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Emma Lela Witt, Student

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Dr. Mark Coyne, Director of Graduate Studies

EVALUATING STREAMSIDE MANAGEMENT ZONE EFFECTIVENESS IN FORESTED WATERSHEDS OF THE CUMBERLAND PLATEAU

DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Agriculture at the University of Kentucky

By
Emma Lela Witt

Director: Dr. Christopher Barton, Professor of Forest Hydrology

Lexington, Kentucky

2012

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ABSTRACT OF DISSERTATION

EVALUATING STREAMSIDE MANAGEMENT ZONE EFFECTIVENESS IN FORESTED WATERSHEDS OF THE CUMBERLAND PLATEAU

Headwater stream systems are important components of the overall hydrologic system. Forestry best management practices (BMP) are effective at minimizing non point source pollution from forest harvesting activities. Streamside management zones (SMZ) are one BMP used to protect surface water quality by maintaining shade near streams, filtering runoff, and minimizing soil disturbance near streams. An evaluation of BMP effectiveness on the watershed scale was conducted at the University of Kentucky's Robinson Forest. Six watersheds were harvested using a two-age deferment harvest with one of three SMZ configurations applied to each watershed. Two unharvested watersheds served as controls.

Treatment 1 was based on the current Kentucky Forest Practice Guidelines for Water Quality Management and included a 16.8 m SMZ with 50% canopy retention for perennial streams, a 7.6 m SMZ with no canopy retention for intermittent streams, and no SMZ or canopy retention for ephemeral streams with unimproved crossings. Treatment 2 also included a 16.8 m perennial SMZ but increased canopy retention to 100%, as well as a 7.6 m intermittent SMZ with 25% canopy retention, and retention of channel bank trees and use of improved crossings for ephemeral streams. Treatment 3 required a 33.5 m perennial SMZ with 100% canopy retention, a 16.8 intermittent SMZ with 25% canopy retention, and a 7.6 m ephemeral SMZ with retention of channel bank trees and use of improved crossings.

Total suspended solids (TSS) concentration and turbidity was measured in storm samples in perennial and ephemeral streams, and in non-storm samples in perennial and intermittent streams. Nitrate-N, ammonium-N, and dissolved oxygen concentrations were also measured in non-storm samples in perennial and intermittent streams. Temperature and water level were recorded every 15 minutes for the duration of the study.

Results showed that treatment 3 was able to maintain TSS concentrations and turbidity levels similar to those measured in unharvested control watersheds. Increases in nitrate-N and mean daily temperature were measured for all treatments. Ammonium-N

and dissolved oxygen concentrations were not different from unharvested control watersheds for any treatment. Storm hydrograph separation did not result in consistent changes post-harvest for any treatment.

KEYWORDS: Forest Harvesting, Streamside Management Zones, Sediment, Ephemeral streams, Best Management Practices

Emma Lela Witt
Student's Signature

June 20, 2012
Date

EVALUATING STREAMSIDE MANAGEMENT ZONE EFFECTIVENESS IN FORESTED WATERSHEDS OF THE CUMBERLAND PLATEAU

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ACKNOWLEDGEMENTS

The following dissertation, while an individual work, benefited from the insights and direction of many people. I gratefully acknowledge my advisor, Dr. Christopher Barton, for his assistance and patience during this process. Additionally, I appreciate the work of my committee, Dr. Jeffrey Stringer, Dr. Randall Kolka, Dr. Christopher Matocha, and Dr. Elisa D'Angelo for their input and guidance, as well as my outside reader, Dr. Anthony Pescatore.

In addition to the assistance provided by my committee, I also received invaluable help at Robinson Forest from Matt Strong, Aaron Klee, Daniel Bowker, David Collett, Ted Sizemore and Jim Marshall. All were instrumental in completing the field component of this dissertation.

Finally, I am grateful for the support of my parents, Dr. William Witt and Dr. Mary Hotze Witt for their unconditional support during this process.

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CHAPTER 1 GENERAL INTRODUCTION

Using forestry best management practices (BMPs) for surface water protection has been shown to be effective in Kentucky and elsewhere (i.e. Wynn et al. 2000, Kochendorfer and Hornbeck 1999, Arthur et al. 1998). An evaluation of BMP effectiveness on the watershed scale was conducted at the University of Kentucky's Robinson Forest and is the subject of this dissertation.

Streamside management zones (SMZs) are one BMP used to protect surface water quality and function to protect surface water quality by maintaining shade near streams to mitigate temperature changes, filter runoff containing nutrients and sediment, minimize soil disturbance near streams by excluding equipment activities near streams, and maintain evapotranspirative demand (Barling and Moore 1994, Binkley and Brown 1993). They also provide habitat for sensitive riparian flora and fauna as well as retaining vegetation important for energy inputs to headwater streams (Richardson and Danehy 2007). While the use of SMZs has been shown to protect surface waters from pollution from forest harvesting better than harvesting without SMZs, the exact width and allowable disturbance in SMZs necessary to maximize these protections is unclear.

Soil disturbance is one of the causes of non-point source pollution resulting from forest harvesting, with skid trail networks a primary source. Skid trails increase the hydrologic and sediment connectivity of the watershed via increased surface runoff and stream crossings (Bracken and Croke 2007, Kreutzweiser and Capell 2001, Lacey 2000). The use of improved crossings including bridges, culverts, and pipe bundles, in ephemeral streams were examined in order to minimize increases in sediment transport.

Robinson Forest is located in the Cumberland Plateau region of southeastern Kentucky, in Breathitt, Perry, and Knott counties. Six watersheds were harvested in this study using a two-aged deferment harvest with one of three SMZ configurations applied to the harvest watersheds. Two additional watersheds remained unharvested to serve as controls. Treatments included SMZs for perennial and intermittent stream segments, as well as SMZs and improved crossings for ephemeral streams. Treatment 1 (noSMZ in chapter 1) was based on the current Kentucky Forest Practice Guidelines for Water Quality Management and included a 16.8 m SMZ with 50% canopy retention for perennial streams, a 7.6 m SMZ with no canopy retention for intermittent streams, and no SMZ or canopy retention for ephemeral streams with unimproved crossings. Treatment 2 (SMZ1 in chapter 1) also included a 16.8 m perennial SMZ but increased canopy retention to 100%, and also required a 7.6 m intermittent SMZ with 25% canopy retention as well as retention of channel bank trees and improved crossings for ephemeral streams. Treatment 3 (SMZ2 in chapter 1) required a 33.5 m perennial SMZ with 100% canopy retention, a 16.8 m intermittent SMZ with 25% canopy retention and a 7.6 m ephemeral SMZ with retention of channel bank trees and use of improved crossings. Harvesting was performed between June 2008 and October 2009.

Chapter 2 examines the impact of BMPs for ephemeral channel protection. Results indicated that the use of any improved crossing type (bridge, culvert, or pipe bundle) significantly decreased total suspended solids concentrations and turbidity levels compared to ephemeral streams crossed with unimproved fords. In combination with improved crossings, ephemeral streams that included a SMZ with an equipment limiting

zone and retention of channel bank trees measured TSS concentrations that were statistically similar to concentrations measured in unharvested control streams.

Chapter 3 details the impact of harvest with various SMZ configurations on TSS concentration, turbidity, nitrate, ammonium, dissolved oxygen concentration, and mean daily temperature. Results showed that treatment 3 was able to maintain TSS concentrations and turbidity levels similar to those measured in unharvested controls for base flow and storm flow conditions. Increases in nitrate and mean daily temperature were measured for all treatments, although changes were not expected to negatively impact overall water quality. Ammonium and dissolved oxygen concentrations were not different from unharvested control watersheds for any treatment.

Chapter 4 contains the results of harvesting impacts on storm flow hydrographs. Changes in the response of stream flow to storm events indicate changes in the storage and conveyance of water through the watershed. Results of hydrograph analysis provided inconsistent evidence of the impact of forest harvest on storm response. In general, the impact of the harvest was not great enough to overcome the rapid water movement through these watersheds and change the volume of water measured in storm responses. Varying characteristics of the SMZ treatments were not sufficient to influence hydrologic response. The watershed storm responses were not changed by the harvest to a degree that would cause channel morphology changes or exacerbate downstream flooding.

CHAPTER 2 : EVALUATING BEST MANAGEMENT PRACTICES FOR EPHEMERAL STREAM PROTECTION FOLLOWING FOREST HARVEST IN THE CUMBERLAND PLATEAU

Introduction

Forestry best management practices (BMPs) have been established in most states to protect water quality and aquatic habitat during forest harvests (Aust and Blinn 2004, Blinn and Kilgore 2001). Frequently, these guidelines vary based on the stream type including order. Generally those with the most frequent flow duration receive the most protective BMP recommendations (Svec et al. 2005). Ephemeral streams are not fish bearing, nor are they generally identified on topographic maps, which disqualifies them from protection under most regulations designed to protect water quality. They are generally afforded less stringent BMP water quality guidelines compared to perennial and intermittent streams.

Ephemeral streams are distinguished from intermittent and perennial streams based on their hydrology. Kentucky's Forestry Best Management Practices describe ephemeral streams as those that flow during or directly after precipitation or in response to snow melt and conduct surface water directly or indirectly to perennial streams (Stringer and Perkins 2001). Perennial streams, are defined as those which flow continuously except in extreme drought conditions, while intermittent streams flow primarily during the wet season (Fritz et al. 2008). Further, ephemeral streams commonly lack the level of channel scour and sorting and settling of materials found in intermittent and perennial streams, and generally have large amounts of organic matter in the channel bed (Hansen 2001). The water table is below the channel bed and groundwater is not a significant source of water (North Carolina Division of Water Quality 2005). These hydrologic conditions can

be difficult to ascertain in the field under some conditions (i.e. during a drought, immediately following precipitation, or during the wet season); therefore methods of identifying stream type that do not rely on hydrologic monitoring are frequently used. For instance, Svec et al. (2005) used channel geometry (width:depth ratio and channel slope) and watershed size to distinguish among the three stream types in eastern Kentucky. In North Carolina, hydrology, channel geomorphology and the presence or absence of biological species associated with flow permanence are used to differentiate among stream types (North Carolina Division of Water Quality 2005).

Ephemeral streams (or channels) are an important component of the headwater stream system, which encompasses first to third order streams draining areas less than two km^2, including perennial, intermittent and ephemeral flow regimes (Adams and Spotila 2005; Horton, 1945). A majority of a watershed's stream length is located in the headwater system. Studies have found that the headwaters can encompass from 60 percent to 80 percent or more of the entire watershed network (Wipfli et al. 2007, Benda et al. 2005, Gomi et al. 2002). Headwater streams are able to deliver water, fine sediment, and fine particulate organic matter downstream, as well as store coarse sediment and large woody debris (MacDonald and Coe 2007, Wipfli et al. 2007). As a component of the overall headwater system, ephemeral streams can provide habitat to a variety of biota (Meyer et al. 2007). For example, a salamander survey of ephemeral streams in eastern Kentucky found that ten salamander species used ephemeral streams, and two species were more abundant in ephemeral streams than perennial streams (Schneider 2010).

During harvesting operations, ephemeral streams are often crossed by driving directly through them rather than crossing with an improved or elevated crossing. This is

particularly true because many ephemeral streams are relatively small and running water is frequently absent at the time of harvest. Harvest road and skid trail ephemeral stream crossings are considered linkages of the road system to the hydrologic system (Croke et al. 2006). These crossings connect a sediment source (skid trail) with the hydrologic system, which can lead to increased sediment movement from the ephemeral streams to downstream reaches (Christie and Fletcher 1999, Davies and Nelson 1993). Improved crossings can potentially decrease the amount of sediment delivered downstream.

The current, mandatory guidelines for ephemeral stream crossings in Kentucky require the installation of bridges or culverts to cross ephemeral streams where feasible. When not feasible, ephemeral streams should be crossed at right angles (Stringer and Perkins 2001). Of the 12 other Appalachian states (AL, GA, MD, MS, NY, NC, OH, PA, SC, TN, VA, WV), eight provide some guidance on ephemeral stream management. Georgia, Tennessee, South Carolina, and Mississippi provide specific recommendations for ephemeral streams (or drains in Mississippi) (Georgia Forestry Commission 2009, Mississippi Forestry Commission 2008, Tennessee Department of Agriculture Division of Forestry 2003, South Carolina Forestry Commission, ND). These recommendations aim to minimize soil disturbance by avoiding using ephemerals as skid trails, limiting the number of crossings and minimizing equipment traffic near ephemeral streams. Additional recommendations include minimizing logging debris in the channel and altering the flow in the channel. Virginia's BMPs recommend the use of bridges, culverts or fords when crossing certain ephemeral drains (Virginia Department of Forestry 2011). In addition to the recommendations noted above to minimize soil disturbance, North Carolina's Forestry BMPs include extension of the SMZ from the perennial or

intermittent stream to the ephemeral transition (Brogan et al. 2006). West Virginia also recommends SMZs of at least 25 feet in width for ephemeral streams (West Virginia Division of Forestry 2009). In these SMZs, equipment is limited to designated crossings and harvesting is permitted provided the trees are removed by cable.

In addition to improved crossings, sediment introduction to ephemeral streams may be limited by the use of a streamside management zone (SMZ) or riparian buffer (Gomi et al. 2005). SMZs have been shown to have positive environmental and biological benefits in perennial stream systems; such as, sediment trapping, nutrient reduction, temperature mitigation, stream bank protection, and maintenance of habitat features, (Perry et al. 2011, Lakel et al. 2010, McBroom et al. 2008, Allmendinger et al. 2005, Lowrance and Sheridan 2005, Aust and Blinn 2004, Jones et al. 1999, Daniels and Gilliam 1996, Lynch and Corbett 1990). SMZ recommendations vary by state, forest type, topography and stream permanence (Blinn and Kilgore 2001). However, limited information exists on SMZ recommendations for ephemeral streams. Because soil/forest floor disturbance and roads/skid trails used during forest harvests are frequently identified as sediment sources, the proximity of these sources to ephemeral streams is of concern. SMZs of minimal width and some overstory retention that focus on minimizing damage to the litter layer have been shown to be effective at trapping sediment in intermittent and perennial streams (Lakel et al. 2010). The purpose of this study was to determine if SMZ principles used in intermittent and perennial reaches would be effective in ephemeral reaches as well, with the specific objective of measuring the impact of SMZs and improved crossings on sediment dynamics in ephemeral streams in harvested areas. As such, an experiment was undertaken to evaluate the effectiveness of SMZs and improved

temporary skidder stream crossings for controlling sediment generation and movement in ephemeral stream reaches located in the Cumberland Plateau region of eastern Kentucky.

Methods

Study Area

The study was conducted at the University of Kentucky's Robinson Forest (37º 27' north latitude and 83º 08' west longitude) located in the Cumberland Plateau region of southeastern Kentucky (Figure 2-1). Topographically, Robinson Forest is characterized by steep slopes with well-drained residuum or colluvial soils formed from sandstone, shale, and siltstone. Elevations on the forest range from 268 to 475 m. Between 1890 and 1920, the Mowbray Robinson Lumber Company harvested all merchantable timber from the forest. The regenerated forest is classified as mixed-mesophytic with oak (*Quercus sp.*), hickory (*Carya sp.),* and yellow-poplar (*Liriodendron tulipifera*) as dominant overstory species.

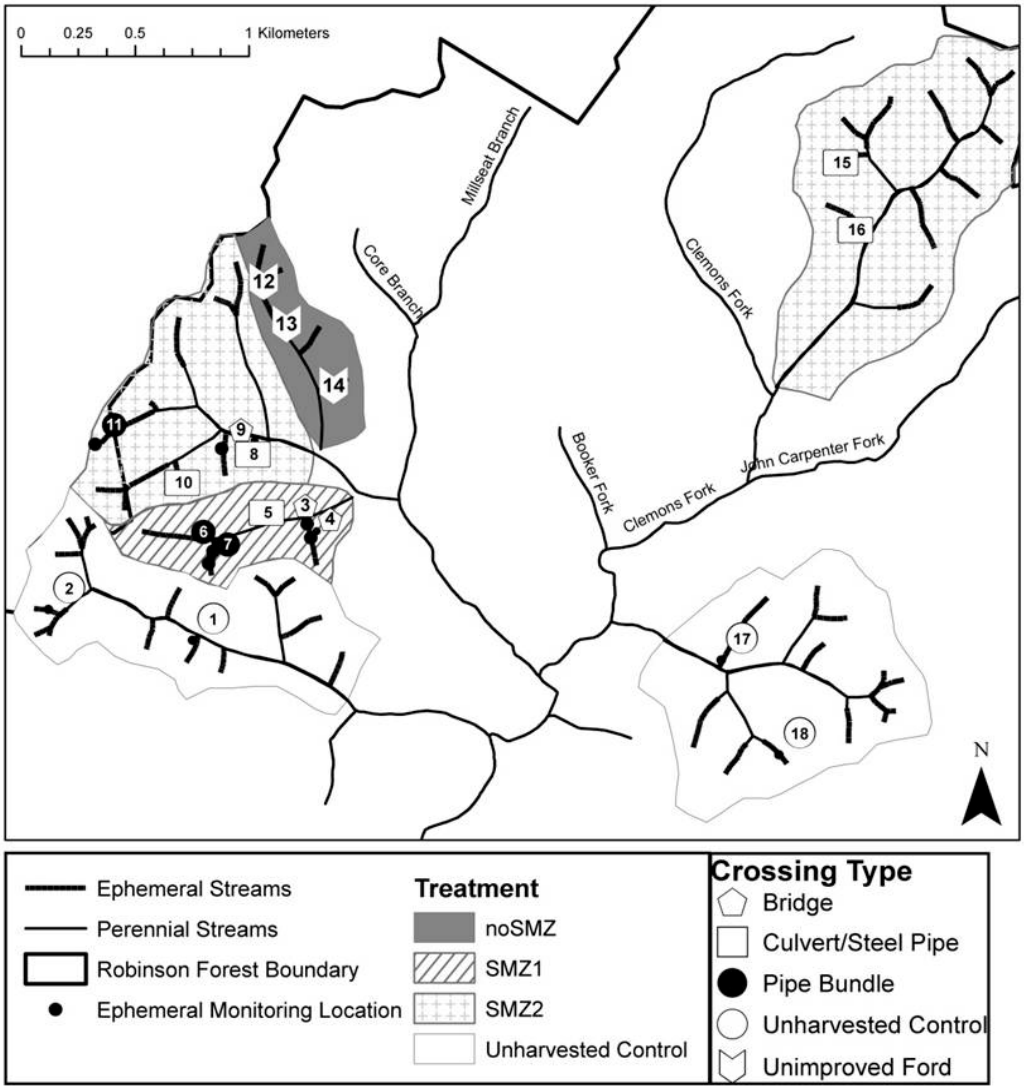

Figure 2-1: Location of treatment watersheds and ephemeral monitoring locations in Robinson Forest.

The climate of Robinson Forest is classified as temperate-humid-continental with warm summers and cool winters. The average annual precipitation for southeastern Kentucky is 116.4 cm while the 26-year average for three precipitation collectors at Robinson Forest is 117.5 cm (Cherry 2006). Average monthly precipitation is 9.79 cm and March tends to be wetter than average and October tends to be drier.

Treatments

All watersheds used in the study were located in the 1,545 ha Clemons Fork watershed. Six first-order headwater watersheds were harvested between June, 2008 and March, 2009. A shelterwood with reserves system, or deferment harvest (Miller et al. 2006, Smith et al. 1989), was used resulting in a two-aged stand with a residual target of approximately 15 square feet of basal area per acre of reserve trees (approximately 10 dominant/co-dominant trees per acre). This system was implemented over the entirety of all harvested watersheds with the exception of the areas next to the streams where differing SMZ specifications were imposed. While SMZs of varying size and management recommendations were implemented at perennial, intermittent and ephemeral locations within the watersheds, this study presents findings for only the ephemeral reaches.

Treatments in the study included: 1) harvest with no equipment restrictions, no forest overstory retention and use of unimproved stream crossings through the ephemeral streams (noSMZ); 2) harvest with no equipment restrictions, mandatory retention of channel bank trees and use of improved crossings (SMZ1); 3) harvest with limited equipment tracking within 7.6 m of the stream, mandatory retention of channel bank trees and use of improved crossings (SMZ2); and 4) no harvest (control) (Table 2-1).

Blockage of ephemeral streams with logging debris (soil, root wads, tree tops or tree sections) is not permitted by the Kentucky Forest Practice Guidelines for Water Quality Management, Kentucky's mandatory BMP law, and was not allowed in any of the treatment watersheds (Stringer and Perkins 2001). Channel bank trees retained in treatments SMZ1 and SMZ2 refer to the nearest overstory tree along the channel on both banks (tree stringer). The equipment restriction requirement in SMZ2 was a 7.6 m zone from each side the stream where equipment traffic was not permitted, except for skid trail crossings. Tree removal in this 7.6 m zone required the use of cables or reach of the swing-arm harvesting equipment.

Table 2-1: Ephemeral stream best management practices applied during treatment. A stringer refers to retention of the nearest overstory tree to the channel along both banks

Treatment	SMZ width (m)	Overstory retention	Crossing type
noSMZ	0	0%	Unimproved
SMZ1	0	Stringer	Improved
SMZ2	7.6	Stringer	Improved
Control	Not harvested	100%	none

All skid trails were constructed with a bulldozer (John Deere models 700 and 800) along the contour at intervals appropriate for the reach of felling and skidding equipment in use. The majority of stream crossings occurred from the use of either cable or grapple skidders (John Deere™ models 540 and 648 and Caterpillar™ models 525 and 545). Additional equipment used during the harvest that crossed ephemeral streams included: Timbco™ swing-armed feller bunchers (model 445 or 445EXL) and John Deere bulldozers (model 650, 700, or 800). The feller bunchers and bulldozers were tracked machines while all skidders were rubber tired.

For all treatments, skid trails were retired following the harvest using best management practices outlined in the Kentucky Forest Practice Guidelines for Water Quality Management (Stringer and Perkins 2001). This included removing all crossing structures and residual fill material from channel, construction of permanent water control structures to divert runoff from trail surfaces prior to the runoff accumulating on the approaches to the crossing, and seeding of the skid trail and fill material directly adjacent to the channel.

For the noSMZ treatment, ephemeral streams were crossed at right angles using unimproved crossings. This involved using a bull dozer to pull bank material from the channel as needed to establish the proper approach for skidding directly across the bottom of the channel. The extracted bank material was placed so that runoff from this material was not directed into the adjacent channel. Improved crossings included portable wooden skidder bridges, steel pipes/culverts, and PVC pipe bundles (Mason and Moll 1995). Portable wooden skidder bridges consisting of three 5 feet wide by 24 feet long panels were installed and removed over streams using grapple skidders. The steel pipe/culvert treatment used either corrugated steel or solid steel pipe placed into channels and backfilled with at least 10 cm of soil. PVC pipe bundles (Mason and Moll 1995) were constructed according to Blinn et al. (1998). The PVC pipe bundles were constructed of at least 20 9 cm PVC pipes threaded together with steel cable (Reeves et al. 2008). Pipe bundles were laid in the channel and allowed to conform to the channel bottom, covered with a layer of geo-textile fabric and overlaid by at least 20 cm of soil. The purpose of the overlain soil was to minimize damage to the pipe bundle during crossing by wheeled skidders as part of normal harvesting operations. The overlain soil

for both the pipe bundle and culverts was not stabilized nor the surface reinforced as is typical for most operational temporary skidder crossings. On average, skid trail crossings were in use for a limited time period, generally two to six weeks. Crossings were removed during skid trail retirement and in the case of the culvert/pipe and PVC pipe bundle the majority of the overlain sediment was removed from within the channel using a bulldozer.

Sample Collection and Analysis

Sixteen ephemeral streams in six watersheds were monitored from July 2008 to August 2010. In two of the 16 streams, multiple stream crossings were monitored from two locations along the stream, for a total of 18 sampling points. Estimated stream catchment areas measured from the sampling point ranged from 0.75 ha to 8.9 ha, with a mean of 3.1 ha (Figure 2-1, estimated from topographic maps and GIS data). Estimated distance from the stream crossing to the monitoring location ranged from 15 m to 57 m with a mean of 37 m. Channel slope for the monitored ephemeral streams ranged from 6 to 50 percent with a mean of 26 percent (Table 2-2).

Precipitation was measured using tipping buckets at four locations on Robinson Forest (Cherry 2006). The tipping bucket data was recorded using Campbell Scientific CR10X data loggers. ISCO automated pump samplers (Teledyne ISCO, Lincoln NE) equipped with liquid level actuators were used to collect samples following storm events that resulted in ephemeral stream flow. Actuators were positioned directly in the bottom of the dry channel bed so that activation occurred only when flow began in response to a precipitation event. Events that were not of sufficient duration or intensity to result in stream flow were not sampled. Samples were composited over time periods ranging from

30 minutes to 24 hours based on the flow duration of the stream. For events that resulted in a complete 24 hour sampling interval by the automated pump sampler a 9.4 L sample was collected. Samples were analyzed as composites to limit the analysis time associated with each event and location.

Table 2-2: Treatment identification and site description at ephemeral monitoring locations within the Clemons Fork watershed of Robinson Forest, KY. Catchment areas were estimated from topographic maps and GIS data. Trail slope refers to the gradient of the skid trail as it approached the ephemeral stream. Trail height refers to the elevation change between the skid trail and stream channel at the crossing point.

Sampler ID	Treatment	Crossing Type	Approx. Area (ha)	Channel Slope (%)	Trail Slope (%)		Trail Height (m)	
					Left	Right	Upslope	Downslope
1	Control†	Control	2.93	34	N/A	N/A	N/A	N/A
2	Control	Control	8.92	40	N/A	N/A	N/A	N/A
3	SMZ 1	Bridge	2.80	24	13	16	0.9	2.1
4	SMZ 1	Bridge	2.39	24	12	7	0.9	2.1
5	SMZ 1	Culvert‡	2.00	20	10	8	0	1.5
6	SMZ 1	Pipe Bundle	2.48	16	19	23	0.6	2.7
7	SMZ 1	Pipe Bundle	1.72	16	4	17	0	2.7
8	SMZ 2	Culvert	1.72	28	6	15	0	1.5
9	SMZ 2	Bridge	2.25	35	5	11	0.6	1.5
10	SMZ 2	Culvert	1.75	10	4	14	0	2.1
11	SMZ 2	Pipe Bundle	0.76	11	6	7	0	0.6
12	noSMZ	Ford	1.45	27	14	12	0	2.1
13	noSMZ	Ford	0.75	50	15	11	0	2.7
14	noSMZ	Ford	2.21	12	6	18	0	1.5
15	SMZ 2	Culvert	3.92	35	5	6	0.6	0.6
16	SMZ 2	Culvert	4.36	25	10	4	0.3	1.2
17	Control	Control	8.03	6	N/A	N/A	N/A	N/A
18	Control	Control	5.16	15	N/A	N/A	N/A	N/A

Samples were analyzed for three parameters: total suspended solids (TSS), turbidity, and settleable solids. TSS was determined gravimetrically according to APHA™ guidelines using a 1.5 µm filter (APHA 1992). Turbidity (measured in formazin turbidity units, FTU) was analyzed using a Hanna™ portable turbidity meter (model HI 93703, Hanna Instruments, Woonsocket RI). Analysis of both total suspended solids and turbidity was performed in duplicate and reported as the mean of the two samples. Settleable solids were measured in Inhoff cones, with a sample volume of one liter and a settling time of one hour following Standard Method 2540 F (APHA 1999).

Each stream was equipped with a data logging pressure transducer, either a miniTroll™ or LevelTroll 500™, (In-Situ Inc., Ft. Collins, CO) which recorded stream stage on a 15 minute interval. Stream cross-section surveys were completed for each sampling location to determine channel geometry. Data from the surveys were input to WINXSPRO version 3.0 (US Forest Service Stream Systems Technology Center, Ft. Collins, CO) to calculate discharge using the Thorne and Zevenbergen equation (Hardy et al. 2005, Thorne and Zevenbergen 1985). The total discharge was calculated for each storm event for the time sampled by the automated pump sampler. Discharge from the sampling interval was multiplied by the total suspended solids concentration to determine sediment transport.

The majority of samples were taken after crossings were retired due to lack of precipitation and subsequent ephemeral stream flow as well as the relatively short duration the crossings were active. Separation of the data into subsets based on the active or retired status of the crossing was not possible due to limited sample size in several of the treatment watersheds. Data from this study are a measure of the combined impacts of

harvesting and improved crossing use on ephemeral stream sediment dynamics both during active logging operations and after retirement. Data grouped by treatment for analysis measured the combined impact of improved crossings and retention of channel bank trees; identifying the specific contribution of each was not possible in this study.

Statistical Analysis

Because monitoring of each stream began as soon as possible following the start of its use as a crossing site, the number of samples for each crossing type and treatment varied. Data were grouped according to treatment and crossing type. Three streams were harvested using the noSMZ treatment protocol, three using the SMZ1treatment, six using the SMZ2 treatment, and four were unharvested controls. Of the 18 crossings, three were crossed with pipe bundles, five with culverts, three with bridges, three were forded without improved crossings, and four remained unharvested. For TSS and turbidity, statistical differences were determined using a protected least significant differences test (one-way ANOVA followed by two sample t-test) following a base ten logarithmic transformation. In the protected least significant differences test, two sample t-tests were performed only if the null hypothesis (the means of each group are equal) of the one-way ANOVA was rejected. The one-way ANOVA was used to determine if there were significant differences in the whole data set based on grouping by treatment or crossing. If the null hypothesis was rejected, two sample t-tests were used to compare the groups (i.e. bridge v. culvert or noSMZ v SMZ 2) and determine which groups were statistically different. Logarithmic transformation corrected the right (positive) skew in the TSS and turbidity data, resulting in normal distribution of transformed data. Percentage comparisons (increase or decrease) were calculated from mean TSS and turbidity

measurements from the ephemeral sampling points. Settleable solids were statistically analyzed using the non-parametric Kruskal-Wallis test to account for measurements below the detection limit.

Calculation of sediment transport for the entire total suspended solids data set was not possible due to intermittent equipment failure. The most common equipment problems encountered were dead batteries in either the pump sampler or water level recorder, and damage to the actuator switch that caused the pump sampler not to activate. However, approximately one third of the samples analyzed for TSS were coupled with corresponding water level data and used to calculate sediment transport. Samples that were used in the sediment transport calculations do not encompass the range of total suspended solids values or the range of precipitation events used in the overall evaluation of treatment and crossing type impacts on total suspended solids, turbidity, and settleable solids. Rather than group these data by crossing type and treatment using the same method that was applied to the other parameters, differences in sediment transport data were determined using a paired t-test following base ten logarithmic transformations to evaluate differences between improved crossings and unharvested controls for specific storm events. All statistical analyses were performed using Minitab Software, Version 15.

Results

Measureable precipitation was recorded on approximately 40 percent of the days in the period sampled (Figure 2-2). Of the 104 total events during the sampling period, 53 (38 percent) had total precipitation of greater than 12.7 mm and 33 (24 percent) had total precipitation of greater than 25.4 mm. The total number of sampled events was 42, with

a mean precipitation of 36 mm (range: 7 mm to 240 mm). Partial events (events that did not activate all samplers) were included in the analyses as differences in sampler deployment dates, precipitation gradients, channel flow differences, and equipment functioning made obtaining a complete sample set from a single event difficult.

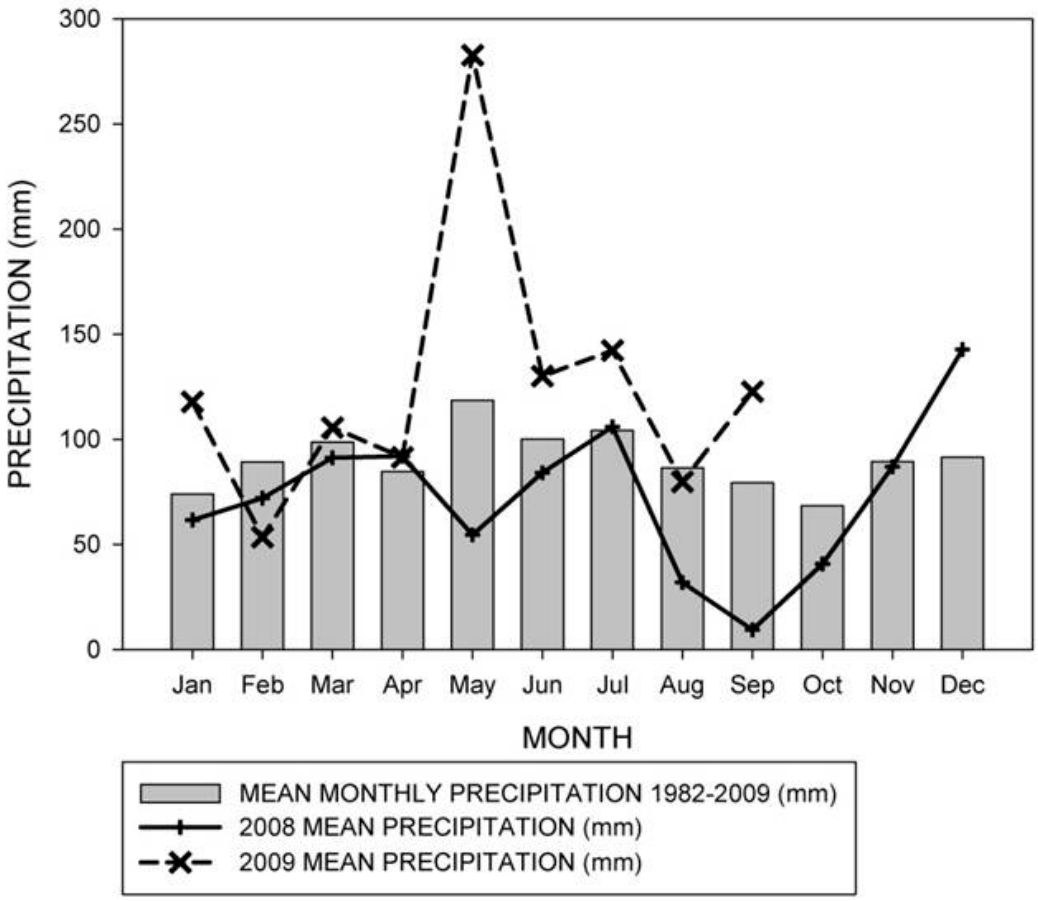

Figure 2-2: Mean monthly precipitation measured at three precipitation collectors in Robinson Forest between 1982 and 2009 (bars), and monthly total for 2008, and 2009 (lines).

A late summer drought in 2008 resulted in no flow at all ephemeral locations during the months of August through October. Total precipitation measured for the period August, 2008 through October, 2008 was 9.7 cm (Figure 2-2). May 2009 was an exceptionally wet month that yielded one 50-year storm event (Office of Surface Mining, personal

communication) with a 24-hour precipitation total of 14.5 cm. This event resulted in significant flooding and damage in the area and was associated with hydrologic monitoring disruption at the study site. Monitoring was disrupted when pump samplers or level recorders were washed away from their sampling points and had to be recovered downstream, their functioning restored, and then set back up at the sampling point.

Differences were observed in TSS ($p < 0.0001$, $n = 123$) and turbidity ($p < 0.0001$, $n = 123$) at the treatment level (Figure 2-3, Figure 2-4). In the noSMZ treatment, TSS was 430% higher than in the SMZ1 treatment ($p = 0.002$, $n = 41$) and was 598% higher than in the SMZ2 treatment ($p < 0.0001$, $n = 63$). In addition, increases in turbidity were measured between the noSMZ and SMZ1 treatments (253% increase; $p = 0.003$, $n = 41$) as well as between the noSMZ and SMZ2 treatments (435% increase, $p < 0.0001$, $n = 63$).

Compared to the unharvested control, TSS concentrations in SMZ1 were 161% higher ($p = 0.012$, $n = 60$) and turbidity was 508% higher ($p < 0.0001$, $n = 60$). TSS concentration in SMZ2 was not different from the unharvested control (62% increase; $p = 0.16$, $n = 82$), however, a 301% increase in turbidity was measured between SMZ2 and the unharvested control ($p = < 0.0001$, $n = 82$).

TSS concentration at the ephemeral stream crossings was nearly 14 times higher in the noSMZ treatment compared to the unharvested control ($p < 0.0001$, $n = 53$). Turbidity was 21 times higher in the noSMZ treatment compared to the unharvested control ($p < 0.0001$, $n = 53$).

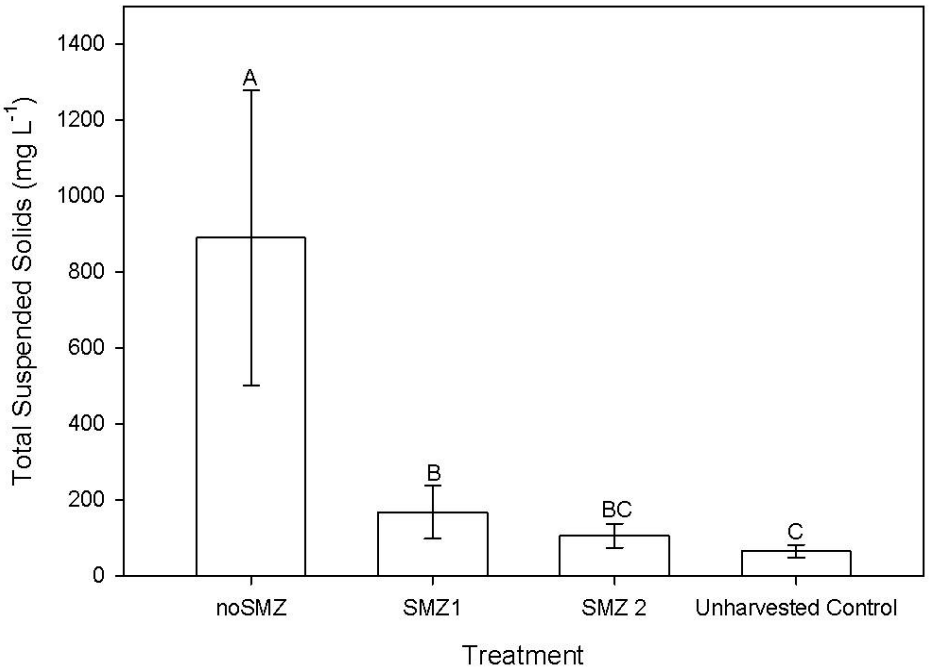

Figure 2-3: Effect of treatment type on total suspended solids. Data are presented as mean + standard error. Letters indicate differences at the α= 0.05 level.

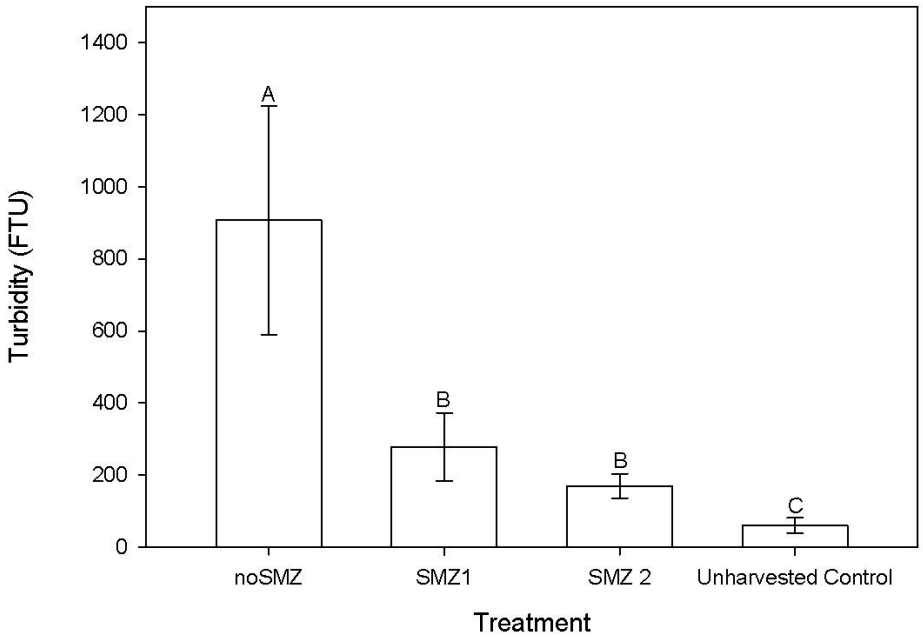

Figure 2-4: Effect of treatment type on turbidity. Data are presented as mean + standard error. Letters indicate differences at the α = 0.05 level. Turbidity was measured in Formazin Turbidity Units (FTU).

Data indicated a pronounced effect on TSS and turbidity when improved crossings were used (TSS: $p < 0.0001$, $n = 123$; turbidity: $p < 0.0001$, $n = 123$) (Figure 2-5, Figure 2-6). When bridges were used, TSS was reduced by 88% compared to unimproved crossings ($p < 0.0001$, $n = 38$). Culverts resulted in an 85% TSS reduction ($p < 0.0001$, $n = 51$) and pipe bundles reduced TSS concentrations by 77% ($p = 0.01$, $n = 32$) compared to unimproved crossings. Similar reductions in turbidity were measured, with bridges resulting in decreases of 83% compared to unimproved crossings ($p < 0.0001$, $n = 39$), culverts reducing turbidity by 77% ($p < 0.0001$, $n = 52$), and pipe bundles reducing turbidity by 68% ($p = 0.009$, $n = 31$). All improved crossings showed a reduction in TSS and turbidity compared to fords and there was no statistical difference among crossing types.

Among the improved crossing types, TSS in channels crossed with PVC pipe bundles was higher (217%) than in unharvested channels ($p = 0.02$, $n = 51$). TSS in channels crossed using bridges or culvert/pipes was statistically similar to unharvested channels. Bridges resulted in the smallest measured increase in suspended solids (58%) compared to unharvested channels ($p = 0.30$, $n = 57$), and TSS in channels using culvert/pipes was 109% higher than in unharvested channels ($p = 0.10$, $n = 70$).

Increases in turbidity were measured between the unharvested control and bridge (153% increase; $p < 0.0001$, $n = 58$), unharvested control and culvert (244% increase; $p < 0.0001$, $n = 71$), and unharvested control and pipe bundle (383% increase; $p < 0.0001$, $n = 50$).

No significant differences were found in settleable solids for either treatment type ($p = 0.11$, $n = 116$) (Table 2-3) or crossing type ($p = 0.19$, $n = 116$) (Table 2-4).

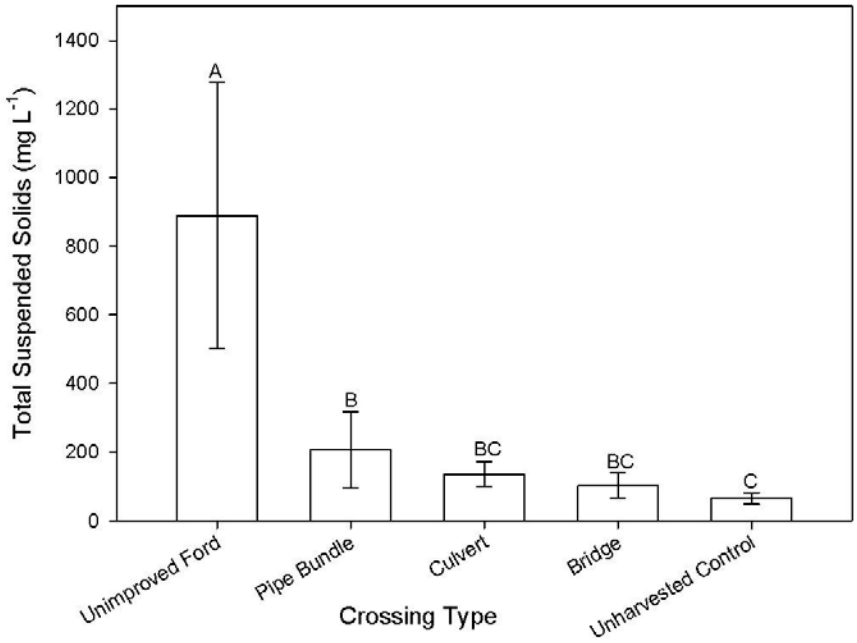

Figure 2-5: Effect of crossing type on total suspended solids. Data are presented as mean + standard error. Letters indicate significant differences at the α = 0.05 level.

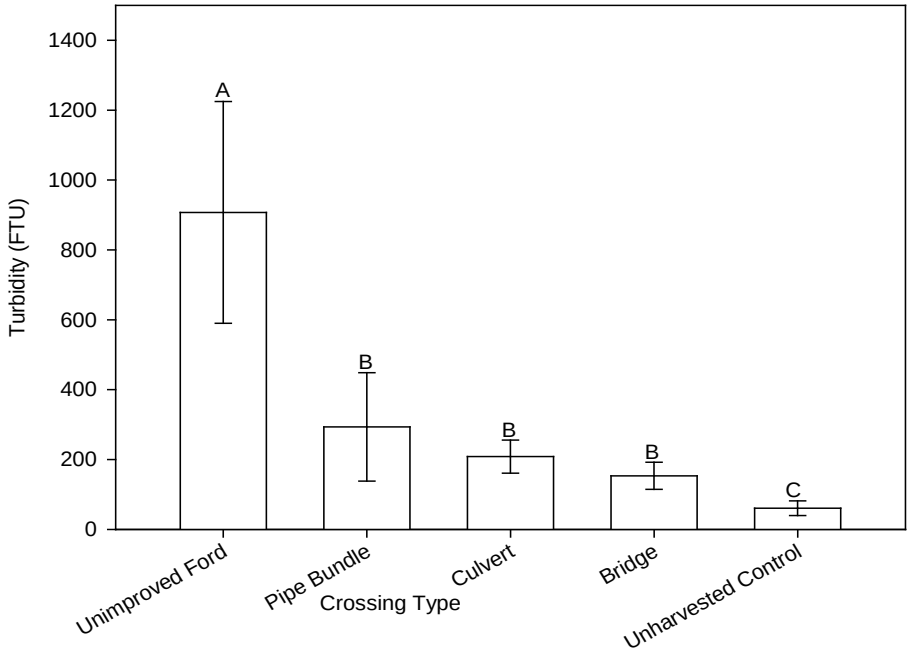

Figure 2-6: Effect of crossing type on turbidity. Data are presented as mean + standard error. Letters indicate significant differences at the α = 0.05 level. Turbidity was measure in formazin turbidity Units (FTU).

Table 2-3: Summary of settleable solids concentration grouped by treatment. Units are mL of sediment per L of water. N BDL refers to the number of samples measured below the detection limit of 0.1 mL sediment per L of water. The median was determined directly from the data. Mean, standard error, and confidence interval were determined using a maximum likelihood estimation due to the number of samples measuring below the detection limit.

