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Effectiveness of Forestry Best Management Practices in minimizing harvesting impacts on streamflow and sediment loading in low-gradient headwaters of the Gulf Coastal Plain

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EFFECTIVENESS OF FORESTRY BEST MANAGEMENT PRACTICES IN MINIMIZING HARVESTING IMPACTS ON STREAMFLOW AND SEDIMENT LOADING IN LOW-GRADIENT HEADWATERS OF THE GULF COASTAL PLAIN

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ABSTRACT

Few studies have examined the effectiveness of timber harvesting Best Management Practices (BMPs) in water quality protection of widely-spread, low-gradient, and highly intermittent headwaters on the Gulf Coastal Plain. Also, a spatial disparity exists between the plot-scale water quality benefits afforded by BMP implementation and the watershed-scale with which most watershed stewardship programs are managed. In this thesis research, paired-watershed and Before-After-Control-Impact (BACI) designs were utilized to quantify plot- and watershed-scale changes in streamflow, as well as baseflow and stormflow Total Suspended Sediment (TSS) concentration and yield for 27 months after clearcut harvesting with and without BMPs in a low-gradient, forested, 3rd-order watershed of north-central Louisiana. Based on analyses of post-harvest baseflow, stormflow, stage-discharge relationships, TSS concentration, and sediment yield, low-intensity (2-8% disturbance of sub-watershed drainage area), clearcut harvesting adjacent to streams and with BMP implementation did not impact streamflow or sediment transport at the plot- or watershed-scale. No difference was found between treatment periods for monthly baseflow discharge measurements or in peak water level response to storm events. Flow duration curve analysis showed that baseflow decreased during the post-harvest period, possibly due to differences in the timing of precipitation between treatment periods. Changes in the stage-discharge relationship were observed downstream of harvesting without BMPs, indicating harvest-induced changes to stream geomorphology. Baseflow and stormflow TSS concentration (mg L^{-1}) and yield (kg ha^{-1} $mo.^{-1}$) were similar between treatment periods and were on the lower end of published results for Coastal Plain sites. Post-harvest TSS yield increased downstream of harvesting without BMP implementation when high flow events were included in yield calculations. These results indicate that current Louisiana BMPs for timber

harvesting are effective in mitigating sediment runoff at the plot- and watershed-scale for conditions similar to the monitored sites, which include an abundance of beaver/debris dams and highly intermittent streamflow. These natural conditions may have further improved sediment reduction from BMP implementation through ponding and reduction of flow rate and carrying capacity. The potential exists for future studies to determine the intermittency and beaver dam impacts to streamflow and sediment transport as forest disturbance increases throughout the watershed.

CHAPTER 1: INTRODUCTION

Headwater streams dominate the cumulative drainage length of a typical river basin (Benda et al., 2005; Freeman et al., 2007). Their contributions to downstream water quantity and quality include streamflow, physical habitat, allocthonous organic material, and aquatic life. Management efforts to minimize nonpoint source (NPS) pollution and maximize the quality and quantity of water resources for downstream users must include stewardship of headwater streams. Although headwater drainages dominated by forested land use are generally considered to have the highest water quality, this is not always the case, as water chemistry and quality depends on factors such as climate, geology, topography, soil type, and historical and present land use (Stuart and Edwards, 2006).

Silviculture is considered by the Environmental Protection Agency to be a major source of NPS pollution to water bodies, even if it is ranked 9^{th} out of 10 on the list, because intensive forest management has the potential to impact water resource quantity and quality and because silvicultural practices occur on vast land resources. Over the past century, a tremendous amount of research (Bosch and Hewlett, 1982; Calder, 1990; Stednick, 1996; Andreassian, 2004) has been conducted to elucidate the relationships among forests, forestry operations, and water. It is widely recognized that a reduction of forest cover increases water yield, mainly through decreases in evapotranspiration (ET), and that the reverse is true. Timber harvesting can increase baseflow and stormflow, as well as the amount of sediment transported to and within stream channels, which can have deleterious effects on aquatic habitat and biota.

Forestry BMPs can include pre-harvest planning for efficient placement and design of logging roads, skidding trails, loading zones, and streamside management zones (SMZs), as well

as restricting operations to dry periods to minimize soil erosion and compaction. The primary purpose of BMP implementation is to protect water quality. However, much of what we know about forests and water and the effectiveness of forestry BMPs has come from studies conducted in mountainous areas with more continuous streamflow and on a small, plot-scale, not far from the operational boundaries of silvicultural practices. Fewer studies have examined low-gradient headwaters of the Gulf Coastal Plain, which are characterized by highly variable hydrology, including long periods of intermittency during the summer season. In addition, watershed-scale natural resource management is increasingly becoming the standard, making it essential to understand the downstream cumulative impacts of intensive forest management at this same scale.

To meet these research needs, a three-part project emphasizing hydrology, water quality, and stream ecology was initiated in the Flat Creek Watershed of north-central Louisiana to examine timber harvesting BMP effectiveness in maintaining and/or improving stream water quality from the headwaters to the watershed outlet. A calibration period of stream monitoring was conducted from December 2005 to August 2007. In the late summer and fall of 2007, four clearcuts occurred in the headwaters of Turkey Creek and Big Creek, which are tributaries to Flat Creek. Forestry BMPs were implemented at the three Turkey Creek harvest sites, but not at the Big Creek harvest site. In addition, another pair of sites was left as an uncut control (Spring Creek). Thus, the research project employed paired-watershed and Before-After-Control-Impact (BACI) designs. Watershed monitoring continued from September 2007 to December 2009 to address the following question: Are Louisiana's recommended forestry BMPs effective in minimizing harvesting impacts to streamflow and sediment concentration and yield at the plot- and watershed-scale? This thesis research presents post-harvest findings related to hydrology

and sediment concentration and yield. Post-harvest findings related to water quality and stream ecology will be presented elsewhere.

This thesis is divided into five chapters. Chapter 2 provides a literature review emphasizing the current state of research and understanding of headwater stream hydrology and the impacts of intensive forest management to streamflow and sediment transport at the plot- and watershed-scales. Chapters 3 and 4 present findings from this paired-watershed and BACI-designed study to determine the effectiveness of forestry BMPs in minimizing harvesting impacts on streamflow (Chapter 3) and stream sediment concentration and yield (Chapter 4) at small and large spatial scales in the low-gradient headwaters of the Flat Creek Watershed of north-central Louisiana. Chapters 3 and 4 are written as stand-alone manuscripts for submission to peer-reviewed journals. There will be some repetition between chapters, as each stand-alone manuscript has its own introduction, methods, results and discussion, and conclusions sections.

CHAPTER 2: LITERATURE REVIEW

2.1 Hydrologic Characteristics of Forested Headwaters

Headwater streams compose over two-thirds of the cumulative drainage length of river basins and serve to link riparian and upland habitats to downstream ecosystems by providing streamflow, physical habitat, allochthonous organic material, and aquatic life (Benda et al., 2005; Freeman et al., 2007). Intensive forest management activities within headwater drainages have the potential to alter downstream water quantity and quality. The value of headwaters to downstream water quality is evident by the fact that New York City spent $300 million in 2007 to conserve land surrounding its drinking water sources in the Catskill Mountains (NYC DEP, 2007). Much effort has been afforded to classify headwater streams, although they have eluded a concrete definition. They have been classified according to hydrology (stream-order, flow frequency), geomorphology (stream gradient, drainage area) and some biological characteristics, including whether or not fish are present (Benda et al., 2005). Generally, headwaters can include zero-order basins, channel heads or initiation zones, ephemeral drains, intermittent streams, and perennial first- and second-order streams.

Headwater stream geomorphology and hydrology have been well documented in more mountainous regions, including the Pacific Northwest, the Rockies, and the Appalachians. Considerably less attention has been given to low-gradient forested headwaters of the Gulf Coastal Plain, which are characterized by highly variable streamflow. These headwater systems are characterized by frequent periods of intermittency during the winter (December through April) and summer (May through November) seasons. Discharge is minimal due to a combination of slowly permeable soils, low-stream gradients, high evapotranspiration rates, and

an abundance of beaver/debris dams. Conversely, heavy rainfall upon wet soils during the winter season can easily bring headwaters to flood stage, and these events can represent a substantial proportion of total annual flow (McBroom et al., 2008).

2.2 Intensive Forest Management Effects on Headwater Streamflow and Sediment

The impacts of forestry operations to streamflow have been assessed worldwide and for nearly a century by way of the paired-watershed design, which utilizes a calibration period and a control watershed to detect changes in hydrology of a treatment watershed. Almost invariably, the result has been that a reduction of forest cover increases annual water yield (Hibbert, 1967; Bosch and Hewlett, 1982; Bruijnzeel, 1990; Calder, 1990; Stednick, 1996; Brown et al., 2005; Moore and Wondzell, 2005). Bosch and Hewlett (1982) concluded that a 10% change in coniferous/eucalypt, deciduous hardwoods, and brush/grasslands cover was associated with an annual change in water yield of approximately 40, 25, and 10 mm, respectively. In addition, the authors concluded that annual water yield increases could not be detected through hydrometric measurement when the reduction of forest cover is less than 20% of the total drainage area. Others have discussed this issue (McMinn and Hewlett, 1975; Stednick, 1996), philosophizing that the effect of zero treatment must be zero, it is simply a difficult task to detect changes in water yield when vegetation removal has not exceeded 20% of the watershed area. The threshold for detection of water yield increases as a result of vegetation removal varies by geographic region. For example, only about 15% of a watershed must be harvested for Rocky Mountain sites, while approximately 45% of the watershed area must be harvested for a detectable increase in annual water yield for Eastern Coastal Plain sites (Stednick, 1996). Water yield increases are generally most pronounced during the initial post-treatment years, with hydrologic recovery occurring at a rate proportional to the region's mean annual precipitation

and productivity. Streamflow increases are generally most apparent during the growing season when soil moisture differences between harvested and control watersheds are greatest.

Many studies have shown that a reduction of forest cover increases baseflow in temperate forested catchments (Hornbeck et al., 1993; Brown et al., 2005). Following clearcut harvesting 43.2 and 40.3 % of two small (23.9 and 22.3 ha, respectively) *Pinus radiata* plantation catchments in the Canabolas State Forest in southeastern Australia, monthly streamflow increased significantly due to a significant increase in baseflow post-harvest (Webb, 2009). Timber harvesting can also cause changes in storm hydrograph characteristics, including increased peakflow rate, initial flow rate, and stormflow volume, duration, and recession time (Guillemette et al., 2005; Eisenbies et al., 2007). The magnitude of harvest-induced effects on stormflow depends on watershed characteristics that affect streamflow responsiveness to precipitation inputs, severity of harvest disturbance, and road density. For instance, timber harvesting in flat terrain landscapes, such as those of the southeast U.S. coastal plain, was reported to have mainly caused water table rise (Xu et al., 2000; Sun et al., 2001) instead of increased streamflow.

Concerns about intensive forest management and alteration of headwater hydrology relate to aquatic habitat. Changes in streamflow, sediment transport, occurrence of bankfull events and channel development (Hicks et al., 1991; Stott and Mount, 2004; Croke and Hairsine, 2006) can degrade physical habitat for aquatic life. In addition, intensive forest management often causes nutrient enrichment in adjacent water bodies (Corbett et al., 1978; Blackburn and Wood, 1990; Ensign and Mallin, 2001), which can alter water chemistry and quality for aquatic life. Forested headwater streams are generally considered to be of high water quality. However, this is not always the case. Water quality depends on a variety of factors including climate, geology,

topography, and historical and present land use. Sediment is the primary pollutant of concern for forested headwater streams (Stuart and Edwards, 2006). Intensive forest management can increase the quantity of sediment delivered to and transported within stream channels (Croke and Hairsine, 2006). Silvicultural operations involve road construction, timber harvesting, skidding and loading, site preparation, and tree planting. Road construction, harvesting, and site preparation are all nonpoint sources of sediment (Binkley and Brown, 1993; Karwan et al., 2007). Timber harvesting generally leaves the hydrologic functions of the forest litter layer intact (Stuart and Edwards, 2006). However, the whole process involves heavy machinery to cut, skid, and load harvested timber, along with the construction of haul roads, which may cross stream channels. Skidding trails and haul roads can increase the connectivity of stormflow runoff to streams, which increases stormflow and sediment delivery to stream channels. The use of heavy machinery can compact soil, thus limiting its capacity to transmit water (Whitehead and Robinson, 1993). Site preparation may involve roller chopping, burning, herbicide application, and plowing and bedding, which exposes mineral soil to the erosive potential of rainfall. However, NPS pollution from intensively managed forested watersheds is generally regarded as being much less than drainage areas dominated by urban areas or farmland (Blackburn et al., 1990). The majority of impact studies regarding intensive forest management, streamflow, and sediment yield have been conducted in headwaters draining steep slopes, which may not be applicable to low-gradient coastal plain headwaters.

2.3 Forestry BMP Effectiveness

The reduction of runoff source strength and delivery of sediment and nutrients to surface water is crucial to minimize the downstream impacts of forestry operations (Croke and Hairsine, 2006). Today, foresters utilize a combination of BMPs to achieve this. BMPs include pre-

harvest planning for efficient forest harvesting, site preparation, and selecting appropriate locations for logging sets and road systems. Streamside Management Zones (SMZs) or buffer strips are used to maintain a sufficient width and density of vegetation on either side of the stream to provide ecosystem services such as bank stabilization, filtration of sediment and other pollutants carried by sheetflow, addition of allocthonous organic material to stream channels, and protection against thermal pollution. Timber harvesting utilizes pre-harvest planning for cutting, skidding, and loading zones to avoid increasing hydrologic and sediment source connectivity to stream channels. Timing of cutting is also considered. Restricting harvesting to dry antecedent soil moisture conditions decreases soil disturbance. Site preparation and regeneration methods are selected to protect water quality and improve soil quality by reducing soil exposure, displacement, and compaction. Other considerations for BMPs include chemical management and the protection of forested wetlands. BMP effectiveness has been validated in topographic regions spanning from mountainous to coastal plain (McBroom et al., 2008), but most studies of BMP effectiveness have been conducted at the small, plot-scale (Grace, 2005). More research is needed to determine if the plot-scale benefits of BMPs translate to the maintenance or improvement of water quality at the watershed-scale.

Protection of water quality is the primary goal of Forestry BMPs (Aust, 1994). BMPs for timber harvesting include pre-harvest planning for skid trails, haul roads, and loading zones, utilizing riparian zone buffers, minimizing stream crossings, and the stabilization and closure of roads. BMP effectiveness in reducing the impact of clearcut harvesting to streamflow has been validated at the plot-scale (Arthur et al., 1998; Wynn et al., 2000; Stuart and Edwards, 2006; McBroom et al., 2008) in many other states, but not in Louisiana.

In 2000, the Louisiana Forestry Association, Louisiana Department of Environmental Quality, and the Louisiana Department of Agriculture and Forestry made revisions to the State's recommended Forestry BMPs. Evaluation of forestry BMP effectiveness is critical due to the dominance of forested lands within the state (nearly half of the total land use) and in the context of an anticipated increase in demand for the South's forest resources in the near future (Wear and Greis, 2002).

2.4 Cumulative Impacts of Intensive Forest Management

Furthermore, performance of timber harvesting BMPs in protecting water quality has rarely been assessed beyond the small watershed-scale. In a worldwide review of vegetal effects on water yield, Bosch and Hewlett (1982) found that the mean size of watersheds studied was only 0.8 km^2. Water resources/quality management is generally based on the watershed-scale. Thus, it is important to understand the cumulative effects of intensive forest management on water quantity and quality on an equal scale and over the long-term (Swank et al., 2001; Scott et al., 2002; Donnelly, 2003; Buttle et al., 2009).

