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Short-term hydrological responses to silvicultural treatments within a stream buffer zone: a case study

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Abstract: The thinning of stream buffer zones (SBZs) is gaining popularity as a silvicultural management practice in order to reduce the risk of wildfire and insect hazard, provide economic return, and improve the effectiveness of SBZs. In this study, streamflow over a 1-year period was monitored at 2 small paired watersheds (treated vs. reference). The short-term impacts of a partial cutting within a SBZ as well as the relative effects of pastoral, forested, and clearcut areas on changes in downstream hydrology were examined. Upstream pastoral areas had a higher water yield than downstream forested sections during the no-harvest (calibration) period of 6 months. The partial cut (about 50% of the basal area) within the SBZ changed the hydrologic pattern by remarkably increasing the water yield on the treated downstream sections during the 6-month-long postharvest period. The harvest operation also caused an increase in direct runoff at 2 downstream sections, WT2 and WT3 (~200% and ~100%, respectively). No significant changes were observed in the water yield pattern of the control watershed. Because harvested areas within the SBZs constitute a fraction of the monitored sub-watersheds and only partial harvesting (~50% of the basal area) was implemented, the observed increase in flow at the treated downstream sections (100% and 250%, respectively) is unprecedented. The partial harvesting within the SBZs also resulted in a significantly flashier hydrological system. Because silvicultural treatments are part of regular, repeated management operations, these short term (in this study, 6-month-long) but substantial changes in water yield, direct runoff, and flashiness could have important implications for water quality, water resources, and downstream biota.

Key words: Partial cutting, streamside buffer zone, watershed, water yield

1. Introduction

Clean water is a vital resource that we rely on in our daily life. Forested watersheds are the main sources of clean water. They are generally associated with high quality water compared to watersheds with other major land use/cover types (Chang, 2006). Southern forests are some of the most productive forests in the United States and are often exposed to intensive management practices (Grace III, 2005). To increase site productivity and reduce rotation time, silvicultural prescriptions, such as site preparation, fertilization, thinning, and harvesting, are often implemented. These intensive management practices may adversely affect water quantity and quality.

In order to determine the effects of decreasing vegetation density and changes in land use/cover on water yield, an understanding of the interaction between the forest canopy and various hydrologic processes is essential (Ganatsios et al., 2010). Removal of forest canopy results in decreased interception and evapotranspiration rates, which consequently leads to increases in surface runoff and total water yield (Douglass, 1979; Swank et al., 1989; Grace III et al., 2003; Hubbart et al., 2007). This is because a greater percentage of precipitation is directly delivered to the forest floor after harvest operations (Troendle and Olsen, 1993). As a result, even a small rain event could bring the soil moisture to its capacity and produce surface runoff (Hubbart et al., 2007). This increased surface runoff following complete or partial overstory removal can accelerate nonpoint source (NPS) pollutants such as sediments (Grace III, 2005; McBroom et al., 2007; Kara et al., 2014). In addition, intensive vegetation removal within stream buffer zones (SBZs) might increase sediment yield to the stream, stream temperature, and nutrient concentration (Kara et al., 2014).

To mitigate the potential adverse impacts of silvicultural operations on water quality, best management practices (BMPs) are often implemented (Norris, 1993). These practices are designed to be at or above the minimum standards necessary to protect and maintain water quality during forestry activities (Alabama Forestry Commission,

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1999). An SBZ is a strip of vegetated land managed to protect the surface water and riparian values from forestry operations (Alabama Forestry Commission, 1999), and is one of the most commonly employed nonstructural BMP types within which harvesting is usually restricted (Studinski et al., 2012). SBZs are not only very effective at protecting and maintaining water quality and quantity (Norris, 1993; Alabama Forestry Commission, 1999), but also promote productive fisheries, provide wildlife habitats, improve aesthetics, and foster recreational opportunities (Alabama Forestry Commission, 1999).

SBZs are generally excluded from intensive harvesting or complete overstory removal. However, in order to reduce the risk of wildfire and insect hazard, provide economic return, and improve the effectiveness of the SBZs, the thinning of forested SBZs is recommended (McBroom et al., 2007). Silvicultural disturbance within SBZs can promote understory vegetation growth. Over time, this can increase infiltration and decrease runoff, which is responsible for increased sediment yield in streams (Anderson and Lockaby, 2011). Although the interest in SBZ thinning is increasing in the Southern USA (Keim and Schoenholtz, 1999), few studies have observed the impacts of harvesting within SBZs on water quality and quantity within the region (Hodges, 2009; Lakel et al., 2010; Studinski et al., 2012; Kara et al., 2014) and the knowledge on the appropriate type of SBZ harvesting to minimize the effect of harvesting on water yield, water quality, and riparian values is limited (Prud'homme and Greis, 2009).

In the present study, an efficient filtration buffer was intended by generating a higher roughness and a well-developed understory within an SBZ having multiple canopy tiers. In order to achieve this, partial cutting was carried out within an SBZ of a small watershed in East Central Alabama, USA. The hydrologic impacts of this partial cutting were assessed by comparing the pre- and postharvest period streamflow. A similarly sized watershed adjacent to the partially harvested watershed served as a reference site. Water yield, surface runoff, and streamflow flashiness from the 6-month-long preharvest period were compared to the same values from the 6-month-long postharvest period. It is hypothesized that the immediate short-term (6-month) impact of partial cutting within SBZs on water yield and the hydrologic regime in general could be significant, which could have important implications for erosion/sedimentation, water quality, and stream habitat.