Treatment Type	N	N BDL	Median	Mean	Std. Error	95% Confidence Interval
Control	37	15	0.2	0.35	0.10	0.20, 0.61
noSMZ	16	2	0.4	1.18	0.56	0.46, 3.01
SMZ1	25	7	0.2	0.43	0.15	0.21, 0.85
SMZ2	38	19	<0.1	0.69	0.30	0.29, 1.61

Table 2-4: Summary of settleable solids concentration grouped by crossing. Units are mL of sediment per L of water. No N BDL refers to the number of samples measured below the detection limit of 0.1 mL sediment per L of water. The median was determined directly from the data. Mean, standard error, and confidence interval were determined using a maximum likelihood estimation due to the number of samples measuring below the detection limit.

Crossing Type	N	N BDL	Median	Mean	Std. Error	95% Confidence Interval
Control	37	15	0.2	0.38	0.13	0.20, 0.74
Ford	16	5	0.4	1.19	0.56	0.45, 3.12
Bridge	21	9	0.1	1.58	1.57	0.23, 11.04
Culvert	28	12	0.1	0.41	0.17	0.18, 0.93
Pipe Bundle	14	5	0.1	0.70	0.57	0.14, 3.4

Five storm events (total precipitation range = 32.8 - 66.5 mm, mean = 49.8 mm) were used for each crossing type in the statistical analysis. Sediment transport rates for the unimproved fords were not analyzed due to an absence of flow data from both unharvested control watersheds and unimproved crossing watersheds for the same storm events. Paired comparisons of TSS concentrations and sediment transport rates for the storm events resulted in increases in culvert (TSS $p = 0.01$, sediment transport rate $p =$

0.05, n = 5) and pipe bundle (TSS p = 0.008, sediment transport rate p = 0.004, n = 5) crossed streams compared to the unharvested controls (Table 2-5). No significant differences were measured between bridge crossed streams for either TSS (p = 0.28, n = 5) or sediment transport rate (p = 0.63, n = 5).

Table 2-5: Mean, standard error (SE), p-value, and number of events analyzed for sediment transport by crossing type.

Crossing Type	Mean (SE) Crossing TSS (mg L^{-1})	Mean (SE) Control TSS (mg L^{-1})	p-value	Mean (SE) Crossing Sediment (kg hr^{-1} ha^{-1})	Mean (SE) Control Sediment (kg hr^{-1} ha^{-1})	p-value	Number of Events
Bridge	22.9 (11.9)	21.6 (5.1)	0.28	0.12 (0.1)	0.10 (0.05)	0.63	5
Culvert	135.4 (43.8)	19.0 (6.0)	0.01	1.5 (0.83)	0.08 (0.06)	0.05	5
Pipe Bundle	152.9 (46.5)	19.0 (6.0)	0.008	3.5 (1.6)	0.08 (0.06)	0.004	5

Discussion

The results of this study indicate that the use of improved temporary skidder crossings and retention of channel bank trees can be important management tools for reducing TSS and sediment delivery to streams. While the inherent design of the study does not make it fully possible to separate the effects of the improved crossings from retention of channel bank trees it is probable that the main effect was from the crossings. Subsurface lateral transport dominates water movement in this landscape under undisturbed conditions (Coltharp and Springer, 1980), but surface runoff from skid trails as a result of increased soil compaction and interception of lateral flow is able to efficiently move sediment to the ephemeral streams at crossing points.

Comparisons among the crossing types showed that any improved crossing type decreased TSS and turbidity when compared to unimproved crossings. A comparison of TSS and sediment transport from unharvested control ephemerals and bridge crossed

ephemerals from a sub-sample of five storm events (ranging in total precipitation of 32 mm to 66 mm) measured only a 6% increase in total suspended solids concentration and 20% increase in sediment transport between the control and bridged ephemerals. These results are similar to those reported by Reeves et al. (2008) and Blinn et al. (1998), which reviewed studies indicating that bridge crossings were effective at limiting sediment introduction in perennial streams.

When culverts were used in ephemeral stream crossings, no difference was measured in TSS concentration relative to the unharvested control streams, but increases were measured in turbidity. Culverts were effective at lowering both TSS concentration and turbidity compared to unimproved fords. These results are similar to those reported by Reeves et al. (2008), which found that culverts reduced total sediment compared to fords but were less effective at preventing sediment increases in headwater streams than bridges. Sediment transport rates measured below culvert crossings after five storm events were higher than rates measured in unharvested streams. Due to the operational circumstances of culvert use and removal, more sediment is available for transport. Sediment is used as fill to protect the culvert during harvesting and is difficult to completely remove from the channel when operations are completed.

Pipe bundles were able to decrease total suspended solids concentrations and turbidity compared to the unimproved crossings and results were statistically similar to culverts and bridges, a result consistent with those found by Reeves et al. (2008). Fill materials used around and on top of pipe bundles created problems during installation and removal of pipe bundles with the steep channel gradients associated with this study. The complication encountered while using pipe bundles in this study resulted from the soil fill

depth required on the downstream side of the crossing to make the skid trail level. Removal of this fill using a bulldozer was difficult, and given that much less fill would be required when using a pipe bundle on a gentler slope, these ephemeral streams may simply be too steep for pipe bundles to be as effective an option as bridges or culverts as an improved crossing. Similar issues involving sediment introduction to streams during pipe bundle removal have been reported (Blinn et al. 1998, Mason and Greenfield 1995).

A measureable decrease of 32% in total suspended solids concentration between SMZ1 and SMZ2 may be evidence of the effectiveness of the equipment limiting zone. These results are similar to those found by Lakel et al. (2010), which showed that SMZs as narrow as 7.6 m wide were effective at trapping sediment. However, the lack of significance in this study between SMZ1 and SMZ2 indicates that sediment originating from areas adjacent to the channel is negligible compared to the sediment introduced from the channel crossings. Channelized flow has the ability to transport sediment through an SMZ (Rivenbark and Jackson 2004), and forest roads and skid trails can be sources of concentrated flow (Croke and Mockler, 2001). SMZs can be effective at trapping sediment; additional practices including minimizing soil and forest floor disturbance near any type of stream and avoiding conditions of channelized sediment delivery to streams are also effective.

Comparison of TSS and turbidity resulted in a strong linear relationship ($p < 0.001$, $df = 123$) (Figure 2-7). Given that turbidity is a much quicker analysis and the continued improvement in datalogging, field-deployable turbidity meters, turbidity could be used in future studies to help estimate sediment transport in similar ephemeral channels. This approach could also be used to provide more detailed information about sediment

transport through development of sedigraphs in a less expensive and quicker manner than analysis of the dozens of TSS samples for one storm event needed for sedigraph development from pump samplers.

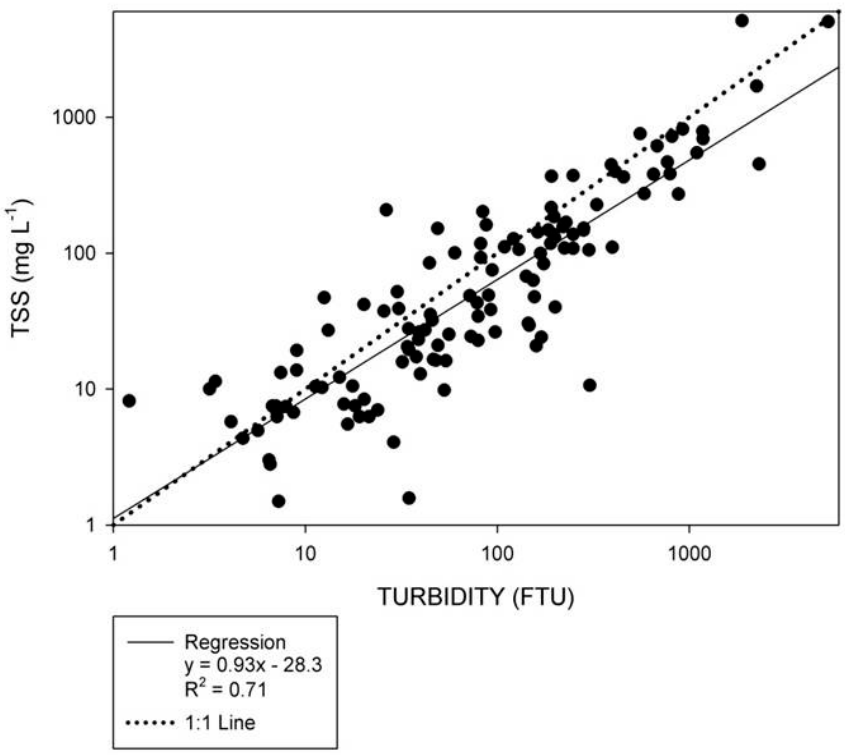

Figure 2-7: Relationship between turbidity and TSS for ephemeral channels.

Conclusion

While the use of improved crossings may be considered the primary control on sediment introduction to ephemeral channels, the retention of channel bank trees and the use of an equipment limiting zone can also aid in sediment reduction. Total suspended solids and turbidity data show the use of any improved crossing type significantly decreases sediment production and transport in ephemeral streams impacted by forest harvesting operations. Increased emphasis on the use of improved crossings in ephemeral streams

during forest harvests would minimize the impact of ephemeral stream crossings as sediment sources in harvesting operations. The benefits of improved crossings would be maximized when the crossing type selected is appropriate to the site, the correct size, and installed and removed correctly.

While it is widely accepted that crossings contribute significantly to TSS this research also indicates that limiting equipment disturbance on or directly adjacent to the channel can result in TSS concentrations similar to concentrations measured in unharvested ephemeral streams. Operationally this can be accomplished by increasing the amount of residual overstory trees left next to ephemeral channels and/or by restricting the operation of equipment next to channels. However, while limiting equipment operations and ground disturbance around channels can help in reducing TSS, the importance of appropriate crossing selection, construction, maintenance and removal cannot be overemphasized. While the appropriate use of crossings is paramount to limiting TSS and limiting bank disturbance further decreases TSS, providing canopy retention around ephemeral channels can offer thermal protection, maintain coarse woody debris inputs, alter carbon and nitrogen dynamics, and change habitat characteristics, all of which should be addressed through further research.

These data indicate that the extension of forestry BMPs to ephemeral streams is effective in reducing sediment from harvesting operations. In states that already have recommendations for ephemeral stream protection, like Kentucky, mandating improved crossing use for all ephemeral crossings is prudent. When further improvements in sediment reduction are warranted, as would be the case with streams containing flora or

fauna particularly sensitive to sedimentation, additional canopy retention and equipment limiting zone recommendations could prove valuable.

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CHAPTER 3 INFLUENCE OF VARIABLE STREAMSIDE MANAGEMENT ZONE CONFIGURATIONS ON SELECTED WATER QUALITY PARAMETERS FOLLOWING FOREST HARVEST

Introduction

Minimizing non-point source pollution from forest harvesting activities is the primary goal of forestry best management practices (BMPs), including those described in the Kentucky Forest Practice Guidelines (Stringer and Perkins 2001). Changes in sediment, nitrate, dissolved oxygen concentration, and stream water temperature that reduce water quality have been associated with forestry activities (Binkley and Brown 1993). Streamside management zones (SMZs) are one forestry BMP used to minimize sediment delivery to streams, minimize temperature increases, and filter surface runoff (Stringer and Perkins 2001).

Undisturbed forests have several characteristics that promote high surface water quality. Minimal overland flow and sediment transport result from high infiltration rates and protection of the soil by the litter layer (Neary et al. 2009, Stuart and Edwards 2006). One consequence of this is low total suspended solids concentrations (TSS). Sediment concentrations measured in streams from forested watersheds are generally less than 10 mg L^{-1} (measured as an annual average), with values from storm flows ranging from 100-1000 mg L^{-1} (Binkley and Brown 1993).

Nitrogen is the limiting nutrient in many forests, and is therefore efficiently cycled in forests. Inputs to forest soils are via long-term inputs of small amounts of nitrogen in precipitation, particulates, dry deposition, and nitrogen fixation (Binkley et al. 2000). Denitrification and hydrologic export are the principle outputs of nitrogen from forested systems (Barnes et al. 1998). From litterfall, the soil nitrogen cycle consists of

mineralization of soluble or insoluble organic nitrogen to ammonium (NH_4^+) , followed by either immobilization via microbial uptake or nitrification to nitrate (NO_3^-). Nitrate may be leached from the soil, immobilized by microbial uptake, taken up by plants, or lost via denitrification (Fisher and Binkley 2000). In a review by Binkley and Brown (1993), stream water concentrations of NO_3^- from unharvested watersheds ranged from 0.01 to 1.7 mg L^{-1}.

In forested headwater streams, the canopy of undisturbed riparian forests shades the entire stream, moderating temperatures and minimizing the influence of solar radiation on the energy budget of streams (Richardson and Danehy 2007). Temperature moderation is important for sensitive aquatic and riparian species and helps maintain high dissolved oxygen (DO) concentrations in stream water (Richardson and Danehy 2007, Brown 1973). Normal DO concentrations in streams typically range from 5 to 10 mg L^{-1}.

Forest harvesting activities generally result in increased TSS and NO_3^- concentrations, increased maximum stream water temperatures and larger temperature fluctuations, and decreased DO concentrations (Binkley and Brown 1993, Beschta 1987, Lynch et al. 1984). Soil compaction and litter disturbance resulting from harvesting operations have been identified as major contributors to increases in overland flow and sediment transport. For example, decreases in permeability of 35% were measured in a harvested area and decreases of 93% were measured on skid trails in one early study of mechanized harvesting techniques (Steinbrenner and Gessel 1955). Since then, many studies have examined the increase in sediment runoff from skid trails and forest roads (e.g. Litschert and MacDonald 2009, Croke et al. 2001, Kreutzweiser and Capell 2001, Reid and Dunne 1984). Sediment transport may also increase as a result of larger peak flows and longer

elevated flow durations that can occur following forest harvests due to decreased evapotranspiration (Troendle 1993). In addition to reduced infiltration and increased runoff potential, skid trails and roads used in harvesting and disturbed ground surfaces may increase the hydrologic and sediment connectivity of the watershed by coupling the trail system and the hydrologic system (Lacey 2000, Bracken and Croke 2007). Ephemeral stream crossings have been identified as a source of increased sediment transport following harvest (Kreutzweiser and Capell 2001), and are a direct link between the trail system and hydrologic system. Further, interflow may be converted to surface flows at skid trail cut banks, increasing runoff (Wemple et al. 1996).

The primary impact of forest harvesting on nitrogen cycling is elevated NO_3^- exports (Martin 1984). Common explanations for increases in NO_3^- export following forest harvesting include: decreased uptake by plants, increases in mineralization and nitrification rates as a result of increased soil temperature and moisture following harvest, reductions in carbon inputs from litter and root exudation followed by reductions in nitrogen immobilization by microbes, and the decay of residues remaining from harvesting activities (Mayer et al. 2007, Prescott 2002, Wynn et al. 2000, Likens 1970). Waide (1988) identified the three parts of the forest nitrogen cycle most vulnerable to changes from forest management as: mineralization from litter and soil organic matter, inputs via nitrogen fixation, and losses from denitrification. Nitrogen may also be lost as a result of erosion and transported to surface waters (Barling and Moore 1994, Dillaha et al. 1989). Nitrate concentration may also decline following harvesting. A review by Van Miegroet and Johnson (2008) described results of studies reporting declines in NO_3^- leaching following harvest, which were a result of either loss of nitrogen fixing species or

a reduction in atmospheric nitrogen due to decreased canopy interception following harvest (Parfitt et al. 2002, Rothe and Binkley 2001, Heitz and Rehfuess 1999, Rothe 1997).

Reviews by Binkley and Brown (1993) and Brown (1973) describe the impact of forest harvesting on DO including increased temperatures resulting from canopy removal, increased fine organic matter inputs from logging debris and alteration of channel characteristics via coarse woody debris inputs. Higher temperatures result in lower saturation concentrations for DO. Increased organic matter in stream waters stimulate microorganism activity and decrease DO concentrations as the microorganisms use more oxygen in the process of breaking down organic materials. Increased coarse woody debris inputs from harvest can result in debris dams, causing stagnation in ponded areas and depressed DO concentrations (Binkley and Brown 1993).

Stream temperature is also susceptible to changes following harvest as canopy removal eliminates shading of surface waters. Forested headwater streams are especially vulnerable to changes in temperature and the associated deleterious impacts, since the fully closed canopy shades the entire stream and results in a reduced role of solar radiation inputs in the stream's energy budget (Richardson and Danehy 2007). Small streams are also vulnerable to large changes in temperature as a result of canopy removal, as their small channel size and water volume rapidly responds to changes in solar radiation (Beschta 1987, Brown 1973, Swift and Messer 1971). Changes in temperature for these small shaded streams is proportional to the amount of the stream surface exposed to sunlight and indirectly proportional to stream discharge (Brown 1973). Increased solar radiation is the primary cause of temperature increases following harvest,

and increased temperatures in tributaries can influence downstream reaches (Beschta 1987, Brown 1973; Swift and Messer 1971). In addition to higher maximum temperatures, canopy removal can result in large diel fluctuations and decreased minimum temperatures as nighttime radiational cooling increases (Beschta 1987, Lynch et al. 1984).

Changes to each of these parameters resulting from forest harvests can negatively impact aquatic and riparian species. Reviews by Bilotta and Brazier (2008) and Henley et al. (2000) provide details of the impacts of elevated sediment and turbidity on aquatic organisms, including: decreased light penetration that in turn leads to reduction in photosynthesis and primary production, clogging of interstitial spaces in the stream bed which can decrease water and oxygen flow and negatively impact benthic macroinvertebrates and fish spawning habitats. Increased sediment may also impact fish respiration through lower DO levels. Elevated suspended sediment levels also affect periphyton and macrophyte communities by scouring and abrasion resulting from elevated suspended sediment levels, which can result in these organisms being dislodged from the substrate on which they are growing and by physical damage that negatively impacts their photosynthetic ability. Pollutants transported with sediment can also negatively impact water quality; for example, nitrogen and phosphorus inputs have been implicated in surface water eutrophication (Vitousek et al. 1997). Increases in sediment and turbidity can also increase the cost to treat drinking water supplies (Holmes 1988).

Elevated NO_3^- concentrations in surface waters can be detrimental to human health (methemoglobinemia) and aquatic systems (eutrophication) (Carpenter et al. 1998). Decreased DO concentrations negatively impact aquatic biota, including benthic

macroinvertebrates. For example, Nebecker (1972) showed 30 day LC 50 values for two mayfly and one stonefly species at DO levels between 4.5 and 5 mg L^{-1}. Emergence of three mayfly species was 0% at DO concentrations between 2.4 and 4.1 mg L^{-1}. One midge species, however, was very tolerant of low DO and able to tolerate levels less than 0.6 mg L^{-1}. In addition to depressed DO, elevated electrical conductivity (EC) can also be detrimental to benthic macroinvertebrates (Pond et al, 2008).

Large fluctuations in temperature from the normal range can negatively impact sensitive aquatic and riparian species (Richardson and Danehy 2007). Increases in light and temperature can also change the stream ecosystem by changing the energy balance. Closed canopy forested headwater streams rely on external inputs of organic matter for energy sources rather than primary producers. Increases in solar energy can increase primary production, altering the types and flow of carbon in the stream (Richardson and Danehy 2007). In addition to impacts to biota and stream energy balance, temperature increases also reduce the solubility of oxygen, as discussed earlier, further impacting biota (Binkley and Brown 1993).

SMZs are used to isolate impacts from harvesting on surface water (Lee 2004). Definitions and delineations of SMZs can vary, but they are generally based on regulatory guidelines and management goals, and include the riparian area and some portion of upland areas necessary to meet those goals (Neary 2009). Streamside management zone width and canopy retention recommendations vary by state. Generally, each state recommends a minimum SMZ width and canopy retention amount for perennial streams and many incorporate similar recommendations for intermittent streams (Blinn 2001). Kentucky's forestry BMPs require SMZs of 7.6 m (25 feet) when

slopes are less than 15% and 16.8 m (55 feet) when slopes are greater than 15% in warmwater habitats. At least 50% of the original tree overstory should be retained for perennial streams to provide shade and maintain water temperature. Canopy retention in SMZs also promotes hardwood regeneration (Meadows and Stanturf 1997). Intermittent streams are protected with equipment limiting zones of at least 7.6 m (25 feet) (Stringer and Perkins 2001). These recommendations are similar to the mean SMZ widths across the United States (mean 24.2 m) for small perennial streams and in the southeast United States (mean 17.5 m) for small perennial streams (Lee et al. 2004). Approximately 80% of jurisdictions allow some harvesting in SMZs across the United States and Canada (Lee et al. 2004).

SMZs have been shown to be effective at mitigating the impacts of harvesting on TSS, NO_3^-, DO, and temperature. For example, an examination of riparian buffer effectiveness conducted in Robinson Forest, KY showed significant increases in sediment following harvest for two watersheds relative to an unharvested control (Arthur et al. 1998). In the study, two adjacent watersheds were clear cut; one with a 15 m riparian buffer and other best management practices including roads constructed with slopes less than 10%, reseeding of roads and landings post-harvest. No BMPs were used on the second watershed. Sediment flux increased for both watersheds following harvest relative to the unharvested control. Additionally, the watershed harvested without BMPs measured increases of 1.5 to 2 times larger than the watershed harvested with BMPs. Seven years post-harvest, significant differences in sediment flux were measured among the three watersheds, with sediment flux highest in the watershed harvested without BMPs and lowest in the unharvested control. In addition to the sediment reductions measured in the

BMP watershed, post-harvest median NO_3^- concentrations were 3.47 mg L^{-1} in the watershed harvested without BMPs and 2.82 mg L^{-1} in the BMP watershed. Changes in stream temperature resulting from the harvest were not measured for either the BMP or no BMP watershed.

SMZs limit TSS increases in streamwater by maintaining high surface roughness and infiltration rates which reduces surface runoff velocity and results in deposition and trapping of sediment (Barling and Moore 1994). Retaining riparian vegetation following forest harvesting minimizes nitrogen increases in surface water by maintaining demand by plants and microbial immobilization, providing soil storage and groundwater mixing, and denitrification (Mayer et al. 2007). The effectiveness of streamside management zones at mitigating nitrate increases following harvest is highest when zones are wide enough and the hydrology, soils, and biogeochemistry promote subsurface removal (Mayer et al. 2007). While wider buffers remove more nitrogen in surface runoff, subsurface removal is more efficient, and management zone width must be adequate to endure residence times that promote denitrification (Mayer et al. 2007, Phillips 1989). Losses via denitrification are limited by the availability of soluble carbon and the presence of hydrology that results in anoxic conditions (Mayer et al. 2007, Burt et al., 1999). Denitrification may be less important in some headwater streams, including those without well defined floodplains, that are incised, and where water residence time in riparian areas is minimal (Burt et al. 1999). Maintaining streamside vegetation mitigates temperature changes, generally to less than 2 degrees C, and helps exclude logging debris from the channel, both of which limit changes in DO (Binkley and Brown 1993, Brown

1973). SMZs can also be effective at minimizing increases in diel temperature fluctuations (Lynch et al. 1984).

While we know the presence of SMZs can minimize non-point source pollution from forest harvesting activities, specific information regarding how the two most common guidelines included in SMZ prescriptions, SMZ width and overstory retention, impact water quality is lacking. The relative importance of SMZ width and disturbance level in surface water protection is not well understood. The necessary SMZ width and canopy retention may differ depending on the parameter of interest as well as watershed characteristics. Additionally, information regarding BMP effectiveness throughout the watershed, including ephemeral, intermittent, and perennial streams, is needed. An assessment of the current Kentucky Forest Practice Guidelines for Water Quality Management has not been conducted in order to evaluate its effectiveness. The objectives of this study were three-fold:

1) Examine the effectiveness of current Kentucky Best Management Practices on TSS, nitrogen, dissolved oxygen, and temperature changes following forest harvest
2) Quantify the impact of canopy removal in SMZs on TSS, nitrogen, dissolved oxygen, electrical conductivity, and temperature changes following harvest
3) Determine the influence of SMZ width on TSS, nitrogen, dissolved oxygen, electrical conductivity, and temperature changes following harvest.

Methods

Site Description

This study was conducted at the University of Kentucky's Robinson Forest (37º 27' north latitude and 83º 08' west longitude), located in the Cumberland Plateau physiographic region of southeastern Kentucky. The forest is approximately 6,000 hectares and was harvested by the Mowbray-Robinson Lumber Company between 1890 and 1920 (Overstreet 1984). The regenerated forest is categorized as mixed mesophytic forest dominated by oak (*Quercus sp.*), hickory (*Carya sp.*), and yellow-poplar (*Liriodendron tulipifera*). The topography is highly dissected, with narrow stream bottoms, elevation ranges of 260 to 460 m, and steep side slopes ranging from 35 to 90%, averaging approximately 45% (Coltharp and Springer 1980).

Soils of Robinson Forest are mainly of the Shelocta, Rigley, and Gilpin soil series (Coltharp and Springer 1980). These soils are all mesic Typic Hapludults with moderate to moderately rapid permeability and are formed from colluvium (Shelocta and Rigley) or residuum (Gilpin) (Soil Survey Staff, accessed December 8, 2011). Geologically, the substrate is Pennsylvanian aged layers of sandstone, siltstone and shale horizontally interbedded with coal (Coltharp and Springer 1980).

The climate of Robinson Forest is classified as temperate-humid-continental with warm summers and cool winters. The average annual precipitation for southeastern Kentucky is 116.4 cm while the 26-year average for three precipitation collectors at Robinson Forest was 117.5 cm (Cherry 2006). Average monthly precipitation is 9.79 cm and March tends to be wetter than average and October tends to be drier. May 2009 was an exceptionally

wet month that yielded one 50-year storm event, hereafter referred to as the 2009 flood, (Office of Surface Mining, personal communication) with a 24-hour precipitation total of 14.5 cm.

Eight first-order watersheds were included in this study (Figure 3-1). Each was located in the 1,545 ha Clemons Fork watershed and equipped with either a 3:1 broad-crested weir or H-flume at the perennial outlet and a trapezoidal or cut-throat flume at the perennial-intermittent transition. Six watersheds were harvested from June, 2008 to October, 2009. The remaining two watersheds remained un-harvested to serve as controls. Both control watersheds (Falling Rock Branch and Little Millseat Branch) are listed as exceptional waters by the state of Kentucky (Kentucky Legislative Research Commission ND). Treatment watersheds were harvested using a shelterwood with reserves, or two-aged deferment (Miller et al. 2006; Smith et al. 1989), harvest method with a target post-harvest basal area of approximately 0.42 square meters per hectare (15 square feet per acre). Harvesting equipment included wheeled cable and grapple skidders (John Deere™ models 540 and 648 and Caterpillar™ models 525 and 545), tracked dozers (John Deere™ models 650, 700, or 800), and tracked feller-bunchers (Timbco™ swing-armed feller bunchers model 445 or 445EXL).

Skid trails were constructed along hillslope contours, where feasible, at various intervals from the top to the bottom of slopes. The skid trail system comprised 6% to 12% of the watershed area. Following harvest, skid trails were retired using best management practices detailed in the Kentucky Forest Practice Guidelines for Water Quality Management (Stringer and Perkins 2001). Retirement practices included construction of water bars and other cross-drained structures as well as re-vegetation of the trail system.

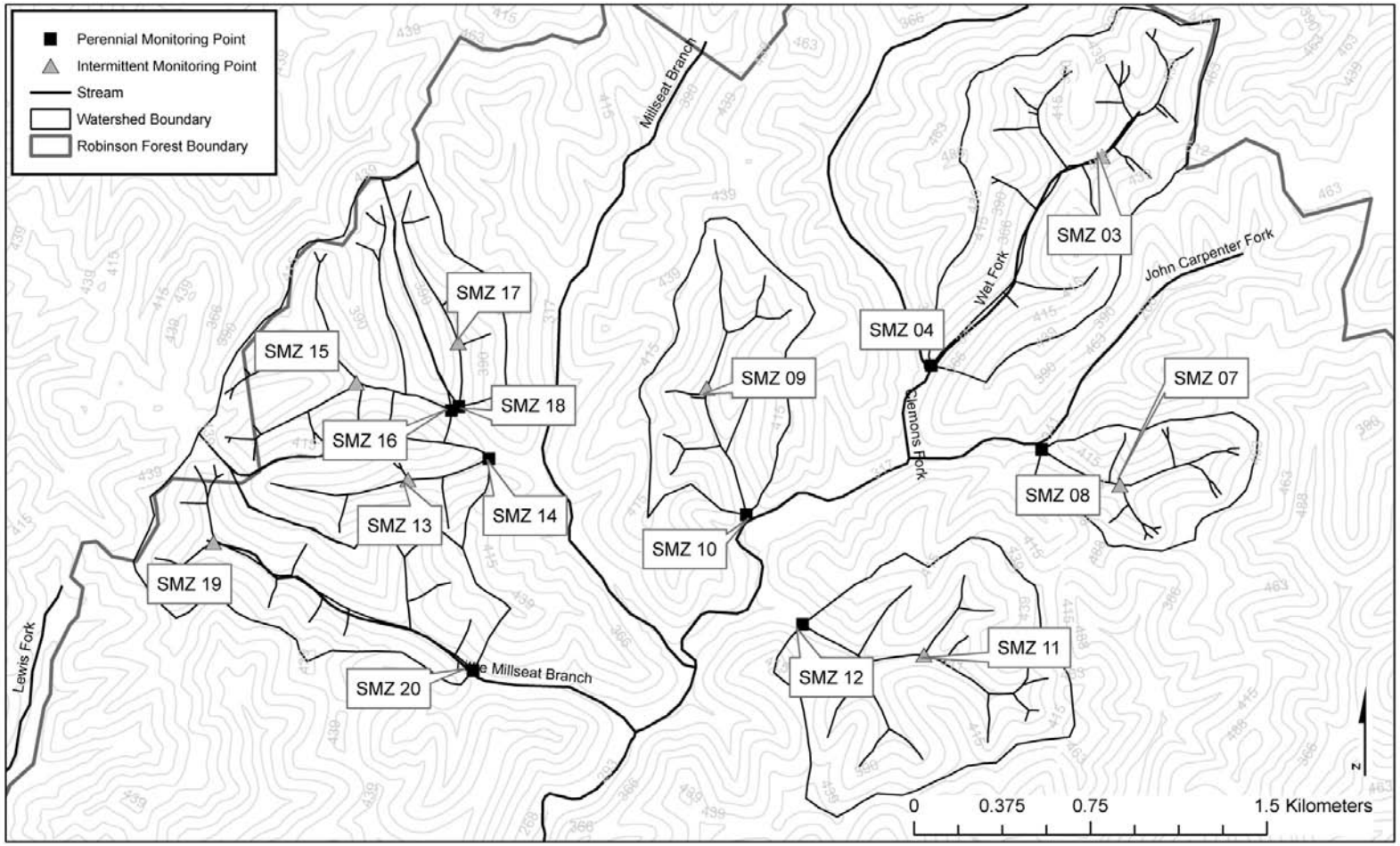

Figure 3-1: Location of perennial and intermittent monitoring locations used in this study.

Treatments

The six harvested watersheds were treated with one of three SMZ combinations (Table 3-1, Table 3-2, Table 3-3). Treatment 1 was based on the current Kentucky best management practices and included a 16.8 m (55 ft) perennial SMZ with 50% overstory retention and a 7.6 m (25 ft) intermittent SMZ with no overstory retention requirement. Treatment 2 maintains the 16.8 m (55 ft) perennial SMZ but requires 100% canopy retention and 25% canopy retention in the 7.6 m (25 ft) intermittent SMZ. In addition, improved crossings were used in ephemeral stream crossings and the nearest channel bank tree was retained. Treatment 3 increased the perennial SMZ width to 33.5 m (110 ft) with 100% canopy retention and the intermittent SMZ width to 16. 8 m (55 ft) with 25% canopy retention and included a 7.6 m (25 ft) SMZ around ephemeral streams. The nearest channel bank tree was also retained and improved stream crossings were used in the ephemeral streams.

Table 3-1: Whole watershed treatment combinations utilized in the study. Each treatment was applied to two watersheds.

Treatment	Perennial SMZ Width (m)	Perennial Canopy Retention (%)	Intermittent SMZ Width (m)	Intermittent Canopy Retention (%)	Ephemeral SMZ Width (m)	Ephemeral Canopy Retention	Improved Crossings (Y/N)
1*	16.8	50	7.6	0	0	0	No
2	16.8	100	7.6	25	0	Stringer**	Yes
3	33.5	100	16.8	25	7.6	Stringer	Yes

*Treatment 1 was based on the current Kentucky best management practice regulations
**A stringer refers to the retention of the overstory tree nearest the channel bank on either side of the stream.

Table 3-2: Characteristics of monitored watersheds at the perennial and intermittent monitoring locations.

Watershed Name	SMZ Number	Monitoring Location	Treatment	Area (ha)	Drainage Density (m m^{-2})	Aspect
Wet Fork	SMZ 03	Intermittent	3	32	0.0061	Southwest
	SMZ 04	Perennial		112	0.0046	
Goff Hollow	SMZ 07	Intermittent	2	31	0.0023	Northeast
	SMZ 08	Perennial		38	0.0058	
Booker Hollow	SMZ 09	Intermittent	1	27	0.0036	Northeast
	SMZ 10	Perennial		59	0.0047	
Falling Rock	SMZ 11	Intermittent	Control	25	0.0071	Northeast
	SMZ 12	Perennial		97	0.0038	
South Shelly Rock	SMZ 13	Intermittent	2	19	0.0040	East
	SMZ 14	Perennial		33	0.0045	
West Shelly Rock	SMZ 15	Intermittent	3	18	0.0106	Southeast
	SMZ 16	Perennial		72	0.0057	
North Shelly Rock	SMZ 17	Intermittent	1	16	0.0061	South
	SMZ 18	Perennial		27	0.0051	
Little Millseat	SMZ 19	Intermittent	Control	27	0.0050	Southeast
	SMZ 20	Perennial		79	0.0048	

Table 3-3: Watershed, skid trail, and crossing data for all watersheds.

Watershed Name	SMZ Number	% of Watershed Occupied by Skid Trails	Ephemeral Crossings	Crossings /ha
Wet Fork	SMZ 04	7.6	12	0.11
Goff Hollow	SMZ 08	8.8	3	0.08
Booker Hollow	SMZ 10	6.8	8	0.14
Falling Rock	SMZ 12	--	--	--
South Shelly Rock	SMZ 14	11	7	0.21
West Shelly Rock	SMZ 16	12	12	0.17
North Shelly Rock	SMZ 18	9.4	5	0.18
Little Millseat	SMZ 20	--	--	--

Sampling and Statistical Methodologies

Precipitation events were sampled at perennial monitoring locations using automated pump water samplers (Teledyne ISCO^{TM}, Lincoln NE) equipped with liquid level actuators. Sampling intervals ranged from 8 to 24 hours following the start of the storm response. Up to 47 samples were taken per event and composited resulting in one sample per monitored storm event. Storm samples were analyzed for total suspended solids concentration, turbidity, and settleable solids.

Non-storm samples were taken from perennial and intermittent monitoring locations periodically (samples were taken pre-harvest monthly and were taken weekly after the harvest began). Non-storm samples were analyzed for TSS and turbidity.

Total suspended solids were determined gravimetrically using a 1.5 µm filter (Whatman 934-AH Glass Microfibre Filters, GE Biosciences Corp, Piscataway NJ) (APHA 1992). Turbidity was analyzed using portable turbidity meter and measured in formazin turbidity units (FTU) (Hanna Instruments model HI 93703, Woonsocket RI). Both TSS and turbidity were analyzed in duplicate and reported as the mean of the two samples. Settleable solids were measured using Inhoff cones, with a sample volume of one liter and a settling time of one hour in accordance with Standard Method 2540 F (APHA 1999).

Nitrate and ammonium concentrations were determined colorimetrically using a Bran Luebbe Auto Analyzer 3 (Bran Luebbe, Norderstedt, Germany). Dissolved oxygen concentration and EC were measured with a Yellow Springs Instruments 556 multi-parameter probe (Yellow Springs Instruments Incoroporated, Yellow Springs OH). Temperature was recorded every 15 minutes using a datalogging miniTROLL instrument (In-Situ Inc, Ft. Collins CO).

TSS data were logarithmically (base 10) transformed prior to analysis to achieve normality. Storm TSS, storm turbidity, and Non-storm TSS samples were compared using a protected least squares difference test, which utilized a one-way ANOVA Fisher's LSD comparisons. All statistical analyses were performed with either Minitab™ Software version 16 or SigmaPlot™ version 11.

Non-storm samples were statistically analyzed using analysis of covariance (ANCOVA) in accordance with the paired watershed approach. Where the ANCOVA was not appropriate due to sampling differences or due to failure to meet the assumptions of the paired watershed analysis approach, a protected least squares difference test was used. For non-storm sample turbidity, the protected least squares difference test used the Kruskall Wallis test to determine if differences were present among the treatments followed by Mann-Whitney comparisons due to the non-parametric character of the non-storm sample turbidity.

Analysis of covariance was performed on intermittent TSS samples in combination with two-sample t-tests and one-way ANOVA. All intermittent statistical analyses were performed on data that had been logarithmically (base 10) transformed following the addition of 0.1 to all data to adjust for samples whose concentrations were below the detection limit.

Nitrate and ammonium concentrations were analyzed using a protected least significant differences test with non-parametric comparisons. Krukal Wallis tests were used to detect differences among treatments followed by Mann-Whitney comparisons if necessary.

Dissolved oxygen and EC data were analyzed using the paired watershed approach. Because normality could not be achieved via transformation, data were not transformed prior to analysis. In addition, a protected least significant difference test was performed using non-parametric tests.

Results

Perennial Storm TSS

A significant increase in storm TSS was measured when samples taken from harvested watersheds were compared to samples from un-harvested watersheds irrespective of the watershed or treatment (two sample t-test $p = 0.001$, $df = 172$). Mean TSS concentration in storm samples from un-harvested watersheds was 75.4 mg L^{-1} $\pm$ 20.7 mg L^{-1} (SE) and mean TSS concentration of harvested watersheds was 295.3 mg L^{-1} $\pm$ 97.1 mg L^{-1} (SE).

Significant changes in storm TSS were also measured among treatments (one-way ANOVA p-value < 0.0001, $df = 160$) (Figure 3-2). Storm TSS was significantly higher in treatment 1 than treatment 2 ($p = 0.02$, $df = 46$), treatment 3 ($p = 0.001$, $df = 41$), and the unharvested control watersheds ($p < 0.001$, $df = 37$). Storm TSS was higher in treatment 2 watersheds than in unharvested control watersheds ($p = 0.02$, $df = 91$) but not higher than treatment 3 watersheds ($p = 0.06$, $df = 41$). Unharvested control watersheds were statistically similar to treatment 3 watersheds for storm TSS ($p = 0.73$, $df = 33$).

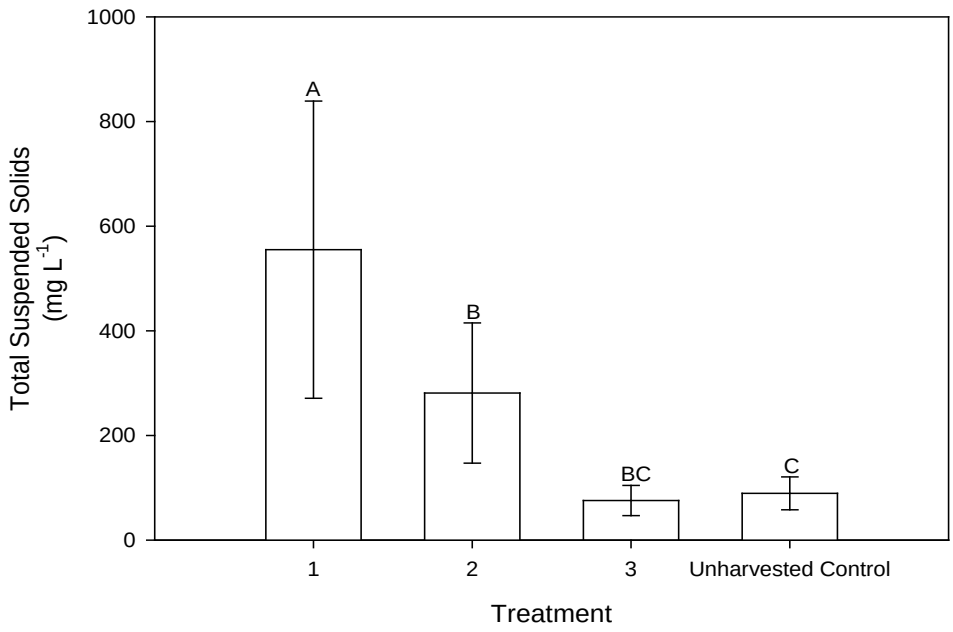

Figure 3-2: Total suspended solids concentration by treatment measured in storm samples collected at perennial monitoring locations. Significant differences at the p = 0.05 level are denoted by different letters (one-way ANOVA followed by two sample t-test).

Intermittent Non-Storm TSS

Analysis of intermittent TSS data did not result in clear significant differences for any comparisons. When data were categorized as un-harvested or harvested irrespective of watershed or treatment, no significant difference was measured between the groups using a two-sample t-test on logarithmic (base 10) transformed data ($p = 0.25$, $df = 486$) or when a non-parametric Mann-Whitney test was performed on un-transformed data ($p = 0.13$). Mean TSS measured at intermittent monitoring points in un-harvested watersheds was 11.56 ± 1.81 (SE) mg L^{-1}. Mean TSS measured at intermittent monitoring points in harvested watersheds was 9.15 ± 1.78 (SE) mg L^{-1}. One-way ANOVA comparing intermittent TSS data from treated watersheds post-harvest and grouped by treatment did not measure any significant differences among the treatments ($p = 0.240$, $df = 292$) (Figure 3-3).

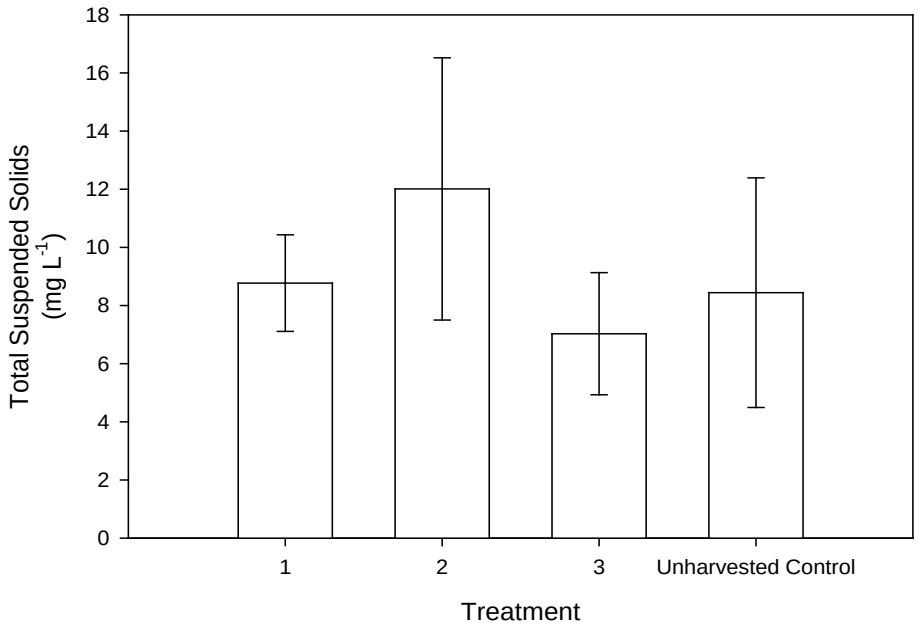

Figure 3-3: Total suspended solids concentration measured from non-storm samples collected at intermittent monitoring locations. No significant differences were measured among the treatments (one-way ANOVA p-value = 0.240, df = 292).

Paired watershed analysis of TSS collected at intermittent monitoring points was performed, however due to the majority of the relationships measuring either pre-harvest or post-harvest regressions that were not statistically valid, the results were of minimal use (Appendix I).

Non-Storm Perennial TSS

Due to differences in sampling methodology before and after harvest, the paired watershed approach was not used for the non-storm samples collected at the perennial monitoring locations. A two-sample t-test measured significant change between samples collected from any watershed pre-harvest and samples collected from watersheds after harvest ($p = 0.02$, $df = 316$). One-way ANOVA measured no significant difference among the un-harvested control watersheds and the harvested treatment watersheds when categorized by treatment ($p = 0.223$, $df = 478$) (Table 3-4).

Table 3-4: Mean TSS concentrations (mg L^{-1}) with standard error by treatment measured in non-storm samples at perennial monitoring locations. No significant differences were measured among treatments (one-way ANOVA p-value = 0.223).

Treatment	Mean TSS Concentration (SE)	Number of Samples
1	4.11 (1.23)	115
2	3.75 (0.71)	129
3	3.03 (0.83)	151
Un-harvested Control	1.72 (0.42)	84

Perennial Storm Turbidity

Turbidity measured at the perennial outlet in storm samples was significantly different among the three treatment groups and the unharvested control ($p < 0.0001$, df = 181) (Figure 3-4). Treatment 1 turbidity in storm samples was significantly higher than treatment 2 storm samples ($p = 0.005$, df = 68), treatment 3 storm samples ($p < 0.0001$, df = 55), and in storm samples collected in unharvested control watersheds ($p < 0.0001$, df = 55). Turbidity in treatment 2 watersheds was significantly higher than in unharvested control watersheds ($p = 0.001$, df = 95) but was statistically similar to turbidity measured in treatment 3 watersheds ($p = 0.134$, df = 68). Turbidity was statistically similar between treatment 3 watersheds and unharvested control watersheds ($p = 0.18$, df = 55).

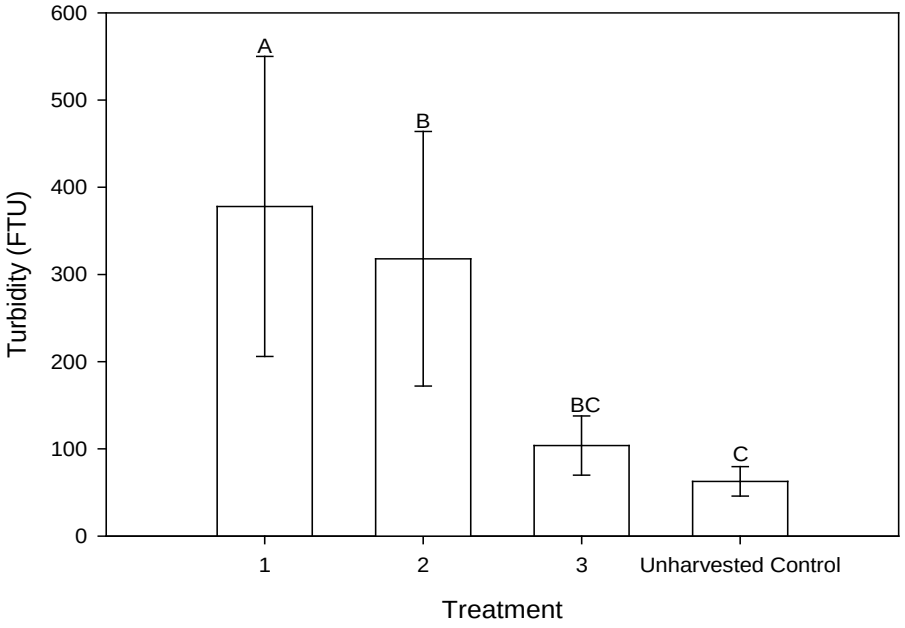

Figure 3-4: Turbidity measured in storm flow samples collected from perennial monitoring locations.

