow response to tropical storms occurring on days 203-211 and 223-226. A total of 110 mm of outflow was measured from the harvested watershed (WS3) compared to only 1 mm from WS6 in response to the two storms. The difference is attributed to differences in ET from the two watersheds during the period between harvest (days 159-178) and the storms. Removal of the trees on WS3 reduced ET compared to WS6. This reduced the water table depth (Figures 7-9) and storage for infiltrating rainfall, prior to the tropical storm events. ET from WS6 lowered the water table between rain events, thereby creating more storage and less outflow during the treatment period in comparison to the harvested watershed. Water yield increases and water table rise in response to rainfall following harvesting operations in this investigation are consistent with previously reported investigations (Hibbert 1966; Williams and Lipscomb 1981; Riekerk 1983; Richardson and McCarthy 1994; Dube et al. 1995; Lebo and Herrmann 1998).

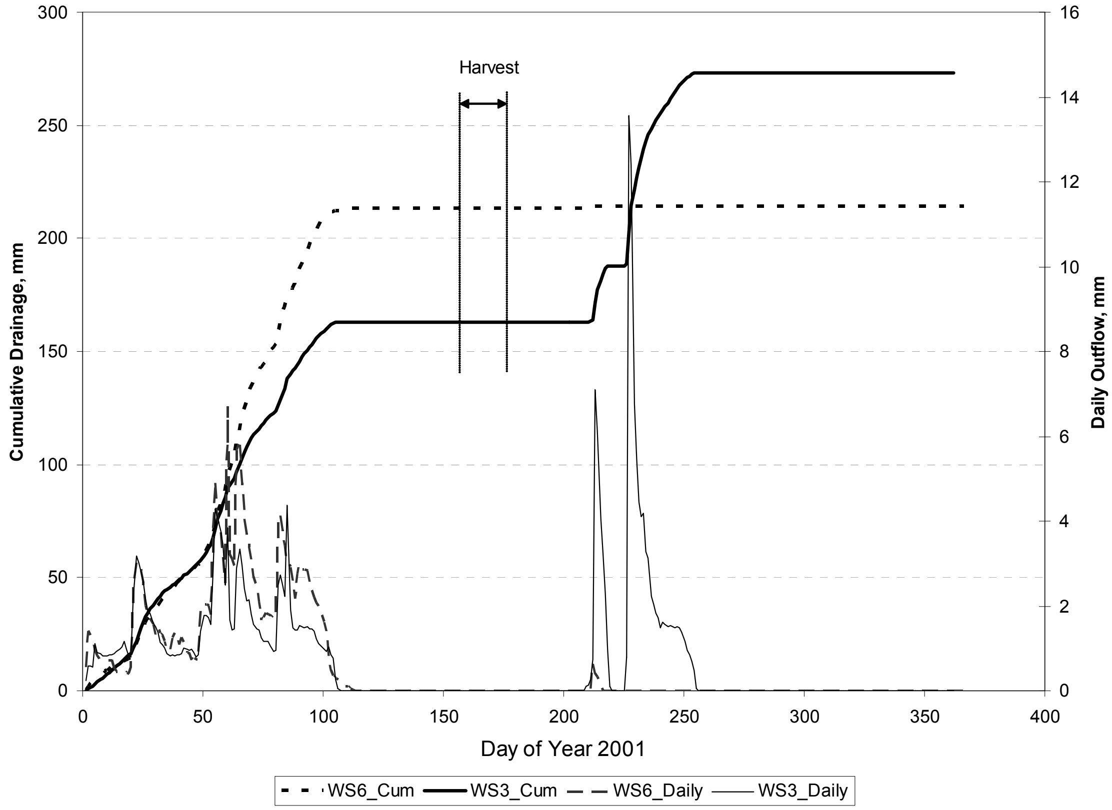