The impacts of continuous intensive forest management over many decades and at the basin-scale to regional hydrology, sedimentation, geomorphology, and aquatic habitat are not fully understood (Chen and Wei, 2008). In the central and south interior of British Columbia, Chen and Wei (2008) tested aquatic habitat indicators, such as in-stream wood loading, frequency of residual pools, substrates, and embedment, for their relationship to historical logging and equivalent clearcut area (ECA), which is an adjusted clearcut area that accounts for the subsequent hydrological recovery of harvested landscapes or stands. The authors found that pool frequency and per piece large woody debris volume were significantly correlated to forest

harvesting disturbance quantified by percent ECA and concluded that physical habitat indicators can be used to determine cumulative impacts of forest harvesting to aquatic systems at the basin-scale.

Dhakal and Sidle (2003) used a physically-based slope stability model to determine the effects of harvesting at various intensities and rotational lengths on landslide initiation and volume in a sub-watershed of Carnation Creek, Vancouver Island, British Columbia. The authors concluded that a combination of forest management practices such as partial cutting, longer rotation length, provision of leave areas, and harvesting with minimal disturbance to understory vegetation were most effective in reducing the occurrence of landslides.

Concerns about salmonid habitat, as well as the occurrence of landslides and their related sediment input to streams, have placed a great deal of importance on understanding the cumulative impacts of forestry operations at the larger basin-scale in the steep slopes of the Pacific Northwest (Dunne, 1998; Wondzell, 2001; Lin and Wei, 2008) and around the world (Lu et al., 2001). Declining turbidity over the past thirty years in the Deschutes River basin of western Washington, USA has been attributed to effective management of runoff from forest roads (Reiter et al., 2009). The importance of landscape and watershed-scale management is gaining widespread recognition, but few studies have examined intensive forest management effects on hydrology and water quality of low-gradient watersheds of the Gulf Coastal Plain.

CHAPTER 3: EFFECTIVENESS OF FORESTRY BEST MANAGEMENT PRACTICES IN MINIMIZING HARVESTING IMPACTS ON STREAMFLOW IN LOW-GRADIENT HEADWATERS

3.1 Introduction

Headwater streams compose over two-thirds of the cumulative drainage length of river basins and serve to link riparian and upland habitats to downstream ecosystems by providing streamflow, physical habitat, allochthonous organic material, and aquatic life (Benda et al., 2005; Freeman et al., 2007). Therefore, headwaters can govern downstream hydrologic conditions and water quality on a regional scale. The impacts of forestry operations, such as timber harvesting, to streamflow within headwater drainages have been assessed worldwide and for nearly a century by way of the paired-watershed design, which utilizes a calibration period and a control watershed to detect changes in hydrology of a treatment watershed. Almost invariably, the result has been that a reduction of forest cover increases annual water yield (Hibbert, 1967; Bosch and Hewlett, 1982; Stednick, 1996; Brown et al., 2005; Moore and Wondzell, 2005). Bosch and Hewlett (1982) concluded that a 10% change in coniferous/eucalypt, deciduous hardwoods, and brush/grasslands cover was associated with an annual change in water yield of approximately 40, 25, and 10 mm, respectively. In addition, the authors concluded that, in general, annual water yield increases could not be detected through hydrometric measurement when the reduction of forest cover is less than 20% of the total catchment area. Water yield increases are most pronounced during the initial post-treatment years, with hydrologic recovery occurring at a rate proportional to the region’s mean annual precipitation and productivity. Streamflow increases are generally most apparent during the growing season, when soil moisture differences between harvested and control watersheds are greatest, as a result of decreased evapotranspiration (ET) on the harvested watershed.

Many studies have shown that a reduction of forest cover increases baseflow in temperate forested catchments (Hornbeck et al., 1993; Brown et al., 2005). Following clearcut harvesting 43.2 and 40.3 % of two small (23.9 and 22.3 ha, respectively) *Pinus radiata* plantation catchments in the Canabolas State Forest in southeastern Australia, monthly streamflow increased significantly due to a significant increase in baseflow post-harvest (Webb, 2009). Timber harvesting can also cause changes in storm hydrograph characteristics, including increased peakflow and initial flow rate, stormflow volume, duration, and recession time (Guillemette et al., 2005; Eisenbies et al., 2007). The magnitude of harvesting-induced effects on stormflow depends on watershed responsiveness to precipitation inputs, severity of harvest disturbance, and road density.

Concerns about timber harvesting and alteration of headwater hydrology relate to aquatic habitat. Changes in streamflow, sediment transport, occurrence of bankfull events and channel development (Hicks et al., 1991; Stott and Mount, 2004; Croke and Hairsine, 2006) can degrade physical habitat for aquatic life. The relationships between timber harvesting and headwater stream hydrology have been well-documented in more mountainous regions, including the Pacific Northwest, the Rockies, and the Appalachians. Considerably less attention has been given to low-gradient forested headwaters of the Gulf Coastal Plain, which are characterized by highly variable hydrologic seasons. These headwater systems are often characterized by long periods of intermittency during the dry summer season (May to November). During this time, discharge is minimal apart from storm events due to a combination of slowly permeable soils, low-stream gradients, high ET, and an abundance of beaver/debris dams. Conversely, heavy rainfall upon wet soils during the winter season can easily bring headwaters to flood stage.

Furthermore, the effects of timber harvesting on streamflow have not often been assessed beyond the small watershed-scale. In a worldwide review of vegetal effects on water yield, Bosch and Hewlett (1982) found that the mean size of watersheds studied was only 0.8 km^2. Water resources/quality management is generally based on a larger watershed-scale. Thus, it is important to understand the cumulative effects of timber harvesting on water quantity and quality on an equal scale.

In light of these research needs, paired-watershed and Before-After-Control-Impact (BACI) designs were utilized from December 2005 to December 2009 to quantify post-harvest changes in baseflow and stormflow at the plot- and larger watershed-scale following clearcut harvesting in the low-gradient headwaters of the Flat Creek Watershed of north-central Louisiana. The overall goal of this study was to determine whether or not Louisiana's current forestry BMPs are effective in streamflow protection.

3.2 Methods

3.2.1 Site Description

The Flat Creek Watershed is a 3rd-order watershed within the Ouachita River Basin of north-central Louisiana and has a drainage area of 369 km^2 (Figure 3.1). Its low-gradient topography is characteristic of the Mississippi River alluvial valley, which contains flat to gently rolling bottomlands and terraces. The range of elevation from the watershed's southern outlet to the northernmost headwaters is 24 to 91 m, respectively, above mean sea level. Analysis of a 2006 LandSat 5 TM image (Saksa, 2007) showed that evergreen and deciduous forests covered 51.4 and 32.6% of the watershed, respectively. Regenerating harvested area (1-3 yrs since harvest), recently harvested area (<1 yr), pasture, and surface water covered 7.0, 5.0, 3.9, and 0.1% of the drainage area, respectively.

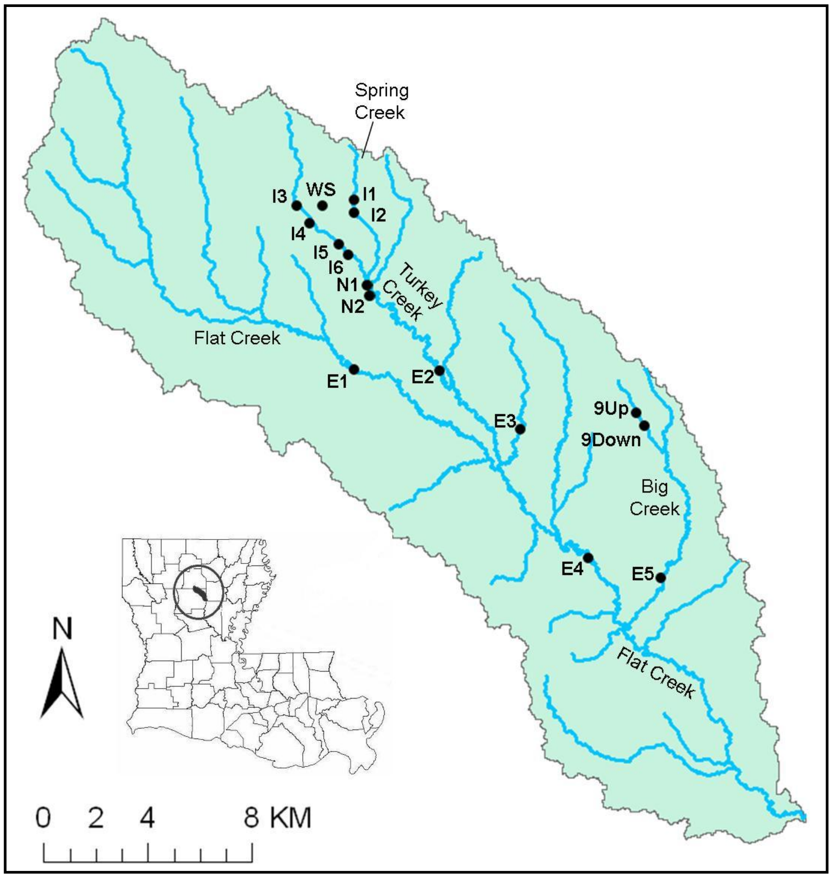

Figure 3.1. Map of monitoring locations throughout the Flat Creek Watershed of north-central Louisiana.

Soil type ranges from the moderately well-drained Sacul-Savannah series (fine sandy loam) in the upland regions to the poorly drained Guyton series (silt loam) along the Flat and Turkey Creek floodplains. Seasonally shallow water tables, ranging in depth from 0.5 to 1.2 m for Sacul-Savannah soils and 0.5 m to ponded water for the Guyton series, are the result of slow permeability (NRCS, 1997). Land slope of the drainage area was derived from a USGS 1 Arc Second (~30 m) National Elevation Dataset with the Spatial Analyst Extension Slope Tool within ArcGIS 9.1. Mean land slope of the entire drainage area was 3.9%, ranging from 0 to 22.8%. Headwater drainages of the northern portion of the watershed had the greatest mean overland slopes (5.5%). Similarly, channel slopes decreased from the headwaters (0.5%) to the watershed outlet (0.1%) (Saksa, 2007).

Meteorological data from 1971-2000 was obtained from the National Climatic Data Center's Winnfield 2W Coop Station, which is located 23 km southwest of the study area (NCDC, 2002). Long-term monthly air temperatures for the 30-yr period averaged 18.2 °C, ranging from 8.0 °C (January) to 27.4 °C (July). Monthly mean air temperature for the study period was 17.8 °C, ranging from 6.4 °C (December 2009) to 28.6 °C (July 2008). Long-term annual rainfall for the 30 years was 1508 mm, ranging from 91 (September) to 158 mm (December). During the study period from 2006 through 2009, annual rainfall totals (1301, 893, 1266, and 1269 mm, respectively) were less or significantly less than the long-term mean of 1508 mm. Rainfall fell short of long-term monthly totals in 38 of 49 months and was highly variable, ranging from 7 mm in August 2007 to 348 mm in October 2009 (Figure 3.2). However, mean rainfall intensity (mm hr-1) was similar between treatment periods, with means of 2.4 and 1.8 for summer and winter season rain events, respectively.

Headwater streams in the Flat Creek Watershed are slow to very slow moving. These low-gradient streams are highly responsive to rainfall in their upstream reaches, especially during periods of wet antecedent soil moisture conditions, but less responsive in the lower reaches due to increased connectivity with backwater areas and localized pooling. Streamflow variability is highest in the first-order streams, ranging from intermittent conditions to water levels exceeding bankfull height throughout the watershed. Physical watershed characteristics including low slopes, elevated water table, beaver and debris dams, and stream geomorphology combine to increase water storage and residence time, reduce peak stormflows, sustain higher baseflows, and influence sediment loading rates in the low-gradient forested watershed (Saksa et al., 2007, 2010).

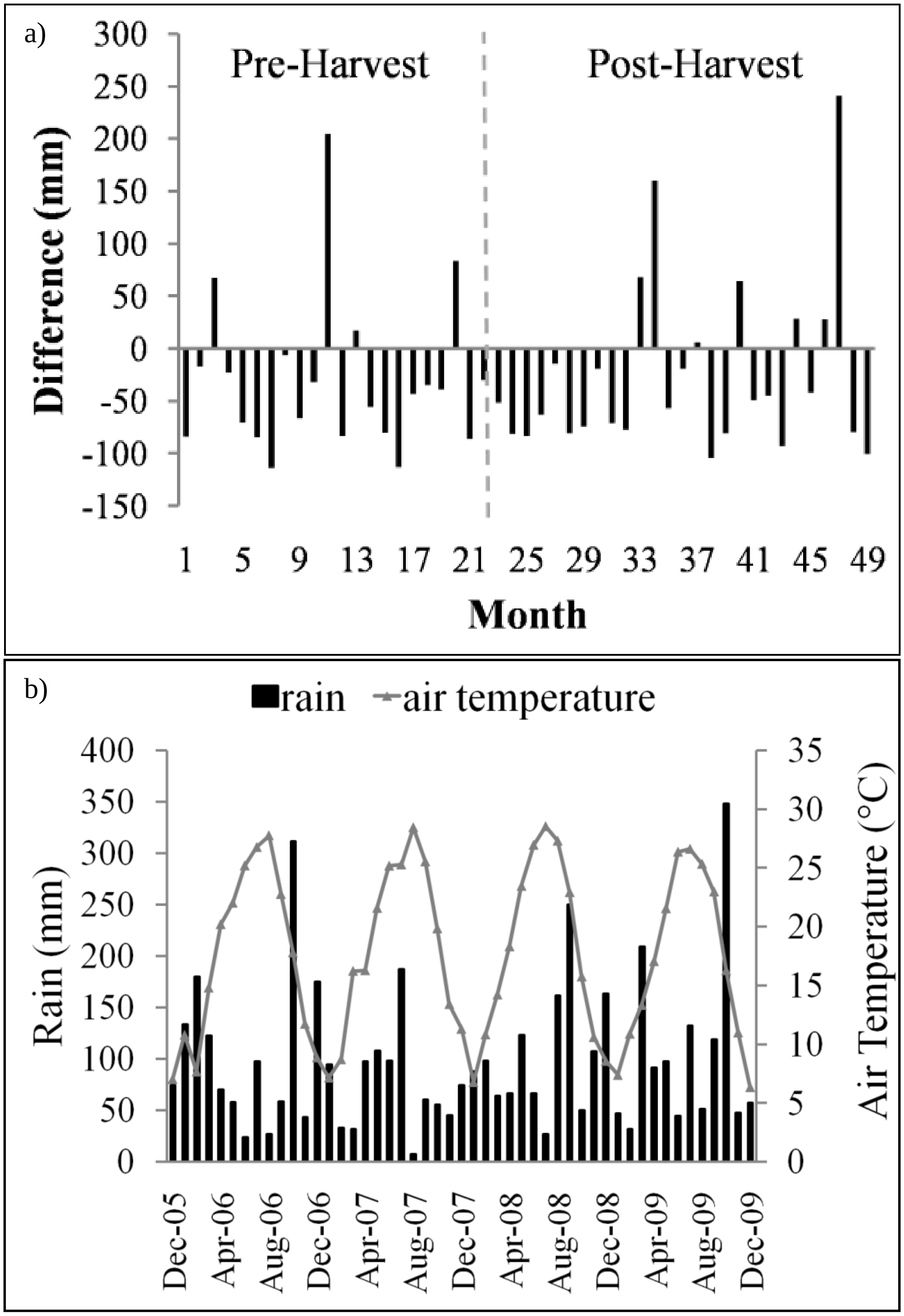

Figure 3.2. a) Monthly rainfall (mm) measured from December 2005 to December 2009 minus the long-term (30-yr) mean monthly rainfall. b) Monthly rainfall totals and mean air temperature from December 1, 2005 to December 19, 2009.