2. Materials and methods

2.1. Study site

The study was conducted at the Mary Olive Thomas Demonstration Forest in Auburn, Alabama, USA (Figure 1). The forest is in a transition zone from a Piedmont upland to a bottomland. The long-term average annual rainfall is 1335 mm, of which ~50% occurs from April to September. Although April to September is generally considered to be the growing season for row crops, the growing season for deciduous trees in the region extends from April to November. About 40% of the annual precipitation occurs during the dormant season of December to March.

Most of the study area has slopes <6%; however, steep slopes are present on some parts of the tract. Pacolet series is the predominant soil type on the property except for narrow bands of Toccoa sandy loam along streams and main drainages. These soils are considered typical soils of the Piedmont plateau, and are fairly productive for forests (McNutt et al., 1981). The lower slopes along the stream also retain much of their original soil since these areas were probably never cleared due to rocky formations in these zones.

The timber on the property is primarily loblolly pine (*Pinus taeda* L.). However, the SBZs (including the study area) are dominated by deciduous species. The average site index for loblolly pine is about 26 m (base age 50 years) on the property. The SBZ stands are well stocked, and, at approximately 20 m in width, are typically wider than required by the State of Alabama guidelines (Alabama Forestry Commission, 1999).

Two small adjacent watersheds, named treatment watershed (W_T) and control watershed (W_C), were chosen for the study. The treatment watershed covers 37 ha while the control watershed is 50 ha. Each watershed was divided into 3 sections (W_{T1}, W_{T2}, W_{T3}, and W_{C1}, W_{C2}, W_{C3}) based on land use/cover or silvicultural treatment (Figure 1). An intact SBZ borders the 2 first order streams for the entire length of the watersheds from point T_1 south to T_3, and from point C_1 south to point C_3 (Figure 1). The SBZs on W_{T2} and W_{T3} cover about 43% and 28% of their respective sections. The area upstream of T_1 on the treatment watershed is dominantly pasture (68%), while upstream of C_1 on the control watershed is mostly low density residential area (60%). There is a retention pond just upstream of both T_1 and C_1 (Figure 1). The central portions of both watersheds, W_{T2} and W_{C2}, are entirely forested. Although the downstream sections W_{T3} and W_{C3} are also forested, there was a clearcut area between the 2 SBZs (Figure 1) during the study period that was harvested in early 2008. Then the site was prepared with herbicide in late summer, windrowed with a root rake in the fall of 2008, and planted during the 2008–2009 dormant season. The total area of the clearcut was 5.3 ha, covering 21% of W_{T3} and 15% of W_{C3}.

ArcSWAT (Neitsch et al., 2005) was used to delineate the watershed boundaries and extract the drainage network of the study area from a Digital Elevation Model (DEM)