Perennial Non-Storm Turbidity

For non-storm sample turbidity, a trend of decreasing turbidity that accompanied increased SMZ width and canopy retention was measured (Figure 3-5). Significant differences in non-storm sample turbidity were measured among the treatment types ($p < 0.0001$, $n = 584$). Non-storm sample turbidity was statistically higher in treatment 1 watersheds than treatment 2 watersheds ($p < 0.0001$, $n = 301$), treatment 3 watersheds ($p < 0.0001$, $n = 322$), and unharvested control watersheds ($p < 0.0001$, $n = 245$). Turbidity in treatment 2 watersheds non-storm samples was statistically higher than treatment 3 ($p = 0.0025$, $n = 339$) but was statistically similar to turbidity measured in unharvested control watersheds ($p = 0.24$, $n = 262$). Turbidity measured in treatment 3 watersheds was statistically similar to turbidity measured in unharvested control watersheds ($p = 0.09$, $n = 283$).

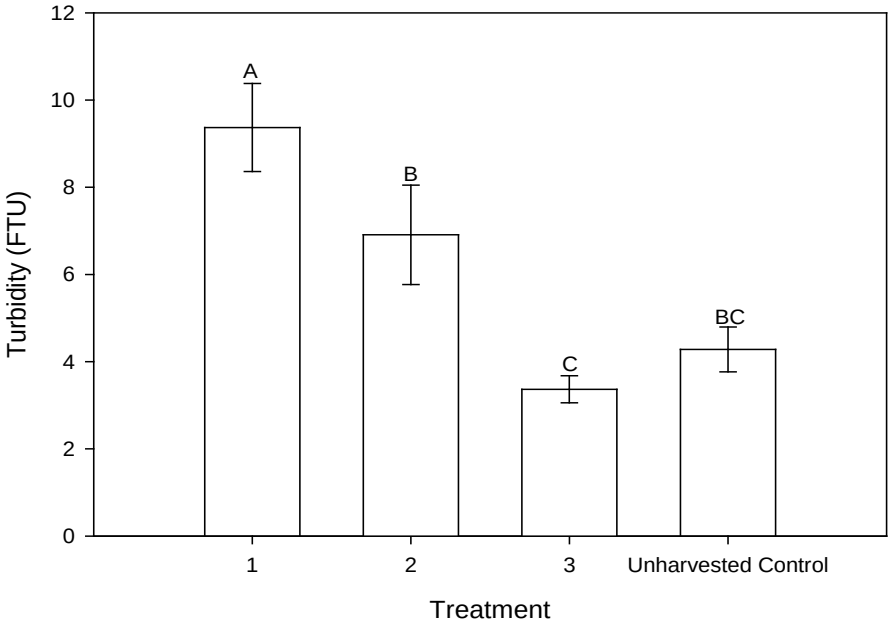

Figure 3-5: Turbidity measured in non-storm samples at perennial monitoring locations.

Intermittent Turbidity

Turbidity measured at the intermittent monitoring locations was significantly different among treatments and unharvested control ($p < 0.0001$, $n = 333$) (Table 3-5). Similar to turbidity measured in non-storm sample and storm flow samples at perennial outlets, turbidity measured at intermittent monitoring locations was significantly higher in treatment 1 than treatment 2 ($p < 0.0001$, $n = 173$), treatment 3 ($p < 0.0001$, $n = 183$), and in the unharvested control watersheds ($p < 0.0001$, $n = 131$). Turbidity measured in the treatment 2 watersheds was significantly higher than in treatment 3 watersheds ($p = 0.0001$, $n = 202$) but was statistically similar to turbidity measured in unharvested control watersheds ($p = 0.12$, $n = 150$). Turbidity measured in treatment 3 watersheds and unharvested control watersheds were statistically similar ($p = 0.12$, $n = 160$).

Table 3-5: Mean and median turbidity (FTU) measurements for non-storm samples made at intermittent monitoring points. Median values followed by different letters were statistically different median values measured using Mann-Whitney comparisons.

Treatment	Mean turbidity (SE)	Median turbidity
1	24.5 (3.8)	14.3[a]
2	10.4 (2.1)	5.0[b]
3	7.2 (1.8)	2.8[c]
Unharvested Control	7.0 (1.3)	3.5[bc]

Perennial Storm Sample Settleable Solids

Settleable solids measured in storm samples at the perennial monitoring locations were statistically similar among all treatments ($p = 0.645$, $n = 178$) (Table 3-6). Due to many readings below the detection limit, data for mean and standard error were estimated using maximum likelihood estimation. Medians were used for statistical comparisons.

Table 3-6: Summary of settleable solids results measured in storm flow samples from perennial monitoring locations. Mean, standard error, and confidence intervals were estimated using a maximum likelihood estimation due to multiple readings below the detection limit (BDL).

Treatment	Total Samples	Number of Samples BDL	Mean (SE) (mL L^{-1})	95% Confidence Interval	Median
1	29	7	0.47 (0.17	0.23, 0.95	0.30
2	51	16	0.64 (0.24)	0.31, 1.32	0.30
3	32	14	0.74 (0.48)	0.21, 2.66	0.45
Unharvested Control	67	34	0.45 (0.18)	0.21, 0.98	0.40

Nitrate-N Concentrations-Perennial Monitoring Points

Significant differences were measured in nitrate concentrations measured in perennial non-storm samples when samples from harvested watersheds were compared to samples from un-harvested watersheds irrespective of the treatment used ($p < 0.0001$, $n = 812$). Mean nitrate concentration in samples from unharvested watersheds was 0.12 ± 0.014 mg L^{-1} and was 0.29 ± 0.015 mg L^{-1} in harvested watersheds. Significant differences were also measured among treatments when post-harvest data from treated watersheds and the

unharvested controls were compared ($p < 0.00001$, $n = 761$) (Figure 3-6). Nitrate concentrations measured at perennial monitoring locations in unharvested control watersheds were lower than concentrations measured at perennial locations in treatment 1 watersheds ($p < 0.0001$, $n = 410$), treatment 2 watersheds ($p < 0.00001$, $n = 428$), or treatment 3 watersheds ($p < 0.0001$, $n = 449$). Nitrate concentrations measured in treatment 1 watersheds were lower than concentrations measured in treatment 2 watersheds ($p < 0.0001$, $n = 312$) and treatment 3 watersheds ($p < 0.0001$, $n = 333$). Nitrate concentrations in treatment 2 watersheds were similar to concentrations measured in treatment 3 watersheds ($p = 0.12$, $n = 351$).

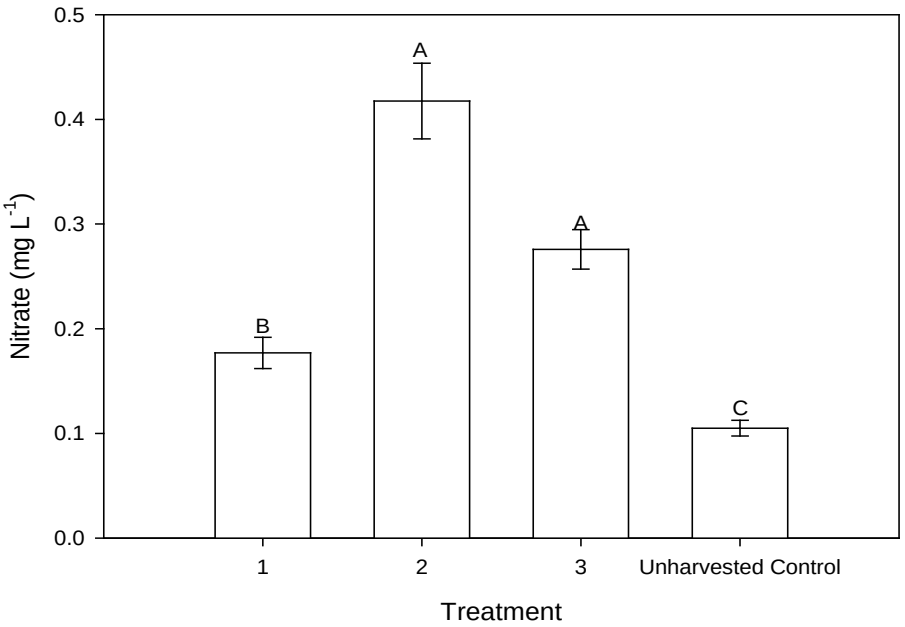

Figure 3-6: Mean (SE) nitrate-N concentrations measured in non-storm samples taken from perennial monitoring locations grouped by treatment. Different letters denote statistical differences at the p = 0.05 level.

Nitrate-N Concentrations-Intermittent Monitoring Points

Differences in nitrate concentration measured at intermittent monitoring locations were similar to those measured at perennial monitoring locations. Comparison of unharvested data to harvested data irrespective of the treatment used measured significant increases in nitrate concentrations ($p < 0.0001$, $n = 369$). Mean nitrate concentration measured at intermittent monitoring locations for unharvested data was 0.11 ± 0.02 mg L^{-1} and mean concentration for harvested data was 0.38 ± 0.02 mg L^{-1}.

Significant differences in nitrate concentration measured at intermittent monitoring locations were measured among treatments when data from the post-harvest phase were considered ($p < 0.0001$, $n = 331$) (Figure 3-7). Nitrate concentrations measured in unharvested control watersheds were lower than concentrations measured in treatment 1 watersheds ($p < 0.0001$, $n = 127$), treatment 2 watershed ($p < 0.0001$, $n = 147$), and treatment 3 watersheds ($p < 0.0001$, $n = 163$). Intermittent nitrate concentrations were also lower in treatment 1 watersheds than treatment 2 watersheds ($p < 0.0001$, $n = 168$) and treatment 3 watersheds ($p < 0.0001$, $n = 184$). Similar nitrate concentrations were measured at intermittent monitoring locations in treatment 2 and treatment 3 ($p = 0.19$, $n = 204$).

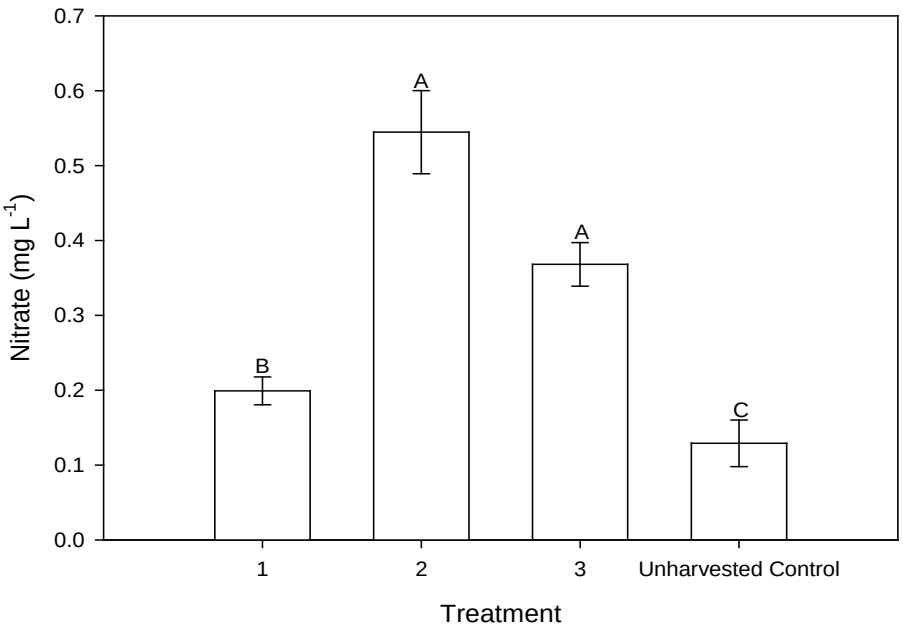

Figure 3-7: Nitrate-N concentrations measured at intermittent monitoring locations grouped by treatment. Different letters denote significant differences at the p = 0.05 level.

Ammonium-N Concentrations

Ammonium concentrations did not differ when unharvested data were compared to harvested data irrespective of the watershed or treatment used for either perennial monitoring locations (p = 0.13, n = 602) or intermittent monitoring locations (p = 0.63, n = 206). Comparisons of ammonium concentrations from treatment watersheds and unharvested control watersheds using treatment period data did not result in statistical differences for either perennial (p = 0.28, n = 556) or intermittent (p = 0.81, n = 173) samples (Figure 3-8).

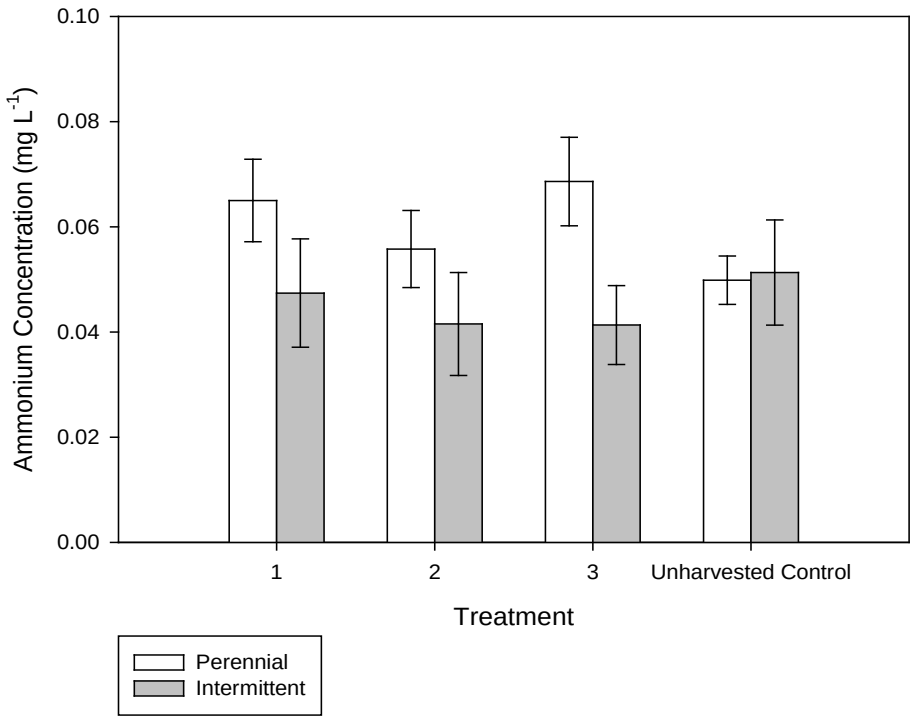

Figure 3-8: Mean ammonium-N concentrations measured at perennial and intermittent monitoring locations grouped by treatment. Significant differences were not measured for either sampling location among the treatments.

Table 3-7: Summary of TSS, turbidity, and settleable solids results. TSS and turbidity are reported as mean (SE). Settleable solids results are reported as the median.

Treatment	Perennial Non-storm sample TSS (mg L^{-1})	Intermittent Non-storm sample TSS (mg L^{-1})	Perennial Storm Flow TSS (mg L^{-1})	Perennial Non-storm sample Turbidity (FTU)	Intermittent Non-storm sample Turbidity (FTU)	Perennial Storm Flow Turbidity (FTU)	Perennial Storm Flow Settleable Solids (mL L^{-1})
1	4.1 (1.3)	8.8 (1.7)	555 (284)	9.4 (1.0)	24.5 (3.8)	378 (172)	0.2
2	3.7 (0.7)	12.0 (4.5)	281 (134)	6.9 (1.1)	10.4 (2.1)	318 (146)	0.2
3	3.0 (0.8)	7.0 (2.1)	76 (29)	3.4 (0.3)	7.2 (1.8)	104 (34)	0.1
Unharvested Control	1.7 (0.4)	8.4 (4.0)	89 (31)	4.28 (0.515)	7.0 (1.3)	63 (117)	<0.1

Table 3-8: Summary of nitrate, ammonium and dissolved oxygen results measured as mg L^{-1}. Temperature data measured as degrees C. Data are reported as mean (SE).

Treatment	Perennial Non-storm sample NO_3-N^-	Intermittent Non-storm sample NO_3^-N	Perennial non-storm sample NH_4^+-N	Intermittent non-storm sample NH_4^+-N	Perennial non-storm sample dissolved oxygen	Mean daily temperature change from control (deg. C)
1	0.18 (0.01)	0.20 (0.02)	0.06 (0.01)	0.05 (0.01)	9.97 (0.3)	0.44
2	0.42 (0.04)	0.54 (0.06)	0.06 (0.01)	0.04 (0.01)	9.98 (0.4)	0.23
3	0.28 (0.02)	0.37 (0.03)	0.07 (0.01)	0.04 (0.01)	11.9 (0.5)	-0.03
Unharvested Control	0.10 (0.01)	0.13 (0.03)	0.05 (0.005)	0.05 (0.01)	10.6 (0.5)	--

Dissolved Oxygen Concentrations

Paired watershed analysis of DO concentrations measured at perennial monitoring locations measured changes ranging from no change to 9% decreases. Of the 12 comparisons, four were significant, for SMZ 08 and SMZ 10 when compared to SMZ 12 (Table 3-9) and for SMZ 14 and SMZ 16 when compared to SMZ 20 (Table 3-10). Comparisons among treatment watersheds measured DO concentration differences ranging from 9% decreases to 5% increases (Appendix II).

Table 3-9: ANCOVA results for dissolved oxygen measured at perennial monitoring locations when SMZ 12 was designated the un-harvested control watershed.

Parameter: Dissolved Oxygen									
Dependent Variable: SMZ 12									
Dependent Variable	Treatment	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	3	Pre-harvest	33	0.86	0.12	1.48	0.86	0.74	-1%
		Post-harvest	32	0.72		2.88		0.93	
SMZ 08	2	Pre-harvest	39	0.67	**0.05**	2.22	0.11	0.79	-9%
		Post-harvest	24	1.01		-1.62		0.78	
SMZ 10	1	Pre-harvest	41	0.67	0.54	3.57	**0.05**	0.83	-8%
		Post-harvest	22	0.76		2.02		0.79	
SMZ 14	2	Pre-harvest	32	0.82	0.76	2.05	0.36	0.84	-3%
		Post-harvest	34	0.84		1.55		0.94	
SMZ 16	3	Pre-harvest	35	0.77	0.18	2.57	0.49	0.72	-2%
		Post-harvest	30	0.89		1.08		0.94	
SMZ 18	1	Pre-harvest	33	0.73	0.76	2.66	0.16	0.76	-5%
		Post-harvest	27	0.70		2.53		0.76	

Table 3-10: ANCOVA results for dissolved oxygen measured at perennial monitoring locations when SMZ 20 was designated the un-harvested control watershed.

Parameter: Dissolved Oxygen									
Dependent Variable: SMZ 20									
Dependent Variable	Treatment	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	3	Pre-harvest	33	0.83	0.60	2.03	0.99	0.76	0%
		Post-harvest	31	0.78		2.52		0.90	
SMZ 08	2	Pre-harvest	39	0.70	0.20	2.05	0.29	0.76	-7%
		Post-harvest	23	0.92		-0.49		0.74	
SMZ 10	1	Pre-harvest	39	0.71	0.97	3.20	0.22	0.84	-5%
		Post-harvest	23	0.71		2.79		0.74	
SMZ 14	2	Pre-harvest	32	0.73	**0.05**	3.04	0.85	0.77	-1%
		Post-harvest	32	0.91		1.15		0.90	
SMZ 16	3	Pre-harvest	33	0.74	**0.03**	2.92	0.93	0.77	-1%
		Post-harvest	31	0.95		0.73		0.90	
SMZ 18	1	Pre-harvest	32	0.69	0.76	3.12	0.46	0.71	-3%
		Post-harvest	28	0.65		3.21		0.68	

Because no transformation of the DO data were able to normalize the data, results from harvested watersheds were compared to unharvested samples irrespective of treatment for the treatment period using a non-parametric Mann-Whitney test. Mean DO concentration from harvested watersheds (10.7 $\pm$ 0.3 mg L-1) was significantly lower than concentrations from unharvested watersheds (11.9 $\pm$ 0.4 mg L-1) ($p = 0.0004$, $n = 561$). Significant differences were also measured when data from the harvest period were grouped by treatment ($p = 0.004$, $n = 497$) (Figure 3-9). No differences were measured between the unharvested control watersheds and treatment 1 watersheds ($p = 0.93$, $n = 203$), treatment 2 watersheds ($p = 0.24$, $n = 225$), or treatment 3 watersheds ($p = 0.054$, $n = 247$). Dissolved oxygen concentrations were higher in treatment 3 watersheds than treatment 1 watersheds ($p = 0.02$, $n = 272$) and treatment 2 watersheds ($p = .0.005$, $n = 294$). Dissolved oxygen concentrations were similar between treatment 2 and treatment 3 watersheds ($p = 0.24$, $n = 250$).

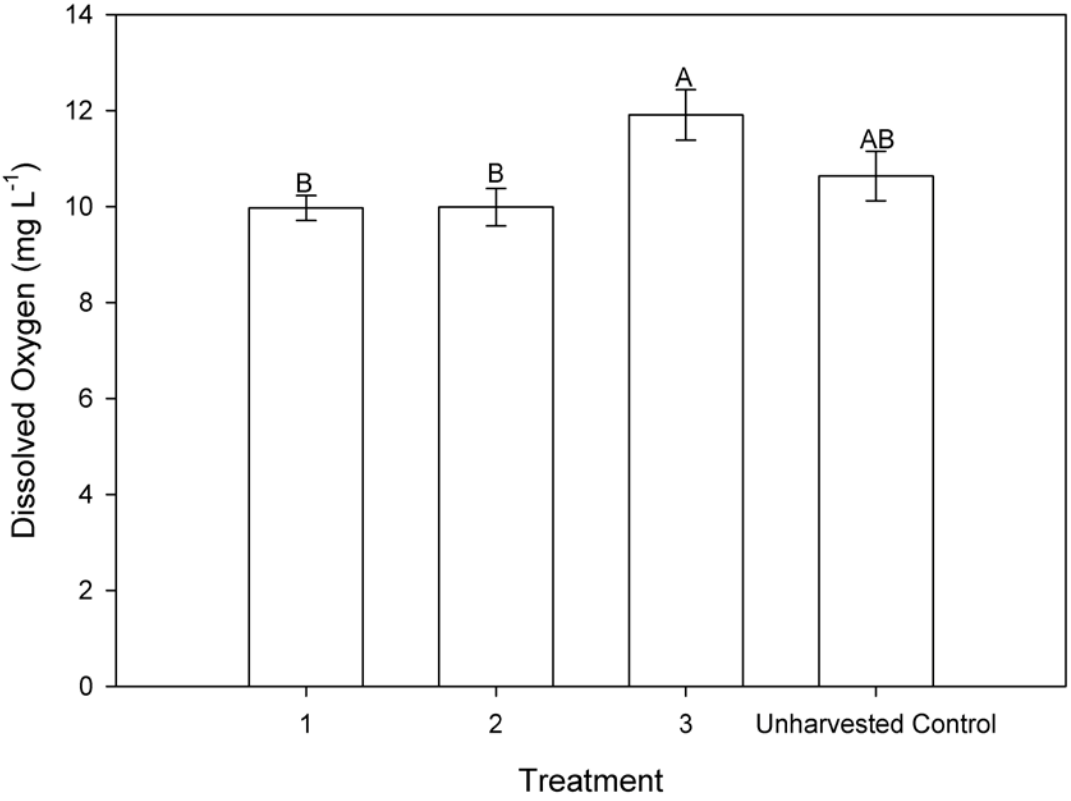

Figure 3-9: Mean dissolved oxygen concentrations measured at perennial monitoring locations. Different letters indicated significant differences at the p = 0.05 level.

Electrical Conductivity

Paired watershed analysis of EC data resulted in significant increases for SMZ 08 and SMZ 14 when compared to SMZ 20. No other relationships between SMZ 20 (Table 3-12) nor any relationship between treatment watersheds and SMZ 12 were significant (Table 3-11).

Table 3-11: Results of paired watershed analysis for electrical conductivity measured at perennial monitoring locations using SMZ 12 (Falling Rock) as the unharvested control watershed for comparison.

Parameter:Conductivity								
Dependent Variable: Falling Rock								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	32	0.93	0.52	0.13	0.66	0.82	11%
	Post-harvest	30	1.02		-0.04		0.69	
SMZ 08	Pre-harvest	37	0.87	0.48	0.18	0.09	0.89	12%
	Post-harvest	22	0.94		0.08		0.83	
SMZ 10	Pre-harvest	39	0.98	0.42	0.01	0.47	0.88	6%
	Post-harvest	19	1.09		-0.15		0.84	
SMZ 14	Pre-harvest	33	0.90	0.25	0.12	0.34	0.85	10%
	Post-harvest	31	1.03		-0.06		0.83	
SMZ 16	Pre-harvest	39	0.88	0.87	0.19	0.96	0.86	14%
	Post-harvest	20	0.90		0.15		0.50	
SMZ 18	Pre-harvest	32	0.69	0.07	0.36	0.28	0.71	17%
	Post-harvest	24	1.03		-0.15		0.58	

Table 3-12: Results of paired watershed analysis of electrical conductivity measured at perennial monitoring locations using SMZ 20 (Little Millseat) as the unharvested control watershed.

Parameter: Conductivity								
Dependent Variable: Little Millseat								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	32	0.92	0.71	0.12	0.52	0.93	7%
	Post-harvest	28	0.87		0.21		0.62	
SMZ 08	Pre-harvest	38	0.88	0.25	0.14	0.01	0.95	8%
	Post-harvest	21	0.78		0.35		0.75	
SMZ 10	Pre-harvest	38	0.98	0.86	-0.01	0.08	0.91	5%
	Post-harvest	19	0.97		0.06		0.84	
SMZ 14	Pre-harvest	32	0.90	0.69	0.11	0.02	0.89	8%
	Post-harvest	28	0.86		0.24		0.75	
SMZ 16	Pre-harvest	33	0.70	0.55	0.46	0.15	0.66	42%
	Post-harvest	27	0.79		0.35		0.53	
SMZ 18	Pre-harvest	31	0.91	0.65	0.03	0.57	0.93	-12%
	Post-harvest	25	0.84		0.16		0.50	

Analysis of EC data using the non-parametric LSD resulted in significant differences among treatments when all data from the post-harvest period were grouped by treatment ($p < 0.001$, $n = 472$). Treatment 1 was significantly different from both treatment 2 ($p < 0.05$, $n = 243$) and treatment 3 ($p < 0.05$, $n = 259$), as well as the unharvested control watersheds ($p < 0.05$, $n = 190$) (Figure 3-10).

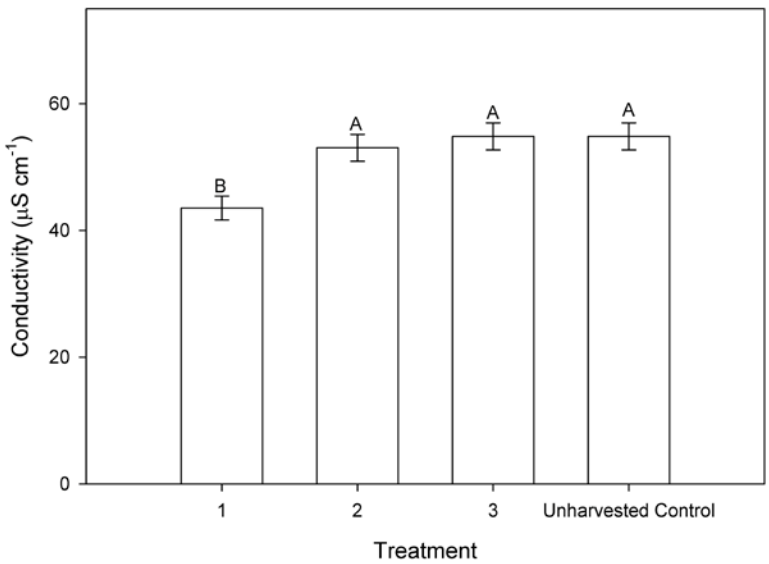

Figure 3-10: Mean (± SE) electrical conductivity from all watersheds grouped by treatment for the post-harvest period. Letters denote significant differences at the p = 0.05 level using a non-parametric LSD procedure.

Mean Daily Temperature

Mean daily temperatures measured at perennial monitoring locations were higher in SMZ 20 than in SMZ 12 (Figure 3-11). The calculated differences between treatment watersheds and control watersheds tended to be positive following harvest (Figure 3-12, Figure 3-13). Paired watershed analysis of daily average temperatures measured changes ranging from -0.71 degrees C to +0.56 degrees C. All comparisons measured significant

differences for average daily temperature with the exception of the SMZ 14-SMZ 20 comparison (Table 3-13, Table 3-14).

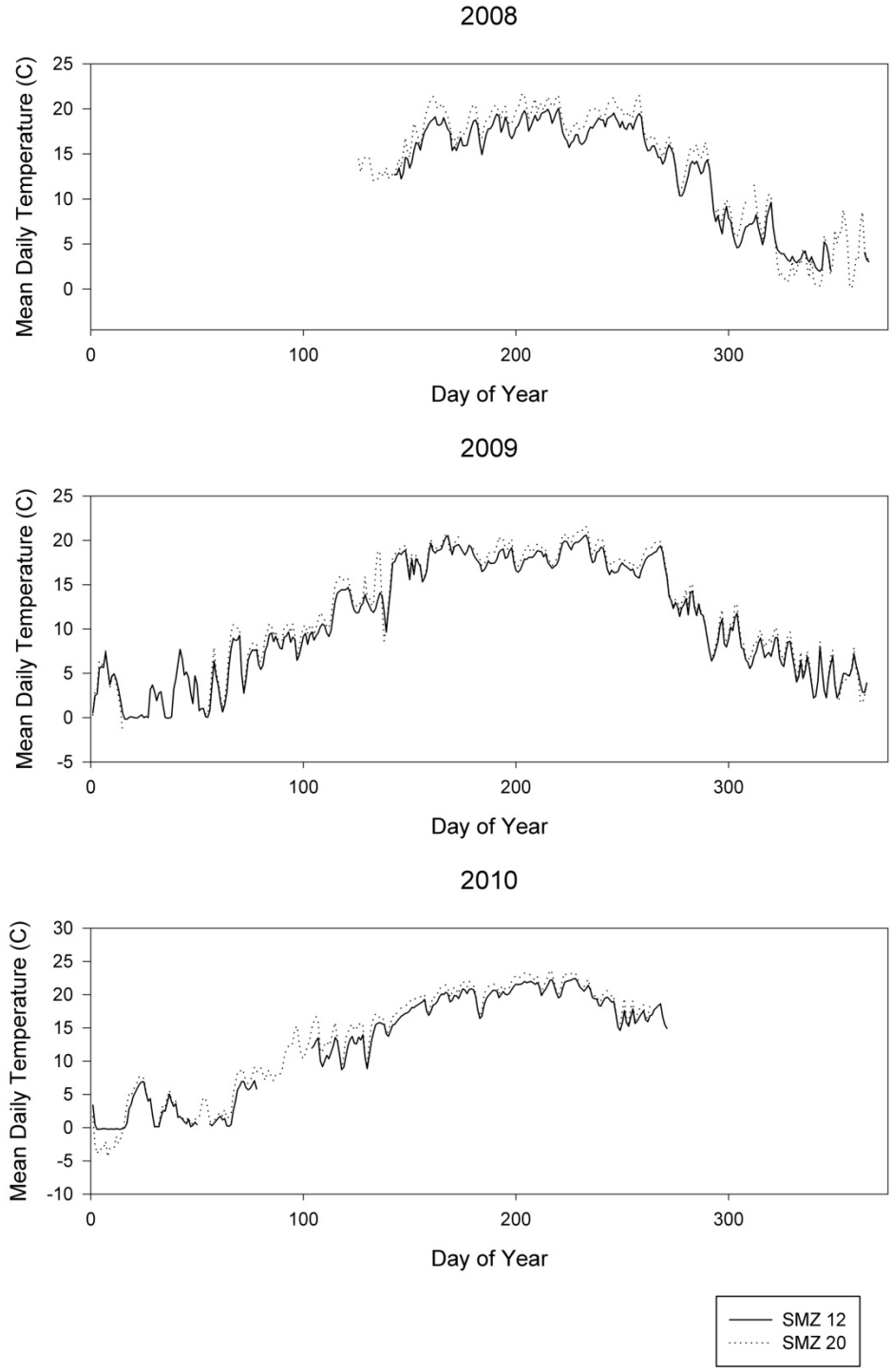

Figure 3-11: Mean daily temperatures measured at perennial monitoring locations for the un-harvested control watersheds for the treatment period.

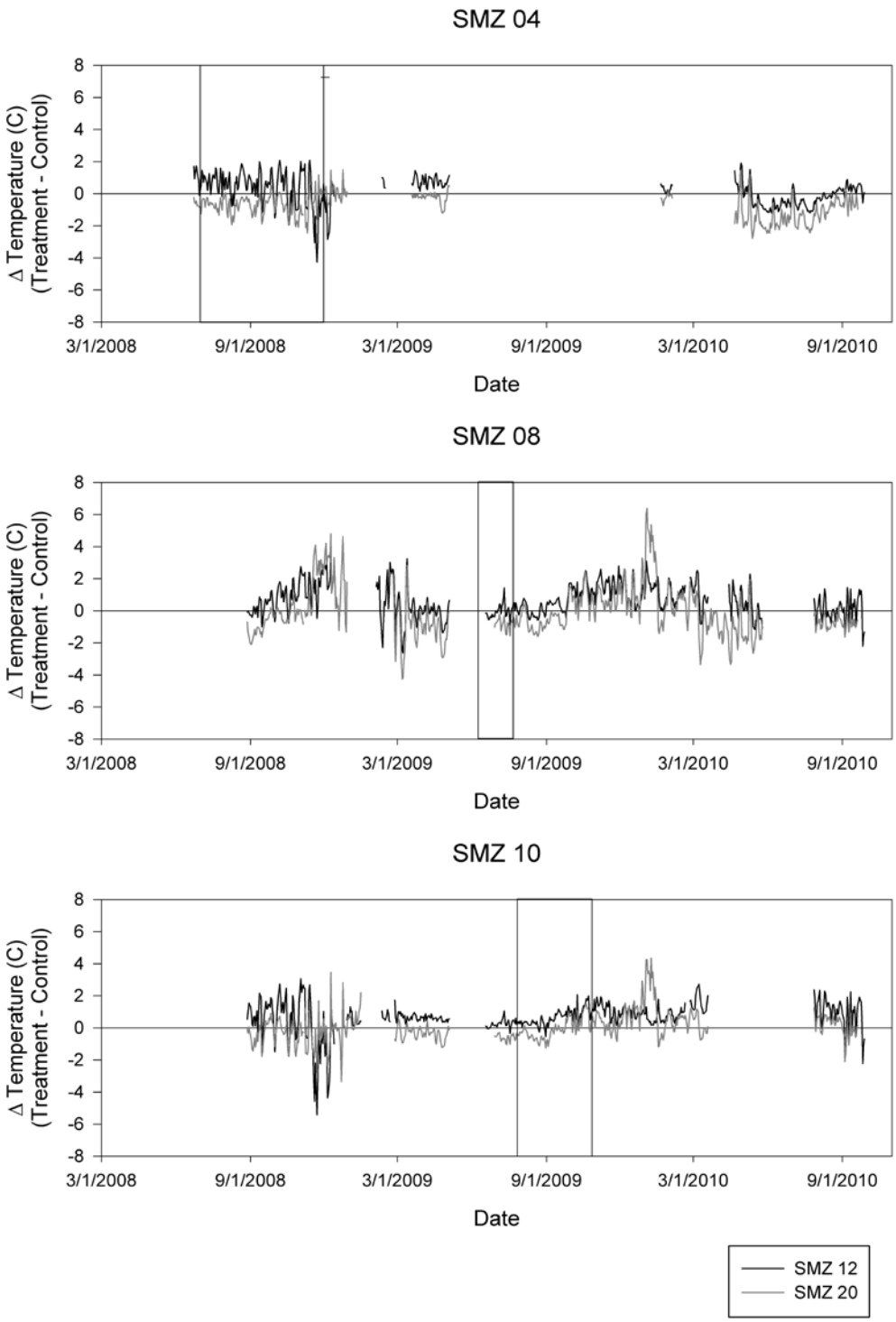

Figure 3-12: Change measured between SMZ 04, SMZ 08, and SMZ 10 watersheds and unharvested control watersheds for the treatment period. Vertical lines denote the start and end dates for harvests.

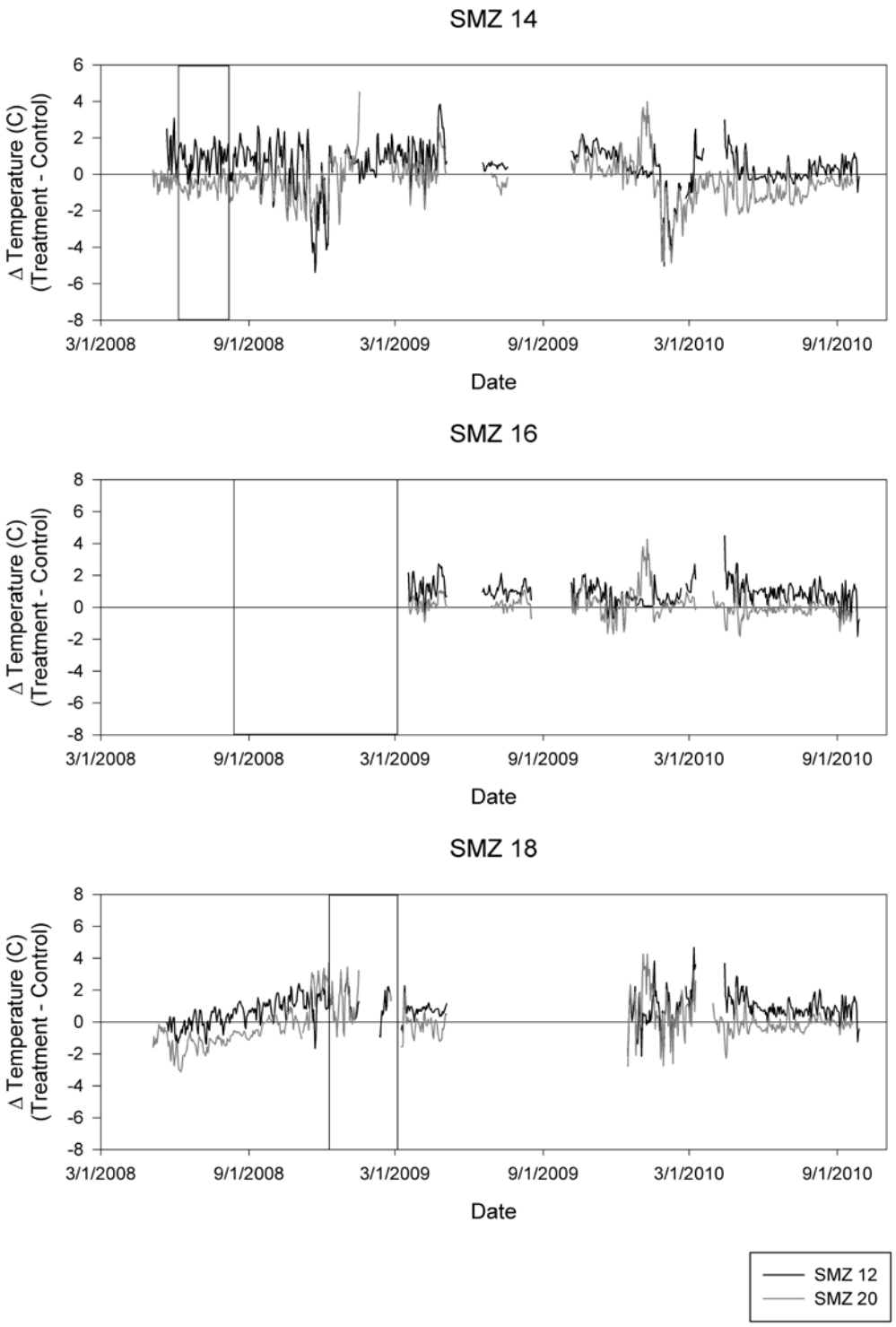

Figure 3-13: Change measured between SMZ 14, SMZ 16, and SMZ 18 watersheds and unharvested control watersheds for the treatment period. Vertical lines denote the start and end dates for harvests.

Table 3-13: ANCOVA results for daily mean temperature when SMZ 12 was designated the unharvested control watershed.

Parameter: Temperature (Daily Mean)									
Dependent Variable: SMZ 12									
Dependent Variable	Treatment	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	Change (deg. C)
SMZ 04	3	Pre-harvest	322	1.00	0.66	0.67	**0.00**	0.96	-0.58
		Post-harvest	374	1.00		0.18		0.97	
SMZ 08	2	Pre-harvest	481	0.84	**0.00**	2.02	**0.00**	0.96	0.53
		Post-harvest	361	0.91		1.66		0.99	
SMZ 10	1	Pre-harvest	604	1.00	0.14	0.52	**0.00**	0.97	0.36
		Post-harvest	283	0.98		1.05		0.99	
SMZ 14	2	Pre-harvest	328	0.98	**0.00**	0.55	**0.00**	0.98	0.10
		Post-harvest	646	1.03		0.08		0.97	
SMZ 16	3	Pre-harvest	182	0.96	**0.00**	0.97	**0.00**	0.98	0.33
		Post-harvest	411	1.02		0.67		0.99	
SMZ 18	1	Pre-harvest	454	0.90	**0.00**	1.79	**0.00**	0.98	0.20
		Post-harvest	324	0.99		0.96		0.99	

Table 3-14: ANCOVA results for mean daily temperature when SMZ 20 was designated the unharvested control watershed.

Parameter: Temperature (Daily Mean)									
Independent Variable: SMZ 20									
Dependent Variable	Treatment	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	Change (deg. C)
SMZ 04	3	Pre-harvest	344	1.05	**0.00**	-0.76	**0.00**	0.96	-0.71
		Post-harvest	374	0.94		0.06		0.99	
SMZ 08	2	Pre-harvest	479	0.81	**0.00**	1.91	**0.00**	0.96	0.30
		Post-harvest	376	0.86		1.55		0.97	
SMZ 10	1	Pre-harvest	628	0.99	**0.00**	-0.09	**0.00**	0.98	0.56
		Post-harvest	281	0.93		1.09		0.99	
SMZ 14	2	Pre-harvest	380	0.99	0.11	-0.28	0.23	0.98	-0.01
		Post-harvest	635	0.97		-0.04		0.98	
SMZ 16	3	Pre-harvest	324	0.98	0.13	0.08	**0.00**	0.98	0.38
		Post-harvest	412	0.96		0.64		0.99	
SMZ 18	1	Pre-harvest	555	0.85	**0.00**	1.72	**0.00**	0.98	0.20
		Post-harvest	335	0.93		1.05		0.98	

Discussion

The paired watershed approach is dependent on the ability to establish relationships between watersheds in both the pre- and post-treatment phases. Absent these relationships, the analysis of covariance cannot be used to determine treatment effects (U. S. EPA, 1993). Difficulties in establishing relationships for TSS concentration and turbidity between watersheds were encountered in the analysis of non-storm samples taken at intermittent monitoring locations, the only samples for which pre-harvest and post-harvest samples were taken using similar methodology. Similar problems in establishing relationships for sediment and turbidity data were encountered by Gokbalak et al. (2008). Arthur et al., (1998) also had problems establishing relationships in sediment concentrations in this landscape, describing two of the watersheds as "weakly paired". High variability in suspended sediment measurements in surface waters has been previously reported (i.e. Binkley and Brown 1993). Even if pre-treatment sediment relationships are established, the response to forest harvesting may vary based on factors including soils, climate, and watershed condition (Neary et al. 2010), as well as the timing of the harvest, harvest intensity, and the harvest crew used. While these factors would hopefully be controlled using watersheds that are in close proximity to one another, even adjacent watersheds may respond differently from one another, especially since it is generally not feasible to simultaneously harvest six watersheds in a uniform manner. Absent the paired watershed approach's statistical control of climate, hydrologic, and temporal changes, the protected least significant difference test was used.

Differences in total suspended solids concentrations were not observed at either the perennial or intermittent monitoring locations under non-storm sample conditions for any

of the treatment watersheds. This similarity was not surprising, as base flow in most forested watersheds, including these, is groundwater fed, with recharge via subsurface lateral flow and limited opportunity for increased sediment load. The lack of change in TSS concentration could be a result of many factors. For example, there could be no sediment sources originating outside the channel resulting from the harvest available for transport under base flow conditions. Increases in base flow quantity and associated increase in sediment from within the stream channels were either not measureable in the concentration data alone and requires flow-weighted mass calculations for identification or did not result from the partial harvest and SMZ configurations. Arthur et al. (1998) found that sediment flux following forest harvesting was closely related to base flow quantity.

Sediment increases in treatment watersheds may have also been measured in un-harvested control watersheds in non-storm sample conditions due to mass sediment movement, perhaps related to the 2009 flood. Past studies (Arthur et al., 1998; Lacey, 2000) have implicated a single large precipitation event and the subsequent stream response as influencing sediment transport response to harvesting activities. One such event occurred May 1-9, 2009, with measured precipitation in one 24 hour period of 14.5 cm and an eight day total of 22.9 cm. Data from the storm event increased mean TSS by 105% in the unharvested watersheds, 81% in treatment 1 watersheds, and 71% in treatment 2 watersheds. Treatment 3 watersheds had a mean increase of only 8%, which can be attributed to incomplete sampling of the storm event.