**Figure 5. Observed outflow for the WS6 (control) and the WS3 (treatment) watersheds during 2001.**

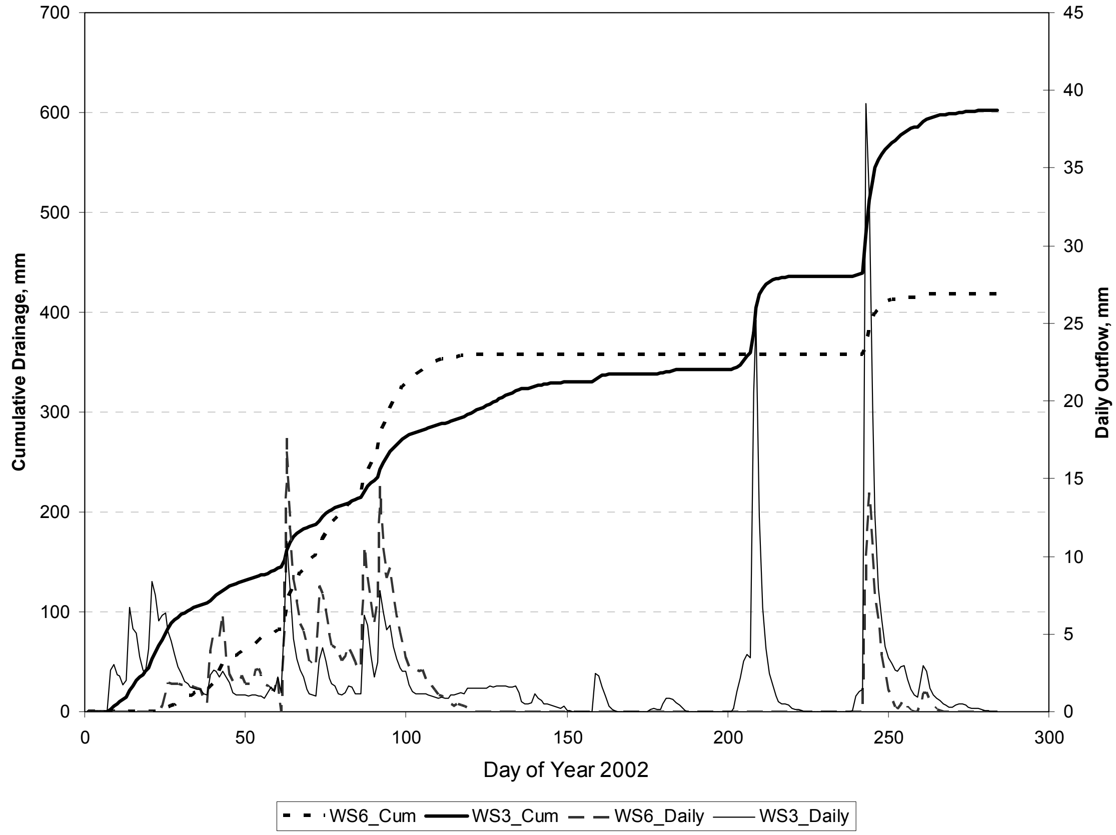


**Figure 6. Observed outflow for the WS6 (control) and the WS3 (treatment) watersheds during 2002.**

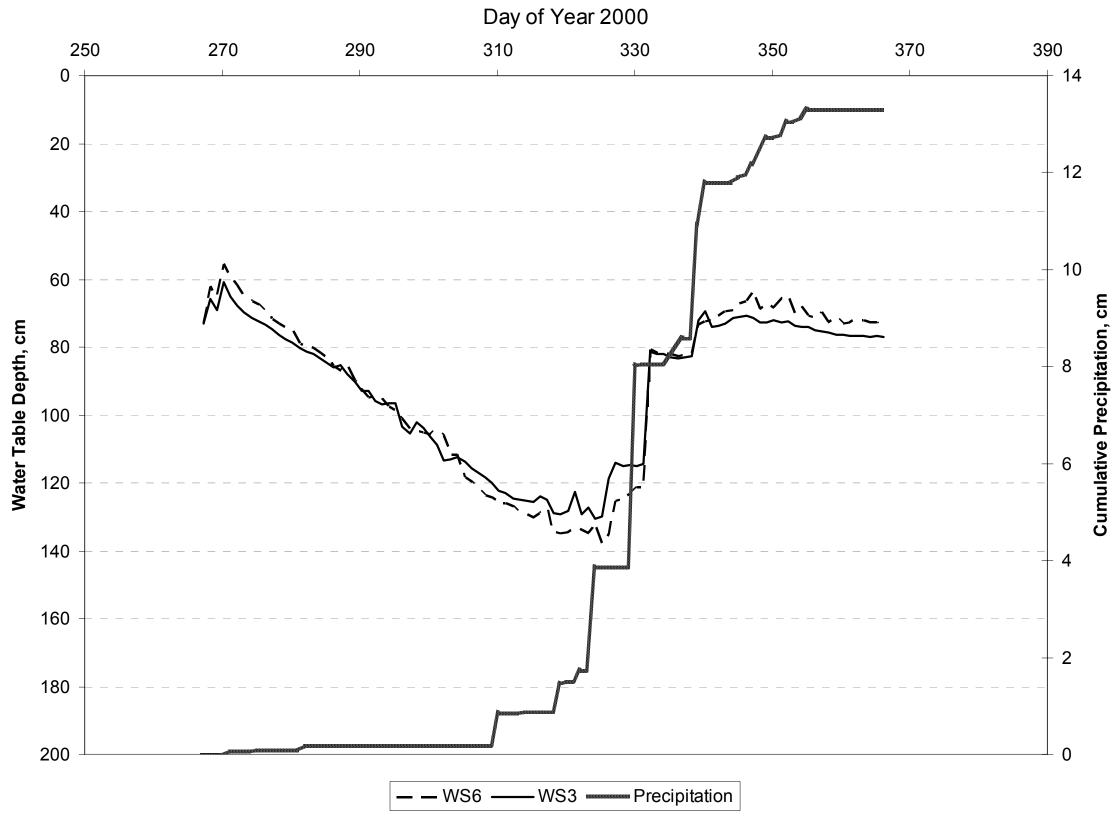


**Figure 7. Daily average mid-point water table depths and precipitation for the WS6 (control) and WS3 (treatment) watersheds during 2000.**

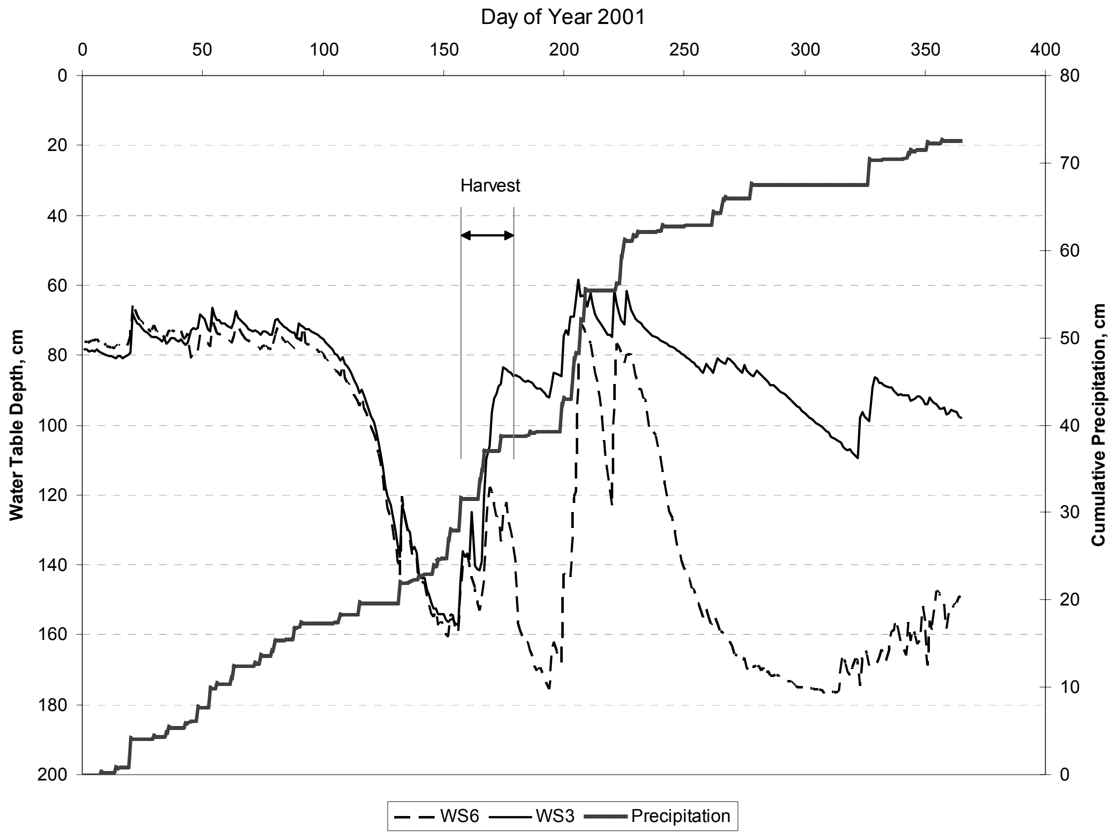


**Figure 8. Daily average mid-point water table depths and precipitation for the WS6 (control) and WS3 (treatment) watersheds during 2001.**