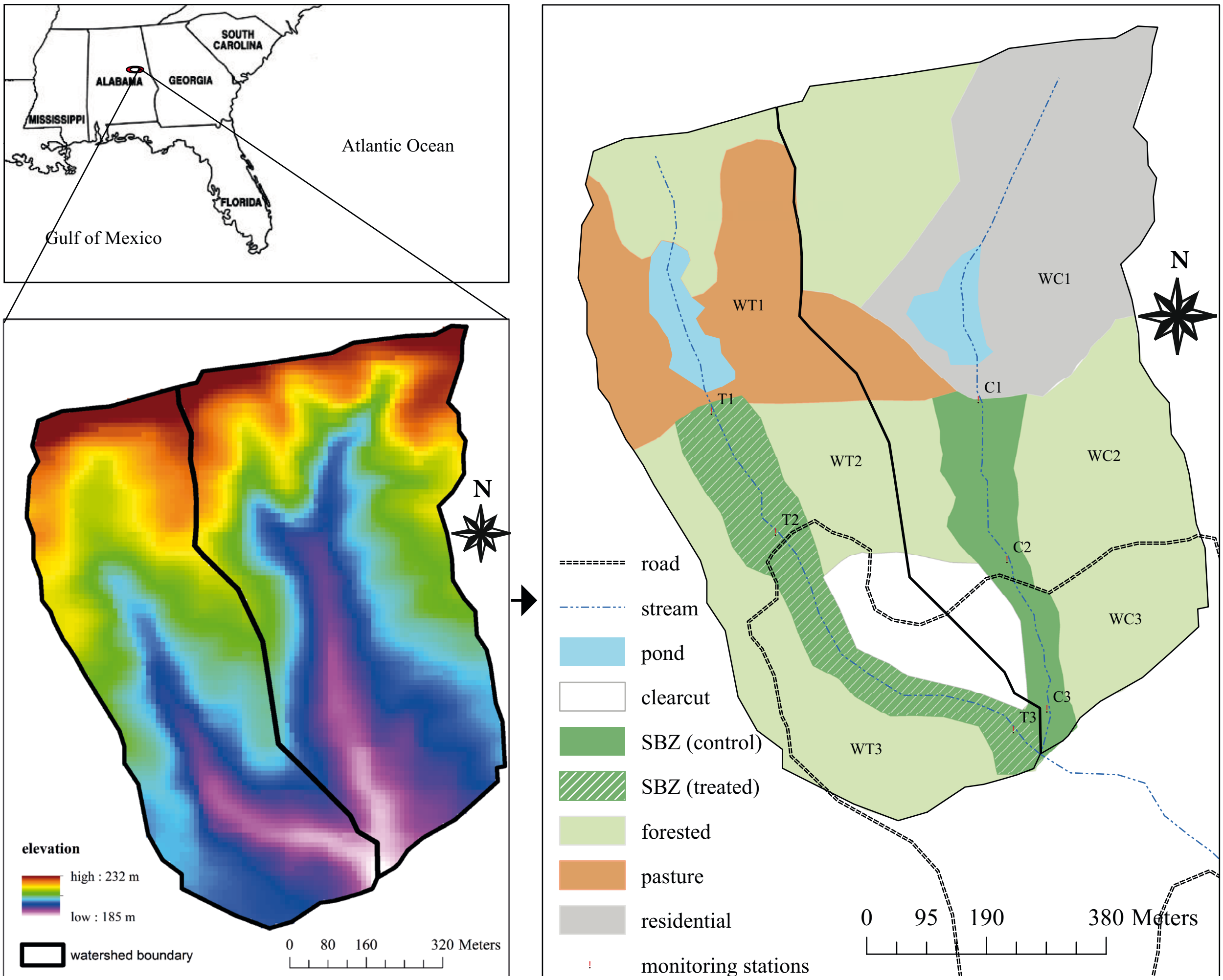

Figure 1. Location and characteristics of the treatment (T) and control (C) watersheds. The area of each section is (in ha) W_{T1} = 11.56, W_{T2} = 10.07, W_{T3} = 15.35, W_{C1} = 22.74, W_{C2} = 12.94, and W_{C3} = 14.04.

with a 10 m horizontal resolution. One monitoring station was established on each section (T_1, T_2, T_3, C_1, C_2, and C_3) to continuously monitor water levels (h) and measure stream discharges (Q). The most upstream stations, T_1 and C_1, were located on the northern boundary of the forested area, and were selected to quantify the contribution of the pastoral and residential areas, respectively, to the forested middle sections. The second group of stations, T_2 and C_2, were located at the upstream edge of the clearcut area so that in comparison to T_1 and C_1, it would be possible to evaluate the effect of intact forest cover on water yield. The 2 most downstream stations, T_3 and C_3, were chosen in order to evaluate the effect of an intact SBZ with a clearcut area draining into them.

2.2. Hydrologic monitoring

Water levels at each site were continuously monitored and recorded every 15 min from 5 April 2009 to 5 April 2010 using Solinst Levelogger Gold Model 3001 pressure transducers (Solinst, 2013). This was a very wet period compared to the long-term average. About 1900 mm of rainfall fell during this period (NCDC station ID: GHCND-US1ALLE0005), which is 570 mm above the long-term average. In addition to continuous water stage recordings done by transducers, stream discharge was measured during storm events (whenever possible and while it was still raining) at each monitoring station using a Marsh-McBirney Model 2000 portable flowmeter during each site visit (Marsh-McBirney Inc., 1990). The standard stream cross-sectional velocity profile method was used to obtain discharge (Hewlett, 1969). Almost all rain events (32) were captured during the study period; however, events associated with lightning were avoided due to safety concerns. Time series of the streamflow were generated using flow-rating curves between water levels and discharge data.

Water levels were associated with discharge measurements taken during each site visit to determine water stage – discharge (Q – h) relationships (rating curves). Rating curves were determined for each monitoring station, and these relationships were then used to generate continuous discharge data at 15-min intervals. The flow generated from each section was estimated by subtracting the flow generated from the upstream section. For instance, at the treatment watershed , , , where denotes flow generated from section W_{Ti}, and denotes flow measured at site T_i. In order to assess the impact of harvesting within the SBZs on direct runoff and base flow, the generated streamflow time series were separated into base flow and surface runoff components using the web-based hydrograph analysis tool (WHAT) (Muthukrishnan et al., 2005).

2.3. Harvest operation

Harvesting was done only in the SBZs located in W_{T2} and W_{T3} (Figure 1). The harvest operation was designed to create an unevenly aged SBZ with multiple canopy layers based on the Proportional-B (Pro-B) method. Pro-B is an unevenly aged marking method that is based on structural control (Brockway et al., 2014). The target structure was defined using a q value of 1.3 (for 5-cm-diameter class) and a largest diameter tree (LDT) of 45 cm. First, the current basal area was measured for 3 product classes (<15 cm, 15–30 cm, and >30 cm). Next, the basal area of the target structure was distributed among these product classes in a ratio of 1:2:3 (Loewenstein, 2005). The target basal area was subtracted from the current basal area for each product class. Then, the proportion of the cut was calculated for each product class (1 – target basal area / current basal area). Finally, a marking guide that gives the proportion of trees to be cut in each of the 3 product classes was obtained (Loewenstein, 2009). For example, if the marking guide for the larger diameter class (> 30 cm) is "2 of 5", 5 trees larger than 30 cm are counted. After that, the 2 most undesirable, poor form, or damaged of these 5 trees are marked. Then the next 5 trees are selected and the same action is repeated. The same process is conducted for each product class throughout the marking. The Pro-B method allows stand marking in one pass (Brockway et al., 2014). This method is well suited for use within an SBZ as it maintains full site utilization with approximately 60% of stand basal area allocated to the saw timber size classes, and allows sufficient growing space for the recruitment of new cohorts as needed (Loewenstein, 2005).