In contrast to the TSS concentration data, both harvest impacts and treatment impacts were measured in turbidity in samples collected from perennial and intermittent non-

storm sample conditions. For both monitoring locations, the impact of the harvest was statistically measured only in the treatment 1 watersheds. Neither treatment 2 nor 3 measured turbidity as statistically different from the un-harvested controls. However, significant differences were measured among the three treatments. The impact of the increased canopy retention was measured in both perennial and intermittent segments, decreasing by 26% in perennial measurements and 58% in intermittent measurements from treatment 1 (50% perennial canopy retention, 0% intermittent canopy retention) to treatment 2 (100% perennial canopy retention, 25% intermittent canopy retention). The widening of the SMZ offered an additional 51% decrease in turbidity at perennial monitoring locations and an additional 31% decrease in turbidity at intermittent monitoring locations from treatment 2 (16.8 m perennial SMZ, 7.6 m intermittent SMZ) to treatment 3 (33.5 m perennial SMZ, 16.8 m intermittent SMZ). Given that these inter-treatment changes were measured under non-storm sample conditions, the differences in turbidity may be related to increased base flow and subsequent channel erosion rather than inputs from outside the channel, such as from concentrated flow paths or runoff from skid trails or soil disturbed from tree extraction in the SMZ. Sediment from flow paths, skid trails, or soil disturbed in the SMZ would be expected to be transported during storm events.

Total suspended sediment concentrations and turbidity measurements in storm flow samples collected at perennial monitoring locations were similar; an overall harvest effect was evident in treatments 1 and 2, and treatment effects were measured among the three treatment configurations. The whole watershed treatment applied to the treatment 3 watersheds (33.5 m perennial SMZ with 100% canopy retention, 16.8 m intermittent

SMZ with 25% canopy retention, 7.6 m ephemeral SMZ with retention of channel bank trees and improved crossings) resulted in TSS concentrations and turbidity readings that were statistically similar to the un-harvested control watersheds. In conjunction with results from ephemeral channel monitoring, which measured TSS concentrations from two types of improved crossings (skidder bridges and culverts) that were statistically similar to concentrations measured in un-harvested control watersheds, it appears that limiting the connectivity of the skid trail system to the hydrologic system as well as providing a large, un-disturbed SMZ are adequate to minimize sediment concentration increases following forest harvests.

The impact of partial harvesting in perennial SMZs is difficult to discern from this data set. What is clear is that the combination of an intact SMZ and improved crossings in ephemeral channels significantly reduced TSS concentrations by 50% and turbidity by 16% relative to treatment watersheds which did not incorporate improved crossings and included 50% basal area removal in perennial SMZs. The impact of the harvest was measured for both TSS and turbidity, but the increases measured are not expected to negatively impact surface water quality.

That treatment differences are measureable in storm samples is not surprising, as precipitation events effectively link the exposed soils of the skid trail system to the hydrologic system via either ephemeral streams or overland flow through the SMZ (sediment path/concentrated sediment movement). The skid trail system effectively concentrates runoff due to reductions in infiltration relative to the intact forest floor and through interception of lateral subsurface flow at trail cuts into the hillslope. The contribution of skid trails to increased sediment following harvesting activities has been

previously observed by Gomi et al. (2006), Kreutzweiser and Capell (2001), Litschert and MacDonald (2009), and Lacey (2000), among others.

Overland flow is not believed to be an important factor in these systems even following forest harvesting, with the exception of the skid trail network influence. The harvested uplands seem to have maintained the rapid infiltration and lateral transport of storm waters. If the conveyance of storm water in the watersheds had changed from primarily lateral subsurface flow to surface runoff, the hydrograph response would be expected to quicken. No consistent change in storm response timing was measured (see Chapter 3).

The overall impact of the harvest on TSS concentration and turbidity was not expected to contribute to a decline in water quality for the harvested units or downstream areas. Mean TSS concentrations measured at perennial monitoring locations was less than five mg L^{-1} for all treatments, which is typical of forested streams (Binkley and Brown 1993). Mean non-storm TSS concentrations from intermittent and perennial monitoring locations were approximately half of annual concentrations measured in predominately agricultural (mean 13.3. mg L^{-1}), urban (mean 20.8 mg L^{-1}), and an urban-agricultural mixed watershed (mean g L^{-1}) watershed in central Kentucky, approximately 100 miles from the study site used in this study (Coulter et al. 2004). Data were also similar for annual mean TSS measured at five agricultural sites in western New York that incorporated various agricultural BMP (annual mean range: 1.5-16.7 mg L^{-1}) (Makarewicz et al. 2009).

Mean storm TSS concentrations (mean 76-555 mg L^{-1}) for harvested watersheds were similar to those measured by Keim and Schoenholz (1999) in forests in Mississippi loess

bluffs with similar SMZ and BMP configurations (mean storm TSS: 197-664 mg L^{-1}), and were similar to median storm event TSS concentrations measured by Wynn et al. (2000) in the Virginia coastal plain (99-3299 mg L^{-1}). Similar TSS concentrations were also measured in Idaho, with TSS concentrations from a 1-inch storm event resulting in 200 mg L-1 TSS for a partially harvested watershed and unharvested control watershed and 1000 mg L-1 for a 50% clearcut watershed (Karwan et al. YEAR), and in Oregon, with peak concentrations of 200-1200 mg L-1 (Paustian and Beschta 1979).

The two streams receiving water immediately downstream from the harvested watersheds, Millseat Branch and Clemons Fork were listed as not impaired in the 2010 Kentucky 303d list (Kentucky Division of Water 2010). Impairments for sediment, total dissolved solids, pathogens, conductivity and turbidity were listed for the two next downstream receiving streams (Buckhorn Creek and Troublesome Creek) with elevated sediment and turbidity attributed to abandoned minelands (Kentucky Division of Water 2010).

Analysis of nitrate and ammonium concentrations at perennial and intermittent monitoring locations measured differences only in nitrate, which has been previously reported by Wynn et al (2000), Martin et al. (1986), and Blackburn and Wood (1990). Increased nitrate concentrations are likely due to decreases in plant uptake due to upland harvesting. Wider perennial SMZs did not influence nitrate concentrations, as there was no difference among treaments 2 and 3. Wider SMZs may be more effective at trapping NO_3^- sorbed to sediments and transported as surface runoff, but are less important at removing NO_3^- in subsurface flow that dominated flows sampled with non-storm samples (Mayer et al. 2007, Phillips 1989). The retention of 100% of canopy trees in perennial

SMZs resulted in higher nitrate concentrations in treatments 2 and 3 relative to treatment 1. Canopy removal in the perennial SMZ of treatment 1 may have increased light and temperature conditions of the stream bed, which increased in-stream productivity by periphyton and assimilation of nitrate. Andrews et al. (2011) noted a similar response on a restored stream segment with open light conditions and no canopy cover. Additionally, the 50% canopy removal in perennial SMZ for treatment 1 resulted in increased light penetration to the ground surface and a flush of herbaceous understory vegetation which may have also contributed to rapid nitrate uptake in treatment 1. Nitrate concentrations measured in these watersheds post-harvest were still very low, with averages near the 0.5 mg L^{-1} threshold that approximately 70% of studies reviewed by Binkley and Brown (1993) reported. Mean concentrations were also similar to the mean streamwater concentrations of NO_3N for the United States, which were reported as 0.31 mg L^{-1}, and to mean concentrations for all hardwood forests, which were 0.46 mg L^{-1}. (NCASI 2001). A review of NO_3-N concentrations for 43 harvesting studies calculated mean unharvested NO_3-N concentrations of 0.21 mg L^{-1} and mean harvested NO_3-N concentrations of 0.44 mg L^{-1} (NCASI 2001). Similar changes were measured for this harvest, with mean pre-treatment NO_3-N concentrations of 0.10 mg L^{-1} and mean post-harvest concentrations of 0.29 mg L^{-1}. These nitrate concentrations were also similar to those measured by Kiffney et al. (2003) in British Columbia (mean pre-harvest NO_3-N concentration: approximately 0.15-0.2 mg L^{-1}, mean post-harvest concentration approximately 0.2-0.4 mg L^{-1}) and to median post-harvest NO_3-N concentrations measured in storm events in the Virginia coastal plain (0.64-0.69 mg L^{-1} for harvested watersheds, 2.5 mg L^{-1} for control watersheds) by Wynn et al. (2000). Concentrations measured both pre-and post-treatment

from this study were larger than measured in Coweeta Creek, a fifth order southern Appalachian stream (baseflow mean 0.042 mg L^{-1}) (Bolstad and Swank 1997) and in control watersheds at Coweeta (range between 0.002 and 0.018 mg L^{-1}) (Swank and Waide 1988), larger than a perennial and intermittent tallgrass prairie stream in Kansas (perennial mean NO_3-N concentration: 0.022 mg L^{-1}, intermittent mean NO_3-N concentration: 0.026 mg L^{-1}) (Tate 2008), and higher than measured in large rivers from New Jersey pine forests (concentrations less than 1 mg L^{-1}) (Zampella 1994). Nitrate-N concentrations measured in this study were lower than measured in headwater agricultural streams in Illinois during the summer (5-15 mg L^{-1} NO_3-N) (Royer et al. 2004), and in water from drainage tiles in Illinois (5-49 mg L^{-1} NO_3-N) (David et al. 1997).

Elevated concentrations of NO_3-N have the potential to cause eutrophication in surface waters and can impact aquatic biota. The impact of elevated nutrient concentrations, including NO_3-N, on forested streams is difficult to determine due to the often conflicting influence of the forest canopy and light limitation and changes in nutrient concentrations following harvest (Smith et al. 1999, Miltner and Rankin 1998). Additionally, the complexities of nutrient cycling and warmwater stream food webs make predicting the response to elevated nutrients in these systems difficult (Miltner and Rankin 1998). Dodds et al. (1998) recommended total N concentrations of 0.7 mg L^{-1} as a boundary between the categories of oligotrophic and mesotrophic streams, and a total N concentration of 1.5 mg L^{-1} as a boundary between mesotrophic and eutrophic streams. Total N concentrations of 1.4 mg L^{-1} were found to result in mean chlorophyll a levels of 100 mg m^{-2} (described as problematic) in western Montana (Dodds et al. 1997). Both the

Index of Biotic Integrity and the Invertebrate Community index were found to be negatively correlated with total inorganic nitrogen and phosphorus in streams throughout Ohio, with a total inorganic N concentrations greater than 3.61 mg L^{-1} resulting in changes in the fish community structure (Miltner et al. 1998).

The highest average annual concentration measured was for SMZ 18, and was measured in the pre-treatment phase (Figure 3-14). Increases in nitrate were similar to the 4X increase in concentration measured by Arthur et al. (1998). The largest differences in nitrate concentration seem to occur in the dormant season of 2008-2009, which may be more indicative of the timing of the harvests than a seasonal effect. Intermittent nitrate concentration trends mirrored those measured at perennial locations, with increased SMZ width having no impact, but with increased canopy retention resulting in increased nitrate concentrations.

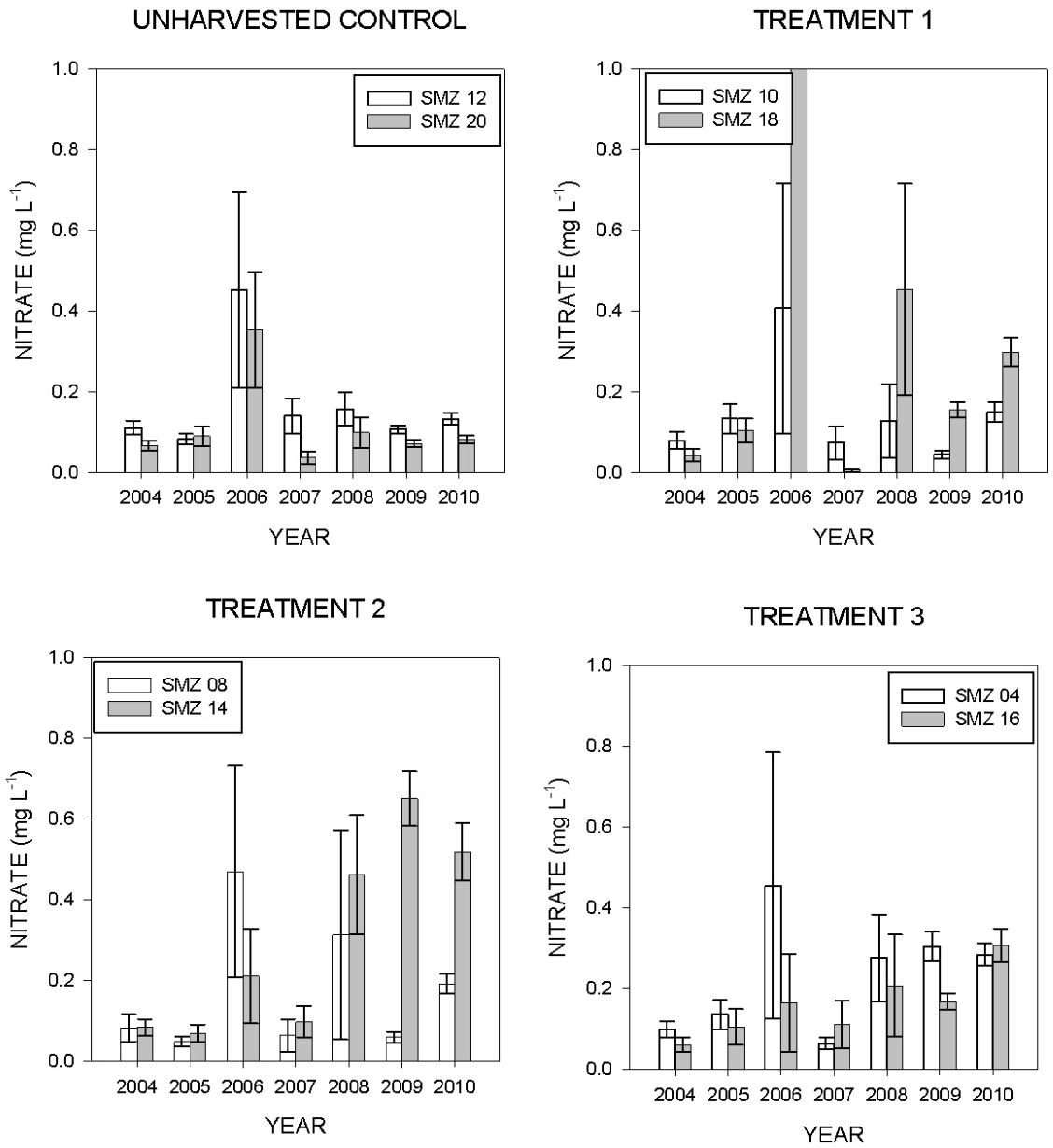

Figure 3-14: Mean annual nitrate concentrations for all watersheds grouped by treatment. Mean concentration measured in 2006 for SMZ 18 was 2.13 ± 1.02 mg L^{-1}.

Changes in dissolved oxygen concentrations were measured among the three treatments, but none were different from the unharvested control watersheds when analyzed using a protected least significant differences test. The four significant differences measured in paired watershed testing were from each of the treatments, and were approximately 1% decreases when compared to SMZ 20 and were 8-9% when compared to SMZ 12. Post-harvest dissolved oxygen concentrations were at the high end of the normal range of 5-10 mg L^{-1} reported by Binkley and Brown (1993). Dissolved oxygen concentrations also exceeded the EPA criteria of mean concentrations of 6.0 mg L^{-1} for warm water aquatic habitat (USEPA 1986). These changes in dissolved oxygen should not have a detrimental impact on aquatic biota.

Changes in EC varied based on the statistical analysis used. Treatment 1 watersheds measured a decrease in electrical conductivity relative to treatments 2 and 3 and the unharvested control watershed. Paired watershed analysis measured increases for the two treatment 2 watersheds relative to SMZ 20, but no change in any watershed relative to SMZ 12. Mean post-harvest EC (45-60 µS cm^{-1}) measured in this study was similar to levels measured in Pennsylvania (32-68 µS cm^{-1}) following a commercial clearcut with a 100 foot riparian buffer (Lynch and Corbett 1990), and to measurements in Washington state following harvest (~100-150 µS cm^{-1}) (Murray et al. 2000). Changes in EC measured in this study were not expected to negatively impact benthic macroinvertebtrates., as they are well below the 300 µS cm^{-1} level proposed by the EPA in this region for the protection of benthic macroinvertebrate species (U.S. EPA 2011).

Similarly, changes in mean daily temperatures, while significant, were small enough that they should not negatively impact sensitive aquatic or riparian species. Growing season

temperatures were more impacted than dormant season temperatures for most watersheds (Figure 3-15, Figure 3-16). Reductions measured in the SMZ 04 comparisons with the two unharvested control watersheds may be attributable to extended winter monitoring in the post-harvest period that was not within the range of temperatures measured in the pre-harvest period.

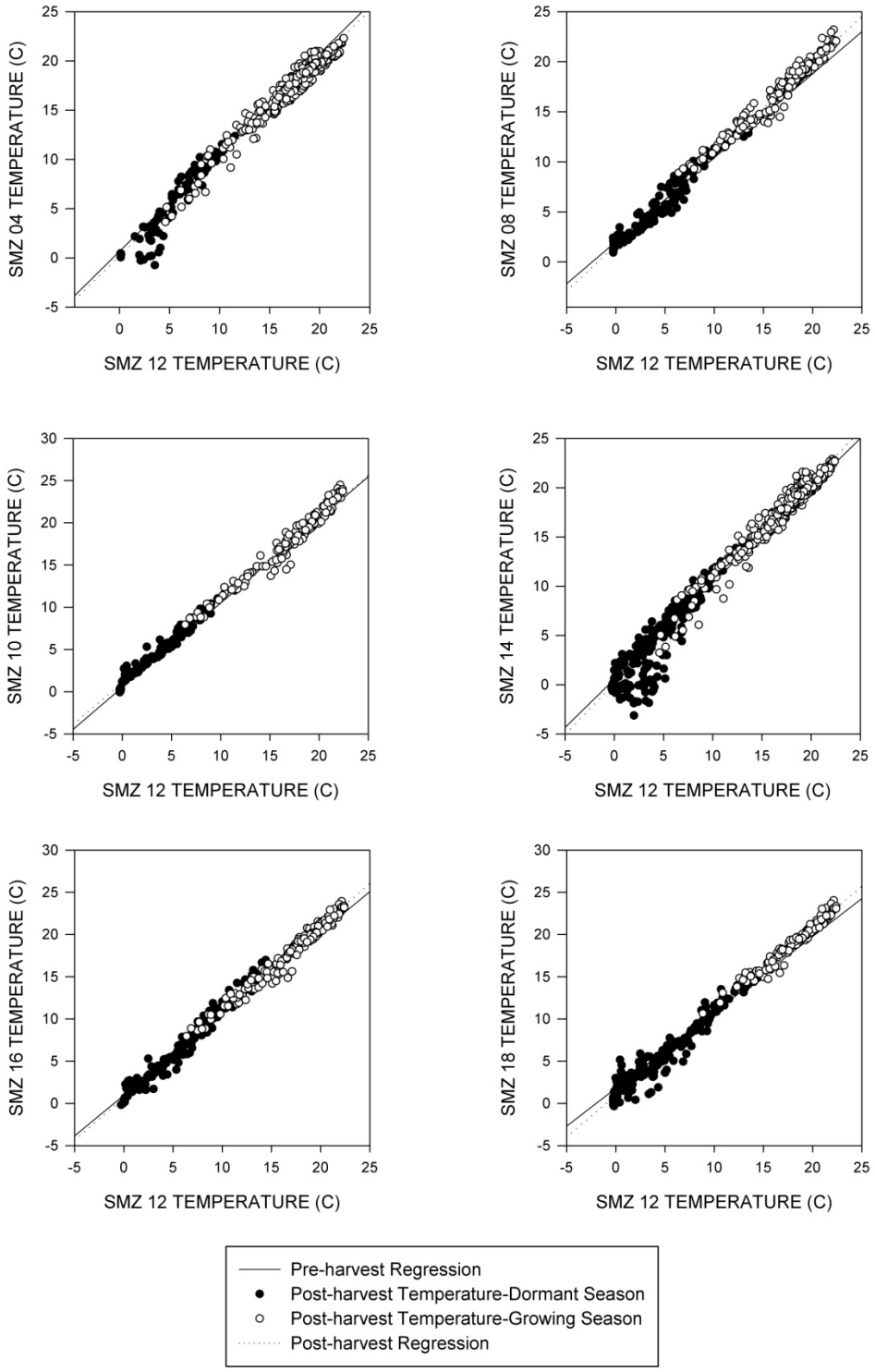

Figure 3-15: Pre-harvest regression and post-harvest regressions and temperatures separated into growing and dormant seasons. SMZ 12 was used as the un-harvested control watershed for comparison.

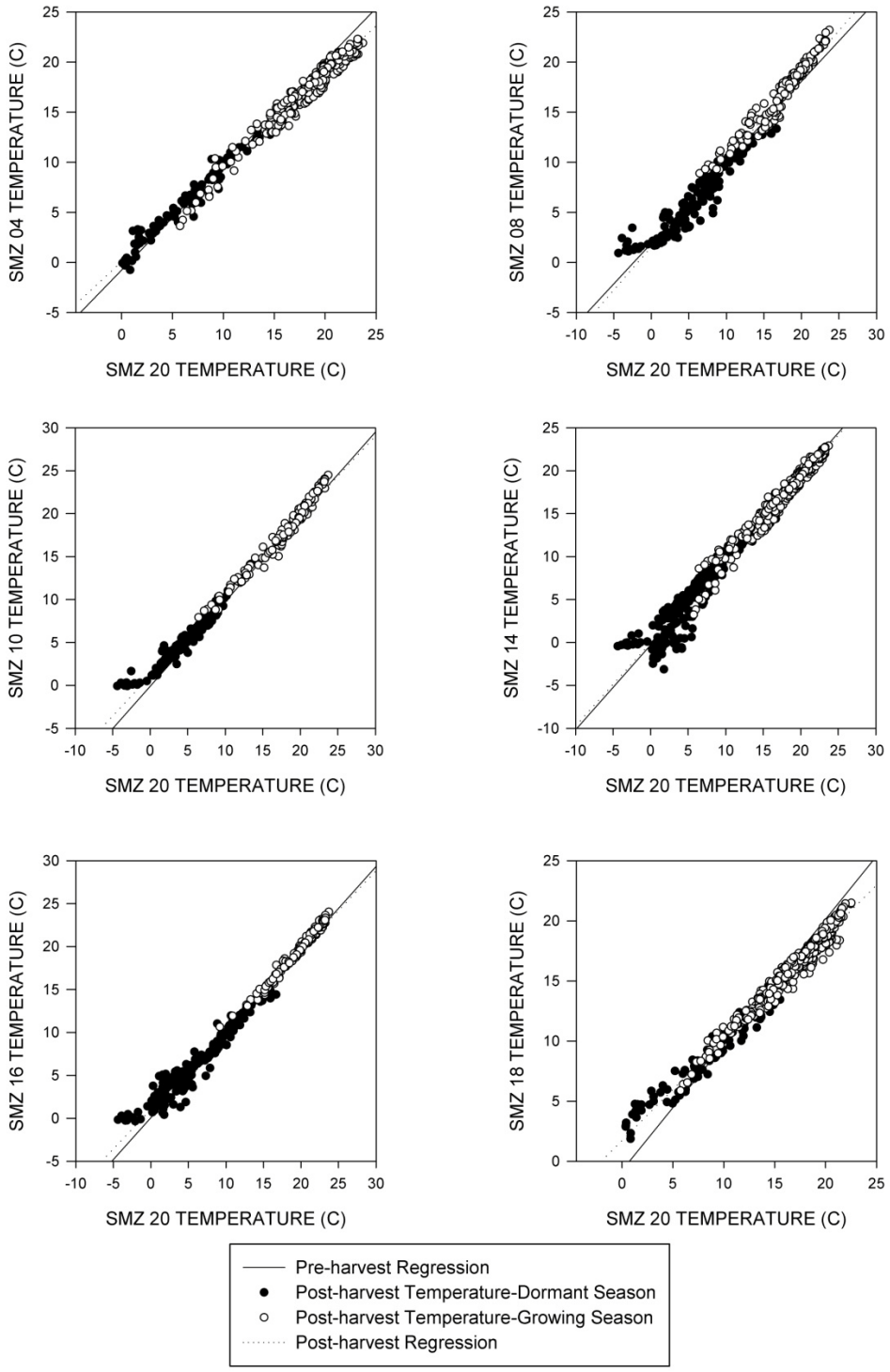

Figure 3-16: Pre-harvest regression and post-harvest regressions and temperatures separated into growing and dormant seasons. SMZ 20 was used as the un-harvested control watershed for comparison.

Conclusion

The current regulations for SMZ width and canopy retention are just as effective at maintaining non-storm sample TSS concentrations as either treatment requiring increased canopy retention or SMZ width. They are significantly less effective at mitigating increases in either TSS or turbidity from storm events than either of the other two treatments. Little statistical difference was measured between the effectiveness of treatment 2 or treatment 3. If significant differences were measured (non-storm sample turbidity for perennial and intermittent locations), the two treatment were statistically similar to the un-harvested control watersheds.

The differences between treatment 1 and treatments 2 and 3 are the use of improved crossings at ephemeral streams and increased canopy retention in perennial, intermittent, and ephemeral segments. While the exact contribution of improved crossings versus increased canopy retention to sediment reduction at the perennial outlet may not be determined from these data, the combination of minimizing the hydrologic and sediment connectivity of the skid trail system and stream network and maximizing the amount of undisturbed forest floor near streams has a definite impact of sediment transport. .

The variability inherent in TSS measurements and the complications encountered in the paired watershed comparisons have been previously reported and impacted these data as well. A common issue with under-representation of large precipitation events and subsequent stream flow and sediment transport was also encountered in this study.

The current regulations for SMZs were also as effective at minimizing nitrate increases, dissolved oxygen decreases, and temperature increases as SMZs that were either wider or had increased canopy retention.

Recommendations for changing the current Kentucky Forest Practice Guidelines for Water Quality Management should focus on minimizing the connectivity of sediment sources to the hydrologic system during storm events. Changes in non-storm sample TSS, turbidity, NO_3^-, DO, and average daily temperature were not high enough to negatively impact water quality for any treatment. Treatment 3 was able to maintain sediment levels similar to control watersheds in both base flow and storm flow conditions. The cumulative impact of improved ephemeral crossings, increased SMZ width, and increased overstory retention was water quality similar to unharvested conditions. Treatment 2 measured increases in TSS and turbidity relative to unharvested controls for storm flow conditions, and although measurably higher than treatment 3 watersheds, not statistically different from treatment 3 watersheds. The combination of improved crossings and increased canopy retention are effective at minimizing increased sediment loads resulting from harvesting activities.

Future studies may focus on the impact of improved ephemeral stream crossings and increased canopy retention individually on sediment reduction following forest harvest. Additionally, sediment source tracing examinations and long term monitoring to determine recovery periods would be useful information.

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CHAPTER 4 : IMPACT OF STREAMSIDE MANAGEMENT ZONE WIDTH AND CANOPY RETENTION ON HYDROLOGIC RESPONSE OF INTERMITTENT AND PERENNIAL STREAMS FOLLOWING FOREST HARVEST

Introduction

The impact of forest harvesting on hydrology has been studied since the first paired watershed experiment was conducted at Wagon Wheel Gap in 1909 (Bosch and Hewlett 1982). Some of the first generalizations resulting from studies of forest harvesting were that water yield increases and responses to harvesting treatments are highly variable and difficult to predict (Hibbert 1967). This chapter examines the hydrologic response of six harvested watersheds at Robinson Forest, KY with varying streamside management zone width and canopy retention.

The water budget

In its most basic form, the water budget can be expressed as:

$$= \Delta \text{Storag}\mathbf{e}$$

(Brooks et al. 2003) Each component of the water budget equation includes several sub components (Figure 4-1).

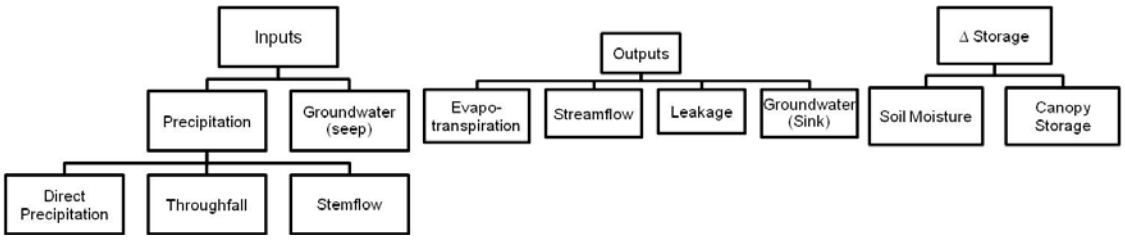

Figure 4-1: Components of the water budget.

The two major contributors to changes in the water budget resulting from forest harvests are vegetation removal and road construction (Moore and Wondzell 2005, Beschta et al. 2000, Jones 2000). Canopy removal impacts water inputs via an increase in the amount of precipitation entering as direct precipitation and decreasing the amount entering the watershed as throughfall. Vegetation removal also impacts the amount of water stored in the watershed by reducing canopy storage. Mostly, vegetation removal impacts evapotranspiration. Forest harvesting reduces the amount of water lost via transpiration, and increased sunlight following tree removal can increase the amount of water lost via evaporation. Road construction can reduce soil moisture through increased soil compaction and lower infiltration rates and increased overland flow (Ballard 2000). Measurement of streamflow following forest harvest is one way to determine the cumulative impact of these changes.

As a result of reduced evapotranspiration, annual water yield generally increases after harvest (Bosch and Hewlett 1982, Hibbert 1967). The magnitude and duration of the increase is related to the percentage of vegetation cover removed, climate and forest type (Stednick 1996; Bosch and Hewlett 1982). Small watersheds harvested in 1983 at Robinson Forest, KY showed significant increases in water yield following harvest for seven years post-harvest from a watershed harvested without BMPs and for five of seven

years post-harvest from a watershed harvested with BMPs (Arthur et al. 1998). Water yield may also vary on a seasonal basis in some climates (Hubbart et al. 2007).

Hydroperiod, or the duration of flow in a stream, may also be impacted by harvesting, particularly in the perennial to intermittent transitions and intermittent to ephemeral transitions. In these transition areas, the increased base flow could result in an upstream migration of the transition zones between perennial-intermittent and intermittent-ephemeral streams. Increases in intermittent hydroperiod have been measured in coastal watersheds following forest harvest (Keppeler 1998). Upslope migration of channel heads and a 28% increase in drainage density were observed in the same coastal watersheds after harvest (Reid et al. 2010).

Physical soil compaction in harvested areas is a common effect of ground-based harvesting operations. Soil compaction increases surface runoff via reduced infiltration (Greacen and Sands, 1980). Harvesting equipment can reduce porosity, which reduces saturated hydraulic conductivity, thereby reducing infiltration capacity (Ballard, 2000). Reduction in porosity generally involves the loss of macropores, resulting in an increase in the proportion of micropores and volumetric water content (Greacen and Sands, 1980). The reduction of macroporosity lowers hydraulic conductivity and infiltration rates (Greacen and Sands, 1980). Infiltration rate and soil bulk density changes have been found to occur after as little as one pass with equipment, and reach their maximum change in four passes (Ballard 2000, Williamson and Neilsen 2000, Lenhard 1986, Steinbrenner and Gessel 1955). The percent of harvest area impacted by these processes varies with the harvest method used. Surface runoff may occur in these compacted areas and may be concentrated in wheel tracks and move as channelized flow (Ballard 2000).

Increases in soil water content and base flows can result in more frequent landslides and increased channel erosion. Mass wasting events can increase in frequency and magnitude as a result of land use activities, including forest harvesting (MacDonald and Coe 2007). Mass wasting events following forest harvests are associated with "reduced soil strength, increased soil-water pore pressure, and altered slope configurations" (Neary et al. 2009). Following harvest, soils can reach saturation with less precipitation, which can increase landslide risk depending on soil type percent slope, and landscape position (Johnson et al. 2007). Channel erosion may occur as a result of increased flows and result in destabilized banks and loss of riparian trees via windthrow, both of which increase sediment loading (Gomi et al. 2005).

Components of the Storm Hydrograph

The storm hydrograph integrates the watershed's hydrologic response to a storm event, and includes channel interception, surface runoff, and interflow (Hewlett and Hibbert 1967). Each of these flow components and the timing associated with the delivery of water via any of the pathways can be impacted by forest harvesting (Eisenbeis et al. 2007, Hewlett and Helvey 1970). Forest removal and road construction have been shown to alter runoff response, but the specific runoff response is impacted by geographical location, road configuration, and other factors (Jones 2000). Several studies have examined changes to the storm hydrograph following forest harvesting (Table 4-1).

Table 4-1: Summary of results from studies examining the impact of forest harvest on the storm hydrograph.

Study	Location	Treatment	Parameter	Change
Hewlett and Helvey, 1970	Coweeta, NC	Complete clearcut	Storm volume	+11%*
			Peak flow	7%
			Rise time	No change
			Fall time	No change
			Storm duration	No change
Swank et al., 2001	Coweeta, NC	Commercial clearcut	Peak flow	+15%*
			Rise time	0%
			Storm volume	+10%*
			Quick flow volume	+6%*
			Storm duration	+5%*
			Fall time	+10%*
Sutardjo, 1989	Robinson Forest, KY	Complete clearcut (one year post-harvest)	Storm volume	+41%*
			Peakflow	+5%
			Storm duration	+14.7%*
			Rise time	-5.8%*
			Fall time	+35%*
		Clearcut with 15.2 m buffer and other BMPs (one year post-harvest)	Storm volume	+59%*
			Peakflow	+6.8%
			Storm duration	+11%*
			Rise time	-4.6%*
			Fall time	+18%*

Study	Location	Treatment	Parameter	Change
Wynn et al., 2000	Virginia Coastal Plain	Complete clearcut	Storm Volume	-12%*
			Peak Flow	No significant change
		Clearcut with 15.2 m SMZ and other BMPs		-21%*
				+15%*
Guillemette et al., 2005	Montmorency Forest, Quebec, Canada	85% clearcut	Lag time	Sig. slope decrease
			Rise time	NSD
			Concentration time	NSD
			Fall time	NSD
			Storm volume	NSD
			Peak flow	+36-54%*
			Quick flow	NSD
			Storm duration	Sig. slope decrease
Jones and Grant, 1996	Western Cascades, Oregon	100% clearcut, no roads 6% roads and 25% clearcut	Peak flow	Significant increase 0-22 yrs post-harvest
			Storm volume	Significant increase 0-22 yrs post-harvest
			Lag time	Significant decrease 0-10 yrs post-harvest
			Rise time	Significant increase 0-5 yrs post-harvest
			Peak flow	Significant increase 0-25 yrs post-treatment
			Storm volume	Significant increase 0-25 yrs post-treatment
			Lag time	Significant decrease 0-25 yrs post-harvest

*Significant at p = 0.05.
NSD=no significant difference

Roads may impact storage and transport by functioning as barriers, sinks, or conduits (Eisenbeis et al. 2007). The compacted surface of forest roads and skid trails could reduce infiltration and increase overland flow or funnel water more quickly to the stream through ditches and culverts (Harr et al. 1975). Cut slopes resulting from road and trail construction could also increase surface runoff by interfering with subsurface water movement downslope (Wemple et al. 1996, Harr et al. 1975). Changes in storm response may indicate modifications of conveyance and storage of water in the watershed resulting from the harvesting activities (Brooks et al. 2003). These modifications have been described by Wemple et al. (1996) as the result of expansion of the hydrologic network via the skid trail and road networks, which results in elevated quickflow volume and accelerates the timing of the stormflow response. Wemple et al. (1996) equates the hydrologic connectivity of the skid trail system to an increase in drainage density in the watershed.

Three flow components of the storm hydrograph are peak flow, quick flow volume, and total storm volume (Figure 4-2). Peak flow is primarily influenced by precipitation intensity and channel factors, while the total storm volume is influenced by the watersheds' storage capacity, which is impacted by changes in evapotranspiration (Hewlett and Helvey 1970). Both quick flow volume and total storm volume are of interest due to their influence on downstream flooding (Brooks et al. 2003). The impact of forest harvesting on peak flow has been studied in a variety of conditions and produced a variety of results (Eisenbeis et al. 2007, Moore and Wondzell 2005).

Five additional components of the storm hydrograph are concentration time, lag time, rise time, fall time, and total storm duration (Figure 4-3). Concentration time (CT) measures

the elapsed time between the end of the precipitation event and the end of the hydrologic response. Concentration time is considered the amount of time necessary for water to travel from the most remote point in the watershed to the watershed outlet. Lag time (LT) refers to the time from the beginning of the precipitation event to the start of the hydrologic response. Lag time may be impacted by harvesting activities if infiltration capacity is decreased and surface runoff increases or if the road and trail system acts as a conduit for water through the watershed (Brooks et al, 2003). Rise time (RT) is the time from the beginning of the hydrologic response to the time of peak flow, and fall time (FT) is the time from peak flow to the end of the hydrologic response. Total storm duration (TSD) is the time from the beginning to the end of the hydrologic response.

Hewlett and Helvey (1970) used the variable source area concept to describe the impact of harvesting on the timing of the storm hydrograph. They suggested that the reduction of evapotranspiration resulted in increased soil water content which favored a more rapid catchment response to precipitation. Additionally, they described an expansion of the channel network resulting from elevated soil water content contributing to increased channel interception and a quickened response, which is compounded by decreased canopy interception.

Forestry best management practices were generally designed to prevent degradation of water quality and site productivity, and do not contain specific recommendations for mitigating changes in water quantity or storm responses (Mortimer and Visser, 2004). However, many BMP recommendations may influence hydrologic changes following forest harvest. The inclusion of BMPs has been shown to impact hydrologic response of watersheds to harvesting (Foster et al. 2005, Arthur et al. 1998). Harvesting in riparian

areas can impact the hydrology of the riparian zone by altering transpiration, diurnal discharge fluctuations, and can increase low flows (Dunford and Fletcher, 1947), therefore retention of riparian trees may impact hydrologic response to upland harvesting. Recommendations for road and skid trail drainage structures include avoidance of concentrated flow on the trails that may accelerate storm response as well as recommendations for dispersed flow off the trail system to avoid concentrated flows in unharvested areas that could also impact storm response (Stringer and Perkins, 2001).

The objectives of this study were to:

1) determine the impact of forest harvest on base flow and storm response in perennial and intermittent streams

2) determine the influence of streamside management zones of varying width and canopy retention on hydrologic response to forest harvest.

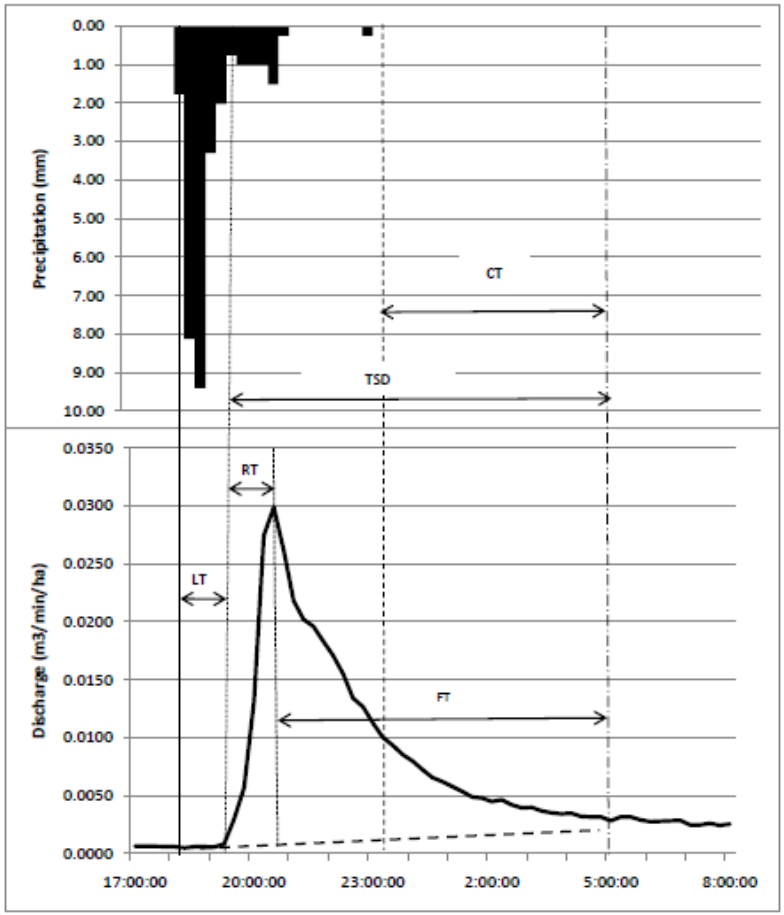

Figure 4-2: Time based components of the storm hydrograph.

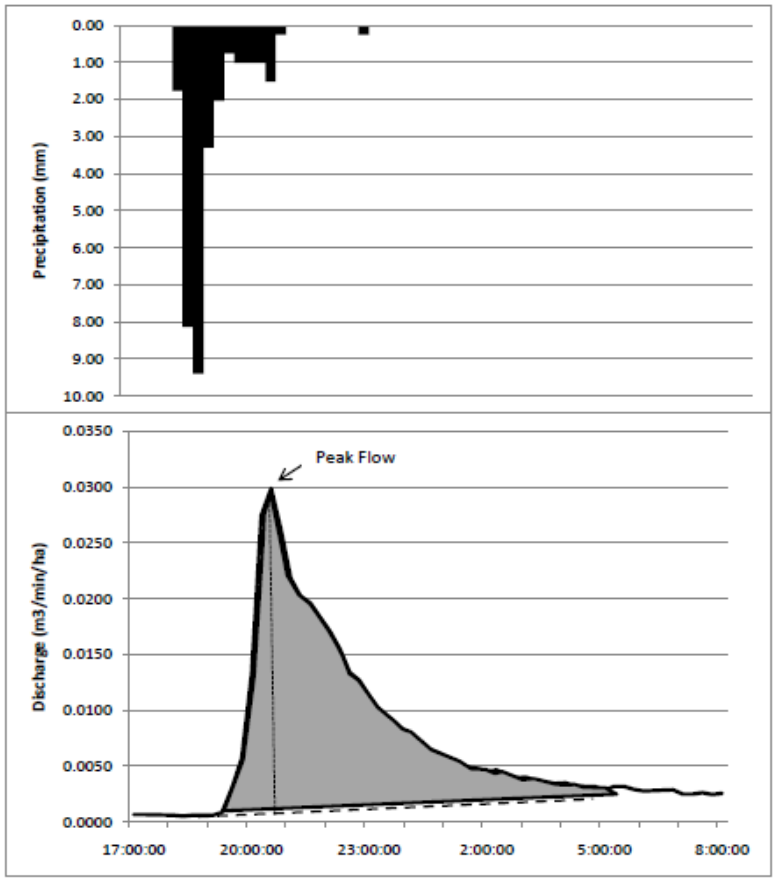

Figure 4-3: Hyetograph and hydrograph for a selected storm event. The three flow-based components are peak flow, quick flow volume (shaded area to the left of the dotted line) and total storm volume (entire shaded area).

Methods and Materials

Study Area

The study was conducted at the University of Kentucky's Robinson Forest (37º 27' north latitude and 83º 08' west longitude) which is located in the Cumberland Plateau region of southeastern Kentucky (Figure 4-4). Topographically, Robinson Forest is characterized by steep slopes with well-drained residuum or colluvial soils formed from sandstone, shale, and siltstone. The sandstone, shale, siltstone and coal are horizontally interbedded and are classified as part of the Breathitt Formation (Hinrichs 1978). The well-drained soils and geologic layers of minimal permeability result in rapid streamflow responses to storm events via sub-surface flow (Coltharp and Springer 1980). Elevations on the forest range from 268 to 475 m.

The forest was last harvested by the Mowbray-Robinson Lumber Company between 1890 and 1920 (Overstreet 1984). The regenerated forest is classified as mixed-mesophytic with oak (*Quercus sp.*), hickory (*Carya sp.)*, and yellow-poplar (*Liriodendron tulipifera*), and American beech (*Fagus grandifolia*) as dominant overstory species, with eastern hemlock (*Tsuga canadensis*) common in riparian zones.

Figure 4-4: Location of Robinson Forest and the Cumberland Plateau.

The climate of Robinson Forest is classified as temperate-humid-continental with warm summers and cool winters. The average annual precipitation for southeastern Kentucky is 116.4 cm while the 26-year average for three precipitation collectors at Robinson Forest is 117.5 cm (Cherry, 2006). Average monthly precipitation is 9.79 cm and March tends to be wetter than average and October tends to be drier.

All watersheds used in the study were located in the 1,545 ha Clemons Fork watershed. Six first-order headwater watersheds were harvested between June, 2008 and March, 2009. Watershed areas ranged from 23.7 ha to 108.7 ha at the perennial outlets (Table 4-2). Each stream was equipped with a flume and data-logger to record water level on a 15 minute interval at the perennial outlet and in an intermittent reach (Figure 4-5).

Table 4-2: Characteristics of monitored watersheds at the perennial and intermittent monitoring locations.

Watershed Name	SMZ Number	Monitoring Location	Treatment	Area (ha)	Drainage Density ($m\ m^{-2}$)	Aspect
Wet Fork	SMZ 03	Intermittent	3	32	0.0061	Southwest
	SMZ 04	Perennial		112	0.0046	
Goff Hollow	SMZ 07	Intermittent	2	31	0.0023	Northeast
	SMZ 08	Perennial		38	0.0058	
Booker Hollow	SMZ 09	Intermittent	1	27	0.0036	Northeast
	SMZ 10	Perennial		59	0.0047	
Falling Rock	SMZ 11	Intermittent	Control	25	0.0071	Northeast
	SMZ 12	Perennial		97	0.0038	
South Shelly Rock	SMZ 13	Intermittent	2	19	0.0040	East
	SMZ 14	Perennial		33	0.0045	
West Shelly Rock	SMZ 15	Intermittent	3	18	0.0106	Southeast
	SMZ 16	Perennial		72	0.0057	
North Shelly Rock	SMZ 17	Intermittent	1	16	0.0061	South
	SMZ 18	Perennial		27	0.0051	
Little Millseat	SMZ 19	Intermittent	Control	27	0.0050	Southeast
	SMZ 20	Perennial		79	0.0048	

A shelterwood with reserves harvest approach was employed that resulted in a two-aged stand with approximately 15 square feet of basal area per acre of reserve trees (approximately 10 dominant/co-dominant trees per acre). SMZs of varying size and management recommendations were deployed at perennial, intermittent and ephemeral locations within the watersheds (Table 4-3).

Skid trails were constructed within the watersheds along the contour at various intervals from the top to the bottom of the slopes. The skid trail network occupied between 6% and 12% of the total watershed area as estimated from a geo-referenced aerial photograph

using methods outlined in Goychuk et al. (2011). Equipment used in the harvest included: Timbco swing-armed feller bunchers (model 445 or 445EXL), John Deere dozers (model 650, 700, or 800) and cable or grapple skidders (John Deere models 540 and 648 and Caterpillar models 525 and 545). The feller bunchers and bull dozers were tracked machines; the skidders used air-filled rubber tires.