3.2.2 Study Design and Harvest Treatment

Sampling sites were selected to facilitate the use of paired-watershed and BACI designs in order to determine hydrologic impacts of harvesting at both the plot- and watershed-scale and to assess the effectiveness of BMPs in mitigating harvest-induced changes to streamflow (Figure 3.1). Treatment types included clearcutting with BMPs, clearcutting without BMPs, and a control (Table 3.1). Timber harvesting began in September 2007 and was completed by November 2007.

Table 3.1. Description of treatment types employed in the paired-watershed and BACI designs. Harvest intensity is presented as the percentage of clearcut area to total drainage area.

Site	Stand Age, Tree Species	Harvested area (km^2)	Intensity (%)	Treatment
I1/I2	Mature hardwood	-	-	Control
I3/I4	29-yr-old loblolly pine	0.24	2	With BMPs
I5/I6	65-yr-old hardwoods	0.12	2	With BMPs
N1/N2	29-yr-old loblolly pine	0.45	2	With BMPs
9U/9D	26-yr-old loblolly pine	0.25	8	Without BMPs

Plum Creek Timber, Inc. owns the forestland where harvest treatments occurred and implemented the following Louisiana recommended forestry BMPs before, during, and after all harvesting operations, with the exception of the No-BMP- harvest at sites 9Up/9Down:

Pre-harvesting Planning

- Identification and delineation of streamside management zones

- Use of aerial photographs to aid in locating skid trails and access roads

- Restricting harvest timing to dry/firm soil conditions

- Planning harvests to minimize stream crossings

Streamside Management Zones

- Precautions given along perennial streams to protect the remaining trees within the SMZ

- Flagging and marking SMZs adjacent to all perennial streams before harvesting

- Locating roads and logging sets outside the SMZ

Harvesting

- Felling trees directionally away from water bodies

- Inspecting all stream courses to be sure they are free from excessive logging debris

- Minimizing the size of log sets

- Locating log sets so skidding will have a minimal impact on the natural drainage pattern

- Locating log sets where skidding will avoid road ditches and sensitive sites

- Stabilize temporary roads and skid trails with logging slash

Streamside management zone widths on either side of stream channels within harvested areas were maintained to the minimum standards recommended for Louisiana, which allot 10.7 m for intermittent streams, 15.2 m for perennial streams < 6.1 m in width, and 30.5 m for perennial streams > 6.1 m in width. In addition to the Louisiana State recommended BMPs, Plum Creek implemented its own intra-company BMPs pre-, during-, and post-harvest, which included facilitation of proper forest road drainage through the use of culverts, ditches, water bars, and turnouts; road maintenance, such as re-grading, mulching, and seeding; stabilization of harvested area with tree tops/other logging slash; stabilization of landings through mulching and seeding, disposal of trash and remediation of oil/chemical spills; installation and restoration of

stream crossings; removal of logging debris from water bodies; minimal stream crossings and damage to stream banks and streambeds.

The No-BMP-harvest was conducted for the purposes of this study only and is in no way indicative of Plum Creek's standards for forestry operations. Table 3.2 shows specific treatments, including target SMZ basal area, site preparation, and off-road equipment accessibility for the three harvest areas (I3/I4, I5/I6, and N1/N2) along Turkey Creek, as well as the No-BMP-harvest treatment in the headwaters of Big Creek (9Up/9Down). In summary, six intensive (I) monitoring locations were utilized to detect plot-scale effects of timber harvesting with BMPs. I1, I2, and I3 were upstream control sites for monitoring stations located downstream of three harvest areas along Turkey Creek. Sites I3/I4, I5/I6, and N1/N2 were positioned (upstream/downstream) of three clearcuts adjacent to Turkey Creek, in which BMPs were employed.

Table 3.2. Pre-harvest prescription for BMP-harvest sites along Turkey Creek (I3/I4, I5/I6, N1/N2) and No-BMP-harvest site (9Up/9Down) in the headwaters of Big Creek.

Site	SMZ Basal Area ($m^2\ ha^{-1}$)	Mechanical Site Prep	Operability	Off-road access
I3/I4	11.5	No	Sensitive site: no rutting, slight compaction acceptable	dry/firm soil conditions only
I5/I6	11.5	No	Sensitive site: no rutting, slight compaction acceptable	summer only
N1/N2	11.5	Yes	SDC3 (75%), SDC4 (20%), SDC5 (5%)	dry/firm soil conditions only
9U/9D	Remove all merchantable timber	Yes	SDC3 (75%), SDC4 (20%), SDC5 (5%)	year-round

SDC3 = Soil Disturbance Class 3: Ruts < 0.31 m, SDC4 = Soil Disturbance Class 4: Ruts 0.31 to 0.51 m, and SDC5 = Soil Disturbance Class 5: Ruts > 0.51 m or churning and liquid soil disturbance as a percentage of the total disturbed area.

Sites 9Up and 9Down straddled a No-BMP-harvest area along the intermittent headwaters of Big Creek. Extensive (E) sites were situated in the downstream reaches of the watershed to detect watershed-scale treatment effects. Site E4 served as the effective watershed outlet, as permission could not be obtained to monitor the true watershed outlet (Figure 3.1).

3.2.3 Watershed Instrumentation and Monitoring

A 3-meter-high weather station was positioned in a forest clearing in the center of the intensive monitoring area to monitor meteorological conditions, including rainfall, air temperature, humidity, solar radiation, and wind speed at 15-minute intervals. Rainfall was recorded with an automatic tipping-bucket rain gauge. Pressure transducers recorded water level at 15-minute intervals at 12 of the monitoring locations. Staff gages were used to record water level at sites E3, 9Up, and 9Down. An atmospheric pressure logger was deployed at site I4 and was used to correct hydrostatic pressure readings from transducers located at the extensive monitoring locations. Water level (*WL* in m) was calculated for these sites with Equation 1:

$$WL = ((P - P_{atm})/(pg))*1000 \qquad (1)$$

where P = hydrostatic pressure (kPa), P_{atm} = atmospheric pressure (kPa), p = temperature-corrected water density (kg/m^3), and g = gravitational constant (i.e. 9.81 m/s^2).

3.2.4 Development of Stage-Discharge Rating Curves

Measurements of stream stage (m) and discharge (m^3/s) were performed at monthly intervals as well as during storm events in both the pre-harvest period (December 2005 to August 2007) (Saksa, 2007) and in the post-harvest period (September 2007 to December 2009) to develop stage-discharge rating curves for all 15 monitoring locations. When streams were

wadeable, an Acoustic Doppler Velocimeter (ADV, SonTek Flowtracker, San Diego, CA, USA) was used to measure streamflow with the USGS mid-section velocity-area method (Figure 3.3a). For high flow events, discharge was measured by towing an Acoustic Doppler Current Profiler (ADCP, SonTek Rivercat, San Diego, CA, USA) across the stream channel with a two-man pulley system (Figure 3.3b). Regression analysis was used to determine the natural-log-transformed relationship between stream stage and discharge at each site (SAS Institute, Inc. 1996). Rating curve coefficients b_0 and b_1, which correspond to the y-intercept and the slope of the relationship, respectively, were used to calculate discharge at 15-minute intervals:

$$\ln(Q(t)) = b_0 + b_1 \ln(L(t)) + \varepsilon(t), \tag{2}$$

where $Q(t)$ represents discharge (m^3/s) and $L(t)$ is stream level (m).

a) b)

Figure 3.3. a) Streamflow measurement with the USGS mid-section velocity-area method and ADV. b): ADCP towing with a two-man pulley system.

3.2.5 Streamflow Frequency and Magnitude Analysis

Flow duration curves (FDCs) plot the full range of streamflow conditions measured at a monitoring location against the probability of exceeding a given flow rate for a given time period. The relationship between the frequency and magnitude of streamflow is depicted by a

FDC for some time interval (daily, weekly, monthly) for a particular monitoring location in a drainage network (Vogel and Fennessey, 1995). Exceedence probability, *P* is calculated as:

$$P = 100*[\ M / (n + 1)\ ] \tag{3}$$

where *P* is the probability that a given flow rate will be equaled or exceeded (% of time), *M* is the ranked position, and *n* is the number of events for the period of record. Mean daily discharge (m^3/s) was calculated and FDCs were created for each site by harvest period and season (winter months: December through April; summer months: May through November). Flow conditions were nominally classified as “High Flows,” “Moist Conditions,” “Mid-range Flows,” “Dry Conditions,” and “Low Flows,” which corresponded to exceedence probabilities less than 10%, 10 - 40%, 40 - 60%, 60 – 90%, and greater than 90%, respectively (Figure 3.4). Mean discharge from each flow class was compared by season between treatment periods with a two-sample t test.

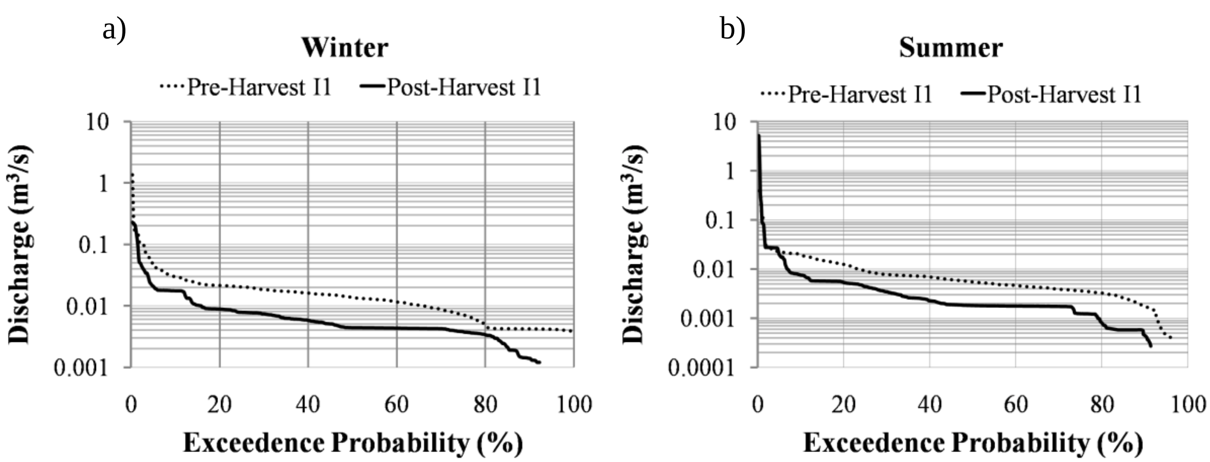

Figure 3.4. Flow duration curves for daily streamflow (m^3/s) at control site I1 by treatment period and season: a) December through April; b) May through November.

3.2.6. Stormflow Analysis

Peak water level response to winter storms was determined for each treatment period. Only winter storms were considered because lower ET rates and higher antecedent soil moisture conditions resulted in improved stream responsiveness to rainfall for both low and high intensity storms. Sites that experienced equipment failure (i.e. level sensor displacement from stormflow debris) prior to reaching peak water level were excluded from analysis.

3.3 Results and Discussion

3.3.1 Baseflow

Flow measurements performed during winter monthly baseflow conditions ranged from 0.01 to 0.10 m^3/s for sites with drainage areas ranging from 3.0 to 45.1 km^2, respectively (Figure 3.5 a through d). Measured flow rates for Flat Creek sites E1 and E4 (109.6 and 285.6 km^2, respectively) were between 0.3 and 1.0 m^3/s during the winter months (Figure 3.5 e and f). All sites experienced low to zero flow during the summer months. A Before-After t-test of mean flow rate by season was used to detect changes in measured baseflow rates between treatment periods. No difference was found for any of the fifteen monitoring locations between treatment periods ($p > 0.05$).

Flow duration curve analysis of mean daily discharge (m^3/s) showed that mean flow rate during baseflow conditions (exceedence probability > 10%) decreased for most of the monitoring locations during the post-harvest period, although there is some variability among sites. Mean flow rate decreased at Spring Creek control site I1 for moist (10-40% exceedence), mid-range (40-60% exceedence), dry (60-90% exceedence), and low flow (>90% exceedence) conditions in the summer and winter months (Table 3.3).

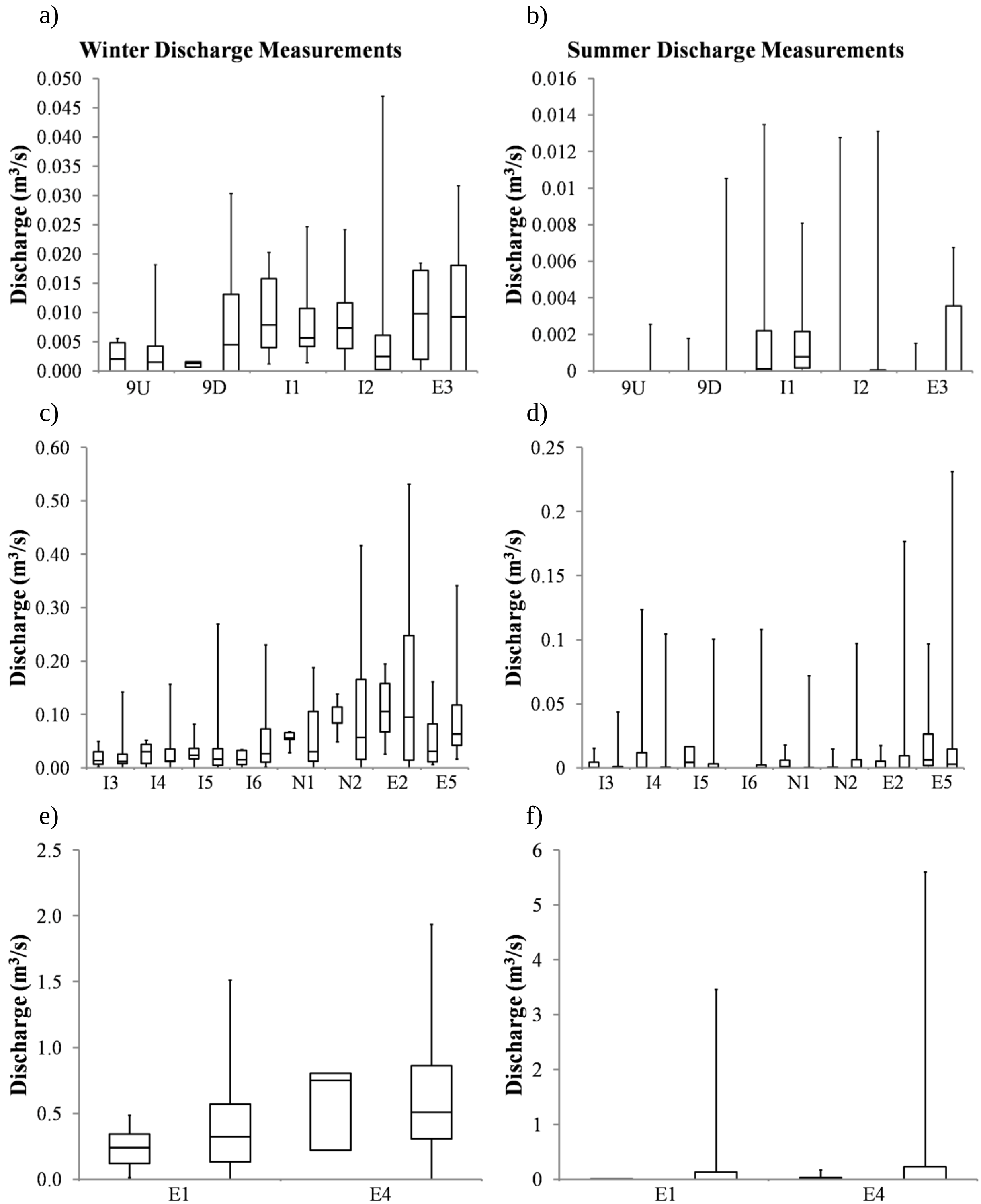

Figure 3.5 a) through f). Box and whisker plots of monthly discharge measurements (m^3/s) by season for all monitoring locations within the Flat Creek Watershed. Two plots are shown for each site, representing flow measurements made during the pre- and post-harvest periods. Box and whisker plots show the median, bounded by the 25th and 75th percentiles. Error bars represent minima and maxima.