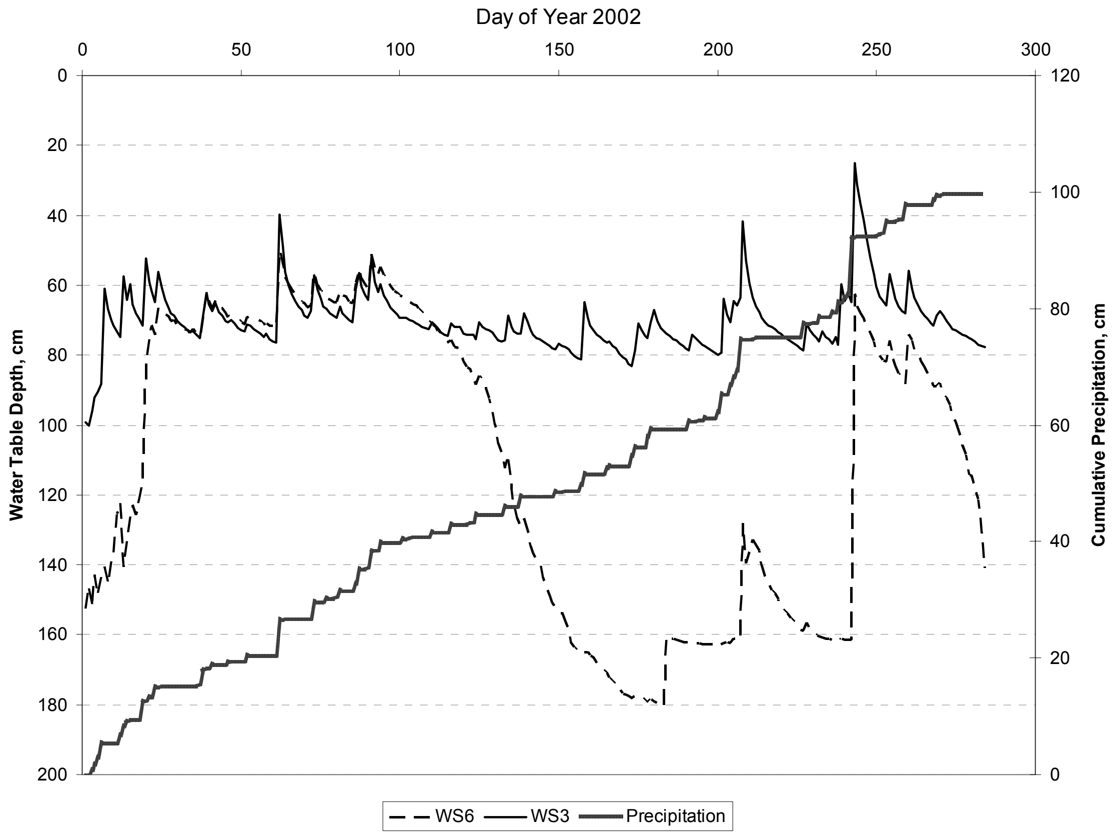


**Figure 9. Daily average mid-point water table depths and precipitation for the WS6 (control) and WS3 (treatment) watersheds during 2002.**

Flow began in the WS3 watershed nearly two weeks earlier than WS6 in 2002 primarily because of the differences in ET, and thus water table depths, during the last four months of 2001 (Figure 5). At the end of 2001, the water table was 98 cm below the surface in WS3 compared to 149 cm for WS6. Nearly a month of recharge by precipitation in January was required before outflow began from WS6 in 2002. Because the initial water table was shallower and there was less storage available for infiltrating rainfall on WS3, the water table rose and outflow began earlier in 2002. Once rainfall recharged the water table in WS6 at the beginning of 2002, outflows from WS6 exceeded WS3 through mid-April (day 110). This is not unexpected. Potential ET is less during the winter and early spring and transpiration from the mostly deciduous trees on the WS6 watershed may be assumed negligible during that period. Thus ET demand from both watersheds would be satisfied primarily by evaporation from the soil surface, so differences in flow due to differences in ET between the two watersheds would not be expected. In the spring when foliage returns and temperatures increase, ET from WS6 caused the water table to rapidly fall well below the ditch depth (Figures 7-9) and drainage ceased. However, WS3 continued to drain long after WS6 outflow had ceased. The water table in WS3 was not drawn down below the ditch level by ET, so flow continued for a longer period of time.

Another factor influencing the difference in drainage response in early 2002 is because WS6 was better drained in comparison to WS3 following the harvesting operation. Logging slash and displaced soil slowed flow in lateral ditches draining WS3 which resulted in a poorer drained condition than WS6. The extended number of outflow days observed from the WS3 watershed supports this assumption.

Daily average water table depths were determined and plotted for both WS6 and WS3 for the study period. Water table depths during 2000 were similar for WS6 and WS3 during days 267-366 (Figure 7). Calibration period water table depths from day 267 in 2000 through application of the harvest operation beginning on day 161 in 2001 showed only minor differences. However, immediately following the initiation of harvest, water table response between the watersheds was quite different (Figure 8). For example, at the initiation of harvest (day 159) the water table was 138 cm below the surface for both watersheds. By the conclusion of harvest (day 178) water tables were 85 and 134 cm for the WS3 and WS6 watersheds, respectively. Four rain events of 21, 11, 22, and 1 mm (55 mm total) during the harvest operation resulted in this water table rise of 4 cm for WS6 and 53 cm for WS3. The WS3 watershed water table remained within 110 cm of the ground surface for the remainder of 2001; whereas WS6 water table depths receded to nearly 180 cm below the surface during the same period. The higher water table depth on WS3 at the end of 2001 and beginning of 2002 (Figure 9) resulted in the initiation of flow at an earlier date in 2002 (Figure 6). This difference in post-harvest water table depths is likely due to both changes in soil properties on the harvested watershed and a difference in ET, with decreased ET losses from the harvested watershed assumed to account for most of the observed differences.