For all treatments, skid trails were retired following the harvest using best management practices outlined in the Kentucky Forest Practice Guidelines for Water Quality Management (Stringer and Perkins 2001) including the construction of water bars and re-vegetation of the skid trail system and landings.

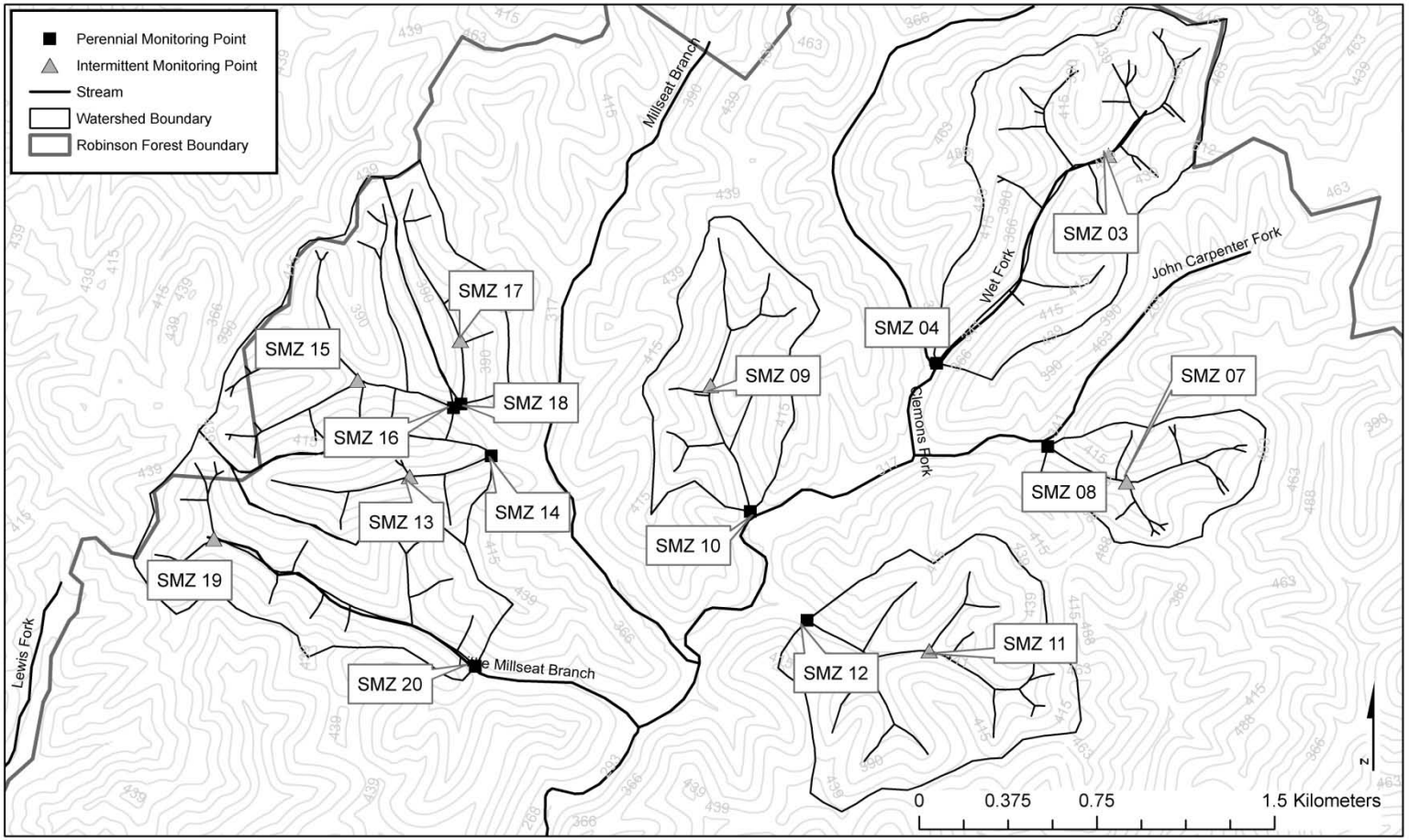

Figure 4-5: Perennial and intermittent monitoring locations in Robinson Forest.

Treatment Structure

Three treatments were applied to two watersheds each, for a total of six harvested watersheds in the study. Two additional watersheds were left un-harvested to serve as controls. The treatments included equipment limitation and overstory retention criteria for perennial, intermittent, and ephemeral stream segments (Table 4-3). Treatment 1 is based on the current Kentucky Forestry Best Management Practices requirements, and includes a 16.8 m (55 ft) perennial streamside management zone with 50% overstory retention, a 7.6 m (25 ft) intermittent equipment limiting zone with no overstory retention requirement, and no equipment limiting zone or overstory retention requirement for ephemeral streams. Treatment 2 requires a 16.8 m (55 ft) perennial streamside management zone with 100% overstory retention, a 7.6 m (25 ft) intermittent streamside management zone with 25% overstory retention, and retention of channel bank trees adjacent to ephemeral streams. Treatment 3 requires a 34 m (110 ft) wide streamside management zone with 100% retention for perennial segments, a 16.8 m (55 ft) streamside management zone with 25% overstory retention in intermittent segments, and a 7.6 m (25 ft) equipment limitation and channel bank tree retention for ephemeral streams.

Table 4-3: Treatment details for perennial, intermittent, and ephemeral streamside management zones

Treatment	Perennial SMZ		Intermittent SMZ		Ephemeral SMZ		
	Width (m)	Canopy Retention	Width (m)	Canopy Retention	Width (m)	Canopy Retention	Crossing Type
1	16.8	50%	7.6	0%	0	0%	Unimpro ved
2	16.8	100%	7.6	25%	0	Stringer*	Improved
3	33.5	100%	16.8	25%	7.6	Stringer*	Improved

*A stringer is the retention of the canopy tree nearest the stream bank on either side of the channel.

Equipment and Measurement Technique

Water level was recorded on 15 minute intervals at every perennial and intermittent monitoring location between March and December from 2004 to 2010. Data was not collected in January and February when the risk of the transducers freezing in the flumes was highest. Water level was determined using miniTROLL or Level TROLL data-logging pressure transducers (In-Situ Inc., Ft. Collins, CO). When transducers were not equipped with vented cables, data was corrected for changes in barometric pressure using barometric pressure data collected by a baroTROLL (In-Situ Inc, Ft. Collins, CO). The pressure transducers were positioned in either a 3:1 v-notch weir, H-flume, cutthroat flume, or trapezoid flume (Table 4-4). Discharge was calculated from the recorded water levels using equations specific to the weir or flume type noted in Appendix III.

Table 4-4: Flume or weir type used at each monitoring station for water level measurement.

Monitoring Location	Stream Type	Equipment Type
SMZ 03	Intermittent	Cutthroat Flume
SMZ 04	Perennial	2.5” H-Flume
SMZ 07	Intermittent	Cutthroat Flume
SMZ 08	Perennial	2” H-Flume
SMZ 09	Intermittent	Trapezoid Flume
SMZ 10	Perennial	2.5” H-Flume
SMZ 11	Intermittent	Cutthroat Flume
SMZ 12	Perennial	3:1 Weir
SMZ 13	Intermittent	Trapezoid Flume
SMZ 14	Perennial	2” H-Flume
SMZ 15	Intermittent	Trapezoid Flume
SMZ 16	Perennial	2” H-Flume
SMZ 17	Intermittent	Trapezoid Flume
SMZ 18	Perennial	2” H-Flume*
SMZ 19	Intermittent	Cutthroat Flume
SMZ 20	Perennial	3:1 Weir

*Changed to 2.5” H-flume in March, 2010.

Precipitation was measured using tipping buckets equipped with Campbell Scientific CR10X data loggers (Campbell Scientific, Logan UT). Data were recorded every 15 minutes.

Hydrograph Separation

Hydrographs were separated into the eight parameters using the straight line method described by McCuen (2005) (Table 4-5). In cases of closely-timed precipitation events when the falling limb did not straighten before interruption by another rising limb, the first event was considered over when precipitation for the second event began.

Table 4-5: Hydrograph separation parameters.

Parameter	Description
Concentration Time	Precipitation event end time – Hydrologic response end time
Lag Time	Hydrologic response start time – Precipitation event start time
Rise Time	Time of peak flow - Hydrologic response start time
Fall Time	Hydrologic response end time – Time of peak flow
Total Storm Duration	Hydrologic response end time - Hydrologic response start time
Peak Flow	Maximum discharge
Quick Flow Volume	Discharge between hydrologic response start time and peak flow
Total Storm Volume	Discharge between hydrologic response start and end times

Paired Watershed Approach and Statistical Analysis

Treatment effects were determined using analysis of covariance (ANCOVA) based on the assumptions of the paired watershed approach and linear regression analysis (U.S. Environmental Protection Agency 1997, U.S. Environmental Protection Agency 1993). Previous work determined that the basic assumptions of the paired watershed design were met prior to treatment (Cherry 2006). Data from the calibration period and treatment period were separated into one of three categories (pre-harvest, post-harvest or inter-harvest) based on the timing of the harvest and the watersheds being compared. Only data from the pre-harvest and post-harvest categories were used in the analyses.

Four assumptions must be met for linear regression to produce valid results:

1) The variables must be linearly related,
2) Data are representative,
3) Variance of the residuals is constant and independent,
4) Residuals are normally distributed,

(U.S. Environmental Protection Agency, 1997).

Data for rise time, fall time, total storm duration, peak flow, quick flow volume, and total storm volume did not meet the last two assumptions. These data were logarithmically (base 10) transformed in order to meet the assumptions. Concentration time and lag time also did not meet the assumptions, but could not be logarithmically (base 10) transformed due to measurements of zero minutes. These data had 0.1 added to all values and were then logarithmically (base 10) transformed.

Once the linear regression assumptions were met, pre-harvest analysis of variance (ANOVA), confidence intervals and difference levels were computed. Values were computed using the equations in Appendix IV and verified using the PROC REG procedure in SAS version 9.2 (SAS Institute, Cary NC) (USEPA, 1993). Following pre-harvest ANOVA calculations, post-harvest and combined ANOVA were performed.

Changes in slope and intercept were determined for each watershed pairing using ANCOVA. Values for the ANCOVA were calculated using the equations in Appendix IV and verified using the PROC GLM procedure in SAS version 9.2 (SAS Institute, Cary NC) (USEPA, 1993). Each treatment watershed was used as the independent variable and compared to each of the other watersheds for a total of 42 separate analyses. The two

control watersheds were not used as independent variables in comparison with any of the treatment watersheds but were compared to each other. The control watersheds were compared using a paired t-test approach for the perennial monitoring locations.

Percent differences were calculated from regression relationships from the original (non-transformed) data. Data from the dependent variable in the post-treatment phase was used in the pre-harvest regression relationship to predict a value for the independent variable. The mean of the predicted data was compared to the measured data mean to determine the percent change.

Results

For the perennial monitoring points, all eight locations were included in both pre-harvest and post-harvest analyses. When comparing the treatment watersheds to the two un-harvested control watersheds, only events monitored at both control watersheds were included in the analyses unless otherwise stated.

Inter-control analysis

Paired t-tests for each parameter measured at the perennial monitoring sites resulted in significant differences between the controls for peak flow ($p < 0.001$, $df = 96$), quick flow volume ($p < 0.001$, $df = 96$), and total storm volume ($p > 0.001$, $df = 96$) (Table 4-6).

Table 4-6: Mean, standard error, and p-values for paired t-test for hydrograph components measured at perennial monitoring locations. For each parameter, 97 pairs of data were analyzed.

PARAMETER	SMZ 12 - FALLING ROCK Mean (SE)	SMZ 20 - LITTLE MILLSEAT Mean (SE)	P-VALUE
Concentration Time (hr)	8.73 (0.06)	9.13 (0.06)	0.31
Lag Time (hr)	1.92 (0.03)	2.03 (0.03)	0.07
Rise Time (hr)	3.72 (0.04)	3.88 (0.04)	0.10
Fall Time (hr)	9.03 (0.06)	9.16 (0.07)	0.44
Total Storm Duration (hr)	12.75 (0.08)	13.04 (0.09)	0.95
Peak Flow (m^3 min^{-1} ha^{-1})	0.15 (0.03)	0.16 (0.04)	<0.001
Quick Flow Volume (m^3 ha^{-1})	13.33 (2.91)	14.64 (3.14)	<0.001
Total Storm Volume (m^3 ha^{-1})	52.51 (9.93)	59.89 (11.0)	<0.001

Hydrograph Separation Parameters

Overall, results of the ANCOVA for the hydrograph separations varied by parameter and which control or treatment watershed was designated the independent variable. Comparison of each treatment watershed to each of the two un-harvested control watersheds was used to determine the impact of the harvest on each of the hydrograph parameters. Comparisons of each treatment watershed to every other treatment watershed were used to determine the impact of varying SMZ width and canopy retention. Few of these comparisons resulted in statistically significant differences from pre-harvest to post harvest.

In general, the impact of the forest harvest was most obvious in the comparison of the treatment watersheds to SMZ 12. Flow-based hydrograph parameters increased, and decreases in fall time resulted in subsequent decreases in concentration time and total

storm duration. Comparisons with SMZ 20 were somewhat different. Overall the flow-based parameters increased, although the increases were not consistent for all the watersheds as was measured in comparison with SMZ 12. Also in contrast with SMZ 12 comparisons, lag time decreased overall and the remaining time-based parameters increased (Table 4-7).

Table 4-7: Mean (±SE) percent changes in hydrograph parameters for treatment watersheds compared to the two control watersheds. Watersheds whose comparisons with the control watershed resulted in a significant change at the p = 0.05 level are included for each parameter.

Control Watershed	SMZ 12		SMZ 20	
Parameter	Mean (SE)	Significant treatment watersheds	Mean (SE)	Significant treatment watersheds
Peak Flow	45.7 (3.9)	SMZ 08, SMZ 14	25.7 (4.1)	SMZ 10, SMZ 14
Quick Flow Volume	28.8 (5.3)	SMZ 08, SMZ 14	38.5 (6.9)	SMZ 10, SMZ 14, SMZ 18
Total Storm Volume	10.2 (1.3)	SMZ 08, SMZ 14	11.5 (4.0)	SMZ 08, SMZ 14
Concentration Time	-12.8 (2.0)	SMZ 18	10 (2.7)	SMZ 16
Lag Time	5.2 (1.3)	--	-5.0 (2.4)	SMZ 16, SMZ 18
Rise Time	-5.5 (1.3)	--	17.5 (2.3)	SMZ 18
Fall Time	-10.5 (1.5)	SMZ 18	12 (2.8)	--
Total Storm Duration	-9.0 (1.3)	SMZ 18	15.2 (2.7)	SMZ 10

Comparisons with SMZ 12 (Falling Rock)

The most consistent results were measured when SMZ 12 was designated the un-harvested control watershed and used as the dependent variable in ANCOVA comparisons with the six treatment watersheds. The same two watershed comparisons were significantly different for peak flow, quick flow volume, and total storm volume (Table 4-8, Table 4-9, Table 4-10).

Table 4-8: ANCOVA results for peak flow measured at perennial monitoring locations using SMZ 12 as the un-harvested control for comparison.

Parameter:Peakflow								
Dependent Variable: SMZ 12 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.76	0.57	-0.78	0.36	0.57	69%
	Post-harvest	26	0.90		-0.40		0.65	
SMZ 08	Pre-harvest	31	1.18	0.28	0.07	**0.0005**	0.87	70%
	Post-harvest	19	1.04		0.21		0.89	
SMZ 10	Pre-harvest	52	1.00	0.92	-0.24	0.16	0.88	8%
	Post-harvest	15	1.02		-0.11		0.92	
SMZ 14	Pre-harvest	33	0.90	**0.01**	-0.21	**0.0003**	0.91	33%
	Post-harvest	32	0.67		-0.31		0.78	
SMZ 16	Pre-harvest	34	0.60	0.29	-0.55	0.33	0.70	43%
	Post-harvest	24	0.72		-0.28		0.77	
SMZ 18	Pre-harvest	48	0.84	0.77	-0.12	0.14	0.85	51%
	Post-harvest	10	0.79		-0.02		0.64	

Table 4-9: ANCOVA results for quick flow volume measured at perennial monitoring locations using SMZ 12 as the un-harvested control for comparison.

Parameter:Quickflow								
Dependent Variable: SMZ 12 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.96	0.95	-0.39	0.59	0.64	52%
	Post-harvest	26	0.94		-0.29		0.58	
SMZ 08	Pre-harvest	31	1.14	**0.01**	-0.30	0.09	0.89	-5%
	Post-harvest	19	0.74		0.13		0.77	
SMZ 10	Pre-harvest	52	1.03	0.51	-0.28	0.15	0.89	27%
	Post-harvest	15	1.11		-0.18		0.88	
SMZ 14	Pre-harvest	33	1.04	**0.004**	-0.20	**0.01**	0.91	4%
	Post-harvest	32	0.73		0.14		0.72	
SMZ 16	Pre-harvest	34	0.70	0.69	0.13	0.45	0.72	15%
	Post-harvest	24	0.75		0.19		0.78	
SMZ 18	Pre-harvest	48	1.00	0.62	-0.03	0.13	0.88	80%
	Post-harvest	10	0.92		0.21		0.73	

Table 4-10: ANCOVA results for total storm volume measured at perennial monitoring locations using SMZ 12 as the un-harvested control watershed for comparison.

Parameter:Total Storm Volume								
Dependent Variable: SMZ 12 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.99	0.68	-0.39	0.43	0.70	17%
	Post-harvest	26	0.89		-0.19		0.62	
SMZ 08	Pre-harvest	31	1.18	**0.01**	-0.40	**0.001**	0.93	18%
	Post-harvest	19	0.90		0.22		0.88	
SMZ 10	Pre-harvest	52	1.09	0.69	-0.37	0.052	0.90	8%
	Post-harvest	15	1.05		-0.17		0.93	
SMZ 14	Pre-harvest	33	1.03	**0.002**	-0.24	**0.005**	0.92	15%
	Post-harvest	32	0.71		0.32		0.77	
SMZ 16	Pre-harvest	34	0.68	0.43	0.42	0.92	0.75	1%
	Post-harvest	24	0.78		0.32		0.75	
SMZ 18	Pre-harvest	48	0.88	0.97	0.21	0.75	0.91	2%
	Post-harvest	10	0.88		0.18		0.76	

Overall, comparisons with SMZ 12 measured consistent increases in the three flow based hydrograph parameters following harvest (Figure 4-6, Figure 4-7, Figure 4-8).

Based on figure 3.7, the decrease in quick flow volume observed between SMZ 08 and SMZ 12 is due to the two largest events measured post-harvest that were below the pre-harvest regression line exerting influence on the percent difference calculations. If the data are analyzed without the two large events, the relationship is still significant at the p = 0.05 level and the percent change in rise time is 44%.

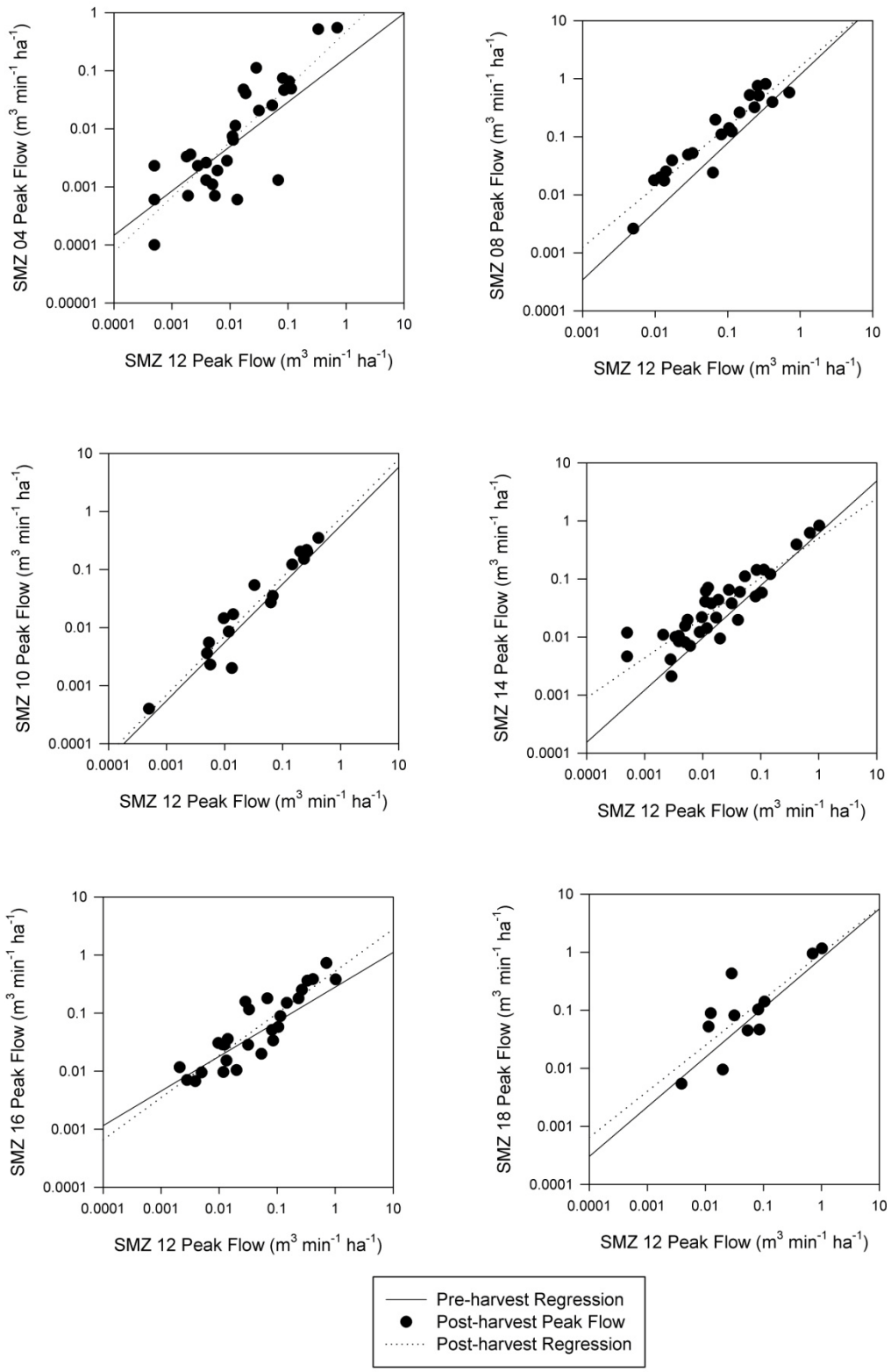

Figure 4-6: Pre-harvest regression, post-harvest peak flow and post-harvest regression for peak flow measured at each treatment watershed and compared to SMZ 12.

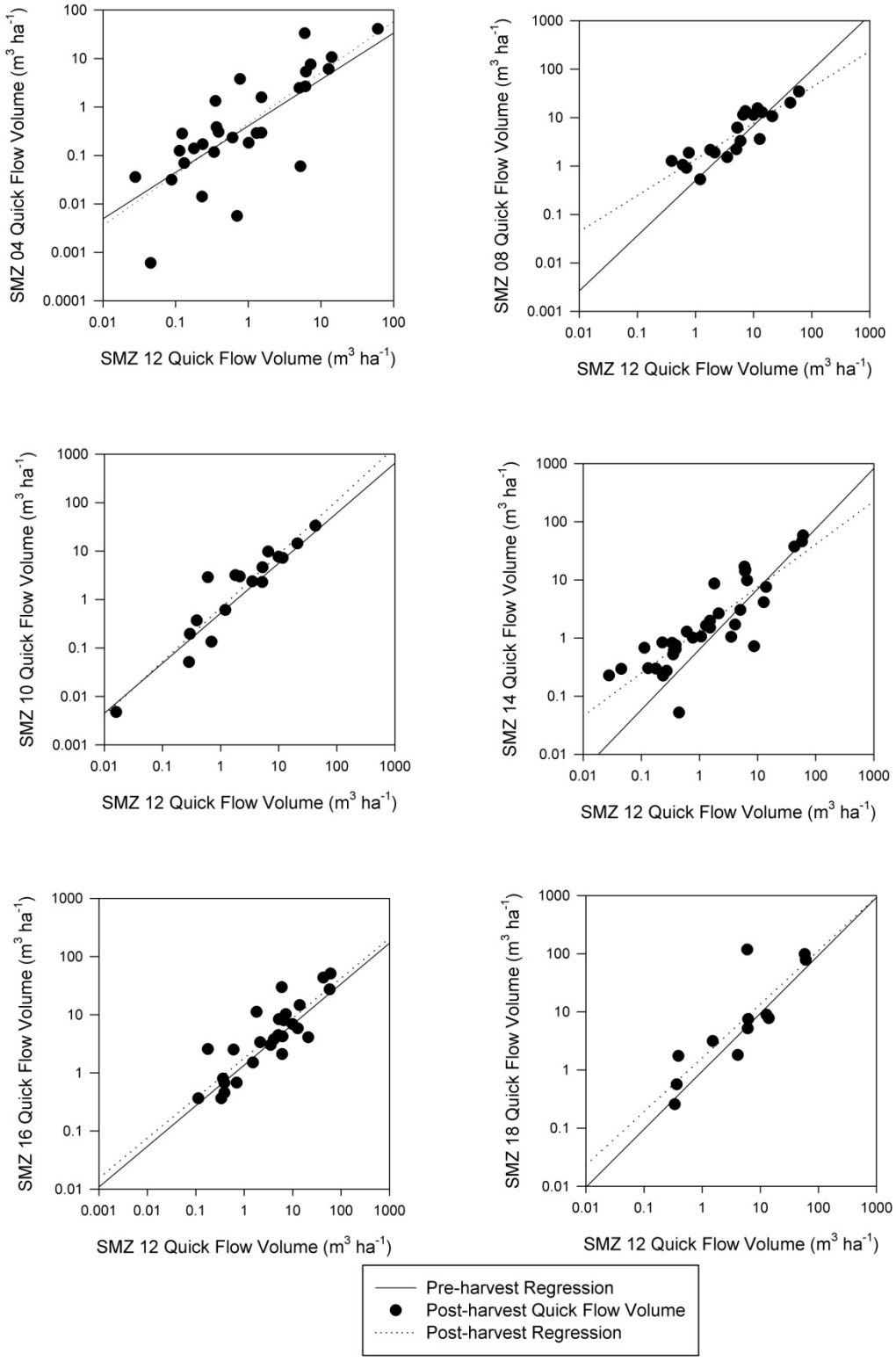

Figure 4-7: Pre-harvest regression, post-harvest quick flow volume and post-harvest regression for quick flow volume measured at each treatment watershed and compared to SMZ 12.

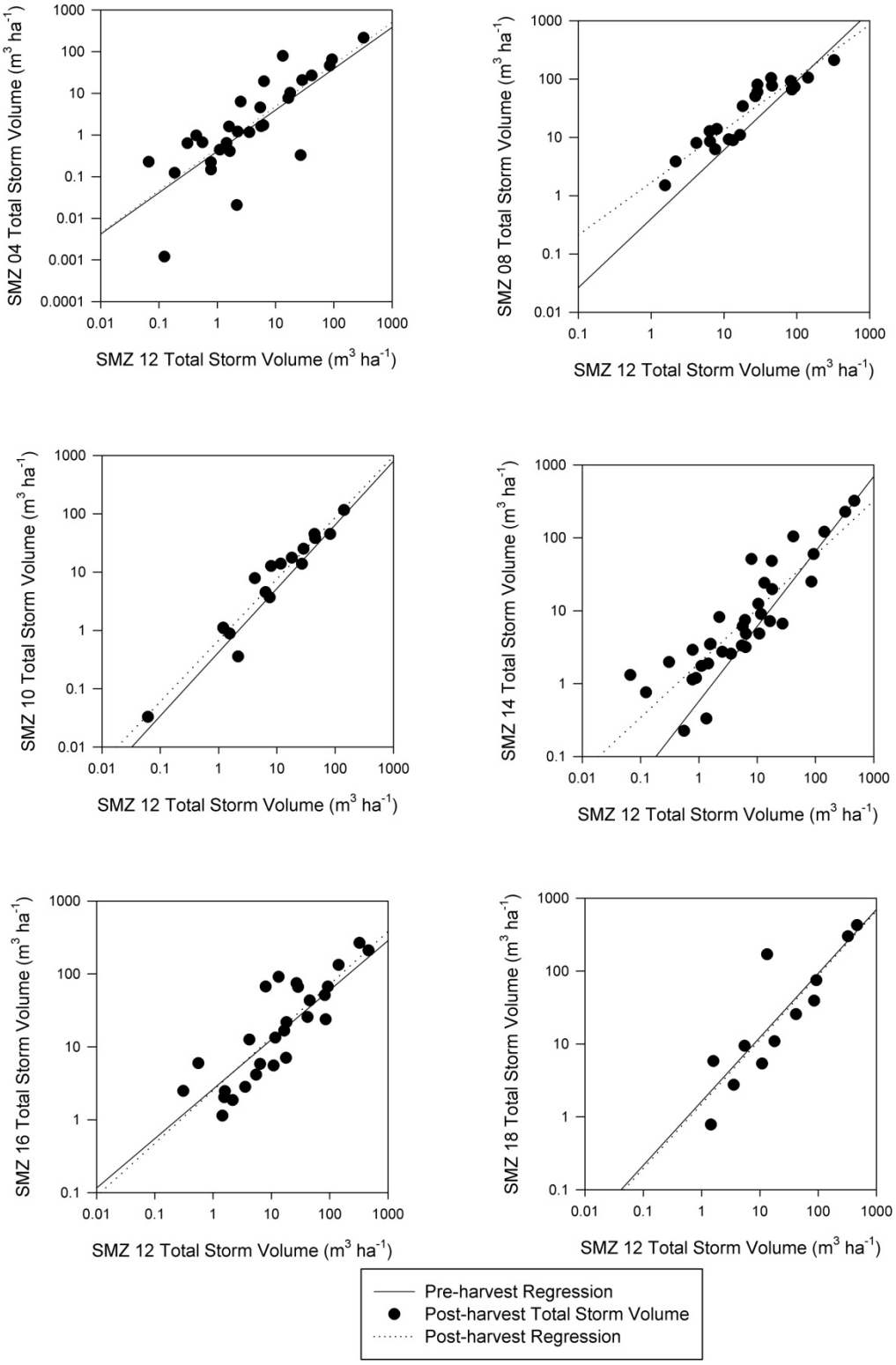

Figure 4-8: Pre-harvest regression, post-harvest total storm volume and post-harvest regression for total storm volume measured at each treatment watershed and compared to SMZ 12.

Analysis of time-based hydrograph parameters using SMZ 12 as the un-harvested control measured significant changes in concentration time, fall time, and total storm duration for the SMZ 18-SMZ 12 relationship. No other significant changes were measured.

Concentration time decreased for each treatment watershed when compared to SMZ 12. Decreases ranged from 2% to 36% with a mean of approximately 13%, or 56 minutes (Table 4-11). Only the SMZ 18-SMZ 12 relationship was significantly different from pre-harvest to post-harvest (slope p-value = 0.67, intercept p-value = 0.0001, df = 58).

Table 4-11: ANCOVA results for concentration time measured at perennial monitoring locations using SMZ 12 as the un-harvested control watershed.

Parameter:Concentration Time								
Dependent Variable: SMZ 12 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.80	0.80	0.19	0.26	0.60	-12%
	Post-harvest	26	0.87		0.03		0.50	
SMZ 08	Pre-harvest	31	0.68	0.52	0.26	0.65	0.30	-12%
	Post-harvest	19	0.82		0.10		0.75	
SMZ 10	Pre-harvest	52	0.87	0.41	0.10	0.76	0.69	-2%
	Post-harvest	15	1.00		-0.02		0.84	
SMZ 14	Pre-harvest	33	0.97	0.40	-0.08	0.06	0.60	-9%
	Post-harvest	32	0.79		-0.01		0.47	
SMZ 16	Pre-harvest	34	0.93	0.29	0.06	0.20	0.66	-6%
	Post-harvest	24	0.71		0.18		0.48	
SMZ 18	Pre-harvest	48	0.82	0.67	0.12	**0.0001**	0.70	-36%
	Post-harvest	10	0.74		-0.02		0.43	

No significant changes were measured for rise time when SMZ 12 was designated the un-harvested control watershed (Table 4-12). Rise time decreased for five of the six treatment watersheds by a mean of 5% or 13 minutes, which is less than the 15 minute sampling interval used in this study. Similarly, the mean increase measured between SMZ 10 and SMZ 12 (8.5 minutes) was less than the sampling interval.

Table 4-12: ANCOVA results for rise time measured at perennial monitoring locations using SMZ 12 as the un-harvested control watershed.

Parameter:Rise Time								
Dependent Variable: SMZ 12 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.73	0.53	0.12	0.45	0.58	-8%
	Post-harvest	26	0.84		0.03		0.72	
SMZ 08	Pre-harvest	31	0.78	0.73	0.06	0.26	0.53	-2%
	Post-harvest	19	0.86		-0.06		0.55	
SMZ 10	Pre-harvest	52	0.96	0.33	0.00	0.97	0.84	5%
	Post-harvest	15	1.11		-0.05		0.74	
SMZ 14	Pre-harvest	33	1.11	0.53	-0.14	0.21	0.83	-15%
	Post-harvest	32	1.01		-0.16		0.65	
SMZ 16	Pre-harvest	34	0.88	0.26	0.06	0.20	0.61	-12%
	Post-harvest	24	1.09		-0.10		0.79	
SMZ 18	Pre-harvest	48	1.03	0.58	-0.15	0.70	0.66	-1%
	Post-harvest	10	1.21		-0.21		0.81	

Fall time decreased in each comparison of treatment watersheds to SMZ 12 (Table 4-13). The SMZ 18-SMZ 12 comparison was the only significant change (slope p-value = 0.45, intercept p-value = 0.001, df = 58). Mean fall time decrease was 11% or 51 minutes.

Table 4-13: ANCOVA results for fall time measured at perennial monitoring locations using SMZ 12 as the un-harvested control watershed.

Parameter:Fall Time								
Dependent Variable: SMZ 12 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.81	0.35	0.17	0.56	0.63	-7%
	Post-harvest	26	0.97		-0.01		0.77	
SMZ 08	Pre-harvest	31	0.66	0.40	0.31	0.14	0.39	-19%
	Post-harvest	19	0.83		0.07		0.77	
SMZ 10	Pre-harvest	52	0.86	0.20	0.11	0.38	0.63	-7%
	Post-harvest	15	1.09		-0.11		0.88	
SMZ 14	Pre-harvest	33	0.98	0.53	-0.09	0.36	0.68	0%
	Post-harvest	32	0.85		-0.02		0.46	
SMZ 16	Pre-harvest	33	0.87	0.94	0.11	0.15	0.68	-6%
	Post-harvest	24	0.89		0.03		0.62	
SMZ 18	Pre-harvest	48	0.73	0.45	0.23	**0.001**	0.63	-24%
	Post-harvest	10	0.89		-0.13		0.50	

No significant change was measured for lag time for any of the treatment watersheds when compared with SMZ 12 (Table 4-14). Increases and decreases were measured for lag time. Mean change in lag time was 7% or approximately 12 minutes.

Table 4-14: ANCOVA results for lag time measured at perennial monitoring locations using SMZ 12 as the un-harvested control.

Parameter:Lag Time								
Dependent Variable: SMZ 12 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.59	0.28	-0.02	0.96	0.29	12%
	Post-harvest	26	0.88		0.01		0.66	
SMZ 08	Pre-harvest	31	0.78	0.72	0.17	0.52	0.49	-5%
	Post-harvest	19	0.71		0.23		0.79	
SMZ 10	Pre-harvest	52	0.96	0.76	-0.01	0.24	0.83	3%
	Post-harvest	15	0.92		0.07		0.91	
SMZ 14	Pre-harvest	33	0.82	0.25	0.03	0.25	0.68	3%
	Post-harvest	32	0.97		-0.05		0.82	
SMZ 16	Pre-harvest	34	0.83	0.56	-0.07	0.71	0.67	16%
	Post-harvest	24	0.92		-0.03		0.73	
SMZ 18	Pre-harvest	48	0.73	0.67	0.09	0.13	0.58	2%
	Post-harvest	10	0.81		-0.10		0.56	

Similar to fall time and concentration time, a significant decrease in total storm duration was measured in the SMZ 12-SMZ 18 relationship (slope p-value = 0.51, intercept p-value = 0.004, df = 58). For the remaining five comparisons, four measured decreases and one measured no change (Table 4-15). The overall mean change in total storm duration was 9% or approximately 60 minutes.

Table 4-15: ANCOVA results for total storm duration measured at perennial monitoring locations using SMZ 12 as the un-harvested control.

Parameter:Total Storm Duration								
Dependent Variable: SMZ 12 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.93	0.61	0.06	0.40	0.78	-7%
	Post-harvest	26	1.01		-0.04		0.84	
SMZ 08	Pre-harvest	31	0.80	0.75	0.19	0.30	0.50	-14%
	Post-harvest	19	0.86		0.08		0.84	
SMZ 10	Pre-harvest	52	0.94	0.35	0.06	0.70	0.78	0%
	Post-harvest	15	1.07		-0.08		0.92	
SMZ 14	Pre-harvest	33	1.18	0.26	-0.30	0.33	0.79	-5%
	Post-harvest	32	0.97		-0.11		0.55	
SMZ 16	Pre-harvest	34	1.04	0.53	-0.05	0.21	0.83	-6%
	Post-harvest	24	0.95		-0.01		0.69	
SMZ 18	Pre-harvest	48	0.90	0.51	0.08	**0.004**	0.75	-22%
	Post-harvest	10	1.03		-0.22		0.62	

Based on the comparison with SMZ 12, the impact of the harvest seems to be an increase in flow combined with a decrease in response duration.

Comparisons with SMZ 20 (Little Millseat)

Results of the ANCOVA when SMZ 20 was the designated un-harvested control watershed and used as the dependent variable were less consistent than when the treatment watersheds were compared to SMZ 12. Of the 48 total comparisons made (6 treatment watersheds and 8 parameters) 12 were significantly changed. Six of the 12 involved one of the treatment 1 watersheds. Relative increases or decreases calculated were inconsistent among watersheds for each parameter and were also inconsistent for within single watersheds across parameters.

Changes in peak flow measured between the treatment watersheds ranged from a decrease of 7% to an increase of 56% (Figure4-9) (Table 4-16). Mean change was 28%. A significant decrease was measured in the SMZ 10-SMZ 20 relationship (slope p-value

= 0.01, intercept p-value = 0.002, df = 67), and a significant increase was measured in the SMZ 14-SMZ 20 relationship (slope p-value = 0.21, intercept p-value = 0.04, df = 65).

Results of comparisons between SMZ 10 and SMZ 20 were impacted by multiple instances of flow measurements in SMZ 20 much higher than those measured in SMZ 10 or in SMZ 12. These data impacted both the significance and magnitude of differences from pre-harvest to post-harvest. The large flow measurements in SMZ 20 peak flow relative to SMZ 10 peak flow resulted in an increase of the average measured peak flow that was used in the percent difference calculations, and resulted in the negative peak flow change, in contrast to the other five watershed comparisons. Exclusion of these points resulted in a 4% increase in peak flow from pre-harvest to post harvest that was not significant in the SMZ 10-SMZ 20 comparison.

Table 4-16: ANCOVA results for peak flow measured at perennial monitoring locations using SMZ 20 as the un-harvested control for comparison.

Parameter:Peak Flow								
Dependent Variable: SMZ 20 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	1.06	0.45	-0.38	0.97	0.74	56%
	Post-harvest	26	1.27		-0.04		0.69	
SMZ 08	Pre-harvest	31	1.31	0.25	0.20	0.13	0.78	42%
	Post-harvest	19	1.07		0.11		0.69	
SMZ 10	Pre-harvest	52	1.13	**0.02**	-0.16	**0.04**	0.89	-7%
	Post-harvest	15	1.52		0.11		0.65	
SMZ 14	Pre-harvest	33	1.06	0.21	-0.05	**0.04**	0.89	1%
	Post-harvest	32	0.94		-0.10		0.84	
SMZ 16	Pre-harvest	34	0.91	0.93	-0.21	0.90	0.85	22%
	Post-harvest	24	0.92		-0.19		0.77	
SMZ 18	Pre-harvest	48	1.02	0.73	0.01	0.29	0.88	40%
	Post-harvest	10	0.97		0.05		0.97	

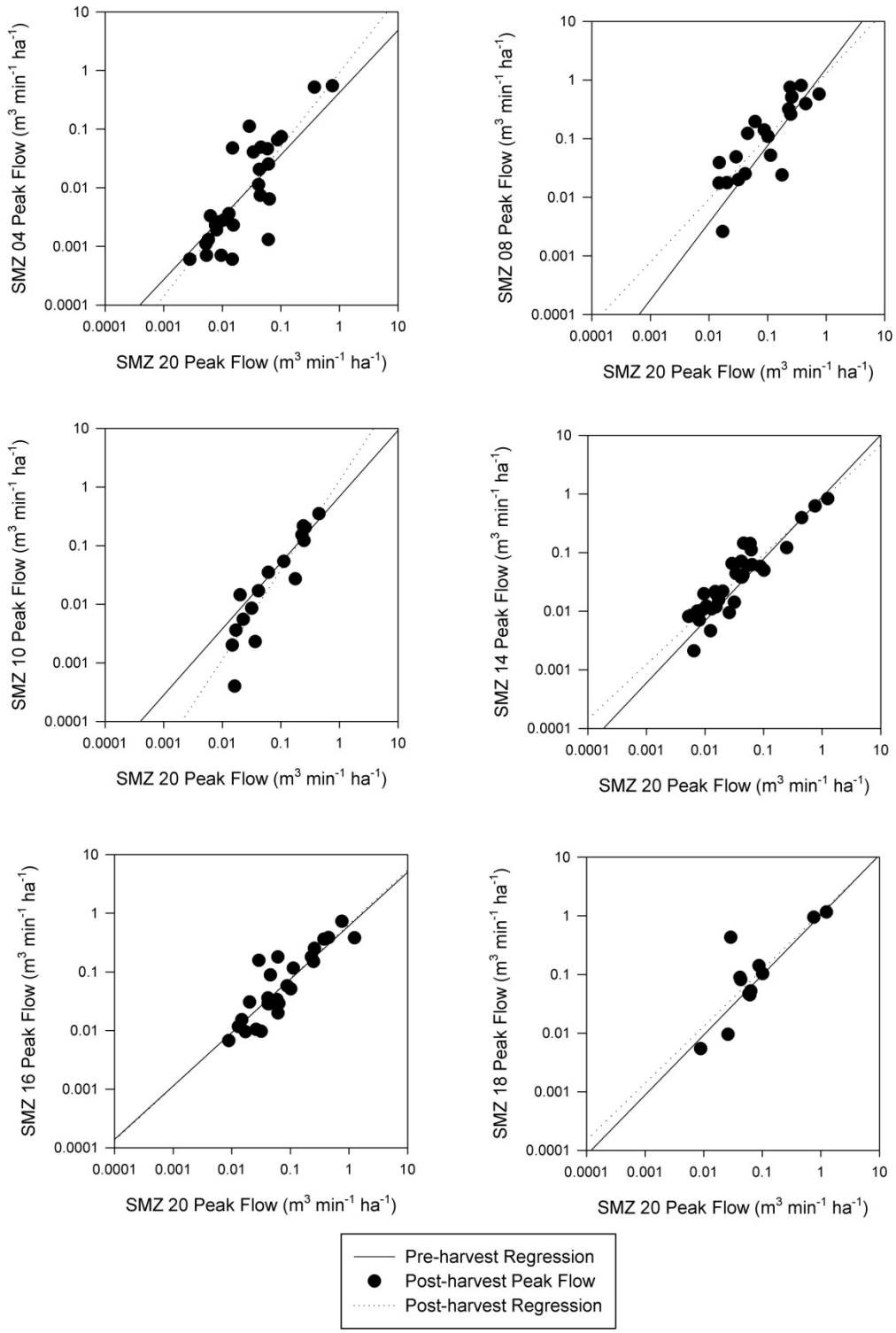

Figure 4-9: Pre-harvest regression, post-harvest peak flow and post-harvest regression for peak flow measured at each treatment watershed and compared to SMZ 20.

Similar to peak flow, changes in quick flow volume measured both increases and decreases. Comparisons of both treatment 1 watersheds resulted in significant changes in quick flow volume (SMZ 10-SMZ 20: slope p-value = 0.006, intercept p-value = 0.70, df = 67; SMZ 18-SMZ 20: slope p-value = 0.66, intercept p-value = 0.03, df = 58). Also similar to peak flow, an increase of was measured from pre-harvest to post-harvest in the SMZ 14-SMZ 20 comparison (slope p-value = 0.26, intercept p-value = 0.02, df = 65). Percent change ranged from a 1% decrease to an 96% increase (Table 4-17, Figure 4-10).

Table 4-17: ANCOVA results for quick flow volume measured at perennial monitoring locations using SMZ 20 as the un-harvested control for comparison.