Table 3.3. Mean seasonal baseflow rate (m^3/s) ± standard deviation for the pre- and post-harvest periods. Flow conditions are labeled as moist (10-40% exceedence), mid-range (40-60% exceedence), dry (60-90% exceedence), and low flow (>90% exceedence).

Winter	**Pre-Harvest**				**Post-Harvest**			
	Moist	Mid-range	Dry	Low	Moist	Mid-range	Dry	Low
I1	0.021±0.003[a]	0.014±0.001[a]	0.007±0.003[a]	0.004±0.000[a]	0.009±0.003[b]	0.005±0.000[b]	0.004±0.001[b]	0.000±0.000[b]
I4	0.057±0.008[a]	0.038±0.003[a]	0.025±0.006	0.009±0.005	0.075±0.022[b]	0.039±0.008[a]	0.000±0.000	0.000±0.000
E1	0.448±0.041[a]	0.343±0.017[a]	0.256±0.039[a]	0.121±0.057[a]	1.442±1.414[b]	0.232±0.034[b]	0.114±0.042[b]	0.006±0.012[b]
E4	1.160±0.094[a]	0.951±0.045[a]	0.668±0.126[a]	0.512±0.007	2.869±2.370[b]	0.419±0.058[b]	0.066±0.095[b]	0.000±0.000
E5	0.097±0.021[a]	0.063±0.005[a]	0.042±0.011[a]	0.011±0.007[a]	0.168±0.040[b]	0.082±0.006[b]	0.055±0.010[b]	0.037±0.003[b]
Summer								
I1	0.011±0.004[a]	0.006±0.001[a]	0.004±0.001[a]	0.001±0.001[a]	0.004±0.001[b]	0.002±0.000[b]	0.001±0.000[b]	0.000±0.000[b]
I4	0.029±0.010[a]	0.010±0.004	0.002±0.001	0.000±0.000	0.024±0.011[b]	0.000±0.000	0.000±0.000	0.000±0.000
E1	0.280±0.067[a]	0.143±0.034[a]	0.050±0.022	0.000±0.000	0.176±0.110[b]	0.023±0.009[b]	0.000±0.000	0.000±0.000
E4	0.812±0.155[a]	0.534±0.032[a]	0.174±0.211	0.000±0.000	0.285±0.119[b]	0.114±0.017[b]	0.000±0.000	0.000±0.000
E5	0.040±0.015[a]	0.014±0.005[a]	0.002±0.002[a]	0.001±0.000[a]	0.079±0.029[b]	0.040±0.004[b]	0.023±0.006[b]	0.005±0.005[b]

Different letters indicate significant differences from a Before-After two-sample t-test (alpha = 0.05). Where no letters exist, flow rates could not be tested for significance because mean flow rate was zero in one or both harvest periods for a given flow condition.

Mean flow rate increased in the post-harvest period at Turkey Creek site I4 for winter moist conditions, but decreased for all other baseflow categories in the winter and summer months. Flow frequency showed a marked decrease at site I4 during the post-harvest period, where streamflow was intermittent for winter dry and low flow conditions and for summer mid-range, dry, and low flow conditions. Post-harvest decreases in flow frequency and magnitude at this site are thought to have resulted in part from a beaver dam located immediately upstream of the monitoring location. Mean flow rate increased at sites E1 and E4 for winter moist conditions, but flow frequency and magnitude decreased for all other flow categories in the winter and summer months. Site E5 was the only site with increased post-harvest flow rates in all baseflow categories for both the winter and summer months. This site is located downstream of the No-BMP-harvest in between sites 9Up/9Down.

Flow duration curve analysis of post-harvest changes in baseflow could not be compared between treatment periods for all sites due to poor-stage discharge relationships during one or both treatment periods, which resulted in the utility of only five monitoring locations: I1, I4, E1, E4, and E5. In this study, during baseflow conditions, measurements of streamflow were highly variable (Figure 3.6). Most sites displayed this trend to varying degrees, but it was most pronounced at sites where hydrology was controlled by beaver dams and localized pooling. Flow measurements that are performed upstream of the pool will be variable until water is deep enough to "drown out" the effects of the dam (Benton McGee, United States Geological Survey, Ruston, LA, personal communication). Otherwise, one is trying to establish a stage-discharge relationship in a pond, which does not have one. Therefore, it is important to establish a stage height above which, discharge increases with depth in a predictable manner.

Even so, the monthly measurements of baseflow discharge and FDC analysis where stage-discharge relationships existed indicated that timber harvesting with BMP implementation did not increase stream baseflow. In addition to the implementation of BMPs, the low intensity of harvesting (2-8% of sub-watershed drainage area; Table 3.1) may have also contributed to streamflow protection.

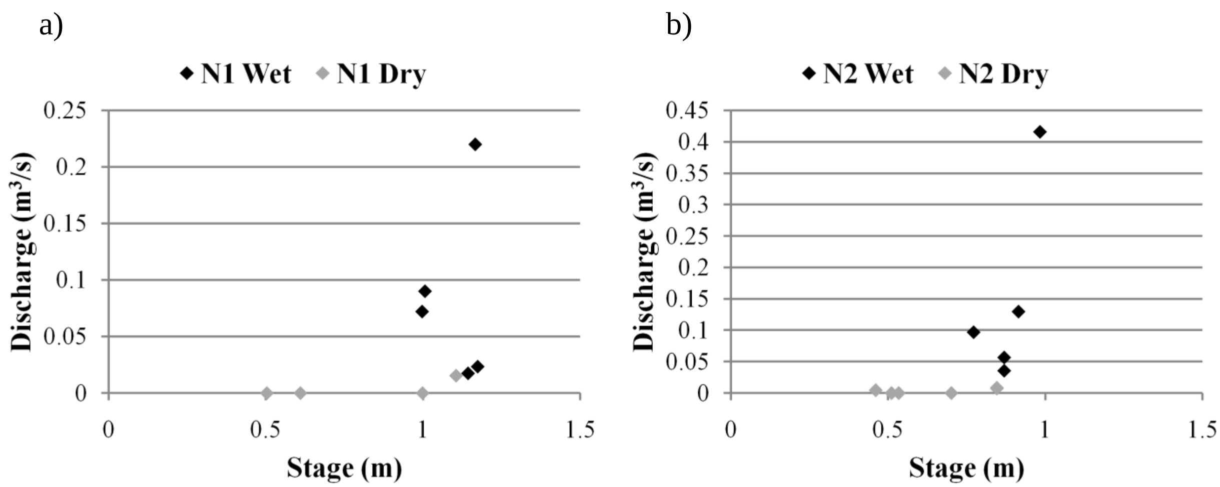

FIGURE 3.6. High variability in baseflow discharge measurements by season during the post-harvest period at sites N1 (a) and N2 (b) on Turkey Creek, where hydrology was controlled by beaver dam-building. The wet season is from December through April. The dry season is from May through November.

In this study, harvested area as a proportion of the total drainage area was always less than two percent. Other researchers (McMinn and Hewlett, 1975; Stednick, 1996) have discussed this issue with regard to the detection of annual water yield changes following disturbance, philosophizing that the effect of zero treatment must be zero, but that it is a difficult task to detect changes in water yield when vegetation removal has not exceeded 20% of the watershed area. The threshold for detection varies by geographic region in accordance with mean annual rainfall and the rapidity with which re-vegetation of the understory occurs. For example, only about 15% of a watershed must be harvested for Rocky Mountain sites, while approximately 45% of the watershed area must be harvested for a detectable increase in annual

water yield for Eastern Coastal Plain sites (Stednick, 1996). Also, spatial distribution of harvesting in the drainage area can play a role. In our study, all harvested areas were directly adjacent to streams and, therefore, a much higher degree of harvest influence on streamflow was expected. The findings in our study suggest that this region is highly resilient to the hydrologic impacts of clearcut harvesting with BMP implementation.

The post-harvest decreases in baseflow during this study are in contrast to the majority of studies in temperate and tropical regions examining the impacts of harvesting to streamflow (Hornbeck et al., 1993; Bari et al., 1996; Brown et al., 2005). Post-harvest increases in baseflow are commonly attributed to increased soil moisture resulting from decreased canopy interception and ET demand. However, exceptions to the general rule have been reported. For example, if post-harvest overland flow is increased to such an extent that it exceeds gains in infiltration and groundwater recharge resulting from decreased ET, then diminished dry season flows may occur (Bruijnzeel, 1988). Because of the low-intensity of forest harvesting in this study, it is more likely that the decreases in baseflow are a result of differences in seasonal rainfall variability between treatment periods.

The decreases in baseflow frequency and magnitude during the winter months of the post-harvest period may be a result of differences in the timing of precipitation between treatment periods. Thirty storms had rainfall intensities of 25.4 mm/day or greater in the post-harvest period, 22 of which occurred during the summer months (May through November). The greatest of these storms was Hurricane Gustav, which dumped 173 mm on the Flat Creek watershed during the first two days of September 2008. Pre-harvest storms of 25.4 mm/day or greater were more evenly distributed seasonally, with 11 of 22 storms occurring during the summer months. Timing of precipitation is important (Sridhar and Nayak, 2010) because a

smaller proportion of rainfall translates to streamflow during the summer season due to higher ET.

3.3.2 Stormflow

Bankfull depth was achieved at Spring Creek control site I1 (drainage area of 3.0 km^2) for rainfall amounts of about 60 mm or more during the wet season (Figure 3.7). Turkey Creek sites I4, I5, and I6 (drainage areas of 14.3, 17.8, and 18.3 km^2, respectively) were characterized by slowly permeable soils, low slopes, an abundance of beaver and debris dams, and localized pooling, which allowed streams to reach bankfull depth for wet season rain events of about 50 mm. The ease with which streams reached bankfull depth was driven primarily by antecedent moisture conditions and secondarily, by rainfall amount. Overall, there was not much difference in peak water level response to wet season storm events between treatment periods.

Post-harvest increases in peak water level response to storm events were expected for lower intensity storms (12.7 to 25.4 mm per event) due to the effects of removing the forest canopy. In general, this effect diminishes as rainfall intensity exceeds 25.4 mm and the interception capacity of the canopy is exceeded. The lack of a difference in peak water level response to storm events between treatment periods indicates that timber harvesting with BMPs did not increase peakflows, which may have been expected because clearcuts represented less than 2% of the total drainage area at sites I4, I5, and I6. Clearcut harvesting at a rate of 20-50% of the sub-watershed drainage area and directly adjacent to stream channels may allow for the detection of streamflow increases, but it is unrealistic for industrial forest owners to clearcut at such rates because of the large watershed size of first- and second-order headwaters in this region. For example, the watershed size of the first-order Spring Creek from this thesis research is 3.0 km^2.

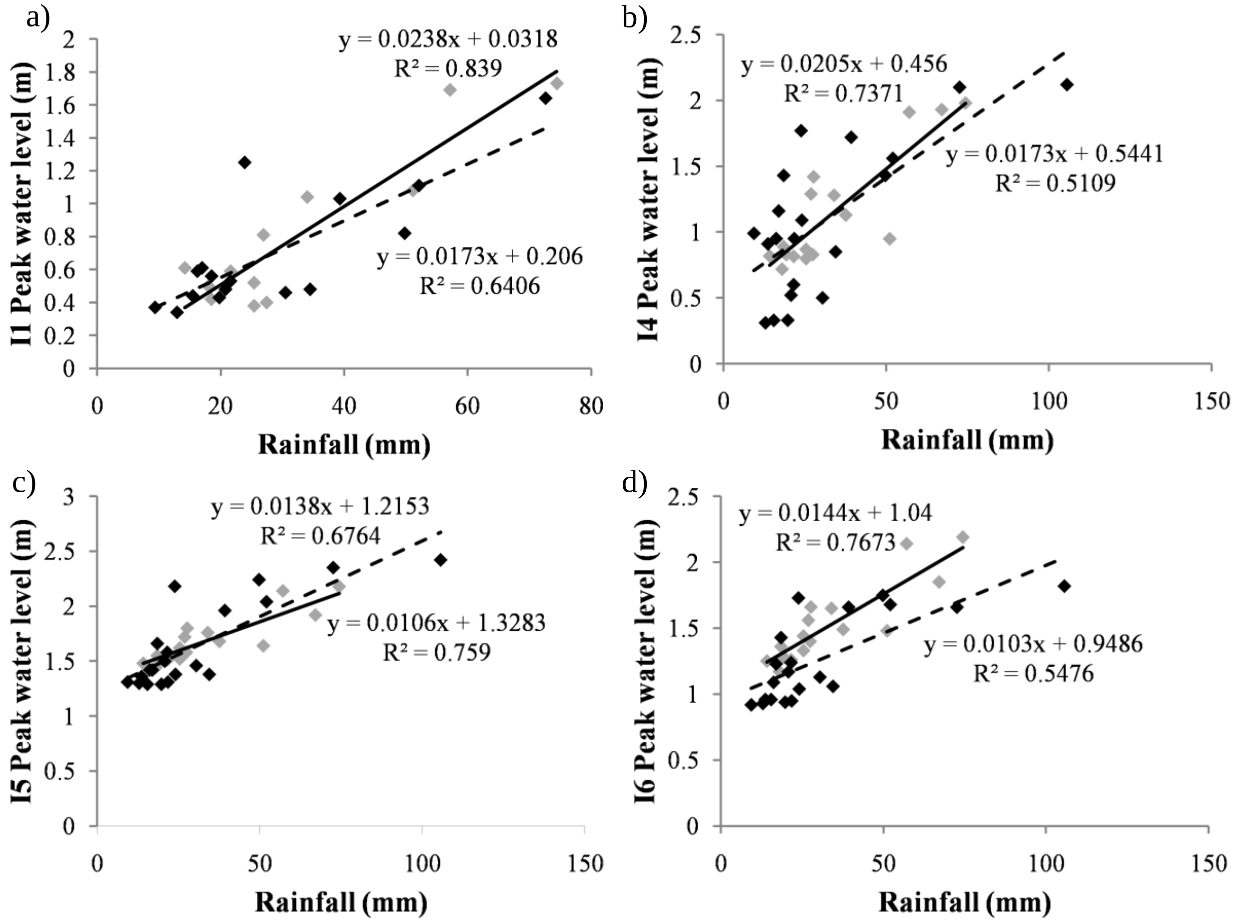

Figure 3.7. Peak water level response to winter rainfall for Spring Creek site I1 ((a); control) and Turkey Creek BMP-implemented harvest sites I4 (b), I5 (c), and I6 (d) before (solid trend line) and after harvesting (dashed trend line).