Cutting and skidding operations were completed during the first week of October 2009. Rubber-tired fellers, bunchers, and skidders were used to cut the marked trees and remove them from the stand. The harvest was conducted in dry weather to avoid compaction and rutting of the soils. In the end, roughly 50% of the trees from the SBZs in W_{T2} and W_{T3} were harvested. Note that although the preharvest period (5 April 2009 to 5 October 2009) was all within the growing season, less than 2 months of the postharvest period (6 October 2009 to 4 April 2010) was within the growing season and most of it within the dormant season. Out of the total 1900 mm of rainfall, 880 mm of it fell during the preharvest period (46%) and the remaining 1020 mm fell during the postharvest period (54%). Although these seasonal differences might make comparison of postharvest hydrology to preharvest hydrology challenging, as explained below, the use of the control watershed as a reference site help remedy this.

2.4. Statistical analysis

The effects of treatment, which is partial cutting within the SBZ in this study, on the streamflow were scrutinized using the paired watershed approach (Hewlett, 1969). Six months of preharvest daily streamflow data were used as the basis for developing calibration regression equations between the treatment and control watersheds using the paired monitoring stations, i.e. T_i with C_i ($i = 1,2,3$). The postharvest comparison relies on the high correlation that normally exists between the streamflows of treatment and control watersheds during the preharvest period. In a paired watershed approach, the effect of treatment is determined based on the significant difference in slope and intercept of regression between the preharvest and postharvest periods (Arthur et al., 1998; Grace III et al., 2006). Given this relationship, changes in water characteristics attributable to the harvest operation can be determined. PASW Statistics 18.0 was used to determine significant differences between the observed and predicted means on the treatment watershed by the paired t test for all mean comparisons. Collection of hydrologic data continued across the treated and untreated watersheds following harvest operations for an additional 6 months. Using the preharvest regression model daily streamflows for the no-harvest scenario was projected at the treatment watershed by using the data from control catchment in the postharvest period.

In order to explore the changes in streamflow patterns following the harvest operation within the SBZ, double mass curves were generated by plotting cumulative streamflow of each paired monitoring stations against each other. Treatment sections were paired with control sections, and linear regression equations were developed for both the preharvest and postharvest periods for each pair. Significant differences in the slopes were checked using analysis of covariance (ANCOVA) in the statistical software R. Note that in this study, streamflow was assumed to be equal to water yield, which is defined as precipitation minus evapotranspiration. This implicitly assumes that there is no groundwater outflow that bypasses the gauging stations and leaves the watersheds underground.

3. Results

The linear regression models developed during the calibration period (Table 1) indicate significant relationships between each pair of the sections' streamflow ($P < 0.05$). The R^2 values between T_1–C_1, T_2–C_2, and T_3–C_3 were 0.64, 0.62, and 0.78, respectively. The regression residuals corresponding to T_1–C_1 and T_2–C_2 have no autocorrelation at $\alpha = 5\%$, but there is a weak autocorrelation (lag – 1) with T_3–C_3. To keep the analysis simple, this autocorrelation was assumed to be negligible. The linear regression equations obtained from these calibration data sets were later used to predict hypothetical flows at the treatment subwatersheds that corresponded to no-harvest conditions during the ensuing treatment period.

3.1. Water yield

At the treatment watershed and during the preharvest (calibration) period, the water yields from the pastoral upstream section W_{T1} and the most downstream section W_{T3}, 21% of which was clearcut, were similar, around 1.43 mm/day (Figure 2). The water yield from the forested middle section W_{T2} was about half of the upstream and downstream sections (Figure 2). This was a clear indication of elevated water use by forests. W_{T3} had higher water yield than either of the 2 upstream sections during interstorm (baseflow dominated) periods. Decreasing slope in downstream direction seems to be the biggest factor for the increasing water yield in W_{T3} during these periods (concave slope effect). The control watershed also had a similar behavior. The forested middle section (W_{C2}) had a smaller water yield than sections W_{C1} and W_{C3} (Figure 2), around 0.75 mm/day, which was same as the water yield from W_{T2}. With the effects of the clearcut and the forest roads, water yield was markedly increased in the downstream section (W_{C3}).

Table 1. Relationships between the average daily flows (mm/day) at the treatment watershed (Q_T) and the average daily flows (mm/day) at the control watershed (Q_C) during the preharvest period.

Paired stations	Relationship
T_1–C_1	$Q_T = 0.523Q_C + 0.455$
T_2–C_2	$Q_T = 0.553Q_C + 0.317$
T_3–C_3	$Q_T = 0.399Q_C + 0.499$

According to the regression equation in Table 1, if there was no harvesting within the SBZ, W_{T2} should have yielded about 0.81 mm/day of water during the postharvest period. In contrast, 3.01 mm/day of water was observed after harvesting during the same period, which is almost 4 times the predicted amount for the no-harvest scenario. Section W_{T3} had a similar response, although on a smaller scale. The observed average daily water yield from W_{T3} during the postharvest period was approximately 2.5 times higher than the predicted water yield corresponding to the no-harvest scenario (3.64 mm/day vs. 1.54 mm/day).