Parameter:Quick Flow Volume								
Dependent Variable: SMZ 20 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	1.29	0.78	-0.79	0.72	0.71	96%
	Post-harvest	26	1.18		-0.68		0.48	
SMZ 08	Pre-harvest	31	1.25	0.25	-0.53	0.10	0.83	-1%
	Post-harvest	19	1.01		-0.16		0.73	
SMZ 10	Pre-harvest	52	1.19	**0.006**	-0.58	0.70	0.84	38%
	Post-harvest	15	2.04		-1.19		0.68	
SMZ 14	Pre-harvest	33	1.25	0.26	-0.52	**0.02**	0.88	2%
	Post-harvest	32	1.10		-0.23		0.77	
SMZ 16	Pre-harvest	34	0.98	0.93	-0.22	0.23	0.82	14%
	Post-harvest	24	0.996		-0.11		0.70	
SMZ 18	Pre-harvest	48	1.20	0.66	-0.40	**0.03**	0.84	82%
	Post-harvest	10	1.11		-0.05		0.74	

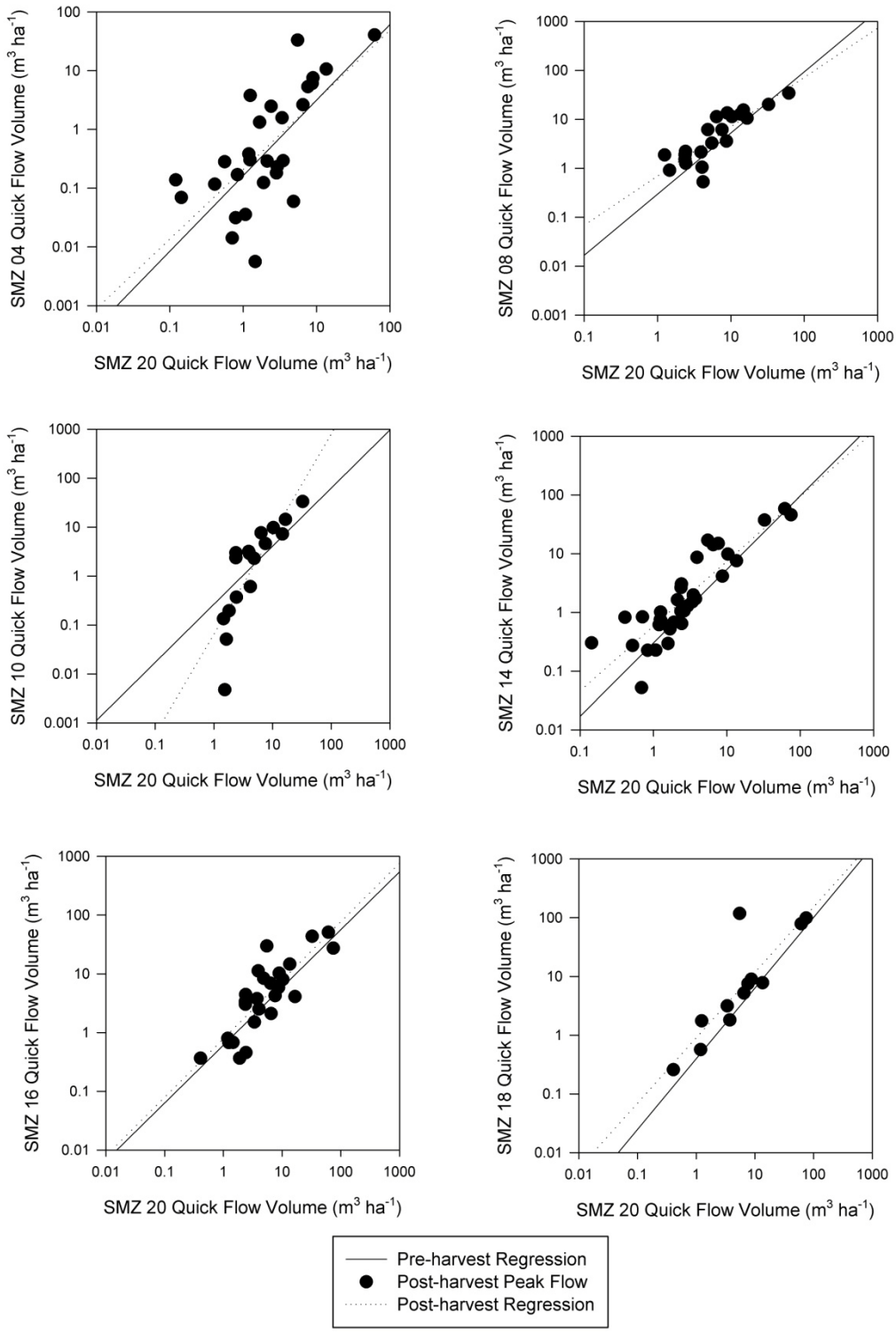

Figure 4-10: Pre-harvest regression, post-harvest quick flow volume and post-harvest regression for quick flow volume measured at each treatment watershed and compared to SMZ 20.

The same issues with SMZ 20 measurements higher that SMZ 10 and SMZ 12 measurements in the peak flow data were also evident in the quick flow volume comparisons of SMZ 10 and SMZ 20. Exclusion of these events results in a 43% increase from pre-harvest to post-harvest that is not statistically significant.

Similar to the relationship between SMZ 12 and SMZ 08 for quick flow volume, the measured decrease in quick flow volume in the SMZ 08-SMZ 20 relationship is influenced by the largest post-harvest magnitude event measuring below the pre-harvest regression line. If the data are analyzed without the largest event, the relationship remains non-significant but measures a 16% increase in quick flow volume.

Significant change in total storm volume was measured from pre-harvest to post-harvest in both treatment 2 watersheds (SMZ 08-SMZ 20 slope p-value = 0.03, intercept p-value = 0.004, df = 50; SMZ 14-SMZ 20 slope p-value = 0.20, intercept p-value = 0.01, df = 65). Measured differences ranged from a decrease of 5% to an increase of 59% (Table 4-18, Figure 4-11).

Table 4-18: ANCOVA results for total storm volume measured at perennial monitoring locations using SMZ 20 as the un-harvested control watershed for comparison.

Parameter:Total Storm Volume								
Dependent Variable: SMZ 20 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	1.12	0.49	-0.70	0.95	0.73	59%
	Post-harvest	26	1.34		-0.89		0.58	
SMZ 08	Pre-harvest	31	1.26	**0.03**	-0.61	**0.004**	0.84	15%
	Post-harvest	19	0.88		0.23		0.76	
SMZ 10	Pre-harvest	52	1.21	0.24	-0.66	0.67	0.89	-2%
	Post-harvest	15	1.43		-0.88		0.73	
SMZ 14	Pre-harvest	33	1.18	0.20	-0.54	**0.01**	0.90	1%
	Post-harvest	32	1.03		-0.16		0.81	
SMZ 16	Pre-harvest	34	0.98	0.62	0.92	0.21	0.84	-5%
	Post-harvest	24	-0.12		0.08		0.72	
SMZ 18	Pre-harvest	48	1.08	0.44	0.98	0.39	0.91	1%
	Post-harvest	10	-0.24		-0.02		0.76	

Measurements in the SMZ 10-SMZ 20 relationship with SMZ 20 discharges higher than the SMZ 10 and SMZ 12 measurements resulted in a negative percent change for total storm volume. When these measurements were not included in the analysis, a non-significant 3% increase resulted from pre-harvest to post-harvest.

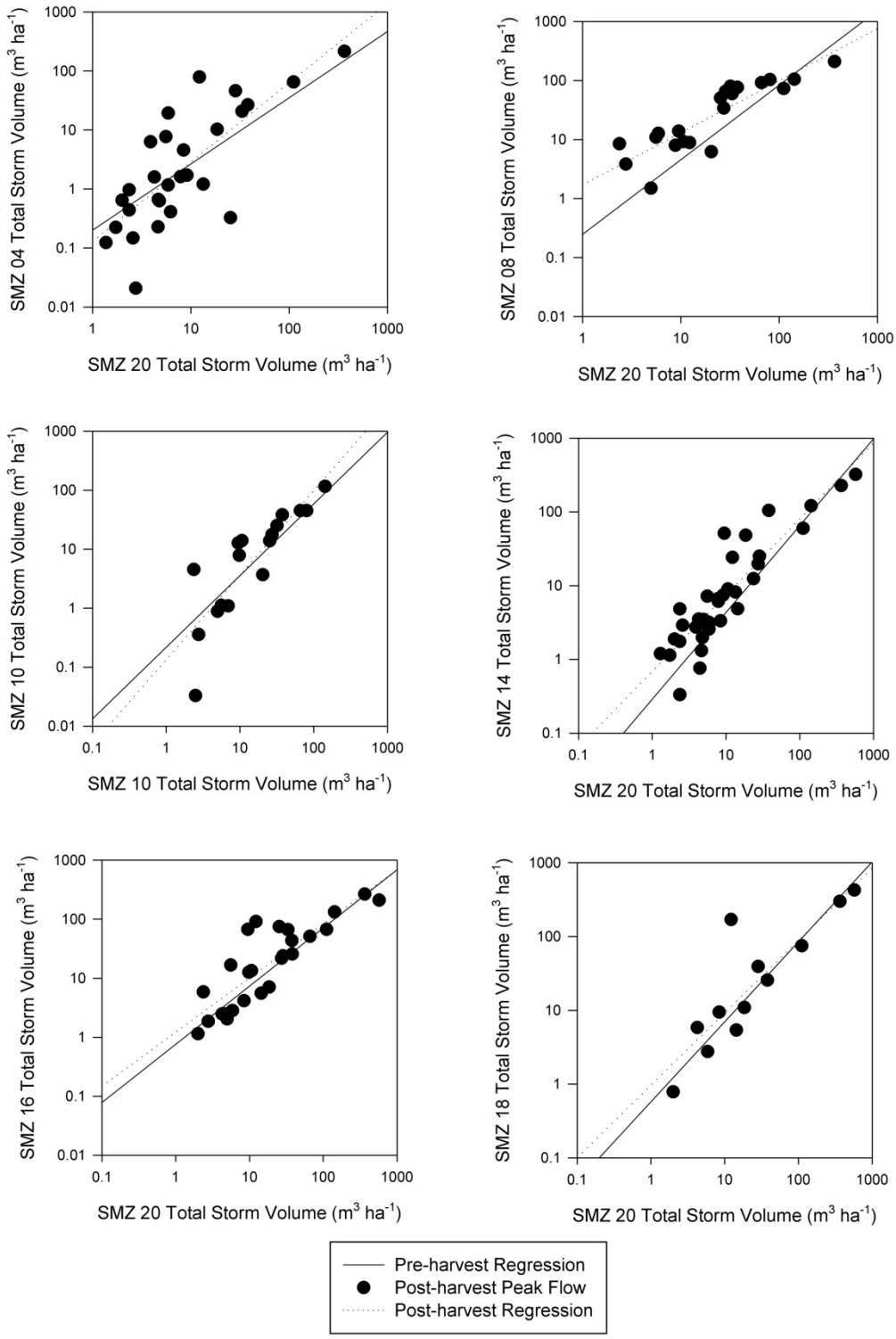

Figure 4-11: Pre-harvest regression, post-harvest total storm volume and post-harvest regression for total storm volume measured at each treatment watershed and compared to SMZ 20.

For the three flow-based hydrograph parameters, three of the watersheds (SMZ 04, SMZ 14, and SMZ 18) measured changes in the same direction (positive or negative). SMZ 04 had increases of similar magnitude (mean 48%) and SMZ 14 measured decreases of 3%-4%. The remaining three watersheds measured a mixture of increases, decreases, and no measured changes. Patterns were similar for comparisons to SMZ 12 and SMZ 20 (Figure 4-12).

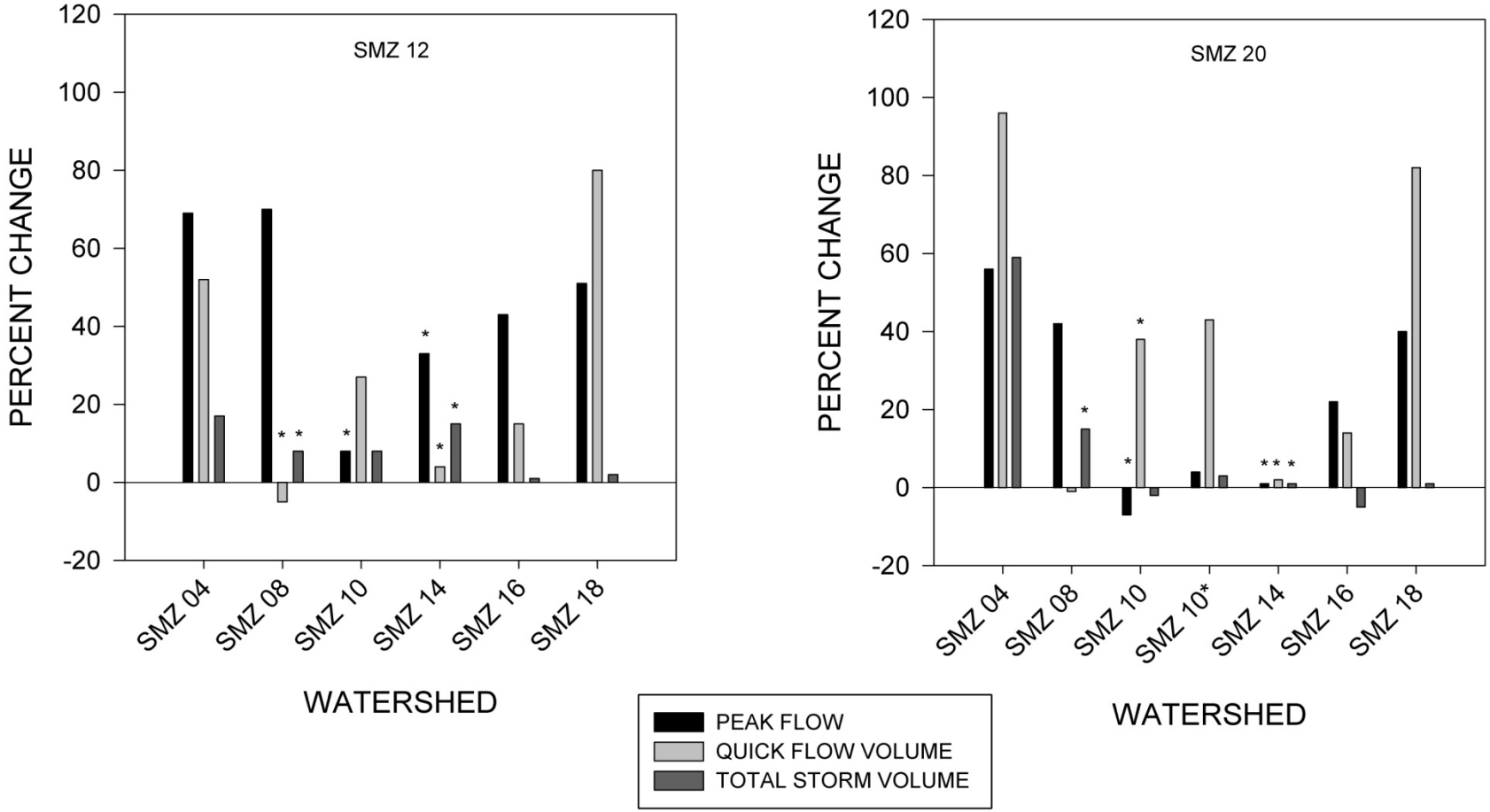

Figure 4-12: Percent change measured for the three flow-based hydrograph parameters by watershed compared to SMZ 12 (left) and SMZ 20 (right). Bars marked with an asterisk measured significant change from pre-harvest to post-harvest when compared to unharvested control watersheds. SMZ 10* denotes the results of ANCOVA when data containing flows from SMZ 20 that were abnormally higher than SMZ 10 were excluded.

Results for the time based hydrograph parameters were as inconsistent as the flow based parameters. In some cases, the comparison with SMZ 20 produced changes that were opposite in direction (positive or negative) from the results measured when SMZ 12 was used as the un-harvested watershed in the ANCOVA.

When SMZ 20 was used as the un-harvested control watershed, concentration time changes ranged from a 10% decrease to a 30% increase. Only the SMZ 16-SMZ 20 relationship measured significant change from pre-harvest to post-harvest (slope p-value = 0.03, intercept p-value = 0.31, df = 58). Mean change in concentration time was 14% or approximately 66 minutes (Table 4-19).

Table 4-19: ANCOVA results for concentration time measured at perennial monitoring locations using SMZ 20 as the un-harvested control watershed.

Parameter:Concentration Time								
Dependent Variable: SMZ 20 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.75	0.69	0.20	0.35	0.63	-2%
	Post-harvest	26	0.89		0.00		0.34	
SMZ 08	Pre-harvest	31	0.64	0.38	0.28	0.67	0.30	6%
	Post-harvest	19	0.89		0.11		0.53	
SMZ 10	Pre-harvest	52	0.90	0.18	0.04	0.22	0.68	28%
	Post-harvest	15	1.21		-0.12		0.64	
SMZ 14	Pre-harvest	33	0.88	0.74	-0.02	0.44	0.55	8%
	Post-harvest	32	0.96		-0.14		0.47	
SMZ 16	Pre-harvest	34	0.62	**0.03**	0.29	0.31	0.39	30%
	Post-harvest	24	1.11		-0.07		0.61	
SMZ 18	Pre-harvest	48	0.84	0.43	0.07	0.16	0.73	-10%
	Post-harvest	10	0.97		-0.11		0.80	

Comparisons of rise time using SMZ 20 as the control watershed resulted in one significant change in the SMZ 18-SMZ 20 relationship (slope p-value = 0.80, intercept p-value = 0.03, df = 58). Whereas comparisons to SMZ 12 resulted in decreases in rise

time for five out of the six treated watersheds, the comparisons to SMZ 20 all resulted in increases, ranging from 9% to 44% (Table 4-20). Mean increase in rise time was 17%, or approximately 33 minutes.

Table 4-20: ANCOVA results for rise time measured at perennial locations using SMZ 20 as the un-harvested control watershed.

Parameter:Rise Time								
Dependent Variable: SMZ 20 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.83	0.36	-0.02	0.77	0.59	7%
	Post-harvest	26	0.63		0.09		0.48	
SMZ 08	Pre-harvest	31	0.79	0.07	0.04	0.84	0.49	17%
	Post-harvest	19	1.29		-0.20		0.70	
SMZ 10	Pre-harvest	52	0.97	0.88	-0.07	0.57	0.72	19%
	Post-harvest	15	0.92		-0.01		0.25	
SMZ 14	Pre-harvest	33	1.15	0.69	-0.24	0.65	0.75	9%
	Post-harvest	32	1.07		-0.18		0.54	
SMZ 16	Pre-harvest	34	0.92	0.91	0.00	0.83	0.64	9%
	Post-harvest	24	0.89		0.02		0.44	
SMZ 18	Pre-Harvest	48	1.08	0.80	-0.23	**0.03**	0.64	44%
	Post-harvest	10	1.15		-0.06		0.93	

Mixed results were measured for fall time. Mean fall time change was 14% and ranged from a 4% decrease to a 35% increase (Table 4-21). None were statistically significant. The magnitude of the change in fall time was different for each treatment watershed depending on the un-harvested control watershed used for comparison (Figure 4-13).

Table 4-21: ANCOVA results for fall time measured at perennial monitoring locations using SMZ 20 as the un-harvested control watershed.

Parameter:Fall Time								
Dependent Variable: SMZ 20 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.69	0.33	0.27	0.86	0.63	2%
	Post-harvest	26	0.86		0.11		0.67	
SMZ 08	Pre-harvest	31	0.56	0.39	0.42	0.76	0.35	-3%
	Post-harvest	19	0.74		0.25		0.58	
SMZ 10	Pre-harvest	52	0.79	0.38	0.17	0.21	0.61	35%
	Post-harvest	15	0.96		0.13		0.70	
SMZ 14	Pre-harvest	33	0.85	0.98	0.03	0.96	0.64	13%
	Post-harvest	32	0.86		0.03		0.48	
SMZ 16	Pre-harvest	33	0.60	0.09	0.33	0.29	0.45	29%
	Post-harvest	24	0.90		0.14		0.66	
SMZ 18	Pre-Harvest	48	0.71	0.054	0.22	0.17	0.69	-4%
	Post-harvest	10	1.01		-0.11		0.88	

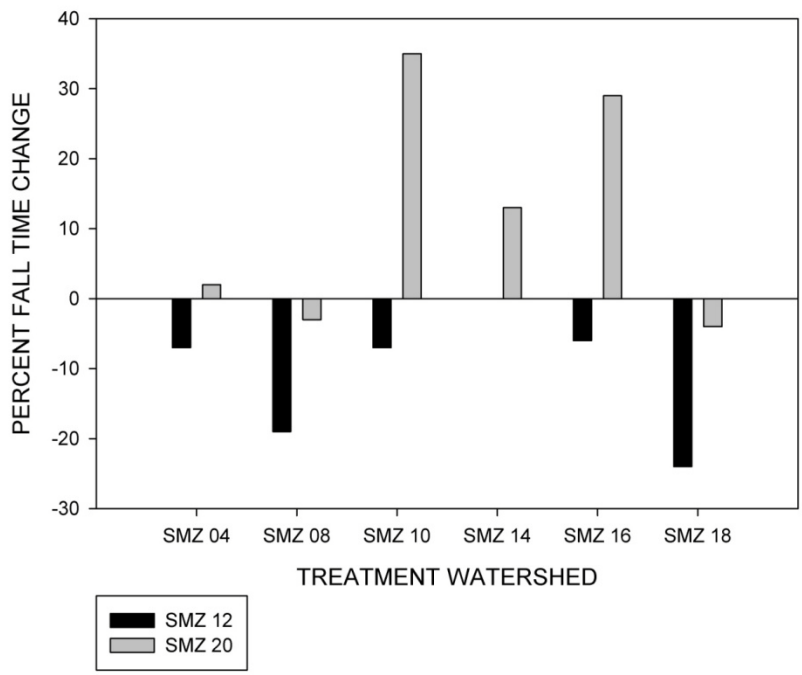

Figure 4-13: Magnitude of change in fall time when compared to the two un-harvested control watersheds. Only the SMZ 18-SMZ 12 relationship was statistically different from pre-harvest to post-harvest.

Lag time resulted in significant changes for two watersheds when SMZ 20 was designated the un-harvested control. A 27% increase in lag time was measured in the relationship between SMZ 16 and SMZ 20 (slope p-value = 0.03, intercept p-value = 0.13, df = 58). A 2% decrease in the SMZ 18-SMZ 20 relationship resulted in statistical significance (slope p-value = 0.01, intercept p-value = 0.03, df = 58). Overall, lag time changed by a mean of 12%, or 20 minutes (Table 4-22).

Table 4-22: ANCOVA results for lag time measured at perennial monitoring locations using SMZ 20 as the un-harvested control.

Parameter:Lag Time								
Dependent Variable: SMZ 20 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.79	0.83	0.07	0.31	0.55	-5%
	Post-harvest	26	0.85		-0.07		0.53	
SMZ 08	Pre-harvest	31	0.66	0.20	0.16	0.34	0.37	-20%
	Post-harvest	19	1.03		-0.07		0.59	
SMZ 10	Pre-harvest	52	0.99	0.07	-0.05	0.06	0.75	-23%
	Post-harvest	15	1.49		-0.40		0.71	
SMZ 14	Pre-harvest	33	0.75	0.49	0.02	0.14	0.59	7%
	Post-harvest	32	0.87		-0.12		0.63	
SMZ 16	Pre-harvest	34	0.81	**0.03**	-0.09	0.13	0.72	13%
	Post-harvest	24	1.18		-0.29		0.76	
SMZ 18	Pre-harvest	48	0.55	**0.01**	0.11	**0.03**	0.42	-2%
	Post-harvest	10	1.05		-0.24		0.79	

Increases in total storm duration were measured from pre-harvest to post-harvest for each watershed when SMZ 20 was designated the un-harvested control watershed, ranging from 3% to 36% (Table 4-23). The SMZ 10-SMZ 20 relationship was significant, with a 36% increase (slope p-value = 0.22, intercept p-value = 0.04, df = 67).

Table 4-23: ANCOVA results for total storm duration measured at perennial monitoring locations using SMZ 20 as the un-harvested control watershed.

Parameter:Total Storm Duration								
Dependent Variable: SMZ 20 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.85	0.74	0.12	0.96	0.71	4%
	Post-harvest	26	0.91		0.06		0.71	
SMZ 08	Pre-harvest	31	0.71	0.39	0.30	0.72	0.45	3%
	Post-harvest	19	0.88		0.15		0.71	
SMZ 10	Pre-harvest	52	0.92	0.22	0.05	**0.04**	0.76	36%
	Post-harvest	15	1.16		-0.06		0.70	
SMZ 14	Pre-harvest	33	1.10	0.52	-0.23	0.72	0.73	10%
	Post-harvest	32	0.97		-0.07		0.54	
SMZ 16	Pre-harvest	34	0.78	0.30	0.17	0.08	0.56	35%
	Post-harvest	24	0.97		0.07		0.69	
SMZ 18	Pre-harvest	48	0.92	0.37	0.02	0.82	0.78	3%
	Post-harvest	10	1.04		-0.10		0.94	

The consistent increases in total storm duration when SMZ 20 was used as the un-harvested control was in contrast to the decreases and zero change measured when SMZ 12 was used as the un-harvested control.

Treatment Effects

No clear trends indicating a treatment impact were measured in the comparisons of the treatment watersheds to the control watersheds. The only consistent significant differences were measured between the treatment 2 watersheds (SMZ 08 and SMZ 14) and SMZ 12 for the three flow-based hydrograph parameters and in the SMZ 18-SMZ 12 relationship for three of the time based hydrograph parameters. A less consistent trend was measured between the treatment 1 watersheds (SMZ 10 and SMZ 18) and SMZ 20 for two of the flow-based parameters. In order to identify differences in SMZ configurations, ANCOVA was performed for the treatment watersheds using each

treatment watershed as the independent variable and comparing it to every other treatment watershed. Similar to the comparisons to the two un-harvested control watersheds, differences among treatments varied depending on the watershed designated the dependent or independent variable.

Comparisons of the three treatments were complicated by multiple findings of non-significance of the post-harvest ANOVA involving SMZ 04, SMZ 08, SMZ 10, and SMZ 18 for the three flow based parameters (Table 4-24).

Table 4-24: Watershed comparisons with post-harvest ANOVA that were non-significant for peak flow, quick flow volume, and total storm volume.

Independent Variable	Dependent Variable	Treatments	Post-Harvest Sample n
SMZ 04	SMZ 08	3 vs. 2	10
SMZ 04	SMZ 10	3 vs. 1	3
SMZ 08	SMZ 04	2 vs. 3	10
SMZ 08	SMZ 18	2 vs. 1	6
SMZ 10	SMZ 04	1 vs. 3	3
SMZ 10	SMZ 18	1 vs. 1	1
SMZ 18	SMZ 08	1 vs. 2	6
SMZ 18	SMZ 10	1 vs. 1	1

ANOVA non-significance in the flow-based parameters seemed directly related to low numbers of samples in the post-harvest period. The non-significance of the post-harvest ANOVA for SMZ 10 and SMZ 18 made comparison of the behavior of the two treatment 1 watersheds impossible. Significant differences were not measured between the two treatment 2 watersheds (SMZ 08 and SMZ 14) or between the two treatment 3 watersheds (SMZ 04 and SMZ 16).

ANOVA non-significance was also an issue in the analysis of the time-based hydrograph parameters, although the occurrences were less consistent than measured in the flow-based parameters. Two of the three watershed pairs that resulted in ANOVA non-significance for time based parameters were not significant for the flow based

parameters. The third watershed pair had non-significance for one comparison and parameter (Table 4-25).

Table 4-25: Watershed comparisons with ANOVA that were non-significant for certain time-based hydrograph parameters.

Independent Variable	Dependent Variable	Parameters
SMZ 04	SMZ 10	Concentration Time, Rise Time, Total Storm Duration
SMZ 10	SMZ 04	
SMZ 08	SMZ 18	Concentration Time, Lag Time
SMZ 18	SMZ 08	
SMZ 14	SMZ 10	Concentration Time

Multiple significant differences were measured for peak flow among the treatment watersheds. Comparisons using SMZ 14 as the dependent watershed were significantly different for every comparison except when compared to SMZ 08 (other treatment 2 watershed) or SMZ 18 (treatment 1)(Table 4-26).

Table 4-26: ANCOVA results for peak flow measured at perennial monitoring locations using SMZ 14 as the dependent variable.

Parameter: Peak Flow								
Dependent Variable: SMZ 14 (South Shelly Rock)								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	25	0.72	**0.03**	-0.81	0.73	0.66	44%
	Post-harvest	30	1.14		-0.19		0.68	
SMZ 08	Pre-harvest	34	0.99	0.85	-0.09	0.80	0.51	-16%
	Post-harvest	14	1.04		0.01		0.79	
SMZ 10	Pre-harvest	56	1.10	0.96	0.00	**0.04**	0.88	-29%
	Post-harvest	7	1.11		-0.20		0.86	
SMZ 16	Pre-harvest	36	0.98	0.60	-0.08	**0.02**	0.92	-13%
	Post-harvest	29	0.93		-0.28		0.80	
SMZ 18	Pre-harvest	52	1.01	0.98	0.18	0.28	0.90	-3%
	Post-harvest	21	1.01		0.10		0.76	

When SMZ 14 was designated the independent variable, significant differences were measured for the same three watersheds when they were designated the dependent variable (Table 4-27).

Table 4-27: ANCOVA results for peak flow measured at perennial monitoring locations using SMZ 14 as the independent variable.

Parameter:Peak Flow								
Independent Variable: SMZ 14								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	25	0.91	**0.04**	0.14	0.15	0.66	-14%
	Post-harvest	30	0.60		-0.35		0.68	
SMZ 08	Pre-harvest	34	0.51	0.14	-0.61	0.97	0.51	22%
	Post-harvest	14	0.76		-0.28		0.79	
SMZ 10	Pre-harvest	56	0.80	0.88	-0.19	**0.03**	0.88	43%
	Post-harvest	7	0.78		-0.03		0.86	
SMZ 16	Pre-harvest	36	0.94	0.38	-0.04	**0.01**	0.92	18%
	Post-harvest	29	0.86		-0.02		0.80	
SMZ 18	Pre-harvest	52	0.89	0.15	-0.32	0.10	0.90	8%
	Post-harvest	21	0.76		-0.38		0.76	

Generally, peak flow shifts toward SMZ 14 irrespective of the treatment applied to the watersheds used for comparison except in the SMZ 04-SMZ 14 relationship. Even though a significant shift was measured in the direction of SMZ 04 for that comparison, at low to moderate peak flows (less than 0.05 m^3 min^{-1} ha^{-1}), the general trend is in the direction of SMZ 14 (Figure 4-14).

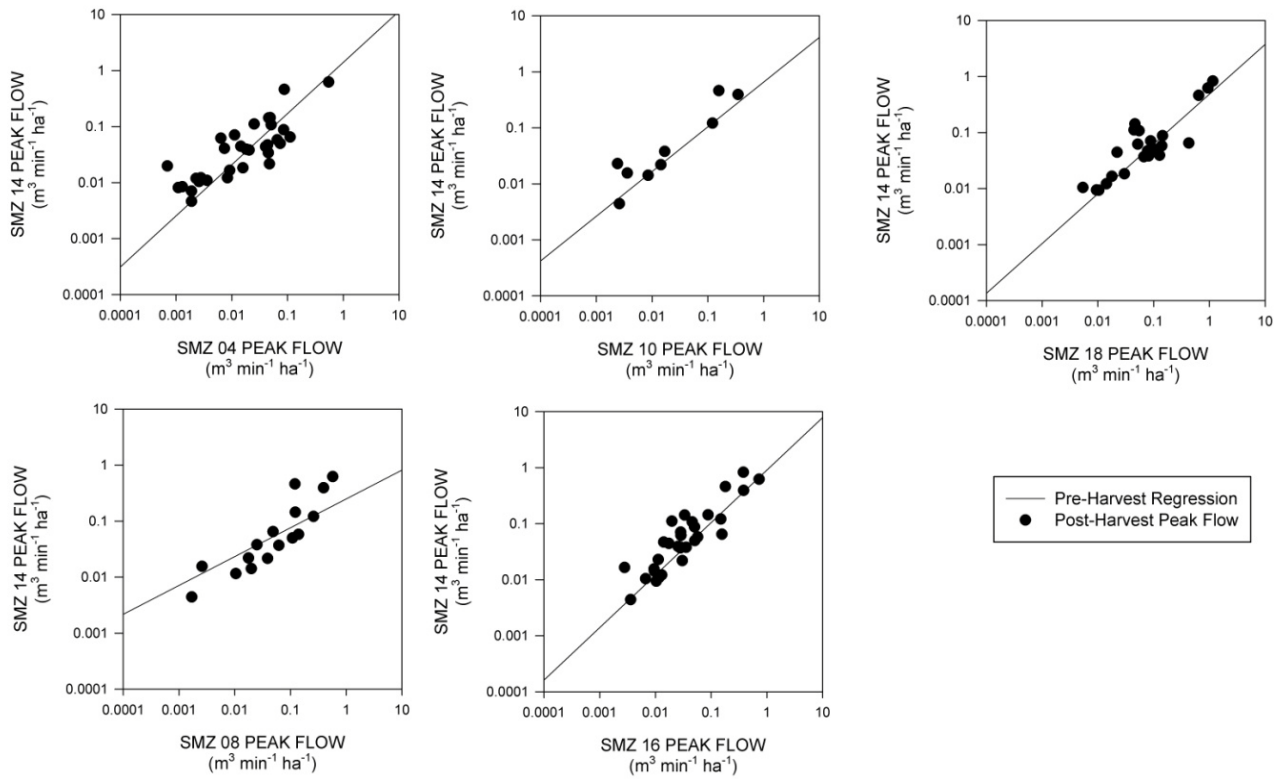

Figure 4-14: Pre-harvest regression and post-harvest peak flows measured at perennial monitoring locations using SMZ 14 as the independent variable.

Differences in peak flow were not only measured in comparisons using SMZ 14, but also comparisons between treatment 1 and treatment 3. Significant differences were measured in the SMZ 16-SMZ 10 and SMZ 16-SMZ 18 relationships irrespective of which watershed was designated the independent variable (Table 4-28).

Table 4-28: ANCOVA results for peak flow measured at perennial monitoring locations for selected treatment 1 and treatment 3 watersheds.

Independent Variable	Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2
SMZ 16	SMZ 10	Pre-harvest	34	0.92	0.14	-0.07	**0.0002**	0.94
		Post-harvest	13	0.80		0.00		0.89
SMZ 10	SMZ 16	Pre-harvest	34	1.02	0.34	-0.02	**0.0002**	0.97
		Post-harvest	13	1.11		-0.16		0.89
SMZ 16	SMZ 18	Pre-harvest	44	0.81	0.58	-0.37	**0.002**	0.87
		Post-harvest	23	0.86		-0.51		0.87
SMZ 18	SMZ 16	Pre-harvest	44	1.08	0.58	0.22	**0.001**	0.87
		Post-harvest	23	1.02		0.35		0.87

The change in peak flow measured between SMZ 16 and the treatment 1 watersheds was different between the SMZ 16-SMZ 10 comparison and the SMZ 16-SMZ 18 comparison. Peak flow shifted towards SMZ 16 when compared to SMZ 10 and shifted away from SMZ 16 when compared to SMZ 18 (Figure 4-15).

No additional significant differences in peak flow were measured for any watershed pairing (Appendix V).

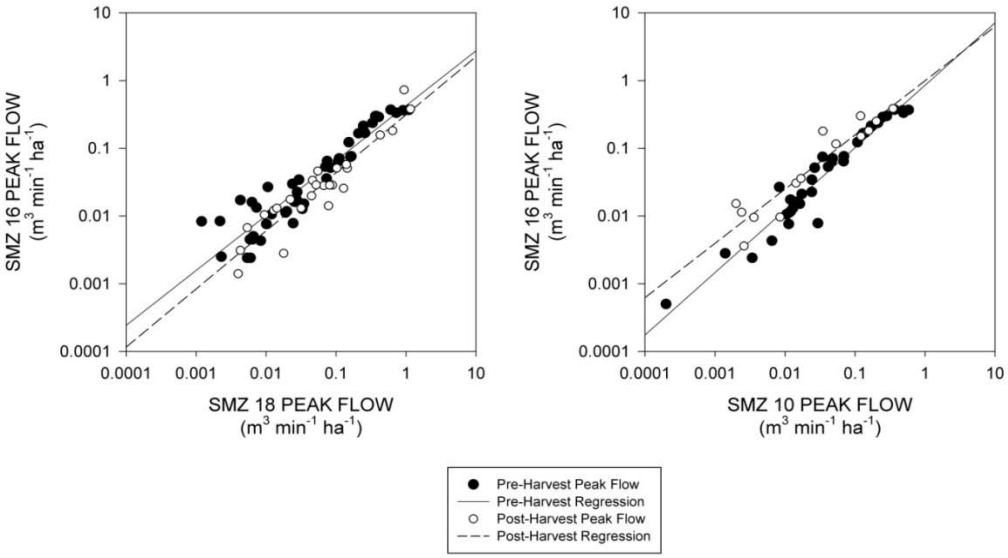

Figure 4-15: Peak flow pre-harvest and post-harvest regressions for SMZ 16 and the two treatment 1 watersheds.

The only significant change measured in quick flow volume was a 24% shift toward SMZ 08 measured when SMZ 08 was designated the independent variable and SMZ 10 was designated the dependent variable (slope p-value = 0.04, intercept p-value = 0.92, df = 66). The comparison using SMZ 10 as the independent variable and SMZ 08 as the dependent variable was not statistically significant (Appendix VI).

Results of the total storm volume analysis were less consistent in measuring significant differences than peak flow (Appendix VII). No significant differences were measured when SMZ 04 or SMZ 08 was designated the independent variable. Significant shifts in total storm volume were measured in the SMZ 16-SMZ 10 relationship, similar to peak flow results. The mean change in total storm volume was 30% when SMZ 10 was designated the independent variable (slope p-value = 0.77, intercept p-value = 0.02, df = 47) and was 24% when SMZ 16 was designated the independent variable (slope p-value

= 0.18, intercept p-value = 0.02, df = 47). Also similar to peak flow measurements, significant differences were measured in the SMZ 16-SMZ 14 relationship (Table 4-29). Significant changes were also measured in the SMZ 14-SMZ 18 relationship, which had not been measured for the other flow-based hydrograph parameters. Total storm volume shifted 24% toward SMZ 14 when SMZ 14 was designated the independent variable (slope p-value = 0.18, intercept p-value = 0.01, df = 73) and 18% when SMZ 18 was designated the independent variable (slope p-value = 0.68, intercept p-value = 0.04, df = 73). The changes measured in the SMZ 14-SMZ 16 and SMZ 14-SMZ 18 relationships were similar (Figure 4-16).

Table 4-29: ANCOVA results for total storm volume for SMZ 14 SMZ 16.

Independent Variable	Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 14	SMZ 16	Pre-harvest	36	0.95	0.50	-0.01	**0.01**	0.95	35%
		Post-harvest	29	0.89		0.21		0.81	
SMZ 16	SMZ 14	Pre-harvest	36	1.00	0.22	0.06	**0.02**	0.95	-28%
		Post-harvest	29	0.90		0.01		0.81	

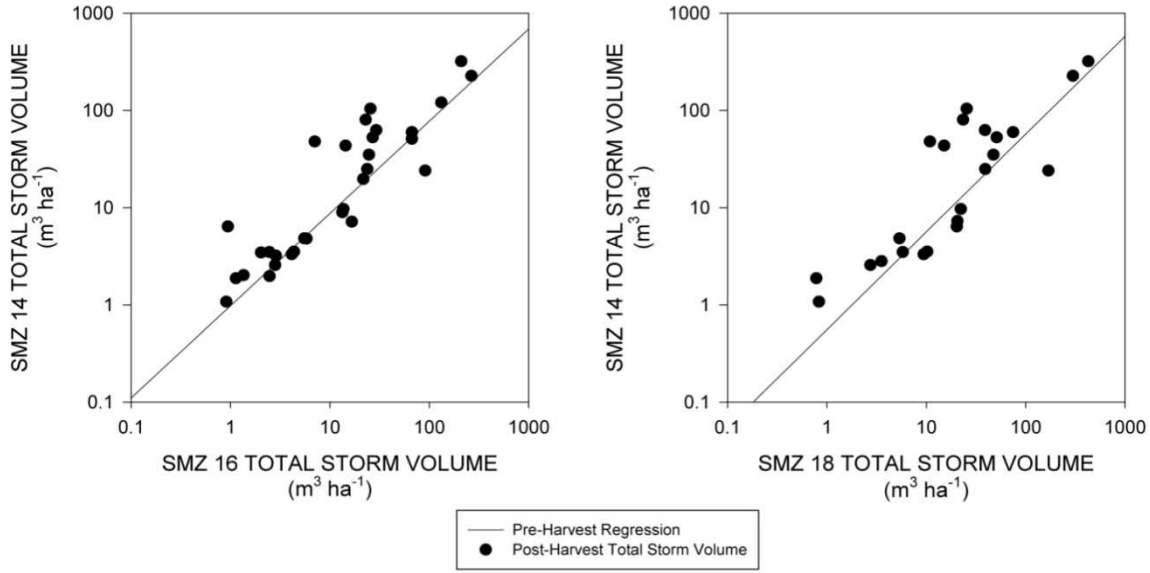

Figure 4-16: Pre-harvest regression and post-harvest total storm volume measurements for SMZ 14-SMZ 16 and SMZ 14-SMZ 18.

Significant differences were not measured for any comparisons between treatments for lag time (Appendix VIII). A significant change in lag time was measured within treatment 3 watersheds when SMZ 16 was designated the independent variable and SMZ 04 was designated the dependent variable (slope p-value = 0.01, intercept p-value = 0.15, df = 32). The shift in lag time towards an increase in SMZ 16 relative to SMZ 04 was measured in the comparison when SMZ 04 was designated the independent variable, but the ANCOVA was not significant for either slope (p-value = 0.38) or y-intercept (p-value = 0.12) (df = 32). Mean change in lag time for all treatment watershed comparisons was 23% or 34 minutes. There was no clear shift in lag time toward any treatment or watershed.

Of the 24 comparisons of fall time (Appendix IX), two were significantly different from pre-harvest to post-harvest, and both involved SMZ 04 designated as the independent variable (Table 4-30). Neither was significantly changed when SMZ 04 was designated the dependent variable. Both comparisons had low sample numbers that generally resulted in post-harvest ANOVA failure in other parameters. Overall, changes in fall time ranged from decreases of 40% to increases of 84% with a mean change of 17% or approximately 80 minutes.

Table 4-30: Selected ANCOVA results for fall time when SMZ 04 was designated the independent variable.

Independent Variable	Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2
SMZ 04	SMZ 08	Pre-harvest	18	0.56	**0.04**	0.44	0.49	0.52
		Post-harvest	8	1.16		-0.14		0.75
SMZ 04	SMZ 10	Pre-harvest	28	0.73	0.22	0.27	**0.01**	0.70
		Post-harvest	1	1.21		-0.36		0.99

Significant changes in rise time were measured in the SMZ 10-SMZ 14 and SMZ 10-SMZ 16 relationships (Table 4-31). The SMZ 10-SMZ 14 relationship measured a mean shift of 36% in the direction of SMZ 10 and the SMZ 10-SMZ 16 relationship measured a mean shift of 30% in the direction of SMZ 10 (Figure 4-17).

Table 4-31: ANCOVA results for rise time measured at perennial monitoring locations for the SMZ 10-SMZ 14 and SMZ 10-SMZ 16 relationships.

Independent Variable	Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2
SMZ 10	SMZ 14	Pre-harvest	56	0.77	0.38	0.17	**0.01**	0.83
		Post-harvest	7	0.64		0.36		0.76
SMZ 14	SMZ 10	Pre-harvest	56	1.08	0.65	-0.12	**0.03**	0.83
		Post-harvest	7	1.18		-0.34		0.76
SMZ 10	SMZ 16	Pre-harvest	34	0.86	0.17	0.02	**0.002**	0.75
		Post-harvest	13	0.67		0.27		0.89
SMZ 16	SMZ 10	Pre-harvest	34	0.86	0.02	0.10	**<0.001**	0.75
		Post-harvest	13	1.33		-0.33		0.89

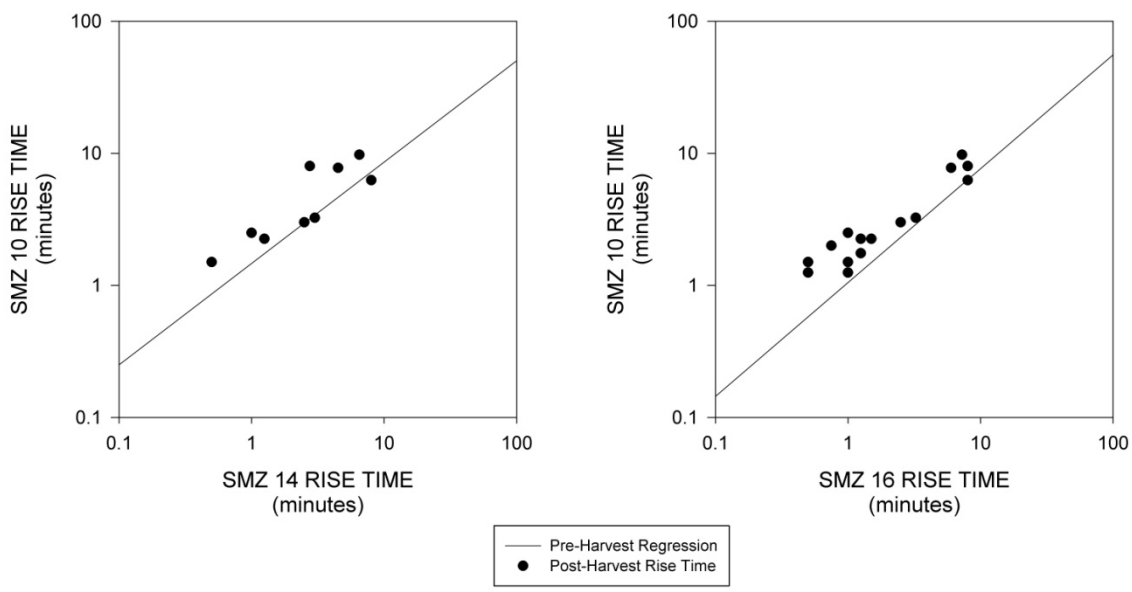

Figure 4-17: Pre-harvest regression and post-harvest rise time measurements for the SMZ 10-SMZ 14 and SMZ 10-SMZ 16 comparisons.

An additional significant change was measured when SMZ 18 was designated the independent variable and SMZ 04 was designated the dependent variable (slope p-value = 0.03, intercept p-value = 0.77, df = 38). In contrast to the relationship of SMZ 10 to the other treatment 3 watershed (SMZ 16), the shift in the SMZ 10-SMZ 04 relationship was measured as 25% shift toward SMZ 04. The reciprocal relationship which designated SMZ 04 as the independent variable and SMZ 18 as the dependent variable was not statistically different.

Changes in rise time ranged from a 42% decrease to an 86% increase with a mean change of 20% or 40 minutes (Appendix X).

Total storm duration changes ranged from a 17% decrease to a 16% increase with a mean change of approximately 8%. (Appendix XI) Only one relationship, SMZ 04-SMZ 08 (independent variable-dependent variable) measured a significant change from pre-harvest to post-harvest (slope p-value = 0.02, intercept p-value = 0.57, df = 26). When SMZ 08 was designated the independent variable and SMZ 04 the dependent, a significant change was not measured (slope p-value = 0.31, intercept p-value = 0.99, df = 26).

Discussion

Moore and Wondzell (2005), Brooks et al. (2003), Beschta et al. (2000), Stednick (1996), Hornbeck et al. (1993), and Bosch and Hewlett (1982) have provided summaries of peak flow and water yield responses following forest harvesting for a variety of locations and geographic scales. Bosch and Hewlett (1982) and Hibbert (1967) provided extensive reviews of many experiments conducted at Coweeta Hydrologic Laboratory, as well as

other experiments from around the U. S. and world. Changes in peak flow following forest harvest have been reported to range from -22% to +200% (Brooks et al. 2003) and -22% to +168% (Guillemette et al. 2005). In addition to changes in peak flow and annual water yield that have been summarized previously, several studies have examined changes to the storm hydrograph (Table 4-1). The results of this study are within the range of results previously reported.