Flow duration curves were used to analyze the upper 10% of flows for the pre- and post-harvest periods, and by season, at sites I1, I4, E1, E4, and E5 (Table 3.4). There was no difference in winter high flows at site I1, but summer high flows were greater in the post-harvest period. This difference was likely caused by two massive summer storms: Hurricane Gustav in September 2008 (173 mm of rainfall) and a 106.7-mm rain event on October 30, 2009, which occurred during wet antecedent soil moisture conditions. The post-harvest period saw huge increases in high flows at sites I4, E1, E4, and E5 for both the winter and summer seasons because during the post-harvest period, where stage-discharge relationships existed, they had the

ability to predict discharge for the high flows. During the pre-harvest period, bankfull and flood events were conservative estimates because these high flows could not be measured.

Table 3.4. Mean and standard deviation of high flows (m^3/s) by season for the winter and summer seasons. Different letters indicate significant differences between treatment periods (alpha = 0.05).

	Pre-Harvest	**Post-Harvest**	**(% Change)**
Site		Winter	
I1	0.110±0.240[a]	0.048±0.060[a]	-56
I4	0.195±0.203[a]	0.472±0.403[b]	142
E1	0.939±0.580[a]	5.638[b*]	500
E4	2.297±1.577[a]	22.673±14.741[b]	887
E5	0.456±0.378[a]	1.610±3.885[a]	253
		Summer	
I1	0.051±0.086[a]	0.167±0.755[a]	227
I4	0.083±0.057[a]	0.242±0.340[b]	192
E1	0.558±0.215[a]	3.729±2.247[b]	568
E4	1.583±0.991[a]	14.303±20.77[b]	804
E5	0.123±0.091[a]	1.610±4.520[b]	1209

*Upper 10% of flow exceedence probability was estimated conservatively at this site.

Measurement of bankfull and flood conditions was challenging because wading was unsafe and ADCP towing was not easily applicable to remote forested headwaters. Flood stage discharge measurements were conducted during the post-harvest period only and are conservative streamflow measurements because extensive overland flow could not be measured. Flood stage flow conditions occurred several times during the pre-harvest period (Philip Saksa, PhD student, University of California, Merced, personal communication) and at least five times during the post-harvest period.

Flooding is not rare in the Flat Creek watershed due to slowly permeable soils, high stream meander, and beaver dams, which can increase overland flow by forcing streamflow to overtop and/or flow around the dam (Westbrook et al., 2006). These high flow events can

account for a large portion of total annual discharge, which makes quantification of these events critical for Total Maximum Daily Loading (TMDL) development (Figure 3.8) (McBroom et al., 2008).

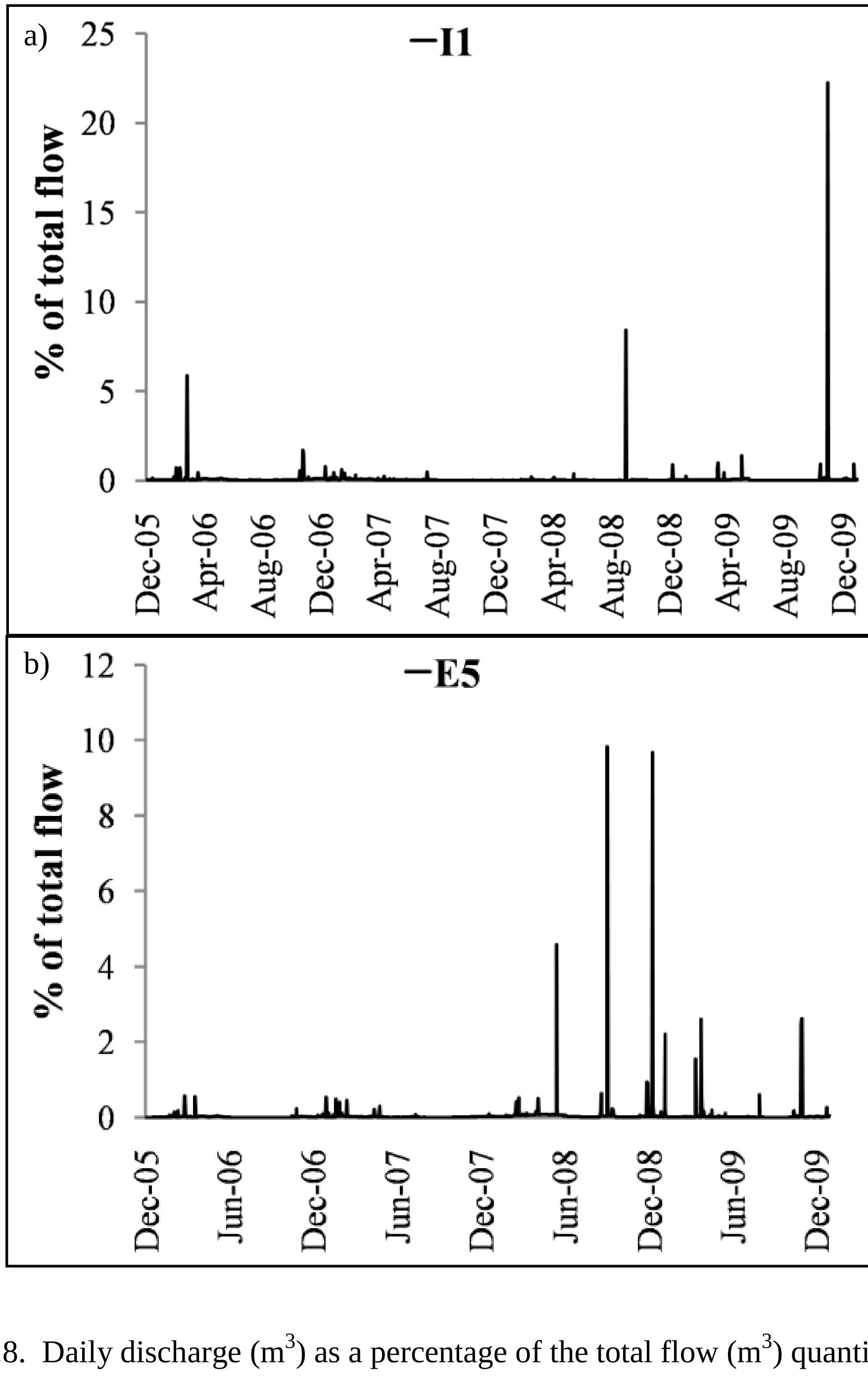

Figure 3.8. Daily discharge (m^3) as a percentage of the total flow (m^3) quantified from December 1, 2005 to December 31, 2009 for sites I1 (a) and E5 (b), whose drainage areas are 3.0 and 23.0 km^2, respectively.

Guillemette et al. (2005) quantified a maximum peak flow increase of 63% after a balsam fir harvest of 61% of a 122 ha basin in Montmorency Forest (Quebec, Canada). This result was toward the upper end of findings from 50 world-wide basin studies that evaluated peak flow increases following harvesting of 45-70% of the basin area. Considering the low-intensity of harvesting in this study (2-8% of sub-watershed drainage area), the extremely large increases in high flow rates are considered to be a result of differences in the development of stage-discharge rating curves.

3.3.3 Changes in Stage-Discharge Relationships

Stage-discharge relationships were analyzed to determine if timber harvesting had any effect on stream geomorphology. Rating curves were relatively similar between treatment periods for control site I1 and 9Up, which is upstream of any impacts from the No-BMP harvest site in the headwaters of Big Creek (Table 3.5, Figure 3.9). The slope of the stage discharge relationship increased to the greatest extent during the post-harvest period at sites I4 and 9Down by 138% and 95%, respectively. Site I4 is downstream of the most upstream harvest location on Turkey Creek, in which BMPs were employed. Site 9Down is downstream of the No-BMP-harvest site in the headwaters of Big Creek. Because sites I1 and 9Up were control sites with post-harvest increases in the slope of the stage-discharge relationship of 29% and 8% respectively, it is reasonable to assume that changes in environmental conditions, such as rainfall timing and magnitude, are responsible for approximately 8-29% of the variability in the slope of the stage-discharge relationships between treatment periods.

The increases in the slope of the stage-discharge relationships that were observed in the post-harvest period at sites 9Down and I4 possibly indicate harvest-induced impacts to headwater stream channel morphology.

Table 3.5. Regression coefficients, b_0 (y-intercept) and b_1 (slope), generated from log-linear regression of stream stage (m) and discharge (cms) for the pre- and post-harvest periods.

Site ID	Treatment Period	b_0	b_1	r-square
I1	Pre-	0.45	3.29	0.89
	Post-	0.34	4.26	0.81
I4	Pre-	-1.38	3.07	0.73
	Post-	-0.67	7.32	0.72
9U	Pre-	0.13	1.98	0.99
	Post-	-0.30	2.14	0.96
9D	Pre-	-0.70	2.01	0.96
	Post-	-0.05	3.91	0.93

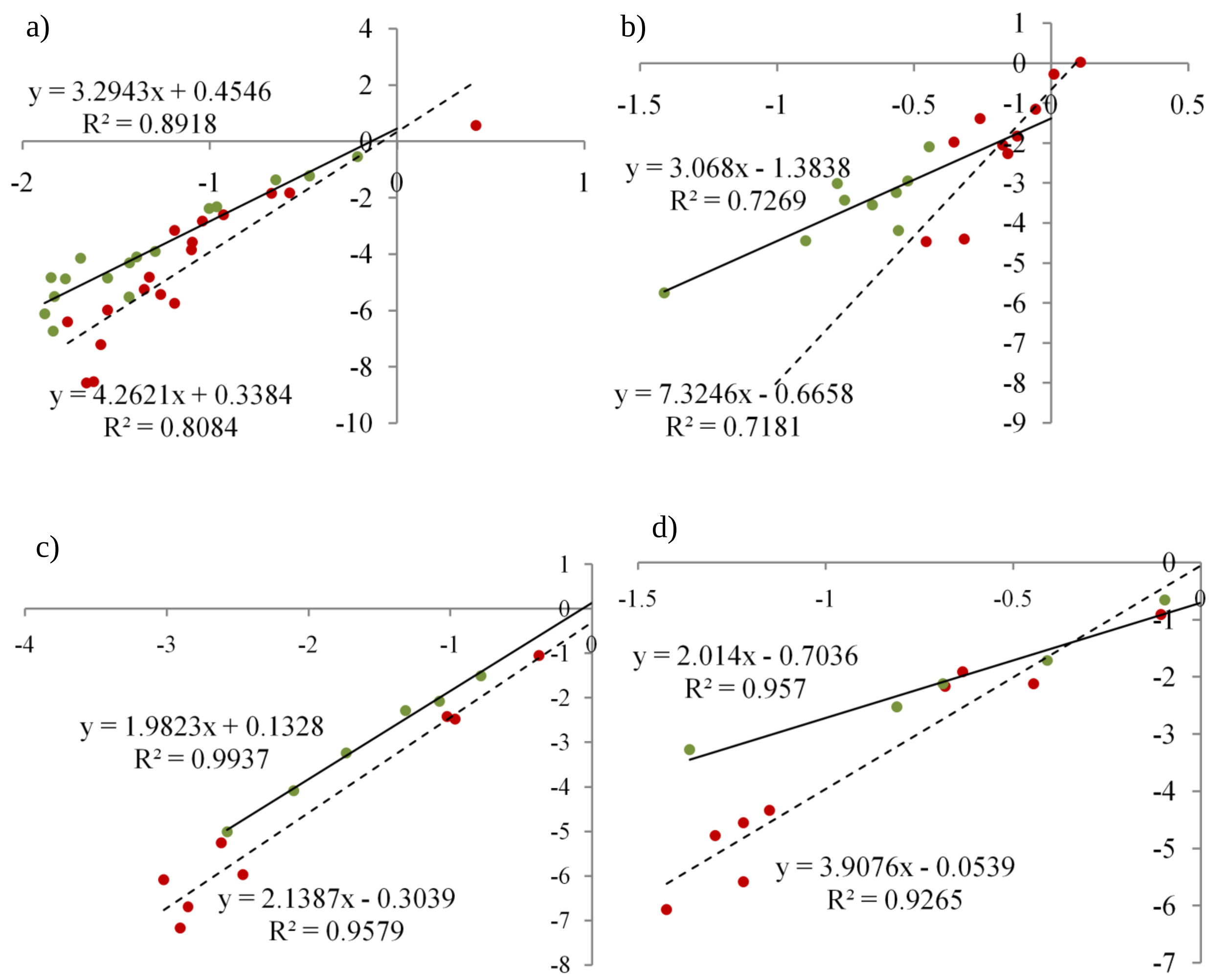

Figure 3.9. Pre-harvest (solid trend line) and Post-harvest (dashed trend line) stage-discharge relationships for sites I1 (a), I4 (b), 9Up (c), and 9Down (d).

Site 9Down shows signs of bank instability, potentially due to harvesting within the riparian zone, and is also likely impacted by a logging trail that crosses the stream channel immediately upstream of the monitoring location (Figure 3.10). Site I4 was harvested with the implementation of BMPs and has a protective riparian buffer of forest vegetation. Therefore, the greater than two-fold increase in the slope of the stage-discharge relationship at this site was unexpected. The majority of the flow measurements performed at this site during both treatment periods were conducted during baseflow conditions and were highly variable due to the hydrologic impacts of a beaver dam located immediately upstream of the streamflow measurement location. The apparent increase in the slope of the stage-discharge relationship is likely a result of high variability in these low flow measurements, especially at the lower end of the post-harvest rating curve (Figure 3.9b).

Many studies have investigated alteration of headwater stream geomorphology as a result of timber harvesting (Ryan and Grant, 1991; Woodsmith and Buffington, 1996; Keim and Schoenholtz, 1999; Gomi and Sidle, 2003; Moore and Wondzell, 2005; Gomi et al., 2006). For example, in a retrospective study of unrestricted clearcut harvesting (circa 1985) impacts to headwater stream morphology in Tasmania, Australia, it was found that 15 years later, regenerating streams were overlain by more logs, were more entrenched, less complex morphologically, with a lower proportion of pools and bars, had increased variability in stream gradient and channel width, and had increased coarse sediment fractions and exposure of bedrock/boulders in comparison with control streams (Davies et al., 2005). The authors concluded that the streams were still adjusting to the indirect effects of harvest-induced streamflow increases, which can include water table changes, changes in the nature of overland

flow, decreased stream bank stability, changes in stream channel profiles, decreased stream sediment retention, and increased sediment transport.

a)

b)

Figure 3.10. Unstable bank conditions (a) and a logging trail with a log crossing (b) at No-BMP-harvest site 9Down.

3.4 Conclusions

Based on analyses of post-harvest baseflow, stormflow, and stage-discharge relationships, low-intensity clearcut harvesting with BMP implementation did not impact

streamflow at the plot- or watershed-scale. No difference was found in monthly baseflow measurements at any site or in peak water level response to winter storm events for the intensive monitoring locations. Flow duration curve analysis showed that baseflow decreased post-harvest, possibly due to differences in the timing of precipitation between treatment periods. Timber harvesting without BMPs, such as maintaining SMZs and improving stream crossings, increased the slope of the stage discharge relationship during the 27-month post-harvest period. Secondary findings include a highly variable, stormflow-dominated flow regime in the low-gradient headwaters of the Flat Creek watershed. In addition, beaver dams impacted hydrology in this low-gradient landscape. Potential exists for future studies to determine long-term cumulative impacts of intensive forest management to headwater streamflow, as forest disturbance increases throughout the watershed.