### *Regression Analysis*

Outflow, rainfall, and water table depths were examined to determine the total number of outflow events for each period. A total of thirteen outflow events were identified during the pre-calibration period and fifteen events during the treatment period. Daily outflows and total event outflows were determined for each identified storm event and used to develop regression relationships for watersheds. Development of calibration period regression relationships required regressing outflows from the treatment (WS3) watershed with outflows from the control (WS6) watershed (Figure 10). Daily outflow from the treatment and control watersheds was highly correlated during calibration and treatment periods, as indicated by correlation coefficients of 0.91 and 0.92 ($R^2$ values of 0.83 and 0.84), respectively (Table 3). The regression models between the two watersheds were significant during both periods at $p<0.0001$. Slopes of the regression relationships between the WS3 and WS6 were significantly different from unity at $p<0.0001$ for both the calibration and treatment periods.

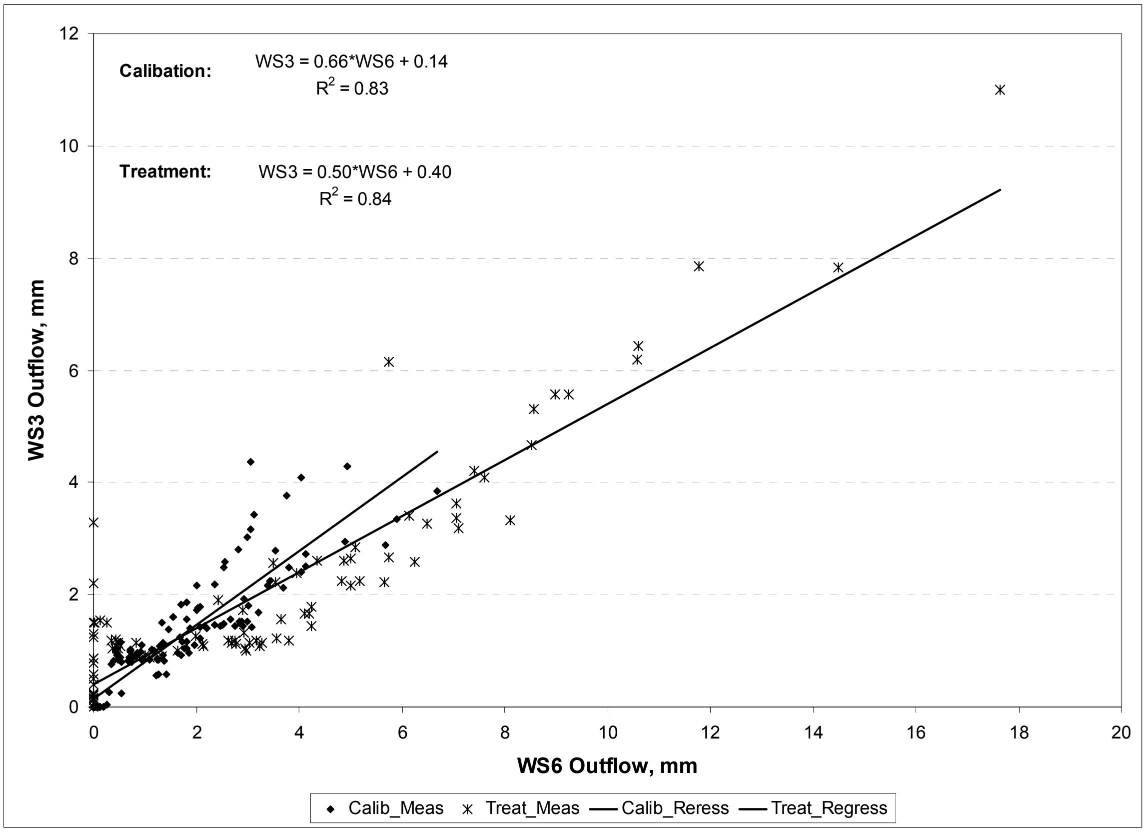


**Figure 10. Measured outflow and regression relationships for the WS6 (control) and WS3 (treatment) watersheds during the treatment and calibration periods.**

Water table depth data were measured and recorded throughout the calibration and treatment periods. Water table data were available for development of regression relationships for the entire study period, including the dry season when outflow seldom occurred. A total of 12 months of water table depths were available during the calibration period and 20 months were available during the treatment period. Water table depths for the WS3 watershed were regressed with WS6 water table depths for both the calibration and treatment periods (Figure 11). Water table depths were highly correlated between WS3 and WS6 watersheds during the calibration and treatment period having correlation coefficients (r) of 0.99 and 0.91 ($R^2$ values of 0.98 and 0.83), respectively (Table 3). The regression model was significant at $p<0.0001$ for the calibration and treatment periods. Slopes of water table depth regression relationships for both periods were significantly different from unity ($p<0.0001$) based on regression analysis.