During the postharvest period, water yields from the 3 sections of the control watershed (W_{C1}, W_{C2}, and

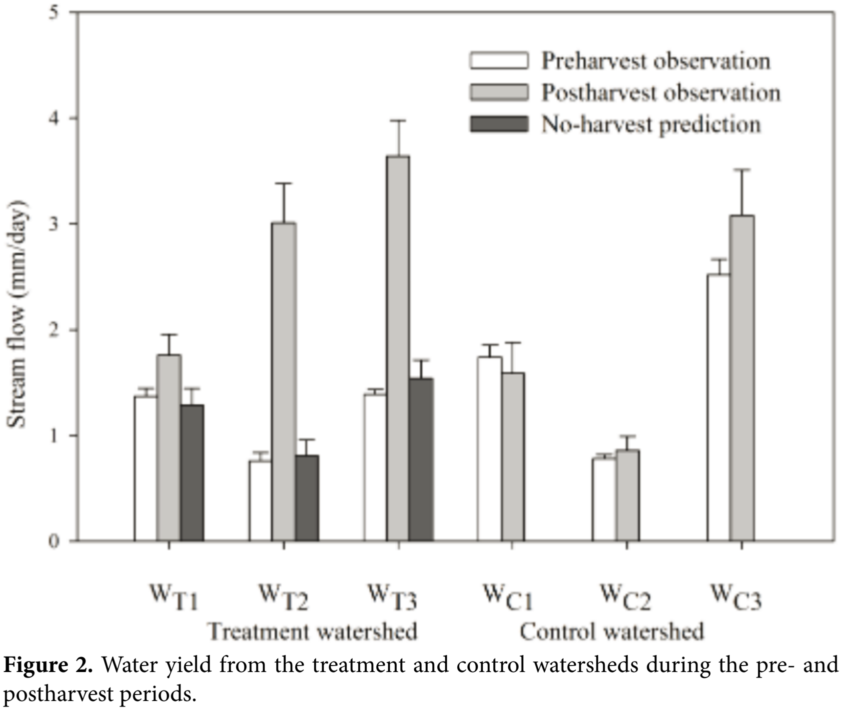

Figure 2. Water yield from the treatment and control watersheds during the pre- and postharvest periods.

W_{C3}) had different responses compared to the preharvest period. Although W_{C2} and W_{C3} experienced 11% and 22% increases in water yield, respectively, water yield from W_{C1} was reduced about 8% (Figure 2). This was in spite of the 16% increase in total rainfall during the postharvest period compared to the preharvest period. This is rather unexpected and it is discussed later. On the other hand, in contrast to the preharvest period, the water yield pattern at the treatment watershed changed markedly after the partial cutting within the SBZ (Figure 2). During this period, both W_{T2} and W_{T3} generated much more water (per unit area) than the upstream pastoral section (W_{T1}). A small increase in water yield was observed at W_{T1}. Although the postharvest period received more rainfall, the fact that water yield in sections W_{T1}, W_{C1}, W_{C2}, and W_{C3} changed little compared to the postharvest changes in water yield from W_{T2} and W_{T3} makes it evident that partial harvests within the SBZ of sections W_{T2} and W_{T3} led to the significant change in water yields during the postharvest period.

3.2. Direct runoff

During a rain event, most of the flow observed in a headwater stream comes from direct runoff (subsurface stormflow + surface runoff + channel precipitation). In contrast, during interstorm periods, there is little to no direct runoff, and streamflow is mainly composed of baseflow. Total rainfall during the 6-month-long preharvest calibration period was 880 mm, during which 4 discrete storm events resulted in direct runoff from each section. The average direct runoff per unit area from W_{T1} was higher than the average direct runoff from downstream sections W_{T2} and W_{T3} during the preharvest period (Figure 3). This demonstrates the effect of forest cover in reducing direct runoff by increasing both interception and evapotranspiration.

Total rainfall during the postharvest period was 1020 mm, during which 11 storm events resulted in direct runoff from each section. All 3 sections had higher direct runoff in this period compared to the preharvest period (Figure 3). However, the increase was much more substantial in sections W_{T2} and W_{T3}. Compared to the no-harvest scenario predictions using the equations in Table 1 for the same period, the observed direct runoff from W_{T2} and W_{T3} were about 3 and 2 times the predicted values, respectively (Figure 3). Unlike the treatment watershed, direct runoff trends at the control watershed during the postharvest period were essentially the same as the preharvest period (not shown in figure). This is a clear indicator that the partial harvests within the SBZs considerably increased direct runoff, which seems to be responsible for the increased water yields.