CHAPTER 4: EFFECTIVENESS OF FORESTRY BMPS IN REDUCING SEDIMENT LOADING FROM HARVESTING IN LOW-GRADIENT HEADWATERS OF THE GULF COASTAL PLAIN

4.1 Introduction

Forested headwater streams are generally considered to be of high water quality. However, this may not always be the case. Water quality depends on a variety of factors including climate, geology, topography, and historical and present land use. Sediment is the primary pollutant of concern for forested headwater streams. Intensive forest management can increase the quantity of sediment delivered to and transported within stream channels (Croke and Hairsine, 2006). Forestry operations involve a series of management practices including, among others, site preparation, weed control, tree planting, thinning, road construction, timber harvesting, and skidding and loading. Studies have shown that road construction, harvesting, and site preparation can especially be significant sources of sediment to stream channels (e.g., Swift, 1984; Bilby, 1985; Robichaud and Waldrop, 1994; Binkley and Brown, 1993; Karwan et al., 2007).

Timber harvesting removes the forest canopy, but the hydrologic functions of the forest litter layer can be left intact (Stuart and Edwards, 2006). However, the whole process often involves heavy machinery to cut, skid and load harvested timber, along with the construction of haul roads, which may cross stream channels. Skidding trails and haul roads can increase the connectivity of stormflow runoff to streams, which increases stormflow and sediment delivery to stream channels. The use of heavy machinery can compact soil, thus limiting its capacity to transmit water (e.g., Whitehead and Robinson, 1993; Xu et al., 2002). Site preparation may involve roller chopping, burning, herbicide application, and mechanical plowing and bedding, which exposes mineral soil to the erosive potential of rainfall. However, nonpoint source (NPS)

pollution from intensively managed forested watersheds is generally regarded as being much less than drainage areas dominated by urban areas or farmland (Blackburn et al., 1990).

In addition to soil erosion, forestry operations can change streamflow through harvest-induced reduction of evapotranspiration (ET) (Hibbert, 1967; Bosch and Hewlett, 1982; Stednick, 1996; Brown et al., 2005; Moore and Wondzell, 2005). Concerns about intensive forest management and alteration of headwater hydrology extend to stream stability and ecological integrity. Changes in streamflow, sediment transport, occurrence of bankfull events and channel development (Hicks et al., 1991; Stott and Mount, 2004; Croke and Hairsine, 2006) can degrade physical habitat for aquatic life. Furthermore, intensive forest management often causes nutrient enrichment in adjacent water bodies (Corbett et al., 1978; Blackburn and Wood, 1990; Ensign and Mallin, 2001), which can alter the chemical environment for aquatic life. Much of our knowledge about forestry operation impacts on streamflow and sediment yield has been gained from studies conducted in headwaters draining relatively steep slopes, which may not be applicable to low-gradient coastal plain headwaters.

The reduction of runoff source strength and delivery of sediment and nutrients to surface water is crucial to minimize the downstream impacts of forestry operations (Croke and Hairsine, 2006). Foresters utilize a combination of best management practices (BMPs) to protect water quality. BMPs include pre-harvest planning for efficient forest harvesting, site preparation, and road systems. Streamside Management Zones (SMZs) or buffer strips are used to maintain a sufficient width and density of vegetation on either side of the stream to provide ecosystem services such as bank stabilization, filtration of sediment and other pollutants in sheetflow, addition of allocthonous organic material, and protection against thermal pollution. Timber harvesting utilizes pre-harvest planning for cutting, skidding, and loading zones to avoid

increasing connectivity with stream channels. Timing of cutting is also considered. Restricting harvesting to dry antecedent soil moisture conditions decreases soil disturbance. Site preparation and regeneration methods are selected to protect water quality and improve soil quality by reducing soil exposure, displacement, and compaction. Other considerations for BMPs include chemical management and the protection of forested wetlands. BMP effectiveness has been validated in hilly upland and mountainous regions, but is less frequently assessed in flat coastal plain sites. In addition, most studies of BMP effectiveness have been conducted at the plot-scale (Grace, 2005). More research is needed to determine if the plot-scale benefits of BMPs translate to the maintenance or improvement of water quality at the watershed-scale.

In 2000, the Louisiana Forestry Association, Louisiana Department of Environmental Quality, and the Louisiana Department of Agriculture and Forestry made revisions to the State's recommended Forestry BMPs. Evaluation of BMP effectiveness is critical due to the current dominance of forestland within the state (nearly half of total land use) and in the context of an anticipated increase in demand for the South's forest resources in the near future (Wear and Greis, 2002).

In light of these research needs, a study with paired-watershed and Before-After-Control-Impact (BACI) designs was initiated in 2005 in the low-gradient headwaters of the Flat Creek Watershed in north-central Louisiana. The study monitored changes in streamflow, water quality conditions, and benthic macroinvertebrate communities from December 2005 to December 2009, during which timber harvest with and without BMPs was conducted in the summer of 2007. The primary goal of the study was to determine whether or not Louisiana's current forestry BMPs are effective in water quality protection. This paper focuses on its major findings in stream sediment

concentration and yield and discusses the effectiveness of timber harvesting BMPs in these unique flat terrain conditions.

4.2 Methods

4.2.1 Site Description

The Flat Creek Watershed is a 3rd-order watershed within the Ouachita River Basin of north-central Louisiana and has a drainage area of 369 km^2 (Figure 4.1). Its low-gradient topography is characteristic of the lower Mississippi River alluvial valley, which contains flat to gently and wide-rolling bottomlands and terraces. The range of elevation from the watershed's southern outlet to the northernmost headwaters is from 24 to 91 m, respectively, above mean sea level. Analysis of a 2006 LandSat 5 TM image (Saksa, 2007) showed that evergreen and deciduous forests covered 51.4 and 32.6% of the watershed, respectively. Regenerating harvested area (1-3 yrs since harvest), recently harvested area (<1 yr), pasture, and surface water covered 7.0, 5.0, 3.9, and 0.1% of the drainage area, respectively.

Soil type ranges from the moderately well-drained Sacul-Savannah series (fine sandy loam) in the upland regions to the poorly drained Guyton series (silt loam) along the Flat and Turkey Creek floodplains. Seasonally shallow water tables, ranging in depth from 0.5 to 1.2 m for Sacul-Savannah soils and 0.5 m to ponded water for the Guyton series, are the result of slow permeability (NRCS, 1997). Land slope of the drainage area was derived from a USGS 1 Arc Second (~30 m) National Elevation Dataset with the Spatial Analyst Extension Slope Tool within ArcGIS 9.1. Mean land slope of the entire drainage area was 3.9%, ranging from 0 to 22.8%. Headwater drainages of the northern portion of the watershed had the greatest mean

overland slopes (5.5%). Similarly, channel slopes decreased from the headwaters (0.5%) to the watershed outlet (0.1%) (Saksa, 2007).

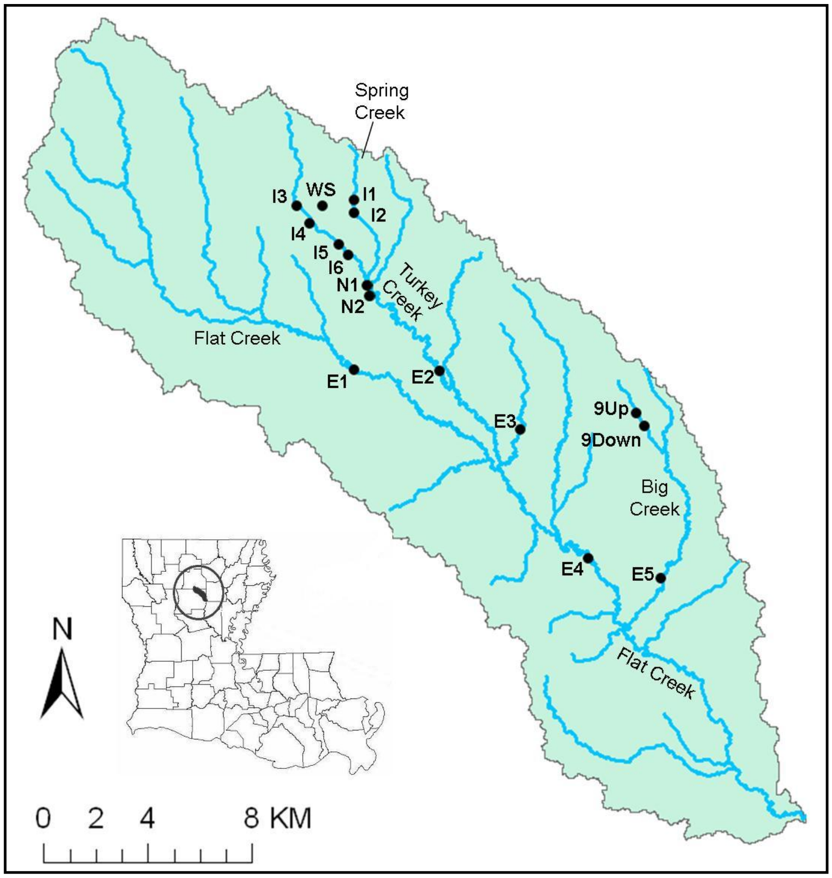

Figure 4.1. Map of monitoring locations in the Flat Creek watershed of north-central Louisiana.

Meteorological data from 1971-2000 was obtained from the National Climatic Data Center's Winnfield 2W Coop Station, which is located 23 km southwest of the study area (NCDC, 2002). Long-term monthly air temperatures for the 30-yr period averaged 18.2 °C, ranging from 8.0 °C (January) to 27.4 °C (July). Monthly mean air temperature for the study period was 17.8 °C, ranging from 6.4 °C (December 2009) to 28.6 °C (July 2008). Long-term annual rainfall for the 30 years was 1508 mm, ranging from 91 (September) to 158 mm (December). During the study period from 2006 through 2009, annual rainfall totals (1301, 893, 1266, and 1269 mm, respectively) were less or significantly less than the long-term mean of

1508 mm. Rainfall fell short of long-term monthly totals in 38 of 49 months and was highly variable, ranging from 7 mm in August 2007 to 348 mm in October 2009 (Figure 4.2). However, mean rainfall intensity (mm hr-1) was similar between treatment periods, with means of 2.4 and 1.8 for summer and winter season rain events, respectively.

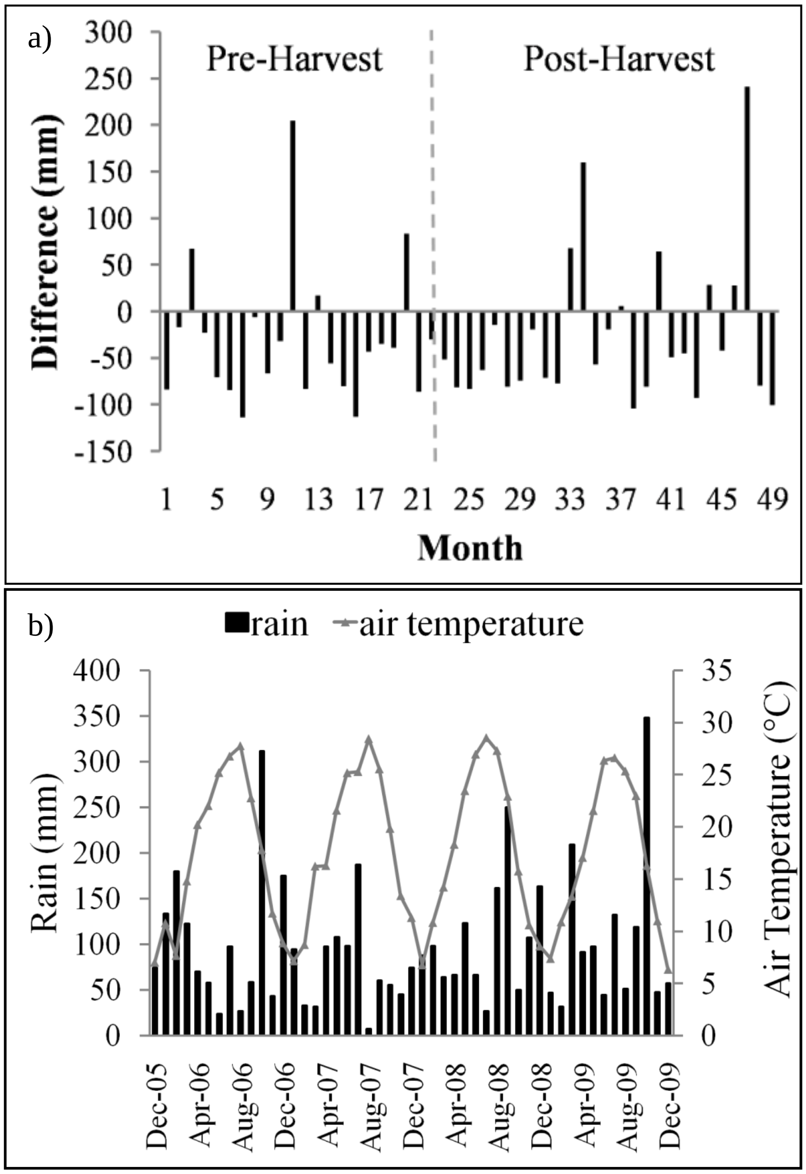

Figure 4.2. a) Monthly rainfall (mm) measured from December 2005 to December 2009 minus the long-term (30-yr) mean monthly rainfall. b) Monthly rainfall totals and mean air temperature from December 1, 2005 to December 19, 2009.

Headwater streams in the Flat Creek Watershed are slow to very slow moving. These low-gradient streams are highly responsive to rainfall in their upstream reaches, especially during periods of wet antecedent soil moisture conditions, but less responsive in the lower reaches due to increased connectivity with backwater areas and localized pooling. Streamflow variability is highest in the first-order streams, ranging from intermittent conditions to water levels exceeding bankfull height throughout the watershed. Physical watershed characteristics including low slopes, elevated water table, beaver and debris dams, and stream geomorphology combine to increase water storage and residence time, reduce peak stormflows, sustain higher baseflows, and influence sediment loading rates in the low-gradient forested watershed (Saksa et al., 2007, 2010)

4.2.2 Study Design and Harvest Treatment

Sampling sites were selected to facilitate the use of paired-watershed and BACI designs in order to determine hydrologic impacts of harvesting at both the plot- and watershed-scale and to assess the effectiveness of BMPs in mitigating harvest-induced changes to streamflow and sediment concentration and yield (Figure 4.1). Treatment types included clearcutting with BMPs, clearcutting without BMPs, and a control (Table 4.1). Timber harvesting began in September 2007 and was completed by November 2007.

Plum Creek Timber, Inc. owns the forestland where harvest treatments occurred and implemented the following Louisiana forestry BMPs before, during, and after all harvesting operations:

Pre-harvesting Planning

- Identification and delineation of streamside management zones

- Use of aerial photographs to aid in locating skid trails and access roads

- Restricting harvest timing to dry/firm soil conditions

- Planning harvests to minimize stream crossings

Streamside Management Zones

- Precautions given along perennial streams to protect the remaining trees within the SMZ

- Flagging and marking SMZs adjacent to all perennial streams before harvesting

- Locating roads and logging sets outside the SMZ

Harvesting

- Felling trees directionally away from water bodies

- Inspecting all stream courses to be sure they are free from excessive logging debris

- Minimizing the size of log sets

- Locating log sets so skidding will have a minimal impact on the natural drainage pattern

- Locating log sets where skidding will avoid road ditches and sensitive sites

- Stabilize temporary roads and skid trails with logging slash

Table 4.1. Description of treatment types employed in the paired-watershed and BACI designs. Harvest intensity is presented as the percentage of clearcut area to total drainage area.