Results of the hydrograph separation support three conclusions. First, the level of harvest and disturbance was not severe enough to result in consistent changes of flow and time based hydrograph parameters for any of the treated watersheds. Second, increases in flow based parameters were pronounced for small events and the impact of harvesting on large events was difficult to determine. Finally, large flow events can alter the hydrology of control watersheds and make discerning between harvest effects and flood effects difficult as well as exert heavy influence on regression relationships.

Overall, the impact of the harvest on the storm hydrograph was minimal. No parameter measured significant changes for more than two of the treatment watersheds irrespective of the control watershed used for comparison. Changes in the storm hydrograph from harvesting activities have been attributed changes in storage and conveyance of water (Brooks et al. 2003). Storage changes are derived from loss of evapotranspiration and canopy interception as well as increases in soil moisture (Guillemette et al. 2005, Moore and Wondzell 2005, Jones 2000, Jones and Grant 1996, Hewlett and Helvey 1970). Conveyance may be altered by road or skid trail systems (Jones 2000, Wemple et al. 1996, , Harr et al. 1975) as well as decreased hydraulic conductivity due to compaction and loss of preferential flow pathways (Moore and Wondzell 2005). In order for

evapotranspiration to impact peak flows and storm response, the influence of evapotranspiration demand must be large relative to other components of the water balance and the change in evapotranspiration from pre-harvest to post-harvest phases must also be large (Jones 2000). In order for the timing of the storm response to change following harvest, a change must occur in the way water moves through the catchment following harvest. This may include increases in overland flow due to soil compaction, increased routing efficiency of water via the road or skid trail system, and interception of lateral subsurface flow by bank cuts in the road system, transforming subsurface flow to surface flow. None of the treatment watersheds measured increases in both flow and time based parameters. One explanation for this similarity between the pre-harvest and post-harvest storm responses is the efficiency of water movement through these watersheds in their untreated state. Hydrologic response in these watersheds is rapid, with nearly all storm flow moving as lateral subsurface flow as precipitation rapidly infliltrates and vertical drainage becomes limited by impermeable strata (Arthur et al. 1998; Coltharp and Springer 1980). Runoff curve numbers for watersheds in Robinson Forest have been measured between 83 and 91, in contrast to curve numbers in the mid 50s measured at Coweeta (Taylor et al. 2009; Hawkins 1993; Springer et al. 1980). Runoff curve numbers are an index used to predict runoff from a storm event (Brooks et al., 2003). The percentage of stream flow that occurs as storm flow was measured at 44% of the annual discharge in SMZ 12 (Coltharp and Springer 1980).

An additional factor in the general similarity from pre-harvest to post-harvest for most of the watersheds and the lack of a consistent trend when comparing treatment watersheds is the overall severity of the treatments applied and the differences among treated

watersheds. In contrast to previous work conducted at Robinson Forest (Sutardjo 1989) and elsewhere (Table 4-1), harvesting was not conducted as a clear cut, but was done as a two age deferment harvest with a target post-treatment basal area of 15 square feet per acre. In addition to the canopy trees remaining as a requirement of the two-aged harvest, many more non-merchantable trees were also left in the watershed as well as the basal area retained in the SMZs. Skid trails occupied 6-12% of the watershed area. Harr et al. (1975) were able to detect changes in storm hydrographs for an Oregon Coast Range watershed that was harvested with 12% roads and slash burned post harvest, but did not measure changes in hydrographs for watersheds with roads that occupied 3-5% of the watershed area. The impact of 6-12% watershed area affected by skid trails was small. Harvesting in this study certainly resulted in areas of compacted soil including the skid trail network and landing areas that would be expected to result in surface runoff. However, the significance of this surface runoff to the storm hydrograph is based on the area disturbed and if runoff is directed to the streams by skid trails or other compacted areas (Moore and Wondzell 2005). If the skid trail network was impacting the storm response, the effects should have been consistently measured in the hydrograph timing. In absence of this response, it appears as though the water control structures installed during retirement of the trail system were effective. Overall, the impact of the amount of timber harvested and associated road network were not sufficient enough to alter the rapid movement of storm flows through these watersheds.

For the two watersheds that measured significant increases in flow based parameters (SMZ 08-SMZ 12 and SMZ 14-SMZ 12), the increases were more pronounced for smaller events than for large events. Post-harvest regressions for these watershed

relationships intersected the pre-harvest regressions at higher flows. These data are similar to the findings of Troendle and Olsen (1993) which described small events as being proportionally more impacted by treatment and that large and extreme events were likely not impacted by treatment, a finding also reported by Beschta et al. (2000) and Moore and Wondzell (2005). The effect of forest harvesting on large events has also been hypothesized to be different from the impacts on smaller events as the impacts of canopy interception and evapotranspiration are rapidly minimized relative to increases in event size and intensity, (Harr et al. 1975) although the ability to accurately measure peak discharges and changes associated with harvesting activities is limited (Beschta et al. 2000). The impact of harvesting on large flow events that may cause flooding is impossible to determine with the limited data from large flow events from this study. The increases in peak flow and total storm volume measured in this study are generally confined to low flow events that would not result in increases in downstream flooding. Seasonality has also been identified as contributing to variability in peak flow changes following forest harvest (i.e. Wynn et al. 2000). Changes in peak flow resulting from harvesting are expected to be more pronounced in the growing season, when the difference in evapotranspiration from pre-harvest to post-harvest phases is greatest (Jones 2000, Coltharp and Springer 1980). Results of regression analysis on data separated into growing (May-October) and dormant (November-April) seasons were similar to data that were not separated by season for comparisons with SMZ 12 (Figure 4-18). The SMZ 08-SMZ 12 relationship measured significant increases in peak flow for both the dormant and growing seasons. The SMZ 14-SMZ 12 relationship measured significant increases in peak flow during the growing season, but not the dormant season. The SMZ 18-SMZ

12 relationship measured significant increases in peak flow during the growing season. The overall trend for seasonality in these data were similar to those measured by Jones (2000) in that the peak flow response was more pronounced when soil moisture is expected to be at a deficit. Peak flow and storm volume changes were primarily measured during events whose magnitude would not be expected to impact downstream flooding.

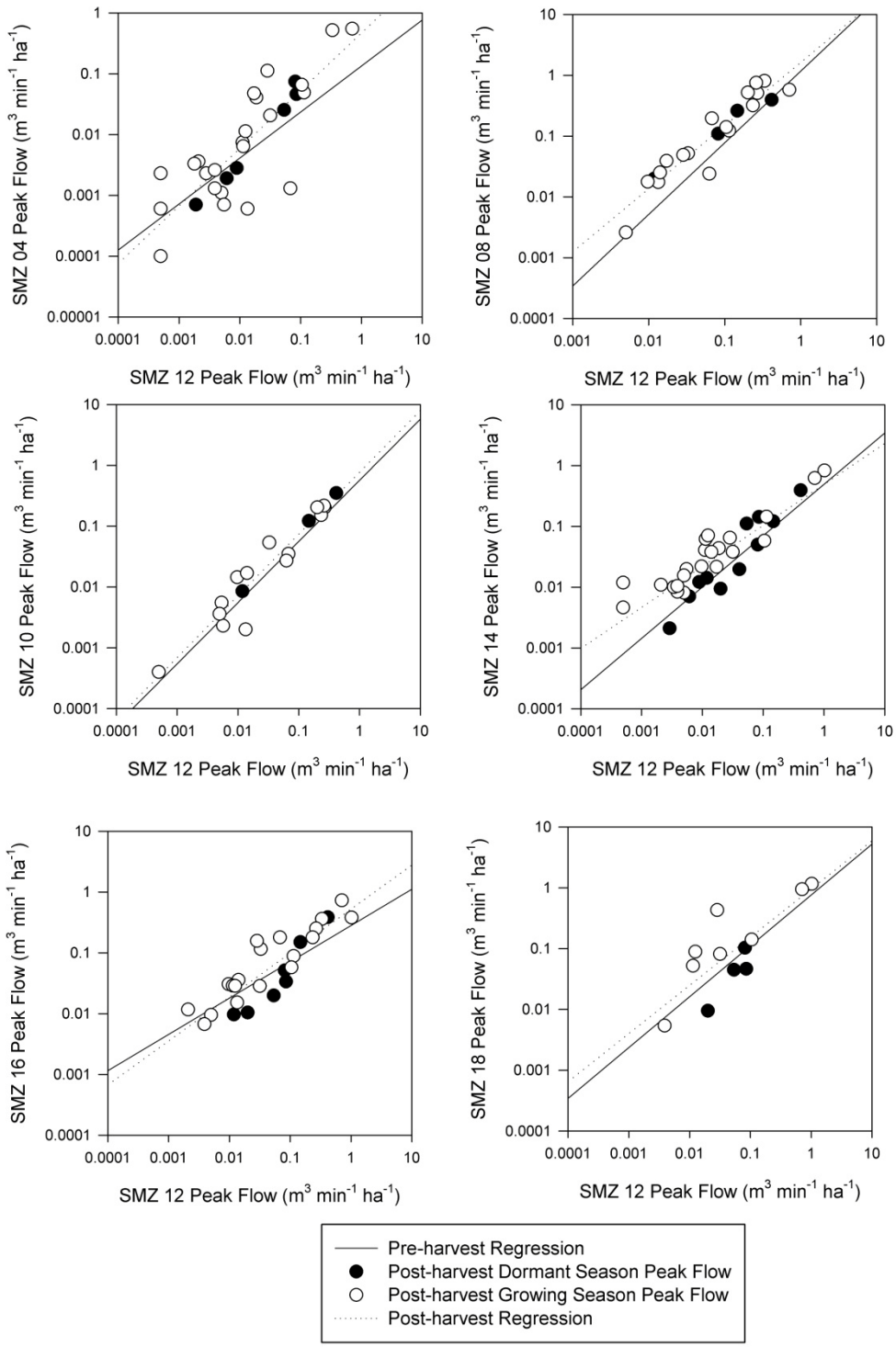

Figure 4-18: Peak flow comparisons with SMZ 12 separated into growing season (May-October) and dormant season (November-April).

Success in paired watershed experiments relies on effective pairing of watersheds, particularly in selecting watersheds of similar geology, soils, topography, and vegetation (Moore and Wondzell 2005). The impact of the treatment can depend on many factors, including the sequence of events measured in the pre and post harvest periods, particularly the occurrence of large events (Moore and Wondzell 2005). Given the 15 month interval between the start and end of harvesting operations the storm events included in each treatment watershed's pre-harvest or post-harvest data set are unique to that watershed. This may explain the absence of a consistent response from comparisons of treatment watersheds. For example, the comparison of the two treatment 2 watersheds SMZ 08 and SMZ 14 relies on post-harvest data that, because SMZ 08 was harvested one year after SMZ 14, is all taken from events that occurred at least one year after harvesting began on SMZ 14. These data should not be expected to result in findings similar to the SMZ 14-SMZ 04 comparison, watersheds that were harvested at approximately the same time and include nearly one year's storm responses that could not be used in the SMZ 14-SMZ 08 comparison. Differences in watershed pairing effectiveness were also evident when comparing the results of the comparison of the control watersheds to SMZ 04 and SMZ 14. Despite measuring large changes in each of the flow-based parameters when compared to either control watershed, SMZ 04 regressions consistently measured among the lowest R^2 values, particularly in the post-harvest phase. Conversely, R^2 values for the SMZ 14 comparisons to the control watersheds were among the highest measured, and although the measured changes in the flow based parameters were small, they were all significant.

The over-representation of small storm events relative to large events that might lead to flooding or alter channel morphology in studies of hydrologic response to disturbance is a common problem (Beschta 2000, Jones and Grant 1996). Sample sizes for such events will always be too small for accurate statistical analysis in the time periods relevant to harvesting impacts alone (not including re-vegetation) (Jones and Grant 1996). When large events do occur, they can be very difficult to measure accurately and can change the regression relationship for either the pre-harvest or post-harvest period, depending on when the event occurs. The impact of large events on pre-harvest relationships was evident in the SMZ 12-SMZ 20-SMZ 10 relationships for peak flow. It was also observed in the SMZ 08-SMZ 12 quick flow volume post-harvest relationship (Figure 4-7), where the impact of the largest events was a change in the mean predicted quick flow resulting in a decrease in quick flow as calculated, when the true impact of the harvest was an increase in quick flow volume.

The impact of flow events that measured large differences in flows between control watersheds and the subsequent impact on the measurement of treatment impacts the differences in flow parameters measured in the SMZ 10 relationships. The differences in the treatment response of SMZ 10 were different depending on the control watershed used for comparison (Figure 4-19). As can be seen in figure 2.20, orders of magnitude difference occurred in both pre-harvest and post-harvest periods, but were consistent among control watersheds for the pre-treatment period and were less so during the post-harvest period.

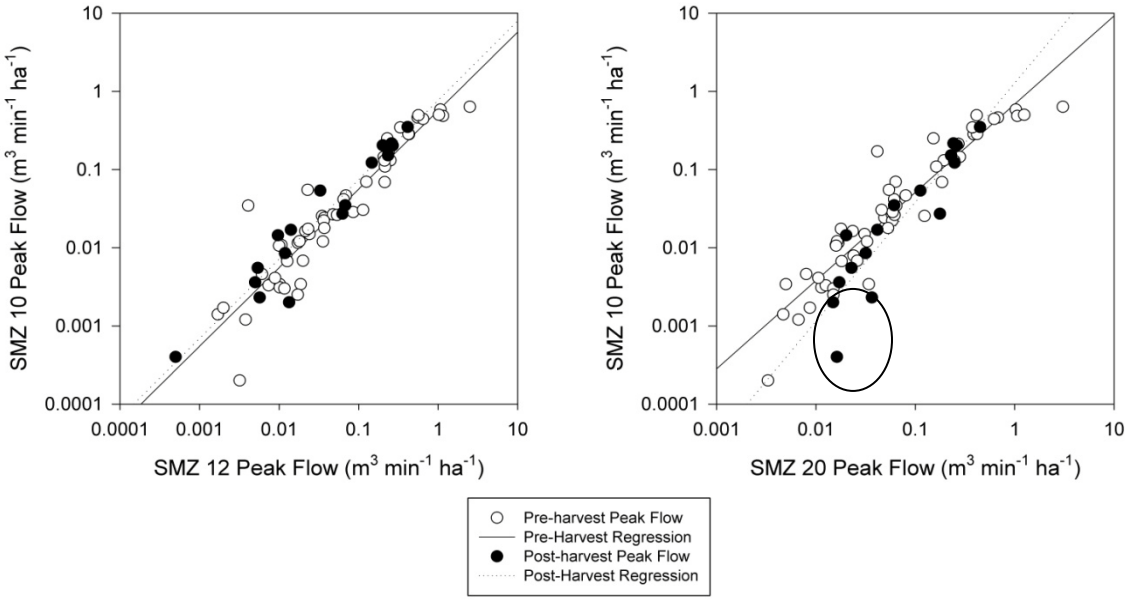

Figure 4-19: SMZ 10 peak flow compared to SMZ 12 and SMZ 20.

The three events circled in figure 21 exert a large influence on the post-harvest regression line and its difference from the SMZ 12 regression line. In these three cases, data was compared to data collected on chart recorders in the two control watersheds, and the difference between the control watershed responses was the same (Table 4-32).

Table 4-32: Comparison of stage measurement equipment for the control watersheds for selected storm events.

Date	SMZ 12 miniTroll stage ht (ft)	SMZ 20 miniTroll stage ht (ft)	SMZ 12 chart recorder stage ht (ft)	SMZ 20 chart recorder stage ht (ft)	SMZ 12 miniTroll calculated discharge (m^3 min^{-1} ha^{-1})	SMZ 20 miniTroll calculated discharge (m^3 min^{-1} ha^{-1})	SMZ 12 chart recoder calculated discharge (m^3 min^{-1} ha^{-1})	SMZ 20 chart recorder calculate discharge (m^3 min^{-1} ha^{-1})
9/11/2009	0.27	0.43	0.26	0.42	0.0054	0.023	0.0049	0.021
9/24/09 (a)	0.1	0.38	0.135	0.32	0.0004	0.01	0.0009	0.008
9/24/09 (b)	0.27	0.51	0.297	0.499	0.005	0.03	0.007	0.03

Since comparison of the two control watersheds using a paired t-test measured significant differences between them for flow-based parameters, they may not be expected to result in similar treatment responses when functioning as control watersheds in a paired watershed study. The largest differences in peak flows between the two control watersheds generally occur in summer or early autumn, although the flows with the large differences represent approximately 10% of the autumn readings and approximately 25% of the summer readings. Causes of the differences in watershed response may include: differences in soil moisture deficit due to the southeast aspect of SMZ 20 and the northeast aspect of SMZ 12 and the interaction of certain types of precipitation events during late summer and early fall dry periods, the presence of a road in SMZ 20, or the influence of mining on the border of SMZ 20. Irrespective of the cause, the overall effect on these results in most pronounced in the SMZ 10-SMZ 20 post-harvest regression relationship, and is an indication that SMZ 10 and SMZ 12 are more suitable pairs than SMZ 10 and SMZ 20.

Conclusion

Detecting changes in the storm hydrograph resulting from forest harvesting and drawing conclusions from the results is difficult for paired basin studies due to the confounding effects harvesting can have on changes to the water budget, the influence of harvesting methods, and the characteristics of storm events used in the analysis. These issues can limit the conclusions that may be drawn in studies that consist of a single set of paired catchments. These issues have certainly impacted the conclusions that can be drawn from this study, which is essentially 42 separate paired comparisons, each with a different data set, and incorporating six watersheds that were harvested by two logging crews over a span of 15 months that included a 100 year storm event.

In general, there was limited and inconsistent evidence that the forest harvest impacted the hydrological response to storm events. Overall, the impact of the harvest was not great enough to counter act the already very rapid transport of water through these catchments and change the volume of water moved. The varying characteristics of the SMZs were not a large enough influence on hydrologic response to measure a treatment effect. Changes in peak flow and storm volume were most obvious for low flow events and the changes trended toward pre-harvest regressions as the event size increased. Based on these data, harvesting in these headwater streams does not appreciably change the watershed storm response in any manner that might result in channel morphology changes or exacerbate downstream flooding.

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APPENDIX I : COMPLETE ANCOVA RESULTS FOR TOTAL SUSPENDED SOLIDS MEASURED AT INTERMITTENT MONITORING LOCATIONS

Table A-I. 1: ANCOVA results for total suspended solids measured in non-storm samples taken from intermittent monitoring locations using SMZ 03 as the independent variable.

Parameter: Total Suspended Solids									
Independent Variable: SMZ 03									
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change	ANOVA p value
SMZ 07	Pre-harvest	21	0.44	0.74	0.42	0.13	0.18	-82%	0.04
	Post-harvest	17	0.53		0.05		0.32		0.01
SMZ 09	Pre-harvest	21	0.56	0.98	0.17	0.11	0.23	-73%	0.02
	Post-harvest	10	0.56		-0.32		0.30		0.06
SMZ 11	Pre-harvest	19	-0.04	0.93	0.60	0.12	0.00	-33%	*0.88*
	Post-harvest	16	-0.07		0.13		0.00		*0.80*
SMZ 13	Pre-harvest	21	-0.23	*0.03*	0.66	0.23	0.05	-22%	*0.32*
	Post-harvest	43	0.34		0.16		0.13		0.01
SMZ 15	Pre-harvest	21	0.30	0.74	0.44	0.26	0.09	-40%	*0.16*
	Post-harvest	39	0.38		0.18		0.14		0.02
SMZ 17	Pre-harvest	21	0.34	0.56	0.39	*0.02*	0.12	-74%	*0.11*
	Post-harvest	37	0.46		-0.14		0.30		0.00
SMZ 19	Pre-harvest	20	0.22	0.95	0.56	*0.03*	0.07	-83%	*0.24*
	Post-harvest	13	0.20		-0.06		0.08		*0.32*

Table A-I. 2: ANCOVA results for total suspended solids measured in non-storm samples taken from intermittent monitoring locations using SMZ 07 as the independent variable.

Parameter: Total Suspended Solids									
Independent Variable: SMZ 07									
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change	ANOVA p value
SMZ 03	Pre-harvest	21	0.42	0.52	0.05	0.55	0.18	-60%	0.04
	Post-harvest	17	0.61		-0.14		0.32		0.01
SMZ 09	Pre-harvest	26	0.63	0.44	-0.15	0.21	0.23	-37%	0.01
	Post-harvest	9	0.34		-0.43		0.12		*0.30*
SMZ 11	Pre-harvest	26	-0.06	0.29	0.24	0.20	0.00	-13%	*0.77*
	Post-harvest	8	0.40		-0.26		0.12		*0.34*
SMZ 13	Pre-harvest	20	0.33	0.90	0.13	0.86	0.08	-8%	*0.21*
	Post-harvest	19	0.37		0.18		0.11		*0.14*
SMZ 15	Pre-harvest	20	0.33	0.15	0.05	0.75	0.10	20%	*0.15*
	Post-harvest	18	0.79		0.03		0.46		0.00
SMZ 17	Pre-harvest	23	0.45	0.43	0.03	0.58	0.20	-76%	0.03
	Post-harvest	17	0.66		-0.17		0.48		0.00
SMZ 19	Pre-harvest	23	0.46	0.28	0.21	0.11	0.16	-80%	0.05
	Post-harvest	7	0.86		-0.44		0.67		0.01

Table A-I. 3:ANCOVA results for total suspended solids measured in non-storm samples taken from intermittent monitoring locations using SMZ 09 as the independent variable.

Parameter: Total Suspended Solids									
Independent Variable: SMZ 09									
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change	ANOVA p value
SMZ 03	Pre-harvest	21	0.41	0.67	0.45	0.73	0.23	-39%	0.02
	Post-harvest	10	0.54		0.35		0.30		0.06
SMZ 07	Pre-harvest	27	0.29	0.85	0.58	0.42	0.14	-42%	0.04
	Post-harvest	9	0.35		0.38		0.12		*0.30*
SMZ 11	Pre-harvest								
	Post-harvest								
SMZ 13	Pre-harvest	22	0.07	0.31	0.63	0.67	0.01	-15%	*0.72*
	Post-harvest	12	0.42		0.54		0.17		*0.15*
SMZ 15	Pre-harvest	22	0.18	0.07	0.60	0.61	0.05	-52%	*0.32*
	Post-harvest	13	0.74		0.40		0.53		0.00
SMZ 17	Pre-harvest	22	0.16	0.19	0.59	0.46	0.04	-56%	*0.37*
	Post-harvest	12	0.53		0.33		0.41		0.01
SMZ 19	Pre-harvest	27	0.10	0.55	0.64	0.90	0.03	-50%	*0.41*
	Post-harvest	5	0.35		0.52		0.40		*0.13*

Table A-I. 4: ANCOVA results for total suspended solids measured in non-storm samples taken from intermittent monitoring locations using SMZ 13 as the independent variable.

Parameter:Total Suspended Solids									
Independent Variable: SMZ 13									
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change	ANOVA p value
SMZ 03	Pre-harvest	21	-0.20	0.02	0.59	0.43	0.05	2%	*0.32*
	Post-harvest	43	0.39		0.16		0.13		0.01
SMZ 07	Pre-harvest	22	0.17	0.67	0.46	*0.01*	0.04	-77%	*0.38*
	Post-harvest	19	0.29		-0.26		0.11		*0.14*
SMZ 09	Pre-harvest	22	0.08	0.39	0.45	*0.01*	0.01	-59%	*0.72*
	Post-harvest	12	0.40		-0.53		0.17		*0.15*
SMZ 11	Pre-harvest	21	0.16	0.37	0.47	0.20	0.03	-40%	*0.41*
	Post-harvest	18	0.44		0.05		0.16		0.08
SMZ 15	Pre-harvest	22	0.06	0.05	0.48	0.37	0.00	33%	*0.78*
	Post-harvest	49	0.59		0.10		0.21		0.00
SMZ 17	Pre-harvest	22	0.17	0.19	0.42	0.15	0.03	-2%	*0.40*
	Post-harvest	43	0.49		-0.05		0.20		0.00
SMZ 19	Pre-harvest	22	0.02	0.21	0.50	0.11	0.00	-62%	*0.93*
	Post-harvest	13	0.41		-0.11		0.19		*0.11*

Table A-I. 5: ANCOVA results for total suspended solids measured in non-storm samples taken from intermittent monitoring locations using SMZ 15 as the independent variable.

Parameter: Total Suspended Solids									
Independent Variable: SMZ 15									
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change	ANOVA p value
SMZ 03	Pre-harvest	21	0.31	0.80	0.20	0.67	0.09	-68%	*0.16*
	Post-harvest	39	0.36		0.08		0.14		0.02
SMZ 07	Pre-harvest	22	0.26	0.23	0.33	0.37	0.07	-68%	*0.22*
	Post-harvest	18	0.58		0.06		0.46		0.00
SMZ 09	Pre-harvest	22	0.25	0.20	0.22	0.35	0.05	-78%	*0.32*
	Post-harvest	13	0.71		-0.27		0.53		0.00
SMZ 11	Pre-harvest	22	-0.27	0.05	0.51	0.40	0.08	-67%	*0.17*
	Post-harvest	15	0.32		0.22		0.16		*0.11*
SMZ 13	Pre-harvest	22	0.07	0.19	0.36	0.76	0.00	-59%	*0.78*
	Post-harvest	49	0.35		0.18		0.21		0.00
SMZ 17	Pre-harvest	22	0.13	0.10	0.33	0.22	0.02	-63%	*0.55*
	Post-harvest	42	0.52		-0.13		0.27		0.00
SMZ 19	Pre-harvest	21	0.01	0.07	0.40	0.34	0.00	-68%	*0.98*
	Post-harvest	13	0.59		-0.07		0.53		0.00

Table A-I. 6: ANCOVA results for total suspended solids measured in non-storm samples taken from intermittent monitoring locations using SMZ 17 as the independent variable.

Parameter: Total Suspended Solids									
Independent Variable: SMZ 17									
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change	ANOVA p value
SMZ 03	Pre-harvest	21	0.34	0.25	0.28	0.28	0.12	-25%	*0.11*
	Post-harvest	37	0.64		0.42		0.30		0.00
SMZ 07	Pre-harvest	23	0.43	0.29	0.38	0.58	0.20	-39%	0.03
	Post-harvest	17	0.72		0.23		0.48		0.00
SMZ 09	Pre-harvest	22	0.23	0.18	0.33	0.29	0.04	-59%	*0.37*
	Post-harvest	12	0.77		-0.25		0.41		0.01
SMZ 11	Pre-harvest	21	0.17	0.22	0.47	0.92	0.03	-43%	*0.43*
	Post-harvest	13	-0.26		0.46		0.07		*0.34*
SMZ 13	Pre-harvest	22	0.19	0.38	0.38	0.34	0.03	-14%	*0.40*
	Post-harvest	43	0.40		0.49		0.20		0.00
SMZ 15	Pre-harvest	22	0.13	0.10	0.43	0.29	0.02	-17%	*0.55*
	Post-harvest	42	0.52		0.52		0.27		0.00
SMZ 19	Pre-harvest	21	0.35	0.31	0.44	0.84	0.17	-39%	0.05
	Post-harvest	13	0.64		0.32		0.45		0.01

APPENDIX II COMPLETE ANCOVA RESULTS FOR DISSOLVED OXYGEN CONCENTRATION MEASURED AT PERENNIAL MONITORING LOCATIONS

Table A-II. 1ANCOVA results for dissolved oxygen measured at perennial monitoring locations using SMZ 04 as the independent variable.

Parameter: Dissolved Oxygen								
Independent Variable: SMZ 04								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 08	Pre-harvest	34	0.94	**0.03**	2.03	0.34	0.80	4%
	Post-harvest	48	0.73		4.10		0.83	
SMZ 10	Pre-harvest	34	1.04	0.11	-0.46	0.08	0.88	5%
	Post-harvest	41	0.90		1.52		0.84	
SMZ 12	Pre-harvest	33	0.86	0.12	1.48	0.86	0.74	-1%
	Post-harvest	32	0.72		2.88		0.93	
SMZ 14	Pre-harvest	31	1.08	0.36	-0.86	0.40	0.90	4%
	Post-harvest	73	1.19		-1.72		0.87	
SMZ 16	Pre-harvest	32	1.04	0.55	-0.51	0.38	0.88	5%
	Post-harvest	67	1.13		-0.98		0.85	
SMZ 18	Pre-harvest	31	1.05	0.83	-0.25	0.31	0.80	3%
	Post-harvest	61	1.04		0.19		0.91	
SMZ 20	Pre-harvest	33	0.83	0.60	2.03	0.99	0.76	0%
	Post-harvest	31	0.78		2.52		0.90	

Table A-II. 2: ANCOVA results for dissolved oxygen measured at perennial monitoring locations using SMZ 08 as the independent variable.

Parameter: Dissolved Oxygen								
Independent Variable: SMZ 08								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	34	0.85	**0.01**	0.13	0.12	0.80	-7%
	Post-harvest	48	1.14		-3.30		0.83	
SMZ 10	Pre-harvest	40	0.92	**0.01**	-0.44	0.89	0.81	-1%
	Post-harvest	42	1.21		-3.41		0.92	
SMZ 12	Pre-harvest	39	0.67	**0.05**	2.22	0.11	0.79	-9%
	Post-harvest	24	1.01		-1.62		0.78	
SMZ 14	Pre-harvest	31	1.05	0.29	-1.93	0.54	0.86	-3%
	Post-harvest	48	1.18		-3.41		0.78	
SMZ 16	Pre-harvest	33	0.97	**0.04**	-1.05	0.56	0.75	-4%
	Post-harvest	48	1.27		-4.25		0.76	
SMZ 18	Pre-harvest	34	0.66	0.88	4.26	0.76	0.82	-1%
	Post-harvest	48	0.67		4.09		0.82	
SMZ 20	Pre-harvest	39	0.70	0.20	2.05	0.29	0.76	-7%
	Post-harvest	23	0.92		-0.49		0.74	

Table A-II. 3ANCOVA results for dissolved oxygen measured at perennial monitoring locations using SMZ 10 as the independent variable.

Parameter: Dissolved Oxygen								
Independent Variable: SMZ 10								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	34	0.84	0.27	1.69	**0.03**	0.88	-5%
	Post-harvest	41	0.94		0.15		0.84	
SMZ 08	Pre-harvest	40	0.88	0.14	2.56	0.31	0.81	-2%
	Post-harvest	42	0.76		3.38		0.92	
SMZ 12	Pre-harvest	41	0.67	0.54	3.57	**0.05**	0.83	-8%
	Post-harvest	22	0.76		2.02		0.79	
SMZ 14	Pre-harvest	32	0.95	0.68	0.53	0.35	0.88	-3%
	Post-harvest	42	0.91		0.70		0.76	
SMZ 16	Pre-harvest	34	0.93	0.77	0.70	0.47	0.88	-2%
	Post-harvest	42	0.96		0.19		0.74	
SMZ 18	Pre-harvest	33	1.02	0.45	0.01	0.32	0.85	-2%
	Post-harvest	42	0.94		0.55		0.79	
SMZ 20	Pre-harvest	39	0.71	0.97	3.20	0.22	0.84	-5%
	Post-harvest	23	0.71		2.79		0.74	

Table A-II. 4ANCOVA results for dissolved oxygen measured at perennial monitoring locations using SMZ 14 as the independent variable.

Parameter: Dissolved Oxygen								
Independent Variable: SMZ 14								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	31	0.83	0.23	1.82	0.57	0.90	-3%
	Post-harvest	73	0.73		2.74		0.87	
SMZ 08	Pre-harvest	31	0.82	**0.04**	3.05	0.89	0.86	1%
	Post-harvest	48	0.66		4.39		0.78	
SMZ 10	Pre-harvest	32	0.93	0.36	0.82	0.78	0.88	1%
	Post-harvest	42	0.84		1.78		0.76	
SMZ 12	Pre-harvest	32	0.82	0.76	2.05	0.36	0.84	-3%
	Post-harvest	34	0.84		1.55		0.94	
SMZ 16	Pre-harvest	32	0.95	0.70	0.50	0.96	0.92	0%
	Post-harvest	71	0.97		0.31		0.98	
SMZ 18	Pre-harvest	31	1.04	0.35	-0.16	0.99	0.92	0%
	Post-harvest	67	0.99		0.39		0.95	
SMZ 20	Pre-harvest	32	0.73	**0.05**	3.04	0.85	0.77	-1%
	Post-harvest	32	0.91		1.15		0.90	

Table A-II. 5ANCOVA results for dissolved oxygen measured at perennial monitoring locations using SMZ 16 as the independent variable.

Parameter: Dissolved Oxygen								
Independent Variable: SMZ 16								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	32	0.84	0.43	1.76	0.68	0.88	-3%
	Post-harvest	67	0.76		2.47		0.85	
SMZ 08	Pre-harvest	33	0.78	**0.05**	3.44	0.70	0.75	0%
	Post-harvest	48	0.60		4.87		0.76	
SMZ 10	Pre-harvest	34	0.94	0.07	0.67	1.00	0.88	1%
	Post-harvest	42	0.77		2.44		0.74	
SMZ 12	Pre-harvest	35	0.77	0.18	2.57	0.49	0.72	-2%
	Post-harvest	30	0.89		1.08		0.94	
SMZ 14	Pre-harvest	32	0.97	0.31	0.34	0.91	0.92	0%
	Post-harvest	71	1.02		-0.13		0.98	
SMZ 18	Pre-harvest	33	1.02	0.41	0.11	0.83	0.89	0%
	Post-harvest	66	0.98		0.54		0.97	
SMZ 20	Pre-harvest	33	0.74	**0.03**	2.92	0.93	0.77	-1%
	Post-harvest	31	0.95		0.73		0.90	

Table A-II. 6ANCOVA results for dissolved oxygen measured at perennial monitoring locations using SMZ 18 as the independent variable.

Parameter: Dissolved Oxygen								
Independent Variable: SMZ 18								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	31	0.76	0.09	2.28	0.19	0.80	-3%
	Post-harvest	61	0.88		0.74		0.91	
SMZ 08	Pre-harvest	34	0.66	0.88	4.26	0.76	0.82	-1%
	Post-harvest	48	0.67		4.09		0.82	
SMZ 10	Pre-harvest	33	0.83	0.97	1.56	0.83	0.85	1%
	Post-harvest	42	0.84		1.57		0.79	
SMZ 12	Pre-harvest	33	0.73	0.76	2.66	0.16	0.76	-5%
	Post-harvest	27	0.70		2.53		0.76	
SMZ 14	Pre-harvest	31	0.88	0.13	1.01	0.84	0.92	-1%
	Post-harvest	67	0.96		0.13		0.95	
SMZ 16	Pre-harvest	33	0.87	**0.01**	1.13	0.99	0.89	0%
	Post-harvest	66	0.99		-0.23		0.97	
SMZ 20	Pre-harvest	32	0.69	0.76	3.12	0.46	0.71	-3%
	Post-harvest	28	0.65		3.21		0.68	

APPENDIX III WEIR AND FLUME DISCHARGE EQUATIONS

Broad-Crested Weir

2.5” H-Flume

2” H-Flume

Cutthroat Flume

Trapezoid Flume

H = height of water in feet

Broad-crested weir and both H-flume measure discharge in cubic feet per second.

Cutthroat and trapezoid flumes measure discharge in gallons per minute.

All measurements were converted to cubic meters per minute and adjusted for watershed area for units of $m^3\ min^{-1}\ ha^{-1}$.

APPENDIX IV ANOVA AND ANCOVA EQUATIONS USED IN PAIRED WATERSHED ANALYSES

ANOVA Equations

Equation 1: Sum of Squares for Y

Equation 2: Sum of Squares for X

Equation 3: Sum of Squares for X•Y

Equation 4: Residual Variance

Regression Equations

Equation 5: Slope Calculation

Equation 6: Intercept Calculation

Equation 7: r^2 Calculation

Table A-IV 1: Equations used in calculation of pre-harvest, post-harvest, and combined ANOVA.

Source	df	Sum of Squares	Mean Squares	F
Regression	1			
Residual				
Total				

Table A-IV 2: Equations used in analysis of covariance (ANCOVA) to determine differences in slope and y-intercept.

Source	df	S_x^2	S_{xy}	S_y^2	b_1	df	Sum of Squares (SS)	Mean Squares (MS)	F
Within									
Pre-harvest	n_{Pre}-1	Equation 2	Equation 3	Equation 1	Equation 5	n_{Pre}-2		Equation 4	
Post-harvest	n_{Post}-1	Equation 2	Equation 3	Equation 1	Equation 5	n_{Post}-2		Equation 4	
				Pooled Error		$\sum$	$\sum$	SS/df	
Slope	$n_{Pre}+n_{Post}$-2	$\sum$	$\sum$	$\sum$	Equation 5	$n_{Pre}+n_{Post}$-3		Equation 4	
				Slope Difference		1	Slope SS-Error SS	SS/df	MS/Error MS**
						1	Combined SS-Slope SS	SS/df	MS/Slope MS***
Intercept	$n_{Pre}+n_{Post}$-1	Equation 2*	Equation 3*	Equation 1*	Equation 5*	$n_{Pre}+n_{Post}$-2			

*Equations use data from combined pre-harvest and post-harvest data.
**Used to determine p-value in evaluating differences in slope.
***Used to determine p-value in evaluating differences in y-intercept.

APPENDIX V : COMPLETE PEAK FLOW ANCOVA RESULTS

Table A-V 1: ANCOVA results for peak flow measured at perennial monitoring locations when SMZ 04 was designated the independent variable.

Parameter:Peak Flow-04								
Independent Variable: SMZ 04								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 08	Pre-harvest	18	0.51	0.10	-0.90	0.68	0.67	7%
	Post-harvest*	8	1.18		-0.28		0.37	
SMZ 10	Pre-harvest	28	0.73	0.25	-0.60	0.01	0.76	-36%
	Post-harvest*	1	1.03		-0.69		0.72	
SMZ 14	Pre-harvest	25	0.72	**0.03**	-0.81	0.73	0.66	44%
	Post-harvest	30	1.14		-0.19		0.68	
SMZ 16	Pre-harvest	8	0.64	0.57	-1.07	0.21	0.64	389%
	Post-harvest	24	0.82		-0.46		0.48	
SMZ 18	Pre-harvest	17	0.76	0.53	-0.80	0.32	0.66	-6%
	Post-harvest	21	0.86		-0.56		0.81	

*ANOVA failed (p > 0.05).

Table A-V 2: ANCOVA results for peak flow measured at perennial monitoring locations when SMZ 08 was designated the independent variable.

Independent Variable: SMZ 08								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	18	1.32	0.004	0.53	0.01	0.67	6%
	Post-harvest*	8	0.32		-0.49		0.37	
SMZ 10	Pre-harvest	51	1.07	0.61	0.17	0.19	0.74	43%
	Post-harvest	15	0.99		0.20		0.82	
SMZ 14	Pre-harvest	34	0.99	0.85	-0.09	0.80	0.51	-16%
	Post-harvest	14	1.04		0.01		0.79	
SMZ 16	Pre-harvest	21	1.13	0.61	0.22	0.45	0.80	-20%
	Post-harvest	19	1.04		0.03		0.79	
SMZ 18	Pre-harvest	33	0.96	0.06	-0.06	0.06	0.85	-45%
	Post-harvest*	4	0.42		-0.66		0.28	

*ANOVA failed (p > 0.05).

Table A-V 3:ANCOVA results for peak flow measured at perennial monitoring locations when SMZ 10 was designated the independent variable.

Parameter:Peak Flow-10								
Independent Variable: SMZ 10								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	28	1.05	0.18	0.13	0.004	0.76	76%
	Post-harvest*	1	0.70		0.03		0.72	
SMZ 08	Pre-harvest	51	0.69	0.25	-0.51	0.44	0.74	-29%
	Post-harvest	15	0.83		-0.41		0.82	
SMZ 14	Pre-harvest	56	1.10	0.96	0.00	**0.04**	0.88	-29%
	Post-harvest	7	1.11		-0.20		0.86	
SMZ 16	Pre-harvest	34	1.02	0.34	-0.02	**0.0002**	0.94	-37%
	Post-harvest	13	1.11		-0.16		0.89	
SMZ 18	Pre-harvest	56	1.04		-0.22		0.94	
	Post-harvest**	-1						

*ANOVA failed ($p > 0.05$).

**Insufficient sample numbers for ANCOVA

Table A-V 4:ANCOVA results for peak flow measured at perennial monitoring locations when SMZ 14 was designated the independent variable.

Parameter:Peak Flow								
Independent Variable: SMZ 14								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	25	0.91	**0.04**	0.14	0.15	0.66	-14%
	Post-harvest	30	0.60		-0.35		0.68	
SMZ 08	Pre-harvest	34	0.51	0.14	-0.61	0.97	0.51	22%
	Post-harvest	14	0.76		-0.28		0.79	
SMZ 10	Pre-harvest	56	0.80	0.88	-0.19	**0.03**	0.88	43%
	Post-harvest	7	0.78		-0.03		0.86	
SMZ 16	Pre-harvest	36	0.94	0.38	-0.04	**0.01**	0.92	18%
	Post-harvest	29	0.86		-0.02		0.80	
SMZ 18	Pre-harvest	52	0.89	0.15	-0.32	0.10	0.90	8%
	Post-harvest	21	0.76		-0.38		0.76	

Table A-V 5:ANCOVA results for peak flow measured at perennial monitoring locations when SMZ 16 was designated the independent variable.

Parameter:Peak Flow								
Independent Variable: SMZ 16								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	8	1.01	0.23	0.36	0.63	0.64	-63%
	Post-harvest	24	0.59		-0.52		0.48	
SMZ 08	Pre-harvest	22	0.70	0.59	-0.44	0.21	0.79	28%
	Post-harvest	19	0.76		-0.26		0.79	
SMZ 10	Pre-harvest	34	0.92	0.14	-0.07	**0.0002**	0.94	44%
	Post-harvest	13	0.80		0.00		0.89	
SMZ 14	Pre-harvest	36	0.98	0.60	-0.08	**0.02**	0.92	-13%
	Post-harvest	29	0.93		-0.28		0.80	
SMZ 18	Pre-harvest	44	0.81	0.58	-0.37	**0.002**	0.87	-21%
	Post-harvest	23	0.86		-0.51		0.87	

Table A-V 6:ANCOVA results for peak flow measured at perennial monitoring locations when SMZ 18 was designated the independent variable.

Parameter:Peak Flow								
Independent Variable: SMZ 18								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.87	0.66	0.12	0.86	0.66	25%
	Post-harvest	21	0.95		0.29		0.81	
SMZ 08	Pre-harvest	33	0.88	0.51	-0.12	0.01	0.85	103%
	Post-harvest*	4	0.66		0.01		0.28	
SMZ 10	Pre-harvest	56	0.90		0.12		0.94	
	Post-harvest**	-1						
SMZ 14	Pre-harvest	52	1.01	0.98	0.18	0.28	0.90	-3%
	Post-harvest	21	1.01		0.10		0.76	
SMZ 16	Pre-harvest	44	1.08	0.58	0.22	**0.001**	0.87	33%
	Post-harvest	23	1.02		0.35		0.87	

*ANOVA failed ($p > 0.05$).

**Insufficient sample numbers for ANCOVA

APPENDIX VI COMPLETE QUICK FLOW VOLUME ANCOVA RESULTS

Table A-VI 1:ANCOVA results for quick flow volume measured at perennial monitoring locations when SMZ 04 was designated the independent variable.

Parameter:Quick Flow Volume-04								
Independent Variable: SMZ 04								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 08	Pre-harvest	18	0.63	0.16	-0.03	0.80	0.64	76%
	Post-harvest*	8	1.38		-0.51		0.30	
SMZ 10	Pre-harvest	28	0.83	0.07	-0.05	0.00005	0.76	-78%
	Post-harvest*	1	1.39		-1.21		0.89	
SMZ 14	Pre-harvest	25	0.75	0.10	-0.16	0.57	0.58	87%
	Post-harvest	30	1.08		-0.28		0.64	
SMZ 16	Pre-harvest	8	1.18	0.58	-0.26	0.42	0.67	33%
	Post-harvest	24	0.93		-0.10		0.45	
SMZ 18	Pre-harvest	17	0.75	0.39	-0.19	0.11	0.83	61%
	Post-harvest	21	0.85		-0.07		0.87	

*ANOVA failed (p > 0.05).

Table A-VI 2:ANCOVA results for quick flow volume measured at perennial monitoring locations when SMZ 08 was designated the independent variable.

Parameter:Quick Flow Volume-08								
Independent Variable: SMZ 08								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	18	1.01	0.01	0.02	0.05	0.64	-42%
	Post-harvest*	8	0.22		0.56		0.30	
SMZ 10	Pre-harvest	51	1.03	**0.04**	-0.01	0.92	0.83	-24%
	Post-harvest	15	0.68		0.17		0.63	
SMZ 14	Pre-harvest	34	0.93	0.18	0.05	0.59	0.70	-42%
	Post-harvest	14	0.64		0.15		0.64	
SMZ 16	Pre-harvest	21	1.01	0.06	0.06	0.10	0.89	-40%
	Post-harvest	19	0.70		0.11		0.61	
SMZ 18	Pre-harvest	33	0.84	0.07	0.11	0.0496	0.74	-69%
	Post-harvest*	4	0.22		0.49		0.07	

*ANOVA failed (p > 0.05).

Table A-VI 3ANCOVA results for quick flow volume measured at perennial monitoring locations when SMZ 10 was designated the independent variable.

Independent Variable: SMZ 10								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	28	0.92	0.20	-0.02	0.0001	0.76	245%
	Post-harvest*	1	0.64		0.79		0.89	
SMZ 08	Pre-harvest	51	0.80	0.46	0.09	0.95	0.83	1%
	Post-harvest	15	0.94		0.02		0.63	
SMZ 14	Pre-harvest	56	0.94	0.62	-0.01	0.75	0.87	1%
	Post-harvest	7	1.03		-0.08		0.87	
SMZ 16	Pre-harvest	34	0.98	0.96	-0.02	0.83	0.92	-7%
	Post-harvest	13	0.99		-0.05		0.70	
SMZ 18	Pre-harvest	56	0.92		-0.11		0.91	
	Post-harvest**	-1						

*ANOVA failed (p > 0.05).

**Insufficient sample numbers for ANCOVA

Table A-VI 4:ANCOVA results for quick flow volume measured at perennial monitoring locations when SMZ 14 was designated the independent variable.