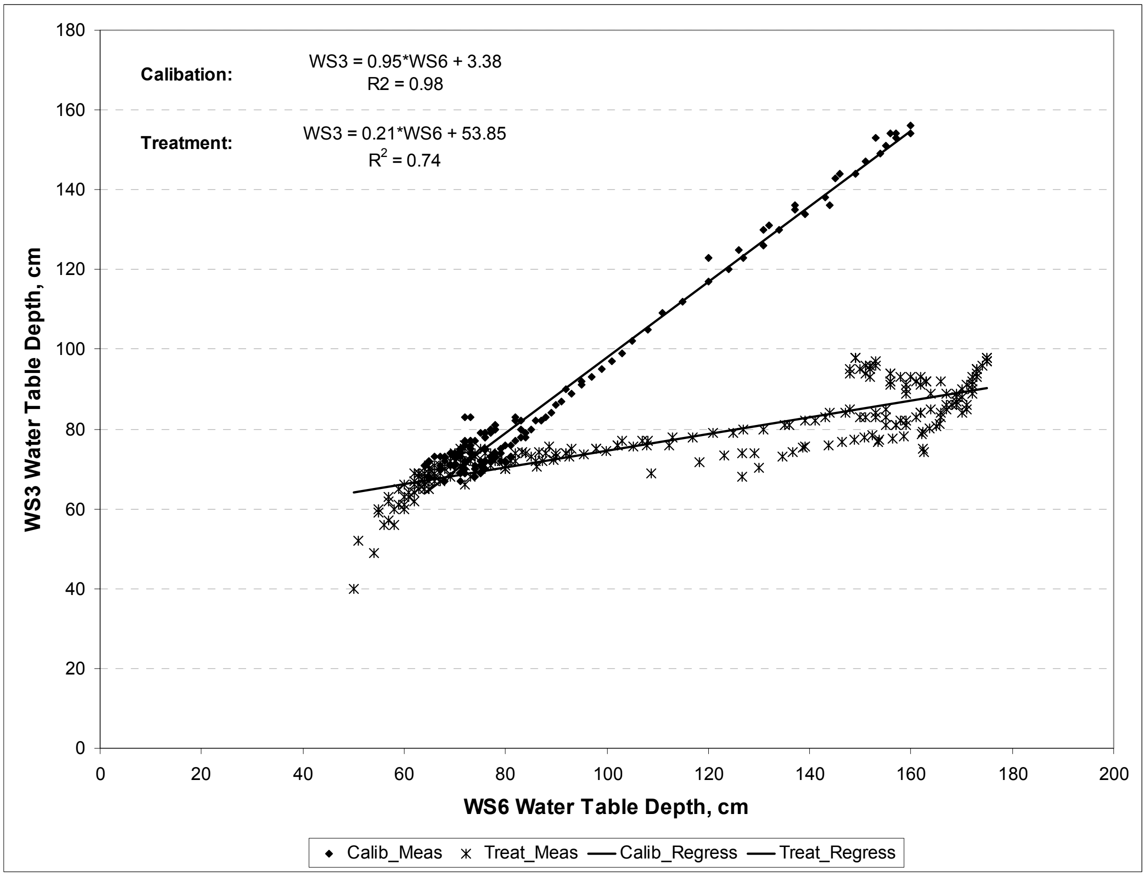


**Figure 11. Measured water table depths and regression relationships for the WS6 (control) and WS3 (treatment) watersheds during the calibration and treatment periods.**

Table 3. Outflow and water table depth regression relationships between WS6 and WS3 watersheds for calibration and treatment periods.

| Period | Regression Equation | Regression $R^2$ | Regression F-value | P-Value Slope | P-Value Intercept |
|---|---|---|---|---|---|
| Calibration | | | | | |
| | WS3_Flow = 0.66*WS6_Flow + 0.14 | 0.833 | 787* | <0.0001 | 0.0026 |
| | WS3_WTD = 0.95*WS6_WTD + 3.38 | 0.977 | 7052* | <0.0001 | <0.0001 |
| Treatment | | | | | |
| | WS3_Flow = 0.50*WS6_Flow + 0.40 | 0.837 | 446* | <0.0001 | 0.0009 |
| | WS3_WTD = 0.21*WS6_WTD + 53.9 | 0.741 | 693* | <0.0001 | <0.0001 |

*Indicates significance of the regression model for the given period at the 0.001 level.