Site	Stand Age, Tree Species	Harvested area (km^2)	Intensity (%)	Treatment
I1/I2	Mature hardwood	-	-	Control
I3/I4	29-yr-old loblolly pine	0.24	2	With BMPs
I5/I6	65-yr-old hardwoods	0.12	2	With BMPs
N1/N2	29-yr-old loblolly pine	0.45	2	With BMPs
9U/9D	26-yr-old loblolly pine	0.25	8	Without BMPs

Streamside management zone widths on either side of stream channels within harvested areas were maintained to the minimum standards recommended for Louisiana, which allot 10.7 m for intermittent streams, 15.2 m for perennial streams < 6.1 m in width, and 30.5 m for perennial streams > 6.1 m in width. In addition to the Louisiana State recommended BMPs, Plum Creek implemented its own intra-company BMPs pre-, during-, and post-harvest, which included facilitation of proper forest road drainage through the use of culverts, ditches, water bars, and turnouts; road maintenance, such as re-grading, mulching, and seeding; stabilization of harvested area with tree tops/other logging slash; stabilization of landings through mulching and seeding, disposal of trash and remediation of oil/chemical spills; installation and restoration of stream crossings; removal of logging debris from water bodies; minimal stream crossings and damage to stream banks and streambeds.

The No-BMP harvest was conducted for the purposes of this thesis research only and is in no way indicative of Plum Creek's standards for forestry operations. Table 4.2 shows specific treatments, including target SMZ basal area, site preparation, and off-road equipment accessibility for the three harvest areas (I3/I4, I5/I6, and N1/N2) along Turkey Creek, as well as the No-BMP-harvest treatment in the headwaters of Big Creek (9Up/9Down). In summary, six intensive (I) monitoring locations were utilized to detect plot-scale effects of timber harvesting with BMPs. I1, I2, and I3 were upstream control sites for monitoring stations located downstream of three harvest areas along Turkey Creek. Sites I3/I4, I5/I6, and N1/N2 were positioned (upstream/downstream) of three clearcuts adjacent to Turkey Creek, in which BMPs were employed.

Sites 9Up and 9Down straddled a No-BMP-harvest area along the intermittent headwaters of Big Creek. Extensive (E) sites were situated in the downstream reaches of the

watershed to detect watershed-scale treatment effects. Site E4 served as the effective watershed outlet, as permission could not be obtained to monitor the true watershed outlet (Figure 4.1).

Table 4.2. Pre-harvest prescription for BMP-harvest sites along Turkey Creek (I3/I4, I5/I6, N1/N2) and the No-BMP-harvest site (9Up/9Down) in the headwaters of Big Creek.

Site	SMZ Basal Area (m^2 ha^{-1})	Mechanical Site Prep	Operability	Off-road access
I3/I4	11.5	No	Sensitive site: no rutting, slight compaction acceptable	dry/firm soil conditions only
I5/I6	11.5	No	Sensitive site: no rutting, slight compaction acceptable	summer only
N1/N2	11.5	Yes	SDC3 (75%), SDC4 (20%), SDC5 (5%)	dry/firm soil conditions only
9U/9D	Remove all merchantable timber	Yes	SDC3 (75%), SDC4 (20%), SDC5 (5%)	year-round

SDC3 = Soil Disturbance Class 3: Ruts < 0.31 m, SDC4 = Soil Disturbance Class 4: Ruts 0.31 to 0.51 m, and SDC5 = Soil Disturbance Class 5: Ruts > 0.51 m or churning and liquid soil disturbance as a percentage of the total disturbed area.

4.2.3 Watershed Instrumentation and Monitoring

A 3-meter-high weather station was positioned in a forest clearing in the center of the intensive monitoring area to monitor meteorological conditions, including rainfall, air temperature, humidity, solar radiation, and wind speed at 15-minute intervals. Rainfall was recorded with an automatic tipping-bucket rain gauge. Pressure transducers recorded water level at 15-minute intervals at 12 of the monitoring locations. Staff gages were used to record water level at sites E3, 9Up, and 9Down. An atmospheric pressure logger was deployed at site I4 and was used to correct hydrostatic pressure readings from transducers located at the extensive monitoring locations. Water level (*WL* in m) was calculated for these sites with Equation 1:

$$WL = ((P - P_{atm})/(pg))*1000 \quad (1)$$

where P = hydrostatic pressure (kPa), P_{atm} = atmospheric pressure (kPa), p = temperature-corrected water density (kg/m^3), and g = gravitational constant (i.e. 9.81 m/s^2).

4.2.4 Development of Stage-Discharge Rating Curves

Measurements of stream stage (m) and discharge (m^3/s) were performed at monthly intervals as well as during storm events in both the pre-harvest period (December 2005 to August 2007) (Saksa, 2007) and in the post-harvest period (September 2007 to December 2009) to develop stage-discharge rating curves for all 15 monitoring locations. When streams were wadeable, an Acoustic Doppler Velocimeter (ADV, SonTek Flowtracker, San Diego, CA, USA) was used to measure streamflow with the USGS mid-section velocity-area method (Figure 4.3 left). For high flow events, discharge was measured by towing an Acoustic Doppler Current Profiler (ADCP, SonTek Rivercat, San Diego, CA, USA) across the stream channel with a two-man pulley system (Figure 4.3 right).

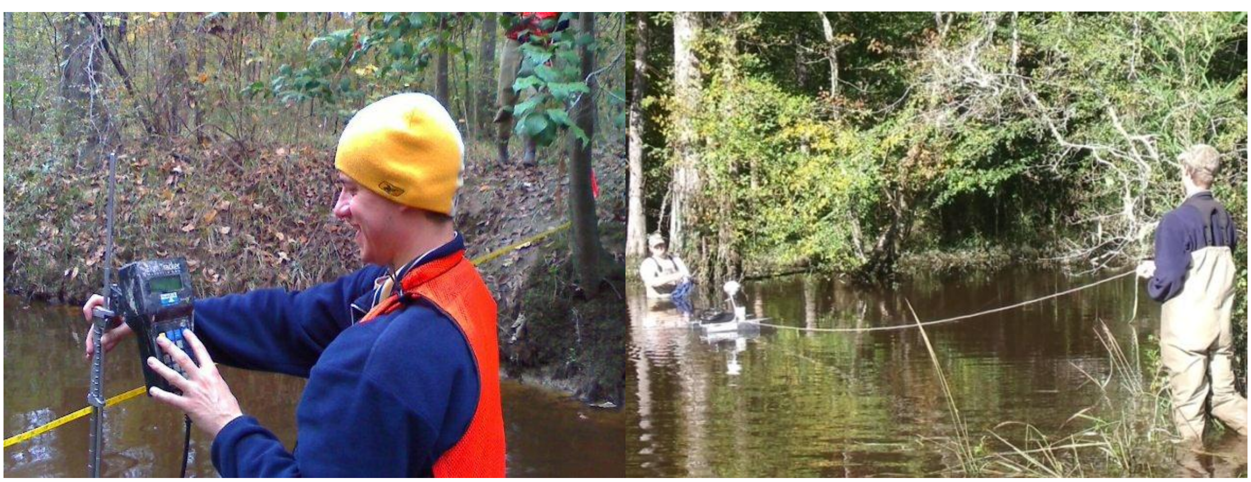

Figure 4.3. Left: Streamflow measurement with the USGS mid-section velocity-area method and ADV; Right: ADCP towing with a two-man pulley system.

Regression analysis was used to determine the natural-log-transformed relationship between stream stage and discharge at each site (SAS Institute, Inc. 1996). Rating curve coefficients b_0 and b_1, which correspond to the y-intercept and the slope of the relationship, respectively, were used to calculate discharge at 15-minute intervals:

$$\ln(Q(t)) = b_0 + b_1 \ln(L(t)) + \varepsilon(t), \qquad (2)$$

where $Q(t)$ represents discharge (m^3/s) and $L(t)$ is stream level (m).

4.2.5 Water Sample Collection and Analysis

Grab samples (1000 mL) were collected at monthly intervals at all non-intensive monitoring locations to determine total suspended solids (TSS) concentration (mg/L) during baseflow conditions. Monthly baseflow water samples were pumped from automatic stormwater samplers (Teledyne Isco, Inc., Lincoln, Ne., USA) at all six intensive monitoring locations (Figure 4.4). Composite stormwater samples were collected at the intensive monitoring locations to determine the impacts of timber harvesting to stormflow sediment concentrations (Harmel and King, 2005). Stormwater samplers were programmed to begin sample collection with a water level rise of 0.15 m over any 24-hr period. Once triggered, 400-mL samples were pumped at hourly intervals for 20 hrs and stored in a single jug. During stormwater sample retrieval (next day), the sample storage jug was removed from the sampler and shaken to re-suspend sediment. One-thousand mL of composite sample was obtained from each intensive site during stormwater sample collection.

Water samples were analyzed for TSS by the Louisiana State University AgCenter Chemistry Laboratory in Baton Rouge, La., USA. Samples were processed according to U.S. EPA procedures, with a holding time of 7 days and storage at 4°C. The detection limit for TSS

was 5.0 mg/L. Water samples with TSS concentrations below the detection limit were estimated at 2.5 mg/L.

Figure 4.4. ISCO automatic stormwater sampler at intensive site I4 (pictured: April BryantMason).

4.2.6 Development of Sediment Rating Curves and Sediment Yield Calculation

Regression analysis was performed to determine the strength of the relationship between flow rate (m^3/day) and sediment concentration (mg/L). Concentrations of TSS were highly variable during high flows, but were generally less than 20 mg/L during baseflow conditions (Figure 4.5a). Concentrations of Total Dissolved Solids (TDS) generally held an inverse relationship with discharge and this trend was most pronounced at sites that were influenced by localized pooling due to beaver and debris dams (Figure 4.5b; Quinn and Stroud, 2002; Saksa, 2007). Variability in TSS concentration during high flows was governed by rainfall intensity, the hysteresis effect, and length of time since the last storm event.

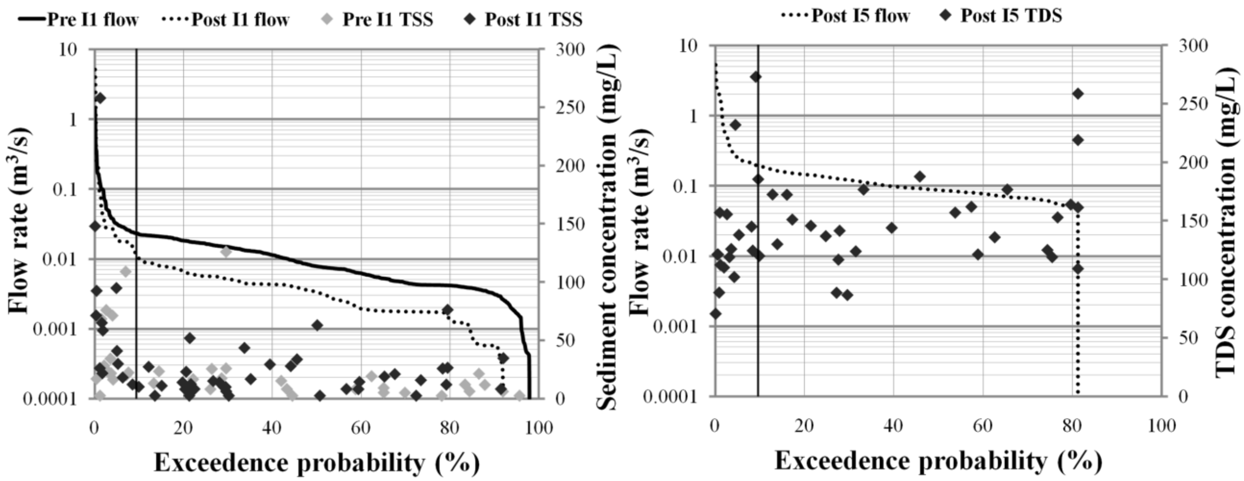

Figure 4.5. a) TSS concentrations (mg/L) compared to daily streamflow frequency (exceedence probability) and daily average discharge (m^3/s) for the pre- and post-harvest periods at control site I1. b) TDS concentrations compared to daily streamflow frequency and daily average discharge for the post-harvest period at harvested site I5. The vertical black distinguishes high flows (exceedence probability < 10%) and baseflow (exceedence probability > 10%).

Sediment loading had a direct relationship to daily flow rate (Table 4.3). A log-linear regression model was developed to predict daily solids loading from daily flow rate:

$$\ln(S(t)) = b_0 + b_1 \ln(Q_{day}(t)) + \varepsilon(t) \qquad (3)$$

where Q_{day} represents discharge (m^3), $S(t)$ daily loading (kg), and $\varepsilon(t)$ an error term assumed to be normally distributed (Figure 4.6).

Daily sediment loads were summed up to monthly and annual yields (kg ha^{-1} mo^{-1} or yr^{-1}). Because of the large variation in annual rainfall between treatment periods (see **4.2.1 Site Description**), sediment yields were standardized for comparison by dividing monthly yield by monthly rainfall (mm).

Table 4.3. Regression coefficients and r-squared values from the natural log-transformed relationship between daily streamflow in m^3 and solids loading in kg (see Equation 3). The y-intercept and slope are indicated by b_0 and b_1, respectively.

	TSS			TDS		
Site	b_0	b_1	r^2	b_0	b_1	r^2
E4	-4.50	1.01	0.95	-1.86	0.97	0.99
E5	-5.02	1.10	0.80	-2.02	0.99	0.97
E1	-4.12	0.97	0.96	-2.13	0.99	0.97
I1	-5.98	1.29	0.81	-2.16	0.99	0.95
I4	-4.11	1.04	0.95	-1.77	0.96	0.99
I5	-4.05	1.03	0.89	-1.56	0.96	0.99
I6	-3.99	1.04	0.95	-2.00	1.00	0.99

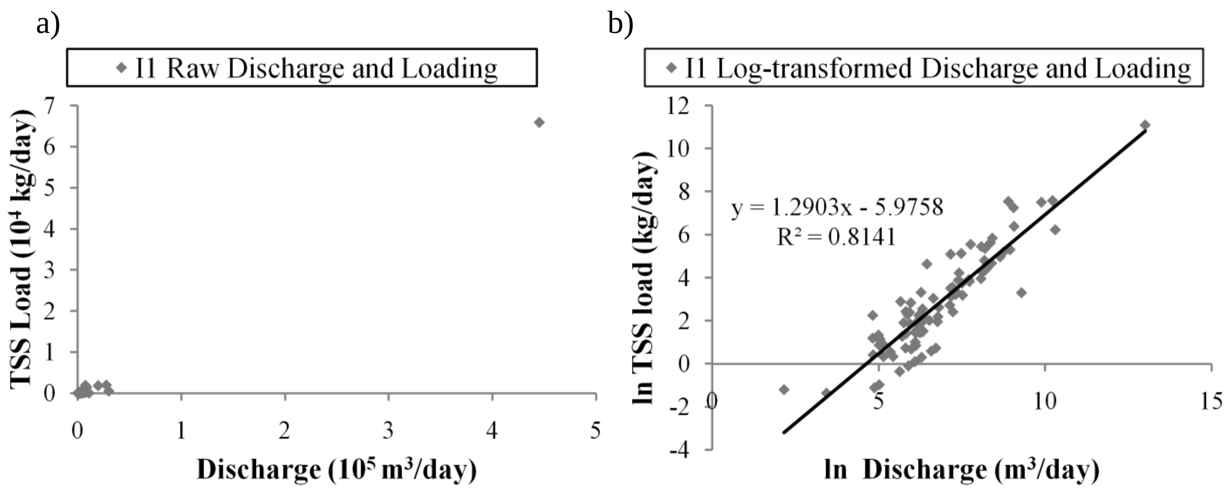

Figure 4.6. Raw (a) and natural log-transformed (b) relationships between daily TSS load and discharge at Spring Creek control site I1.