Parameter:Quick Flow-14								
Independent Variable: SMZ 14								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	25	0.77	0.25	0.08	0.07	0.58	-51%
	Post-harvest	30	0.60		0.28		0.64	
SMZ 08	Pre-harvest	34	0.75	0.31	0.13	0.56	0.70	21%
	Post-harvest	14	1.01		0.07		0.64	
SMZ 10	Pre-harvest	56	0.93	0.61	0.05	0.62	0.87	-10%
	Post-harvest	7	0.84		0.14		0.87	
SMZ 16	Pre-harvest	36	0.94	0.30	0.01	0.07	0.91	14%
	Post-harvest	29	0.83		0.20		0.71	
SMZ 18	Pre-harvest	52	0.96	0.19	-0.18	0.18	0.85	-20%
	Post-harvest	21	0.80		0.04		0.76	

Table A-VI 5:ANCOVA results for quick flow volume measured at perennial monitoring locations when SMZ 16 was designated the independent variable.

Parameter:Quick Flow								
Independent Variable: SMZ 16								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	8	0.57	0.73	0.03	0.20	0.67	-10%
	Post-harvest	24	0.49		0.23		0.45	
SMZ 08	Pre-harvest	22	0.88	0.92	0.04	0.16	0.88	22%
	Post-harvest	19	0.86		0.19		0.61	
SMZ 10	Pre-harvest	34	0.94	0.08	0.06	0.86	0.92	-8%
	Post-harvest	13	0.71		0.17		0.70	
SMZ 14	Pre-harvest	36	0.96	0.32	0.02	0.11	0.91	-22%
	Post-harvest	29	0.86		-0.05		0.71	
SMZ 18	Pre-harvest	44	0.76	0.81	0.07	0.13	0.79	-38%
	Post-harvest	23	0.73		-0.06		0.77	

Table A-VI 6:ANCOVA results for quick flow volume measured at perennial monitoring locations when SMZ 18 was designated the independent variable.

Parameter:Quick Flow Volume								
Independent Variable: SMZ 18								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	1.10	0.66	0.21	0.46	0.83	-40%
	Post-harvest	21	1.03		0.14		0.87	
SMZ 08	Pre-harvest	33	0.89	0.21	0.13	0.02	0.74	159%
	Post-harvest*	4	0.34		1.01		0.07	
SMZ 10	Pre-harvest	56	0.99	0.23	0.16	0.35	0.91	-46%
	Post-harvest*	2	0.73		0.15		0.71	
SMZ 14	Pre-harvest	52	0.88	0.61	0.23	0.42	0.85	24%
	Post-harvest	21	0.95		0.13		0.76	
SMZ 16	Pre-harvest	44	1.04	0.98	0.00	0.08	0.79	54%
	Post-harvest	23	1.05		0.20		0.77	

*ANOVA failed ($p > 0.05$).

**Insufficient sample numbers for ANCOVA

APPENDIX VII COMPLETE TOTAL STORM VOLUME ANCOVA RESULTS

Table A-VII 1: ANCOVA results for total storm volume measured at perennial monitoring locations using SMZ 04 as the independent variable.

Parameter:Total Storm Volume-04								
Independent Variable: SMZ 04								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 08	Pre-harvest	18	0.59	0.17	0.25	0.53	0.72	18%
	Post-harvest*	8	1.22		-0.73		0.30	
SMZ 10	Pre-harvest	28	0.76	0.10	0.08	0.00002	0.77	-79%
	Post-harvest*	1	1.17		-1.27		0.85	
SMZ 14	Pre-harvest	25	0.78	0.14	-0.01	0.63	0.71	32%
	Post-harvest	30	1.03		-0.25		0.67	
SMZ 16	Pre-harvest	8	0.72	0.65	-0.20	0.43	0.70	223%
	Post-harvest	24	0.89		-0.10		0.51	
SMZ 18	Pre-harvest	17	0.88	0.41	-0.21	0.13	0.75	32%
	Post-harvest	21	0.99		-0.17		0.92	

*ANOVA failed (p > 0.05).

Table A-VII 2: ANCOVA results for total storm volume measured at perennial monitoring locations using SMZ 08 as the independent variable.

Parameter:Total Storm Volume-08								
Independent Variable: SMZ 08								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	18	1.20	0.001	-0.13	0.04	0.72	-14%
	Post-harvest*	8	0.11		1.28		0.09	
SMZ 10	Pre-harvest	51	1.05	0.14	0.00	0.24	0.83	8%
	Post-harvest	15	0.82		0.37		0.70	
SMZ 14	Pre-harvest	34	0.99	0.50	0.08	0.70	0.67	-34%
	Post-harvest	14	0.83		0.21		0.65	
SMZ 16	Pre-harvest	21	0.98	0.49	0.08	0.23	0.84	-20%
	Post-harvest	19	0.86		0.10		0.69	
SMZ 18	Pre-harvest	33	0.87	0.28	0.23	0.10	0.77	-38%
	Post-harvest*	4	0.42		0.78		0.11	

*ANOVA failed (p > 0.05).

Table A-VII 3: ANCOVA results for total storm volume measured at perennial monitoring locations using SMZ 10 as the independent variable.

Parameter:Total Storm Volume-10								
Independent Variable: SMZ 10								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	28	1.02	0.001	0.00	0.40	0.77	261%
	Post-harvest*	1	0.29		0.58		0.63	
SMZ 08	Pre-harvest	51	0.79	0.67	0.19	0.27	0.83	-21%
	Post-harvest	15	0.85		0.01		0.70	
SMZ 14	Pre-harvest	56	1.01	0.72	-0.03	0.15	0.88	-26%
	Post-harvest	7	1.08		-0.26		0.84	
SMZ 16	Pre-harvest	34	0.98	0.77	-0.03	**0.02**	0.95	-30%
	Post-harvest	13	1.01		-0.25		0.85	
SMZ 18	Pre-harvest	56	1.06		-0.28		0.94	
	Post-harvest**	-1						

*ANOVA failed ($p > 0.05$).

**Insufficient sample numbers for ANCOVA

Table A-VII 4: ANCOVA results for total storm volume measured at perennial monitoring locations using SMZ 14 as the independent variable.

Parameter:Total Storm Volume-14								
Independent Variable: SMZ 14								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	25	0.92	0.07	0.16	0.11	0.71	-22%
	Post-harvest	30	0.64		0.47		0.67	
SMZ 08	Pre-harvest	34	0.68	0.58	0.33	0.71	0.67	31%
	Post-harvest	14	0.78		0.26		0.65	
SMZ 10	Pre-harvest	56	0.87	0.54	0.14	0.13	0.88	25%
	Post-harvest	7	0.78		0.37		0.84	
SMZ 16	Pre-harvest	36	0.95	0.50	-0.01	**0.01**	0.95	35%
	Post-harvest	29	0.89		0.21		0.81	
SMZ 18	Pre-harvest	52	1.01	0.18	-0.25	**0.01**	0.89	24%
	Post-harvest	21	0.86		0.13		0.72	

Table A-VII 5: ANCOVA results for total storm volume measured at perennial monitoring locations using SMZ 16 as the independent variable.

Parameter:Total Storm Volume-16								
Independent Variable: SMZ 16								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	8	0.97	0.17	0.30	0.32	0.70	-95%
	Post-harvest	24	0.45		0.58		0.44	
SMZ 08	Pre-harvest	22	0.86	0.68	0.13	0.19	0.84	10%
	Post-harvest	19	0.80		0.35		0.69	
SMZ 10	Pre-harvest	34	0.97	0.18	0.09	0.02	0.95	24%
	Post-harvest	13	0.84		0.39		0.85	
SMZ 14	Pre-harvest	36	1.00	0.22	0.06	**0.02**	0.95	-28%
	Post-harvest	29	0.90		0.01		0.81	
SMZ 18	Pre-harvest	44	0.87	0.62	0.09	0.12	0.85	-20%
	Post-harvest	23	0.92		-0.09		0.86	

Table A-VII 6: ANCOVA results for total storm volume measured at perennial monitoring locations using SMZ 18 as the independent variable.

Parameter:Total Storm Volume-18								
Independent Variable: SMZ 18								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.86	0.58	0.37	0.48	0.75	-23%
	Post-harvest	21	0.93		0.26		0.92	
SMZ 08	Pre-harvest	33	0.89	0.06	0.13	0.04	0.77	67%
	Post-harvest*	4	0.26		1.46		0.11	
SMZ 10	Pre-harvest	56	0.89		0.32		0.94	
	Post-harvest**	-1						
SMZ 14	Pre-harvest	52	0.88	0.68	0.35	**0.04**	0.89	-18%
	Post-harvest	21	0.84		0.24		0.72	
SMZ 16	Pre-harvest	44	0.98	0.70	0.07	0.10	0.85	22%
	Post-harvest	23	0.94		0.24		0.86	

*ANOVA failed ($p > 0.05$).

**Insufficient sample numbers for ANCOVA

APPENDIX VIII : COMPLETE LAG TIME ANCOVA RESULTS

Table A-VIII 1:ANCOVA results for lag time measured at perennial monitoring locations when SMZ 04 was designated the independent variable.

Parameter:Lag Time								
Independent Variable: SMZ 04								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 08	Pre-harvest	18	0.73	0.16	-0.22	0.82	0.52	68%
	Post-harvest	8	1.19		-0.38		0.67	
SMZ 10	Pre-harvest	28	0.82	0.49	-0.01	0.99	0.62	-13%
	Post-harvest	1	0.98		-0.02		1.00	
SMZ 14	Pre-harvest	25	0.78	0.88	-0.05	0.71	0.58	11%
	Post-harvest	30	0.80		-0.01		0.67	
SMZ 16	Pre-harvest	8	1.51	0.38	0.05	0.12	0.43	-45%
	Post-harvest	24	0.98		-0.04		0.96	
SMZ 18	Pre-harvest	17	0.83	0.997	-0.17	0.68	0.41	-8%
	Post-harvest	21	0.83		-0.11		0.63	

Table A-VIII 2:ANCOVA results for lag time measured at perennial monitoring locations when SMZ 08 was designated the independent variable.

Parameter:Lag Time								
Independent Variable: SMZ 08								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	18	0.71	0.50	0.28	0.84	0.52	-29%
	Post-harvest	8	0.56		0.30		0.67	
SMZ 10	Pre-harvest	51	0.70	0.81	0.23	0.84	0.54	7%
	Post-harvest	15	0.74		0.21		0.51	
SMZ 14	Pre-harvest	34	0.71	0.39	0.13	0.051	0.51	57%
	Post-harvest	14	0.54		0.33		0.40	
SMZ 16	Pre-harvest	21	0.85	0.44	0.12	0.13	0.75	29%
	Post-harvest	19	0.71		0.28		0.56	
SMZ 18	Pre-harvest	33	0.88	0.21	0.14	0.21	0.74	22%
	Post-harvest	4	0.55		0.24		0.37	

*ANOVA failed ($p > 0.05$).

Table A-VIII 3:ANCOVA results for lag time measured at perennial monitoring locations when SMZ 10 was designated the independent variable.

Parameter:Lag Time								
Independent Variable: SMZ 10								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	28	0.76	0.28	-0.04	0.66	0.62	35%
	Post-harvest	1	1.02		0.02		1.00	
SMZ 08	Pre-harvest	51	0.77	0.62	-0.17	0.88	0.54	-1%
	Post-harvest	15	0.68		-0.13		0.51	
SMZ 14	Pre-harvest	56	0.83	0.24	-0.03	0.77	0.70	5%
	Post-harvest	7	1.03		-0.03		0.91	
SMZ 16	Pre-harvest	34	0.79	0.06	0.04	0.25	0.73	-5%
	Post-harvest	13	1.03		-0.03		0.96	
SMZ 18	Pre-harvest	56	0.92		-0.09		0.74	
	Post-harvest*							

*Insufficient sample numbers for ANCOVA.

Table A-VIII 4:ANCOVA results for lag time measured at perennial monitoring locations when SMZ 14 was designated the independent variable.

Parameter:Lag Time								
Independent Variable: SMZ 14								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	25	0.75	0.59	-0.01	0.32	0.58	-4%
	Post-harvest	30	0.84		-0.09		0.67	
SMZ 08	Pre-harvest	34	0.71	0.92	-0.13	0.10	0.51	-31%
	Post-harvest	14	0.74		-0.34		0.40	
SMZ 10	Pre-harvest	56	0.84	0.75	-0.02	0.75	0.70	1%
	Post-harvest	7	0.89		0.02		0.91	
SMZ 16	Pre-harvest	36	0.89	0.99	0.06	0.15	0.83	-17%
	Post-harvest	29	0.88		-0.04		0.79	
SMZ 18	Pre-harvest	52	0.95	0.88	-0.02	0.76	0.79	-2%
	Post-harvest	21	0.93		0.00		0.81	

Table A-VIII 5:ANCOVA results for lag time measured at perennial monitoring locations when SMZ 16 was designated the independent variable.

Parameter:Lag Time								
Independent Variable: SMZ 16								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	8	0.29	**0.01**	-0.01	0.15	0.43	105%
	Post-harvest	25	0.98		0.03		0.96	
SMZ 08	Pre-harvest	22	0.88	0.65	-0.13	0.26	0.75	-21%
	Post-harvest	19	0.79		-0.23		0.56	
SMZ 10	Pre-harvest	34	0.92	0.98	-0.08	0.21	0.73	9%
	Post-harvest	13	0.93		0.02		0.96	
SMZ 14	Pre-harvest	36	0.93	0.73	-0.08	0.09	0.83	35%
	Post-harvest	29	0.89		0.03		0.79	
SMZ 18	Pre-harvest	44	0.84	0.44	-0.17	0.15	0.60	30%
	Post-harvest	23	0.95		-0.04		0.79	

Table A-VIII 6:ANCOVA results for lag time measured at perennial monitoring locations when SMZ 18 was designated the independent variable.

Parameter:Lag Time								
Independent Variable: SMZ 18								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.50	0.19	0.09	0.39	0.41	10%
	Post-harvest	21	0.76		0.03		0.63	
SMZ 08	Pre-harvest	33	0.84	0.51	-0.14	0.15	0.74	-24%
	Post-harvest	4	0.66		-0.33		0.37	
SMZ 10	Pre-harvest	56	0.80		0.06		0.74	
	Post-harvest*							
SMZ 14	Pre-harvest	52	0.83	0.67	-0.01	0.83	0.79	9%
	Post-harvest	21	0.87		-0.01		0.81	
SMZ 16	Pre-harvest	44	0.71	0.34	0.09	0.31	0.60	-12%
	Post-harvest	23	0.83		0.03		0.79	

*Insufficient sample numbers for ANCOVA.

APPENDIX IX : COMPLETE FALL TIME ANCOVA RESULTS

Table A-IX 1:ANCOVA results for fall time measured at perennial monitoring locations when SMZ 04 was designated the independent variable.

Parameter:Fall Time								
Independent Variable: SMZ 04								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 08	Pre-harvest	18	0.56	**0.04**	0.44	0.49	0.52	3%
	Post-harvest	8	1.16		-0.14		0.75	
SMZ 10	Pre-harvest	28	0.73	0.22	0.27	**0.01**	0.70	-40%
	Post-harvest	1	1.21		-0.36		1.00	
SMZ 14	Pre-harvest	25	0.60	0.67	0.48	0.67	0.50	-4%
	Post-harvest	30	0.67		0.40		0.53	
SMZ 16	Pre-harvest	7	0.55	0.31	0.40	0.64	0.43	6%
	Post-harvest	24	0.85		0.14		0.74	
SMZ 18	Pre-harvest	17	0.84	0.52	0.20	0.86	0.46	-8%
	Post-harvest	21	0.67		0.36		0.51	

Table A-IX 2:ANCOVA results for fall time measured at perennial monitoring locations when SMZ 08 was designated the independent variable.

Parameter:Fall Time								
Independent Variable: SMZ 08								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	18	0.92	0.32	0.06	0.95	0.52	-9%
	Post-harvest	8	0.65		0.31		0.75	
SMZ 10	Pre-harvest	51	0.79	0.24	0.18	0.15	0.73	-24%
	Post-harvest	15	0.63		0.25		0.62	
SMZ 14	Pre-harvest	34	0.51	0.83	0.51	0.38	0.35	-19%
	Post-harvest	14	0.55		0.41		0.46	
SMZ 16	Pre-harvest	20	0.60	0.62	0.36	0.32	0.45	-14%
	Post-harvest	19	0.69		0.21		0.62	
SMZ 18	Pre-harvest	33	0.72	0.85	0.76	0.69	0.76	8%
	Post-harvest	4	0.30		0.29		0.67	

Table A-IX 3: ANCOVA results for fall time measured at perennial monitoring locations when SMZ 10 was designated the independent variable.

Parameter:Fall Time								
Independent Variable: SMZ 10								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	28	0.96	0.72	0.01	0.06	0.70	84%
	Post-harvest	1	0.83		0.30		1.00	
SMZ 08	Pre-harvest	51	0.92	0.69	0.09	0.98	0.73	13%
	Post-harvest	15	1.00		0.03		0.62	
SMZ 14	Pre-harvest	56	0.65	0.96	0.38	0.37	0.59	-30%
	Post-harvest	7	0.63		0.32		0.52	
SMZ 16	Pre-harvest	33	0.82	0.67	0.16	0.46	0.81	-14%
	Post-harvest	13	0.77		0.16		0.70	
SMZ 18	Pre-harvest	56	0.87		0.14		0.67	
	Post-harvest							

*Insufficient sample numbers for ANCOVA.

Table A-IX 4:ANCOVA results for fall time measured at perennial monitoring locations when SMZ 14 was designated the independent variable.

Parameter:Fall Time								
Independent Variable: SMZ 14								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	25	0.84	0.84	-0.05	0.50	0.50	9%
	Post-harvest	30	0.79		0.03		0.53	
SMZ 08	Pre-harvest	34	0.69	0.63	0.20	0.79	0.35	21%
	Post-harvest	14	0.83		0.10		0.46	
SMZ 10	Pre-harvest	56	0.87	0.82	0.01	0.51	0.67	42%
	Post-harvest	7	0.82		0.10		0.52	
SMZ 16	Pre-harvest	35	0.92	0.95	-0.01	0.31	0.81	17%
	Post-harvest	29	0.91		0.04		0.76	
SMZ 18	Pre-harvest	52	0.92	0.82	-0.01	0.10	0.73	21%
	Post-harvest	21	0.89		0.10		0.67	

Table A-IX 5:ANCOVA results for fall time measured at perennial monitoring locations when SMZ 16 was designated the independent variable.

Parameter:Fall time								
Independent Variable: SMZ 16								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	7	0.78	0.78	0.12	0.54	0.43	10%
	Post-harvest	25	0.87		0.09		0.74	
SMZ 08	Pre-harvest	21	0.75	0.58	0.23	0.77	0.45	10%
	Post-harvest	19	0.89		0.14		0.62	
SMZ 10	Pre-harvest	33	0.98	0.68	0.00	0.71	0.81	16%
	Post-harvest	13	0.91		0.07		0.70	
SMZ 14	Pre-harvest	35	0.88	0.67	0.16	0.46	0.81	-11%
	Post-harvest	29	0.83		0.17		0.76	
SMZ 18	Pre-harvest	43	0.91	0.93	0.07	0.23	0.71	13%
	Post-harvest	23	0.92		0.12		0.76	

Table A-IX 6:ANCOVA results for fall time measured at perennial monitoring locations when SMZ 18 was designated the independent variable.

Parameter:Fall Time								
Independent Variable: SMZ 18								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	18	0.62	0.54	0.30	0.47	0.48	-3%
	Post-harvest	21	0.76		0.12		0.51	
SMZ 08	Pre-harvest	33	1.05	0.54	-0.10	0.64	0.76	-10%
	Post-harvest	4	0.88		0.04		0.67	
SMZ 10*	Pre-harvest	56	0.77		0.17		0.67	
	Post-harvest							
SMZ 14	Pre-harvest	52	0.80	0.75	0.24	0.11	0.73	-18%
	Post-harvest	21	0.76		0.20		0.67	
SMZ 16	Pre-harvest	43	0.78	0.74	0.18	0.23	0.71	-6%
	Post-harvest	23	0.82		0.09		0.76	

*Insufficient sample numbers for ANCOVA.

APPENDIX X : COMPLETE RISE TIME ANCOVA RESULTS

Table A-X 1: ANCOVA results for rise time measured at perennial monitoring locations using SMZ 04 as the independent variable.

Independent Variable: SMZ 04								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 08	Pre-harvest	18	0.69	0.30	0.17	0.81	0.51	18%
	Post-harvest	8	0.99		0.09		0.86	
SMZ 10	Pre-harvest	28	0.80	0.86	0.14	0.01	0.72	-42%
	Post-harvest*	1	0.56		-0.05		0.32	
SMZ 14	Pre-harvest	25	0.63	0.48	0.28	0.68	0.65	8%
	Post-harvest	30	0.72		0.23		0.71	
SMZ 16	Pre-harvest*	8	0.45	0.16	0.09	0.01	0.29	86%
	Post-harvest	24	0.81		0.16		0.73	
SMZ 18	Pre-harvest	17	0.59	0.21	0.32	0.96	0.86	22%
	Post-harvest	21	0.74		0.27		0.71	

*ANOVA failed ($p > 0.05$).

Table A-X 2: ANCOVA results for rise time measured at perennial monitoring locations using SMZ 08 as the independent variable.

Parameter:Rise Time								
Independent Variable: SMZ 08								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	18	0.73	0.61	0.10	0.35	0.51	-19%
	Post-harvest	8	0.87		-0.04		0.86	
SMZ 10	Pre-harvest	51	0.67	0.50	0.12	0.21	0.47	-2%
	Post-harvest	15	0.82		-0.04		0.48	
SMZ 14	Pre-harvest	34	0.61	0.75	0.24	0.81	0.53	18%
	Post-harvest	14	0.53		0.29		0.25	
SMZ 16	Pre-harvest	21	0.85	0.23	0.00	0.67	0.64	20%
	Post-harvest	19	0.58		0.16		0.38	
SMZ 18	Pre-harvest	33	0.75	0.83	0.13	0.94	0.62	-5%
	Post-harvest	4	0.68		0.17		0.72	

Table A-X 3: ANCOVA results for rise time measured at perennial monitoring locations using SMZ 10 as the independent variable.

Independent Variable: SMZ 10								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	28	0.90	0.81	-0.03	0.08	0.72	37%
	Post-harvest*	1	0.57		0.21		0.32	
SMZ 08	Pre-harvest	51	0.70	0.56	0.21	0.70	0.47	-19%
	Post-harvest	15	0.59		0.22		0.48	
SMZ 14	Pre-harvest	56	0.77	0.38	0.17	**0.01**	0.83	39%
	Post-harvest	7	0.64		0.36		0.76	
SMZ 16	Pre-harvest	34	0.86	0.17	0.02	**0.002**	0.75	33%
	Post-harvest	13	0.67		0.27		0.89	
SMZ 18	Pre-harvest	56	0.80		0.17		0.73	
	Post-harvest**							

*ANOVA failed ($p > 0.05$).

**Insufficient sample numbers for ANCOVA

Table A-X 4: ANCOVA results for rise time measured at perennial monitoring locations using SMZ 14 as the independent variable.

Parameter:Rise Time								
Independent Variable: SMZ 14								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	25	1.03	0.78	-0.21	0.49	0.65	-10%
	Post-harvest	30	0.98		-0.15		0.71	
SMZ 08	Pre-harvest	34	0.87	0.16	0.00	0.86	0.53	-25%
	Post-harvest	14	0.47		0.19		0.25	
SMZ 10	Pre-harvest	56	1.08	0.65	-0.12	**0.03**	0.83	-34%
	Post-harvest	7	1.18		-0.34		0.76	
SMZ 16	Pre-harvest	36	0.90	0.83	-0.05	0.24	0.64	-1%
	Post-harvest	29	0.87		0.02		0.80	
SMZ 18	Pre-harvest	52	1.00	0.99	-0.02	0.78	0.85	-8%
	Post-harvest	21	1.00		-0.03		0.90	

Table A-X 5: ANCOVA results for rise time measured at perennial monitoring locations using SMZ 16 as the independent variable.

Parameter:Rise Time								
Independent Variable: SMZ 16								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest*	8	0.65	0.43	0.22	0.03	0.29	-21%
	Post-harvest	24	0.90		-0.04		0.73	
SMZ 08	Pre-harvest	22	0.68	0.89	0.25	0.08	0.58	-24%
	Post-harvest	19	0.65		0.12		0.38	
SMZ 10	Pre-harvest	34	0.86	0.02	0.10	0.00	0.75	-26%
	Post-harvest	13	1.33		-0.33		0.89	
SMZ 14	Pre-harvest	36	0.71	0.11	0.20	0.37	0.64	1%
	Post-harvest	29	0.92		0.07		0.80	
SMZ 18	Pre-harvest	44	0.69	0.35	0.21	0.67	0.65	-1%
	Post-harvest	23	0.83		0.13		0.70	

*ANOVA failed ($p > 0.05$).

Table A-X 6: ANCOVA results for rise time measured at perennial monitoring locations using SMZ 18 as the independent variable.

Parameter:Rise Time								
Independent Variable: SMZ 18								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	1.46	**0.03**	-0.43	0.77	0.86	-25%
	Post-harvest	21	0.96		-0.14		0.71	
SMZ 08	Pre-harvest	33	0.83	0.58	0.12	0.71	0.62	-7%
	Post-harvest	4	1.06		-0.04		0.72	
SMZ 10	Pre-harvest	56	0.92		-0.05		0.73	
	Post-harvest*							
SMZ 14	Pre-harvest	52	0.85	0.58	0.07	0.63	0.85	7%
	Post-harvest	21	0.90		0.07		0.90	
SMZ 16	Pre-harvest	44	0.94	0.55	-0.09	0.32	0.65	2%
	Post-harvest	23	0.84		0.01		0.70	

*Insufficient sample numbers for ANCOVA

APPENDIX XI : COMPLETE TOTAL STORM DURATION ANCOVA RESULTS

Table A-XI 1: ANCOVA results for total storm duration measured at perennial monitoring locations using SMZ 04 as the independent variable.

Parameter:Total Storm Duration								
Independent Variable: SMZ 04								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 08	Pre-harvest	18	0.64	**0.02**	0.41	0.57	0.61	7%
	Post-harvest	8	1.24		-0.23		0.88	
SMZ 10	Pre-harvest	28	0.73	0.23	0.32	0.003	0.74	-40%
	Post-harvest*	1	1.21		-0.38		0.99	
SMZ 14	Pre-harvest	25	0.63	0.69	0.50	0.72	0.65	-1%
	Post-harvest	30	0.68		0.44		0.61	
SMZ 16	Pre-harvest	8	0.51	0.20	0.50	0.90	0.51	14%
	Post-harvest	24	0.86		0.18		0.77	
SMZ 18	Pre-harvest	17	0.78	0.97	0.30	0.68	0.63	1%
	Post-harvest	21	0.79		0.32		0.74	

*ANOVA failed ($p > 0.05$).

Table A-XI 2: ANCOVA results for total storm duration measured at perennial monitoring locations using SMZ 08 as the independent variable.

Parameter:Total Storm Duration								
Independent Variable: SMZ 08								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	18	0.94	0.31	0.04	0.99	0.61	-11%
	Post-harvest	8	0.71		0.28		0.88	
SMZ 10	Pre-harvest	51	0.78	0.54	0.22	0.19	0.76	-17%
	Post-harvest	15	0.70		0.25		0.62	
SMZ 14	Pre-harvest	34	0.59	0.88	0.50	0.87	0.53	-8%
	Post-harvest	14	0.56		0.51		0.62	
SMZ 16	Pre-harvest	21	0.71	0.97	0.30	0.60	0.62	-9%
	Post-harvest	19	0.70		0.28		0.66	
SMZ 18	Pre-harvest	33	0.76	0.68	0.29	0.79	0.80	6%
	Post-harvest	4	0.86		0.20		0.78	

Table A-XI 3: ANCOVA results for total storm duration measured at perennial monitoring locations using SMZ 10 as the independent variable.

Parameter:Total Storm Duration								
Independent Variable: SMZ 10								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	28	1.01	0.61	-0.05	0.03	0.74	67%
	Post-harvest*	1	0.81		0.32		0.99	
SMZ 08	Pre-harvest	51	0.97	0.68	0.05	0.997	0.76	9%
	Post-harvest	15	0.90		0.12		0.62	
SMZ 14	Pre-harvest	56	0.76	0.29	0.32	0.87	0.74	-13%
	Post-harvest	7	0.59		0.49		0.58	
SMZ 16	Pre-harvest	34	0.86	0.31	0.15	0.82	0.87	-4%
	Post-harvest	13	0.74		0.27		0.77	
SMZ 18	Pre-harvest	56	0.89		0.16		0.80	
	Post-harvest**							

*ANOVA failed ($p > 0.05$).

**Insufficient sample numbers for ANCOVA

Table A-XI 4: ANCOVA results for total storm duration measured at perennial monitoring locations using SMZ 14 as the independent variable.

Parameter:Total Storm Duration								
Independent Variable: SMZ 14								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	25	1.03	0.50	-0.22	0.56	0.65	3%
	Post-harvest	30	0.90		-0.05		0.61	
SMZ 08	Pre-harvest	34	0.90	0.49	0.04	0.95	0.53	8%
	Post-harvest	14	1.10		-0.19		0.62	
SMZ 10	Pre-harvest	56	0.98	0.99	-0.08	0.90	0.74	16%
	Post-harvest	7	0.98		-0.08		0.58	
SMZ 16	Pre-harvest	36	1.00	0.75	-0.08	0.31	0.84	9%
	Post-harvest	29	0.97		-0.01		0.85	
SMZ 18	Pre-harvest	52	0.99	0.65	-0.05	0.12	0.80	14%
	Post-harvest	21	0.93		0.07		0.77	

Table A-XI 5: ANCOVA results for total storm duration measured at perennial monitoring locations using SMZ 16 as the independent variable.

Parameter:Total Storm Duration								
Independent Variable: SMZ 16								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	8	1.00	0.78	-0.06	0.75	0.51	0%
	Post-harvest	24	0.89		0.07		0.77	
SMZ 08	Pre-harvest	22	0.86	0.71	0.16	0.84	0.61	3%
	Post-harvest	19	0.94		0.07		0.66	
SMZ 10	Pre-harvest	34	1.02	0.89	-0.02	0.56	0.87	4%
	Post-harvest	13	1.04		-0.07		0.77	
SMZ 14	Pre-harvest	36	0.84	0.71	0.22	0.43	0.84	-6%
	Post-harvest	29	0.87		0.17		0.85	
SMZ 18	Pre-harvest	44	0.91	0.79	0.11	0.28	0.78	9%
	Post-harvest	23	0.94		0.12		0.84	

Table A-XI 6: ANCOVA results for total storm duration measured at perennial monitoring locations using SMZ 18 as the independent variable.

Parameter:Total Storm Duration								
Independent Variable: SMZ 18								
Dependent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 04	Pre-harvest	17	0.80	0.47	0.13	0.64	0.63	-2%
	Post-harvest	21	0.94		-0.05		0.74	
SMZ 08	Pre-harvest	33	1.05	0.61	-0.08	0.69	0.80	-9%
	Post-harvest	4	0.91		0.06		0.78	
SMZ 10	Pre-harvest	56	0.90		0.05		0.80	
	Post-harvest*							
SMZ 14	Pre-harvest	52	0.81	0.87	0.24	0.12	0.80	-12%
	Post-harvest	21	0.83		0.17		0.77	
SMZ 16	Pre-harvest	44	0.86	0.68	0.12	0.32	0.78	-6%
	Post-harvest	23	0.90		0.05		0.84	

*Insufficient sample numbers for ANCOVA

APPENDIX XII :COMPLETE INTERMITTENT ANCOVA RESULTS

Analysis of data collected at intermittent monitoring locations was difficult to complete due to low sample numbers and multiple instances of ANOVA non-significance. Similar to measurements made at the perennial monitoring locations, results varied in magnitude and direction (positive or negative change) depending on the control watershed used in the comparison. Additionally, neither of the treatment 1 watersheds had adequate sample numbers for ANCOVA.

No significant changes were measured in peak flow at the intermittent locations irrespective of the control watershed used for comparison. Quick flow volume results were similar to peak flow results. Six of the eight comparisons measured non-significant ANOVA. The remaining two comparisons measured decreases in quick flow volume that were not statistically different from pre-harvest to post-harvest. Total storm volume is the only flow-based parameter that measured a significant change from the intermittent monitoring locations. A significant increase was measured for the SMZ 03-SMZ 19 relationship. Of the other 7 relationships, five measured non-significant ANOVA and the remaining two measured decreases of 3% and 63%.

Similar issues with ANOVA significance were present in the ANCOVA for time-based hydrograph parameters. No significant changes were measured for concentration time, rise time, or total storm duration. A significant increase in lag time was measured in the SMZ 07-SMZ 11 relationship, and significant increases in fall time were measured in the SMZ 13-SMZ 19 and SMZ 15-SMZ 19 relationships. No other significant differences in timing were measured at the intermittent monitoring points.

ANCOVA results for the hydrograph separation from the intermittent monitoring in treatment watersheds compared to control watersheds are presented in this appendix.

Table A-XII 1: ANCOVA results for peak flow measured at intermittent monitoring locations using SMZ 11 as the un-harvested control watershed.

Parameter:Peak Flow								
Dependent Variable: SMZ 11 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest	9	0.98	0.055	-0.15	0.73	0.82	1%
	Post-harvest	4	1.79		0.69		0.98	
SMZ 07	Pre-harvest	9	1.25	0.10	0.42	0.60	0.79	-42%
	Post-harvest	3	2.15		1.18		0.99	
SMZ 13	Pre-harvest	12	0.64	0.55	-0.31	0.78	0.89	13%
	Post-harvest*	4	0.32		-0.67		0.03	
SMZ 15	Pre-harvest	9	0.97	0.89	0.04	0.59	0.85	-16%
	Post-harvest	1	0.89		-0.16		1.00	

*ANOVA failed (p > 0.05)

Table A-XII 2: ANCOVA results for peak flow measured at intermittent monitoring locations using SMZ 19 as the un-harvested control watershed.

Parameter:Peak Flow								
Dependent Variable: SMZ 19 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest	9	1.19	0.93	-0.04	0.18	0.65	10%
	Post-harvest*	4	1.24		0.34		0.60	
SMZ 07	Pre-harvest*	9	0.95	0.15	0.19	0.95	0.88	-51%
	Post-harvest	3	3.17		2.48		0.38	
SMZ 13	Pre-harvest*	12	0.85	0.07	-0.16	0.42	0.82	2%
	Post-harvest	4	2.09		1.35		0.63	
SMZ 15	Pre-harvest	9	1.41	0.65	0.35	0.93	0.88	-8%
	Post-harvest	1	1.90		0.83		1.00	

*ANOVA failed (p > 0.05)

Table A-XII 3: ANCOVA results for quick flow volume measured at intermittent monitoring locations using SMZ 11 as the un-harvested control watershed.

Parameter:Quick Flow Volume								
Dependent Variable: SMZ 11 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest	9	1.06	0.50	-0.08	0.24	0.96	-14%
	Post-harvest	4	1.29		-0.40		0.67	
SMZ 07	Pre-harvest	9	1.07	0.32	0.13	0.07	0.84	-72%
	Post-harvest	3	1.48		-0.53		0.81	
SMZ 13	Pre-harvest	12	0.84	0.02	0.27	0.17	0.92	-27%
	Post-harvest*	4	-0.63		0.94		0.15	
SMZ 15	Pre-harvest	9	1.14	0.37	-0.12	0.28	0.86	-62%
	Post-harvest*	1	0.53		-0.17		0.56	

*ANOVA failed (p > 0.05)

Table A-XII 4: ANCOVA results for quick flow volume measured at intermittent monitoring locations using SMZ 19 as the un-harvested control watershed.

Parameter:Quick Flow Volume								
Dependent Variable: SMZ 19 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest	9	1.18	0.40	-0.32	0.06	0.85	78%
	Post-harvest*	4	0.69		0.32		0.23	
SMZ 07	Pre-harvest	9	0.82	0.35	0.48	0.51	0.83	-67%
	Post-harvest*	3	1.21		0.17		0.61	
SMZ 13	Pre-harvest	12	0.98	0.02	0.11	0.996	0.84	-60%
	Post-harvest*	4	-0.83		0.70		0.24	
SMZ 15	Pre-harvest	9	1.32	0.15	-0.40	0.68	0.88	-56%
	Post-harvest*	1	0.37		0.01		0.37	

*ANOVA failed (p > 0.05)

Table A-XII 5: ANCOVA results for total storm volume measured at intermittent monitoring locations using SMZ 11 as the un-harvested control watershed.

Parameter:Total Storm Volume								
Dependent Variable: SMZ 11 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest	9	1.05	0.07	-0.18	0.75	0.93	-3%
	Post-harvest	4	2.03		-1.47		0.85	
SMZ 07	Pre-harvest	8	1.12	0.13	-0.02	0.25	0.79	-63%
	Post-harvest	3	2.22		-1.75		0.83	
SMZ 13	Pre-harvest	12	0.81	0.03	0.35	0.39	0.90	-19%
	Post-harvest*	4	-1.12		2.78		0.18	
SMZ 15	Pre-harvest	9	0.99	0.57	0.10	0.16	0.90	-40%
	Post-harvest*	1	1.33		-0.64		0.93	

*ANOVA failed (p > 0.05)

Table A-XII 6:ANCOVA results for total storm volume measured at intermittent monitoring locations using SMZ 19 as the un-harvested control watershed.

Parameter:Total Storm Volume								
Dependent Variable: SMZ 19 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest	9	1.34	0.81	-0.78	**0.004**	0.77	237%
	Post-harvest	4	1.49		-0.11		0.69	
SMZ 07	Pre-harvest	8	0.82	0.29	0.48	0.94	0.87	-70%
	Post-harvest*	3	1.45		-0.11		0.48	
SMZ 13	Pre-harvest	12	1.06	0.12	-0.11	0.50	0.77	-41%
	Post-harvest*	4	-0.44		1.61		0.02	
SMZ 15	Pre-harvest	9	1.34	0.81	-0.65	0.03	0.89	-40%
	Post-harvest*	1	1.17		0.09		0.68	

*ANOVA failed (p > 0.05)

Table A-XII 7: ANCOVA results for concentration time measured at intermittent monitoring locations using SMZ 11 as the un-harvested control watershed.

Parameter:Concentration Time								
Dependent Variable: SMZ 11 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest	12	0.50	0.18	0.47	0.22	0.52	-11%
	Post-harvest	8	0.84		0.15		0.69	
SMZ 07	Pre-harvest	15	1.16	0.36	-0.27	0.52	0.53	-26%
	Post-harvest*	3	0.35		0.29		0.55	
SMZ 13	Pre-harvest	15	0.68	0.40	0.24	0.66	0.38	10%
	Post-harvest*	8	0.37		0.50		0.15	
SMZ 15	Pre-harvest	12	0.84	0.26	0.17	0.85	0.44	0%
	Post-harvest*	5	0.30		0.57		0.12	

*ANOVA failed (p > 0.05)

Table A-XII 8: ANCOVA results for concentration time measured at intermittent monitoring locations using SMZ 19 as the un-harvested control watershed.

Parameter:Concentration Time								
Dependent Variable: SMZ 19 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest	12	0.67	0.72	0.32	0.20	0.62	-9%
	Post-harvest	8	0.58		0.28		0.45	
SMZ 07	Pre-harvest	15	0.91	0.30	-0.23	0.37	0.25	23%
	Post-harvest*	3	0.10		0.44		0.10	
SMZ 13	Pre-harvest	15	1.10	0.08	-0.12	0.32	0.84	15%
	Post-harvest	8	0.67		0.29		0.53	
SMZ 15	Pre-harvest	12	1.04	0.15	-0.02	0.57	0.63	-2%
	Post-harvest	5	0.55		0.39		0.65	

*ANOVA failed (p > 0.05)

Table A-XII 9: ANCOVA results for rise time measured at intermittent monitoring locations using SMZ 11 as the un-harvested control watershed.

Parameter:Rise TIme								
Dependent Variable: SMZ 11 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest	12	0.76	0.44	0.16	0.51	0.63	-10%
	Post-harvest	8	1.03		-0.01		0.68	
SMZ 07	Pre-harvest	15	0.81	0.25	0.01	0.17	0.55	5%
	Post-harvest	3	2.21		-0.40		0.85	
SMZ 13	Pre-harvest	15	0.89	0.50	0.05	0.91	0.67	3%
	Post-harvest	8	1.12		-0.05		0.65	
SMZ 15	Pre-harvest	12	0.78	0.31	0.07	0.90	0.63	21%
	Post-harvest	5	1.25		-0.12		0.66	

Table A-XII 10: ANCOVA results for rise time measured at intermittent monitoring locations using SMZ 19 as the un-harvested control watershed.

Parameter:Rise TIme								
Dependent Variable: SMZ 19 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest	12	0.91	0.26	0.07	0.97	0.74	-15%
	Post-harvest	8	0.63		0.17		0.61	
SMZ 07	Pre-harvest	15	0.73	0.83	0.02	0.62	0.35	-2621%
	Post-harvest*	3	0.60		-0.11		0.42	
SMZ 13	Pre-harvest	15	0.95	0.46	0.05	0.94	0.70	-11%
	Post-harvest	8	0.77		0.13		0.68	
SMZ 15	Pre-harvest	12	0.85	0.58	0.07	0.79	0.73	-8%
	Post-harvest	5	0.71		0.09		0.68	

*ANOVA failed ($p > 0.05$)

Table A-XII 11: ANCOVA results for total storm duration measured at intermittent monitoring locations using SMZ 11 as the un-harvested control watershed.

Parameter:Total Storm Duration								
Dependent Variable: SMZ 11 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest	12	0.80	0.28	0.24	0.93	0.78	6%
	Post-harvest	8	1.09		-0.02		0.75	
SMZ 07	Pre-harvest	15	0.97	0.43	-0.03	0.11	0.74	-32%
	Post-harvest*	3	0.55		0.16		0.47	
SMZ 13	Pre-harvest	15	0.89	0.81	0.11	0.56	0.71	11%
	Post-harvest	8	0.96		0.09		0.67	
SMZ 15	Pre-harvest	12	0.92	0.12	0.11	0.67	0.86	17%
	Post-harvest	5	1.47		-0.41		0.78	

*ANOVA failed (p > 0.05)

Table A-XII 12: ANCOVA results for total storm duration measured at intermittent monitoring locations using SMZ 19 as the un-harvested control watershed.

Parameter:Total Storm Duration								
Dependent Variable: SMZ 19 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest	12	0.94	0.06	0.07	0.55	0.87	5%
	Post-harvest	8	0.64		0.41		0.86	
SMZ 07	Pre-harvest	15	0.87	0.13	0.05	0.76	0.66	68%
	Post-harvest*	3	0.28		0.42		0.39	
SMZ 13	Pre-harvest	15	0.93	0.14	0.09	0.44	0.83	5%
	Post-harvest	8	0.68		0.38		0.81	
SMZ 15	Pre-harvest	12	0.87	0.15	0.16	0.46	0.81	3%
	Post-harvest	5	0.60		0.47		0.86	

*ANOVA failed (p > 0.05)

Table A-XII 13: ANCOVA results for lag time measured at intermittent monitoring locations when SMZ 11 was designated the un-harvested control.

Parameter:Lag Time								
Dependent Variable: SMZ 11 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest*	12	0.76	0.89	-0.07	0.44	0.20	-9%
	Post-harvest	8	0.84		-0.23		0.55	
SMZ 07	Pre-harvest	15	1.15	**0.02**	-0.13	**0.01**	0.71	88%
	Post-harvest	3	0.36		0.47		0.83	
SMZ 13	Pre-harvest*	15	0.85	0.89	-0.17	0.48	0.22	-12%
	Post-harvest	8	0.80		-0.04		0.83	
SMZ 15	Pre-harvest	12	1.08	0.37	0.05	0.07	0.68	-45%
	Post-harvest	5	0.86		-0.12		0.92	

*ANOVA failed (p > 0.05)

Table A-XII 14: ANCOVA results for lag time measured at intermittent monitoring locations when SMZ 19 was designated the un-harvested control.

Parameter:Lag Time								
Dependent Variable: SMZ 19 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest*	12	0.77	0.97	-0.13	0.67	0.25	39%
	Post-harvest*	8	0.79		-0.23		0.27	
SMZ 07	Pre-harvest	15	0.44	0.42	0.23	0.81	0.24	0%
	Post-harvest	3	0.94		0.07		0.92	
SMZ 13	Pre-harvest	15	0.84	0.81	-0.23	0.40	0.34	45%
	Post-harvest*	8	0.73		-0.05		0.32	
SMZ 15	Pre-harvest	12	0.95	0.41	0.04	0.44	0.75	-7%
	Post-harvest*	5	0.57		-0.03		0.17	

*ANOVA failed (p > 0.05)

Table A-XII 15: ANCOVA results for fall time measured at intermittent monitoring locations when SMZ 11 was designated the un-harvested control.

Parameter:Fall Time								
Dependent Variable: SMZ 11 (Falling Rock)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest	12	0.66	0.21	0.32	0.61	0.67	7%
	Post-harvest	8	1.02		0.06		0.69	
SMZ 07	Pre-harvest	15	0.88	0.23	0.05	0.11	0.65	-45%
	Post-harvest*	3	0.23		0.33		0.14	
SMZ 13	Pre-harvest	15	0.83	0.94	0.13	0.44	0.63	13%
	Post-harvest	8	0.85		0.18		0.54	
SMZ 15	Pre-harvest	12	0.93	0.24	0.11	0.78	0.80	13%
	Post-harvest	5	1.49		-0.34		0.71	

*ANOVA failed (p > 0.05)

Table A-XII 16: ANCOVA results for fall time measured at intermittent monitoring locations when SMZ 19 was designated the un-harvested control.

Parameter:Fall Time								
Dependent Variable: SMZ 19 (Little Millseat)								
Independent Variable	Treatment Phase	df	Slope	p-value	Intercept	p-value	R2	% Change
SMZ 03	Pre-harvest	12	0.72	0.35	0.27	0.63	0.61	-5%
	Post-harvest	8	0.54		0.45		0.81	
SMZ 07	Pre-harvest	15	0.95	0.04	-0.07	0.88	0.70	-10%
	Post-harvest*	3	0.21		0.39		0.37	
SMZ 13	Pre-harvest	15	1.05	**0.03**	-0.08	0.21	0.82	8%
	Post-harvest	8	0.52		0.46		0.56	
SMZ 15	Pre-harvest	12	1.07	**0.01**	-0.06	0.15	0.87	8%
	Post-harvest	5	0.49		0.53		0.77	

*ANOVA failed (p > 0.05)

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