3.3. Runoff ratio and flashiness

Runoff ratio (RR) represents the fraction of precipitation that becomes runoff. Over the preharvest period, section W_{T2} converted the smallest percentage of precipitation to streamflow (RR = 12%) because this section was undisturbed forest, which is associated with a high rate of evapotranspiration (Table 2). This section was also predicted to convert the smallest percentage during the postharvest period (RR = 17%) if there was no harvesting within the SBZ. However, the observed RR was 63%, which was more than twice the predicted RR for section W_{T1}. Section W_{T3} had almost the same RR (23%) as W_{T1} before harvesting. During the postharvest period, the RR of W_{T3} increased to 76%. These increases in RR in

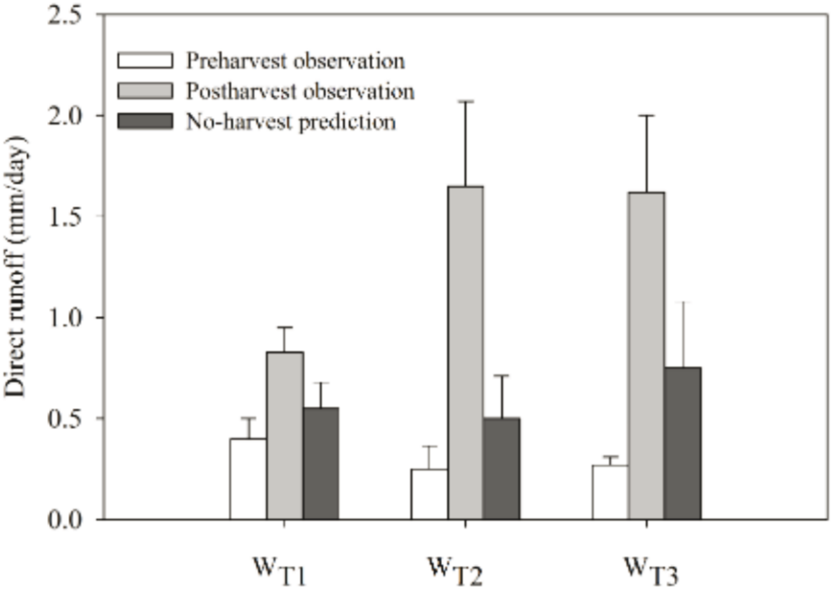

Figure 3. Average direct runoff rates on the treatment watershed.

Table 2. Effects of partial harvesting within the SBZs on runoff ratio (RR) and Richards–Baker flashiness index (RB).

Section	Period	RR (%)	RB
W_{T1}	Preharvest observed	22	0.26
	Postharvest observed	36	0.05
	Postharvest predicted	26	0.07
W_{T2}	Preharvest observed	12	0.23
	Postharvest observed	63	0.06
	Postharvest predicted	17	0.11
W_{T3}	Preharvest observed	23	0.22
	Postharvest observed	76	0.11
	Postharvest predicted	32	0.12
W_{C1}	Preharvest observed	61	0.22
	Postharvest observed	65	0.10
W_{C2}	Preharvest observed	15	0.15
	Postharvest observed	20	0.05
W_{C3}	Preharvest observed	58	0.18
	Postharvest observed	78	0.14

sections W_{T2} and W_{T3} can be attributed to the decrease in evapotranspiration after the harvest. For the control watershed, similar RR values were observed during the pre- and postharvest periods. The forested middle section (W_{C2}) converted the smallest percentage of precipitation to streamflow in both periods (15% and 20%). Sections W_{C3} and W_{C1} had similar RR values.

Flashiness of a system can be described with the Richard–Baker Index (RB) (Baker et al., 2004).

$$RB = \frac{\sum_{i=0}^{n-1} |Q_{i+1} - Q_i)|}{\sum_{i=0}^{n} Q_i}$$

where Q_i is streamflow (m^3/s) on day i. Streams where streamflow rises and falls quickly are considered flashier than those that maintain a more consistent flow. Flashiness is mostly affected by vegetation, soil, watershed size, and amount of impervious surface; forested watersheds generally show less flashy characteristics than open areas (Fongers et al., 2004). The treatment watershed section W_{T1} was flashier than the downstream sections, while section W_{T3} was the least flashy during the preharvest period (Table 2). However, after the harvest operation, sections W_{T3} and W_{T2} became flashier than section W_{T1} due to the effects of harvesting. At the control watershed, the pattern did not change as expected; the forested middle section (W_{C2}) was the least flashy section during both the pre- and postharvest periods (Table 2).

3.4. Double mass curves

Streamflow trends were assessed through double mass curves (Figure 4). Double mass curves represent changes in streamflow patterns of the treated sections following harvesting. The slopes were statistically significantly different at the $\alpha = 5\%$ level in Figures 4a and 4b only. This indicates a significant change in streamflow patterns and trends in sections W_{T2} and W_{T3} after harvesting. Figures 4c and 4d indicate no difference in slopes, which means that sections W_{T1}, W_{C1}, W_{C2}, and W_{C3} had similar streamflow patterns before and after harvest or the changes in their stream patterns were similar. In each set of data, one corresponds to the preharvest period and one corresponds to the postharvest period. A linear line is fit to each set of data in each figure. The slopes of the linear regression lines for the pre- and postharvest periods were compared with the ANCOVA test for difference. Since regression residuals are autocorrelated, the ANCOVA test was performed by considering autocorrelated errors. Partial autocorrelation functions (PACF) of the residuals indicated a significant autocorrelation at lag – 1. Thus, an autoregressive model of lag 1 (AR(1)) was introduced to ANCOVA.