### *Outflow responses to Treatment*

During the calibration period, outflow occurred a total of 125 and 140 days for WS3 and WS6 watersheds, respectively. During the treatment period, outflow occurred from WS3 on a total of 190 days, which was nearly twice that observed for WS6 (99 days). Observed outflow was grouped by storm events in the determination of treatment effects on outflow. Thirteen storm events were identified for the calibration period and an additional fifteen events were identified during the treatment period. SAS GLM was used to test for differences in storm event outflow, peak outflow, and number of flow days observed from the watersheds between periods.

Event outflow characteristics (total outflow, peak flow, and flow days) were similar between WS6 and WS3 watersheds during the calibration period (Table 4). However, these characteristics were significantly different between the control and treatment watersheds during the treatment period. For example, peak flow rates from WS3 and WS6 following the harvest operation were 104.0 and 40.6 $m^3$/hr, respectively. This represents an event peak flow increase of 60 percent from WS3 in comparison to WS6 ($p=0.041$). In addition to an increase in event peak flow, mean event outflow for the harvested watershed (WS3) was 47.3 mm, which was more than 100 percent greater than from the control (22.6 mm) (Table 4). Similarly, mean number of flow days for WS3 was more than twice the number of flow days observed on WS6 ($p=0.002$). Based on this analysis it may be concluded that the harvest operation on WS3 significantly impacted event outflow compared to the control. The differences in event outflow from WS3 and WS6 for the treatment period is perhaps best illustrated graphically (Figures 5 & 6), which clearly shows a difference in outflow following the harvest.

Table 4. Watershed means and statistics computed for calibration and treatment periods.

| Parameter | Watershed | Period | Mean* |
|---|---|---|---|
| Event Outflow, mm | | | |
| | WS3 | Calibration | 21.6b |
| | WS3 | Treatment | 47.3a |
| | WS6 | Calibration | 28.6b |
| | WS6 | Treatment | 22.6b |
| Event Peak Flow, $m^3$/hr | | | |
| | WS3 | Calibration | 20.9b |
| | WS3 | Treatment | 104.0a |
| | WS6 | Calibration | 28.1b |
| | WS6 | Treatment | 40.6b |
| Event Flow Days, day | | | |
| | WS3 | Calibration | 15.6a |
| | WS3 | Treatment | 18.4a |
| | WS6 | Calibration | 17.5a |
| | WS6 | Treatment | 8.6b |

*Means with different letters for a given parameter are statistically different at the0.05 level.

The increase in event outflow from WS3 is largely due to increased flow days and peak flow rates instead of a difference in daily outflow. This effect is best explained by analyzing regression relationships developed for each of the fifteen calibration period storm events and thirteen treatment period storm events (Figure 10). SAS GLM procedure was used to test for differences in daily outflow and daily peak flow regression slopes and intercepts from the watersheds between periods. The mean regression slopes for daily outflow between WS3 and WS6 watersheds of 0.61 and 1.19 for the calibration and treatment periods were not significantly different (Table 5). Daily peak flow mean regression slopes for the calibration and treatment periods were similar with mean values of 0.37 and 1.57, respectively. In addition, regression intercepts for daily outflow and peak flow between the WS3 and WS6 watersheds were statistically similar. The similarity of the regression of WS3 daily outflow and peak flow with WS6 daily outflow and peak flow for the calibration and treatment periods is perhaps best illustrated graphically in Figure 10, which shows very little change between the periods. Based on the paired watershed approach, no treatment effects on daily outflow were detected since there were no significant differences between slopes and intercepts between calibration and treatment periods. However, the power to detect a change of 50 percent in daily outflow was 50 percent in this regression analysis ($\alpha$= 0.05) due to the variability in watershed outflow. The standard error in the daily outflow and peak flow comparisons was 0.67 and 0.82, respectively, so slope changes of ± 1.3 and ±1.6 are considered non-significant.

Table 5. Mean regression slopes and intercepts for WS6 and WS3 watersheds during the calibration and treatment periods.

| Parameter | | Calibration Mean | Treatment Mean |
|---|---|---|---|
| Daily outflow, mm† | | | |
| | Regression Slope | 0.61a | 1.19a |
| | Regression Intercept | 0.57a | 1.14a |
| Daily Peak Flow, $m^3$/hr | | | |
| | Regression Slope | 0.37a | 1.57a |
| | Regression Intercept | 3.18a | 8.98a |
| Water table depth, cm† | | | |
| | Regression Slope | 0.83a | 0.63a |
| | Regression Intercept | 11.35a | 6.92a |

†Mean values in rows with the same letter for parameters were not statistically different at α = 0.05.

Water table depth regression relationships were developed for the calibration and treatment periods (Figure 11). Slopes and intercepts of the water table depth regression relationships between the WS3 and WS6 watersheds were analyzed for differences between the periods (Table 5). The standard error in the comparison was less than 0.25 so differences in regression slopes of ± 0.5 were considered non-significant. Mean water table depth regression slopes between WS3 and WS6 watersheds of 0.83 and 0.63 for the calibration and treatment periods, respectively, were statistically similar. Similarly, ANOVA detected no significant differences in water table depth regression intercepts.

Previous work has shown water table rise following harvesting operations (Williams and Lipscomb 1981; Sun et al. 1998, 2000; Riekerk 1989; Amatya et al. 2000; Dube et al. 1995). This analysis was unable to detect any effects of harvesting on water table rise; however mean water table depths during the treatment period for WS3 and WS6 were 68 and 97 cm, respectively. The minimum detectable difference in the analysis was 40 cm due to the large variability between water table depths during the extremely dry conditions during 2001.

Regression analyses in the paired watershed approach did not show a significant effect of harvest on daily outflow, peak flow, or water table depths. These results are contrary to analysis of variance which showed that harvest had a significant effect on event outflow, event peak flow rates, and number of days with measurable outflow. It is also contrary to a nonstatistical analysis of the mechanisms affecting flow based on plotted cumulative outflow and water table depths.

As discussed previously, harvesting reduced ET and increased event outflow and peak outflow rates. The effect of harvest on both outflow and water table depths appeared to be greater during the summer and fall months when PET is high (Figures 5, 6, 8, and 9). However, during the winter and early spring months, PET is low and the ET (primarily by evaporation) from the harvested watershed would be expected to be similar to the control (i.e. ET is limited by atmospheric conditions, not the soil-water-plant condition). This causes the effects of harvest on ET, daily outflow, peak flow, and water table depth to be dependent on both season and the sequence of weather events. This dependency results in relatively high variability (and decreased power to detect differences) in the relationships between outflows and water table depths from harvested and control watersheds. The inability of the paired watershed approach to detect a significant harvesting effect on daily outflow, peak flow, and water table depths may be an influence of the high variability from season to season and the sequence of weather events.

## Summary and Conclusions

Paired watersheds were used to evaluate the impact of harvesting a 23-ha mature natural primarily hardwood forest stand. The investigations were conducted in eastern North Carolina on organic soil sites with organic matter content greater than 80 percent. The effect of harvesting on outflow, water table depth, and event peak flow was evaluated over a study period from December 1999 to October 2002. Outflow and water table depths were first tested for correlations and then tested for treatment effects using a paired watershed approach.

The 23-ha natural watershed was clear-cut harvested using shovel logging techniques following a 1 ½ -year calibration period. Twenty-eight outflow events were identified on the WS6 (control) and WS3 (treatment) watersheds. Thirteen of these events occurred during the calibration period and the remaining fifteen events during the treatment period. Regression analysis revealed that the regression model had predictive value ($p<0.0001$) in predicting WS3 daily outflow based on WS6 daily outflow during both calibration and treatment periods. Relationships developed for outflow events during both periods had correlation coefficients greater than 0.90. Analysis of variance detected significant treatment effects on event outflow, event peak flow, and number of event flow days from the harvested watershed. The harvested watershed was also more responsive to precipitation following treatment which can be attributed to decreased ET and saturated hydraulic conductivity following the harvesting operation. This was apparent from WS3 outflow events during periods when WS6 had no measurable outflow as well as earlier initiation of flow at the beginning of the 2002 flow season. Annual outflow from the treatment watershed was 180 mm more than the control during 2002.

Regression relationships developed for water table depths for the calibration and treatment period revealed that the regression model had predictive power ($p<0.0001$) in predicting WS3 water table depths based on WS6 water table depths during the periods. The paired watershed analysis indicates that treatment did not significantly affect water table depths on the WS3 watershed. However, mean water table depths for WS3 and WS6 were 68 and 97 cm, respectively. Variability of water table response to harvesting was high due to seasonal effects on ET. The minimum detectable difference in the analysis was 40 cm, which likely influenced conclusions from this investigation. In a result similar to the outflow from the harvested watershed, the water table rose earlier at the beginning of the wet season indicating a wetter site following harvest. These differences in outflow and peak flow are attributed to timber removal from WS3, which greatly reduced ET.


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