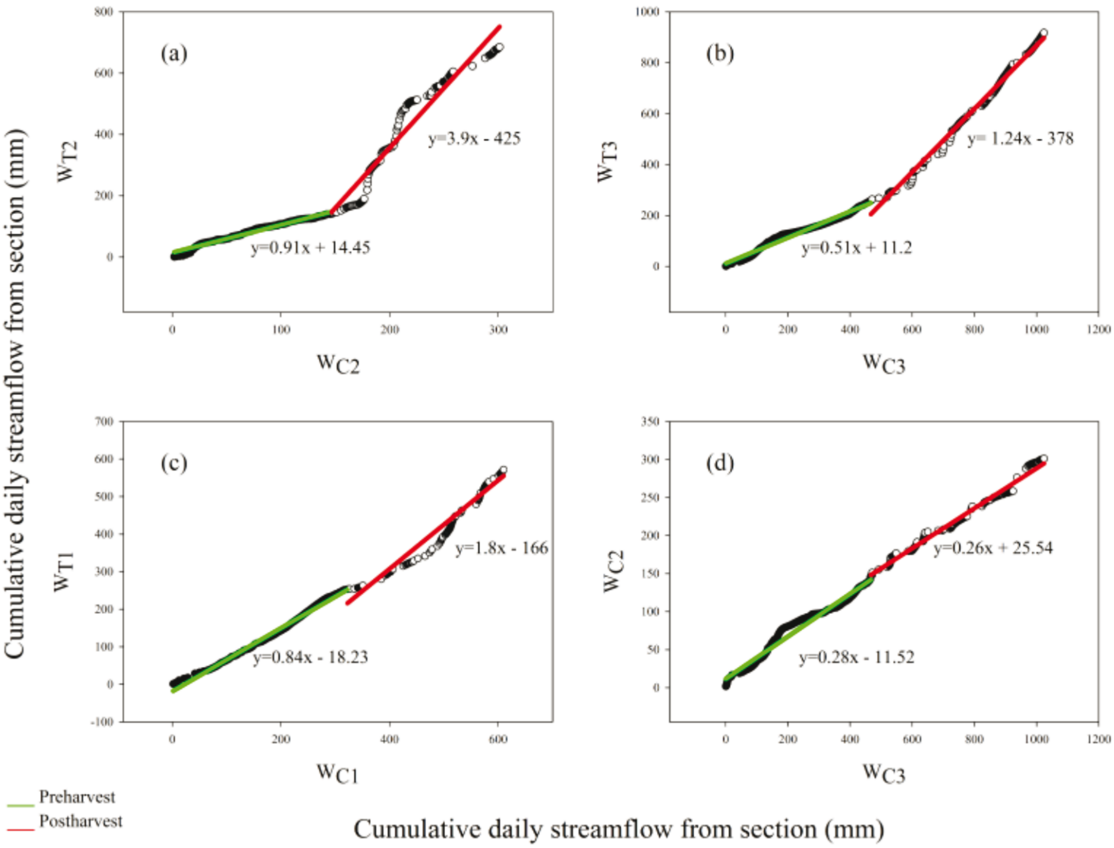

Figure 4. Double mass curves for the pre- and postharvest periods between a) W_{T2}–W_{C2}, b) W_{T3}–W_{C3}, c) W_{T1}–W_{C1}, and d) W_{C2}–W_{C3}.

4. Discussion

The smaller water yields from the forested sections during the preharvest period are the result of higher water use by trees. Bosch and Hewlett (1982) reviewed 94 catchment experiments worldwide and showed that there is an adverse relationship between water yield and vegetation cover, i.e. increasing vegetation results in decreasing water yield. According to Stednick (1996), responses of water yield to silvicultural treatments are usually variable, complex, and unpredictable. Several studies in the literature support this. Studies that observed the change in water yield following tree removal documented varying amounts of increase ranging from 15% to 116% (Rothacher, 1970; Grace III, 2006; Hubbart et al., 2007; Ganatsios et al., 2010) (Table 3).

In this study, water yield increased following a partial cutting within an SBZ. Similarly, several other studies also monitored increase in water yield following varying amounts of reduction in basal area in a mixed hardwood forests (Reinhart, 1963; Grace III, 2006). In a study conducted in the coastal plain of North Carolina, Grace III (2006) documented a 115% increase in water yield following a 69% reduction in basal area. Reinhart et al. (1963) found a 19% increase in water yield in the first year following an 85% removal of basal area in the mountains of West Virginia. Converted to an annual scale, the observed increase in water yields in this study is much higher. Following a 50% removal of basal area only within the SBZs, water yield increased by 250% and 100% from sections W_{T2} and W_{T3}, respectively, over the 6-month-long postharvest period. Considering the fact that the harvested areas constitute a fraction of sections W_{T2} and W_{T3}, and there was only partial harvesting within the SBZ, the observed increase in flow is unprecedented. Ziemer (1986) stated that the maximum increase in water yield is observed following the removal of vegetation that transpires at the maximum rate and for the maximum duration. Ziemer (1986) further suggested that riparian vegetation is one example of these conditions, and removal from riparian zones would result in the maximum increase in water yield. This may also explain why the increase in water yield was significant from the treated sections but insignificant from the untreated sections during the postharvest period.

Changes in water yield during the postharvest period at the control watershed were mixed. Increases in runoff at

Table 3. Studies on the effects of vegetation removal on water yield.

Vegetation type	Soil	Mean annual precipitation (mm)	Tree removal (%)	Increase in water yield (%)	Source
Fir	Soft tuff	2250	30	31	Rothacher, 1970
Hardwood–Pine	Belhaven series	1160	69	116	Grace, 2006
Conifer	Silt loam	1450	50	24	Hubbart et al., 2007
Hardwood	Clay loam	983	50	15	Ganatsios et al., 2010

the 2 downstream sections W_{C2} and W_{C3} can be explained by the higher amount of precipitation and almost 4 months of dormant season. Note that the number of rainy days was almost the same during the pre- and postharvest periods (78 and 77, respectively). The preharvest period had 28 days with at least 12.7 mm (0.5 inches) of precipitation, whereas the postharvest period had 25 such days. The standard deviation of daily rainfall during the postharvest period (14 mm) was also higher than its counterpart from the preharvest period (11 mm). These all show that rain fell more frequently and evenly during the preharvest period, thus helping the soil moisture. The contribution of the smaller events to water yield was likely minimal during both periods. Interestingly, compared to the preharvest period, a slight decrease in water yield was observed at the upstream section W_{C1}. This is rather unexpected and hard to explain. About 60% of this section is composed of low-density residential housing. We can speculate that watering of lawns during the growing season might have helped runoff generation by adding moisture to the soil.

Bosch and Hewlett (1982) suggested that annual water yield would increase about 25 mm for each 10% removal of trees in hardwood forests. Given this value, our observed water yield during the 6-month-long postharvest period seems to be substantial. However, over a longer period, water yield will certainly decrease with the establishment of new vegetation. Indeed, Brown et al. (2005) support this argument by stating that changes in water yield are especially short-lived in hardwood forests due to faster regrowth from the same root systems. Reinhart et al. (1963) found a 34% reduction in water yield in the second year of harvesting (85% basal area removal) compared to the increase in water yield in the first year due to the recovery of vegetation following the harvesting. In addition, Johnson and Kovner (1954) observed a change in water yield as the forest come back through sprouting and regrowth following a clearcut, and found that the increase in water yield following the harvest was 60%, 40%, and 36% during the first, second, and third year, respectively.

Partial cutting within the buffer zone caused an increase in direct runoff during the 6-month-long period. The increases were about 200% and 100% at sections W_{T2} and W_{T3}, respectively. Sorensen et al. (2009) monitored increases in runoff following forest harvest, and concluded that the average runoff during the 2 years following a clearcut increased by 35%. In a similar study, Rosen (1984) observed a 119% increase in runoff following a clearcut in the first year. Moreover, Iroume et al. (2006) observed changes in runoff during the 3 years following a clearcut, and stated that the clearcut caused an average of 110% increase in runoff. Given the type of harvest and the amount of increased runoff in other studies, the observed increase in runoff in this study appears to be excessive. This is likely due to the significantly above normal rainfall (+570 mm). Ziemer (1986) suggested that an increase in runoff following vegetation removal is higher during wetter years than in drier years. The rainfall–runoff relationship is nonlinear in nature. The most important reason for this is the effect of the antecedent conditions; the wetter the watershed prior to a unit input of rainfall, the greater the volume of generated runoff (Beven, 2004). During a wet period, the soil moisture will frequently be close to or above the field capacity. Therefore, runoff can be disproportionally greater than the runoff during a normal year.

Of the all disturbances associated with timber harvest, logging and skidding are considered to cause the most serious disturbances during forest operations because of their higher potential for exposing mineral soil by dragging trees on the ground. Increased soil exposure and compaction following logging and skidding may result in increasing surface runoff. When careful and alternative logging practices such as cable logging and winter harvesting are followed, the impact of logging on the hydrology of a watershed can be mitigated (Kreutzweiser et al., 2009). We think that the water yield still would have increased even if logging and skidding had been more carefully practiced within the treated SBZ, but the increase may have been less than was observed. Considering the fact that silvicultural treatments are part of the regular management operations, this short-term (in this case 6-month-long) increase in water yield is worthy of attention. Brown et al. (2005) also suggested that the influence of vegetation change on seasonal water yield is less well understood, but is as important an influence on annual water yield.

The results of this study showed that water yield can substantially increase (up to 3–4 times) even after partial harvesting within an SBZ during an initial 6-month-long postharvest period. Partial cutting within the SBZ also resulted in flashier streams and increased the ratio of streamflow to precipitation. Although these changes were observed in a relatively short period (6 months), partial harvesting within the SBZs can be repeated as part of a regular silvicultural management practice, and therefore these changes could have significant implications even in the long run. One of the benefits of thinning or other harvesting methods is to increase water yield in countries with long periods of limited rainfall or a prolonged drought (Ganatsios et al., 2010); however, unfavorable results such as increased sediment yield may occur in the case of improper operations. When silvicultural treatments are used to increase water yield, more attention should be given during harvesting operations in order to mitigate the impact of logging equipment. Increase in streamflow and direct runoff could have very important implications for erosion/sedimentation, water quality, and stream habitat. On the other hand, it may be considered a benefit when there is concern about a lack of water resources, in which case increased water yield is desirable. Clearly there are some management and economic benefits of thinning SBZs. However, the ecological and environmental tradeoffs need critical consideration.

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