Two types of standardized sediment yields were calculated: One incorporated monthly yield for the entire range of flow conditions, which was divided by total monthly rainfall. The other incorporated monthly yield during baseflow conditions only (flow exceedence probability > 10 %), which was divided by monthly rainfall totals that were calculated by summing rainfall only for those days when flow exceedence probability was greater than 10 %. Although this approach is not entirely accurate due to the complexity of infiltration under different antecedent soil moisture conditions, this standardization allows for a quasi-comparison that minimizes rainfall-induced differences in yield between treatment periods.

4.3 Results and Discussion

4.3.1 Changes in Baseflow Total Suspended Sediment Concentration

Total suspended sediment concentrations from monthly samples, which were grabbed at all 15 monitoring locations at random times in between storm events, lacked any clear spatial or temporal pattern throughout the Flat Creek Watershed (Figure 4.7). Drainage area of the monitoring locations ranges from about 3.0 to 286 km^2, but monthly concentrations of TSS were similar among all sites and were commonly less than 20 mg/L. Post-harvest changes in TSS concentration during baseflow conditions could not be compared between treatment periods for all sites due to poor stage-discharge relationships during one or both treatment periods, which resulted in the utility of only five monitoring locations: I1, I4, E1, E4, and E5. In this study, during baseflow conditions, measurements of streamflow were highly variable.

Most sites displayed this trend to varying degrees, but it was most pronounced at sites where hydrology was controlled by beaver dams and localized pooling.

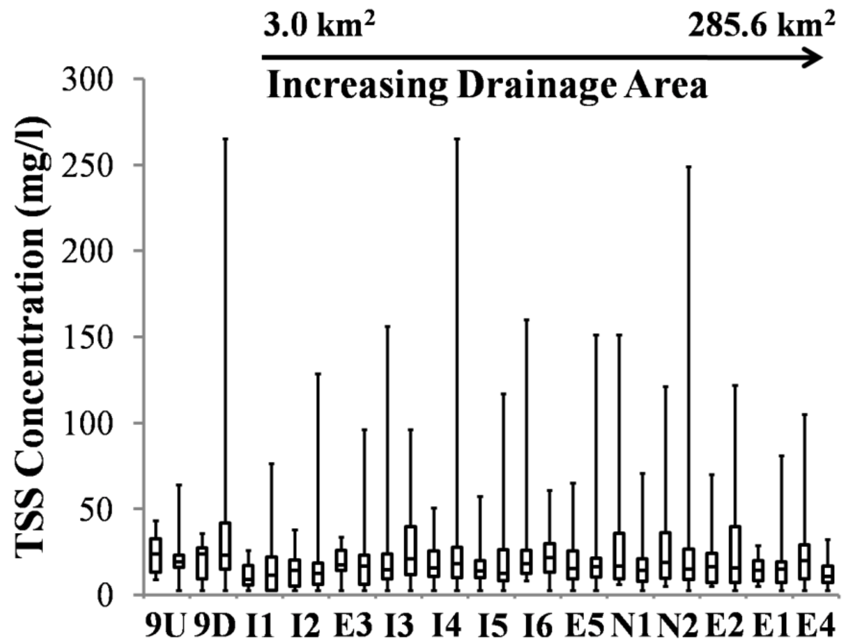

Figure 4.7. Box and whisker plots of monthly TSS concentrations (mg/L) for all monitoring locations before and after harvesting and by drainage area. Two plots are presented for each site (left: Pre-Harvest; right: Post-Harvest). Box and whisker plots show the median, bounded by the 25th and 75th percentiles. Bars represent minimum and maximum values.

Flow measurements that are performed upstream of the pool will be variable until water is deep enough to "drown out" the effects of the dam (Benton McGee, United States Geological Survey, Ruston, LA, personal communication). Otherwise, one is trying to establish a stage-discharge relationship in a pond, which does not have one. Therefore, it is important to establish a stage height above which, discharge increases with depth in a predictable manner.

Where stage-discharge relationships existed, Flow Duration Curve (FDC) analysis was used to distinguish high flows (exceedence probability < 10 %) and baseflow (exceedence probability > 10 %). No difference was found between treatment periods for TSS concentration during baseflow conditions at site I1, I4, E1, E4, or E5 (Table 4.4). Baseflow TSS concentration decreased ($p = 0.07$) at effective watershed outlet site E4. These results indicate that low-intensity clearcutting adjacent to streams and with BMP implementation did not impact sediment transport during baseflow conditions at either the plot- or watershed-scale. Sediment reduction

from forestry BMPs was also likely aided by frequent periods of intermittency and an abundance of beaver and debris dams, which can act as sediment sinks, as shown by other studies (e.g., Naiman et al., 1988; Butler and Malanson, 1995; Burns and McDonnell, 1998; Gurnell, 1998; Butler and Malanson, 2005).

Table 4.4. Total suspended solids and total dissolved solids concentration (mg L^{-1}) by treatment period for sites I1, I4, E1, E4, and E5 during baseflow conditions. Baseflow was considered to be any average daily discharge (m^3/s) with an exceedence probability greater than 10 %.*

	TSS Concentration (mg L^{-1})		**TDS Concentration (mg L^{-1})**	
Site	Pre-harvest	Post-harvest	Pre-harvest	Post-harvest
I1	23.1 ± 38.5[a]	19.2 ± 17.1[a]	*100.5 ± 22.8[a]*	*126.6 ± 41.2[b]*
I4	20.3 ± 10.5[a]	31.5 ± 47.5[a]	*118.3 ± 24.4[a]*	*151.8 ± 42.4[b]*
E1	13.7 ± 7.3[a]	17.4 ± 15.9[a]	110.7 ± 21.6[a]	118.1 ± 40.1[a]
E4	22.7 ± 22.3[a]	12.8 ± 7.8[a]	125.1 ± 43.0[a]	157.0 ± 165.2[a]
E5	17.4 ± 13.8[a]	23.2 ± 28.7[a]	125.0 ± 26.0[a]	125.1 ± 34.8[a]

*Means followed by the same letter within a row are not significantly different at the 0.05 level.

Baseflow TSS concentrations were well within the range of other published studies in the Gulf Coastal Plain region regarding the impacts of forestry operations, such as timber harvesting and site preparation, to stream sediment concentration. Mean sediment concentration of undisturbed forest streams in the southeast U.S. has been reported to be 62 mg/L (Patric, 1976; Beasley and Granillo, 1988). In a study of the effectiveness and functioning of silvicultural streamside management zones (SMZs) in the highly-erodible Deep Loess region of Mississippi, mean TSS concentrations 15 months after harvesting were 244.2, 272.0, and 147.4 mg/L for unrestricted harvesting with no SMZ, cable-only harvesting within the SMZ, and no harvesting within the SMZ, respectively, as compared to the control (83.7 mg/L) (Keim and Schoenholtz, 1999). Beasley and Granillo (1988) observed annual means of 208 and 14 mg/L in years one and two, respectively, following clearcut harvesting and mechanical site preparation adjacent to headwaters within the Gulf Coastal Plain of Arkansas. The authors concluded that flat

topography and the meandering nature of streams resulted in low streamflow velocities and low erosive potential, thus ameliorating the impacts of harvesting impacts on water quality. Riekerk (1983) actually measured higher sediment concentrations (37.1, 44.2, and 55.8 mg/L for minimum disturbance harvesting and regeneration, maximum disturbance, and control watersheds, respectively) during the calibration period in the poorly drained flatwoods of Florida. These higher concentrations were reported to have resulted from disturbance caused by road grading, coupled with a relatively wet year, during the calibration period. Harvesting and regeneration with maximum disturbance caused a statistically significant increase in sediment concentration in comparison to the control watershed in the first year post-harvest, but the mean concentration was only 14.4 mg/L (Riekerk, 1983).

Comparatively, sediment concentrations from monthly grab samples and during baseflow conditions in this study are on the lower end of the published literature regarding harvesting impacts to sediment concentrations in low-gradient coastal plain headwaters. The highest mean sediment concentration in the two-year post-harvest was 39.4 mg/L and corresponded to site 9Down, which was located adjacent to clearcut harvesting up to the stream banks and without BMP implementation within the plot boundaries. No cumulative impacts to monthly TSS concentration were observed in this study. Mean post-harvest sediment concentrations for sites I4, I5, I6, N1, and N2, which are nested watersheds draining low-intensity (with respect to total drainage area), but spatially extensive clearcut harvesting with BMPs adjacent to Turkey Creek, were 31.5, 21.4, 22.6, 17.2, and 33.5 mg/L, respectively. These results indicate that low-intensity forest clearcutting adjacent to streams and with BMP implementation did not impact water quality during baseflow conditions. The effectiveness of BMP implementation was likely

aided by the highly intermittent nature of streamflow and abundance of beaver dams because both act to store sediment within the stream channel.

4.3.2 Changes in Stormflow Total Suspended Sediment Concentration

There was no difference in TSS concentration (mg/L) of storm event samples for any of the intensive monitoring locations between harvest periods (Figure 4.8). Stormflow TSS concentrations were generally greater for storms preceded by long dry periods and for storms of high rainfall intensity. Following large rain events and/or periods of frequent rainfall, sediment concentration commonly decreased in subsequent events.

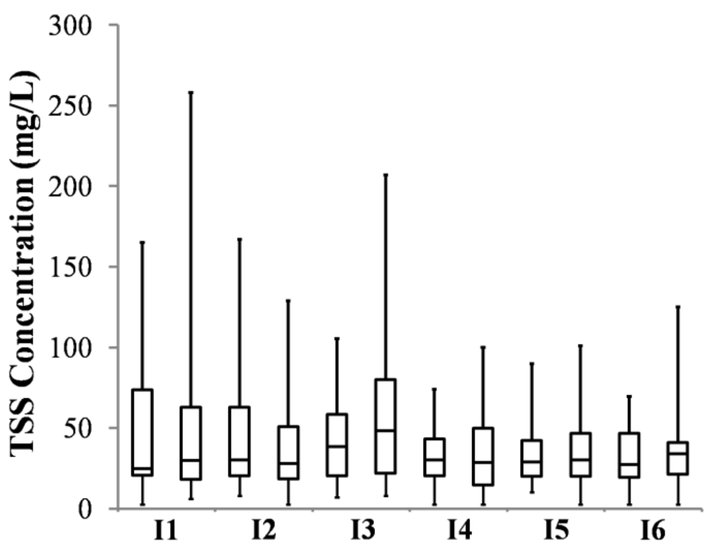

Figure 4.8. Box and whisker plots of stormflow TSS concentration (mg/L) for intensive sites 1 through 6, before and after harvesting. Two plots are presented for each site corresponding to the pre-harvest (left) and post-harvest periods (right). Box and whisker plots show the median, bounded by the 25th and 75th percentiles. Bars depict minima and maxima.

Flow duration curve analysis was used to distinguish high flow conditions and concentrations of TSS during these events were compared with a two-sample t-test at intensive sites I1 (control) and I4 (immediately downstream of the most upstream harvest site on Turkey Creek). Sites E1, E4, and E5 were not included in this analysis due to low sample size during

high flow conditions at these sites. There was no statistical difference in TSS concentration during high flows between treatment periods for sites I1 and I4 (Table 4.5).

Table 4.5. Total suspended solids and total dissolved solids concentration (mg L^{-1}) by treatment period for sites I1 and I4 during high flow conditions. High flow was considered to be any average daily discharge (m^3/s) with an exceedence probability less than 10 %.*

	TSS Concentration (mg L^{-1})		**TDS Concentration (mg L^{-1})**	
Site	Pre-harvest	Post-harvest	Pre-harvest	Post-harvest
I1	45.2 ± 42.9[a]	66.0 ± 65.3[a]	103.6 ± 29.6[a]	120.0 ± 40.0[a]
I4	35.9 ± 21.8[a]	42.4 ± 27.0[a]	109.2 ± 27.9[a]	114.0 ± 23.6[a]

*Means followed by the same letter within a row are not significantly different at the 0.05 level.

Studies regarding timber harvesting impacts on TSS of headwater streams under stormflow conditions on the Gulf Coastal Plain are rare. As with the aforementioned baseflow TSS concentrations, stormflow TSS concentrations in our study were found to be low in comparison with the findings of two other studies (Beasley and Granillo 1988; Keim and Schoenholtz 1999). Mean stormflow sediment concentrations in the two years after harvesting were 42.4, 36.2, and 38.3 mg/L for sites I4, I5, and I6, which are downstream of clearcut harvesting with BMPs on Turkey Creek. Mean stormflow sediment concentration during the post-harvest period was actually highest at control sites I1 and I3 (50.6 and 66.0 mg/L, respectively), indicating that timber harvesting with BMPs had minimal impact on stormflow TSS concentration. This finding may indicate a dominance of within-channel sources of sediment (i.e., pronounced channel erosion), as opposed to sediment sources from areas disturbed by harvesting and/or increased storage of sediment within the channel by beaver and debris dams at sites I4, I5, and I6.

4.3.3 Total Suspended Sediment Transport and Watershed Yield

Total suspended solids yield in the pre-harvest period was generally greatest during the winter months, frequently with peaks corresponding to peak discharge from heavy rain events from February and October of 2006. The post-harvest period began with a fairly dry period from September 2007 to March 2008 (Figure 4.2), with much of the yield resulting from heavy rainfall in early April and mid-May 2008. The rest of the post-harvest period was dominated by high flow events in September 2008 (Hurricanes Gustav and Ike), December 2008, March 2009, and October 2009.

Total suspended solids yield (kg/ha) generally decreases, while loading increases, with increasing drainage area. Sediment loss in this study was comparable to natural erosion rates from undisturbed forestland of the southeast U.S., which are trace amounts to 58 kg ha^{-1} $mo.^{-1}$ (Figure 4.9; Blackburn et al., 1990) and very low compared to the published literature regarding harvesting impacts in the Gulf of Mexico coastal plain. For example, Beasley and Granillo (1988) summarized first-year sediment losses for clearcutting with intensive site preparation at sites from the Piedmont of North Carolina to the Coastal Plain of east Texas and found that sediment loss ranged from 2,802 to 14,570 kg ha^{-1} yr^{-1}, respectively. However, the drainage area of watersheds in this study ranges from 300 to 28,560 ha, which is much greater than the small drainage areas typically studied. As discussed above, TSS flux generally decreases with increasing drainage area.

Site E5, which is downstream close to the No-BMP-harvest at sites 9 Up/9 Down, displayed a greater TSS flux than would be expected from its relatively large drainage area (23 km^2) (Figure 4.9b). Increased connectivity of storm runoff from a logging trail that crossed the stream between sites 9Up/9Down may have contributed to the increased discharge and loading in the post-harvest period (Figure 4.10). In a study of unpaved county roads within the Stillwater

Creek, Oklahoma Watershed (715 km^2), it was estimated that roads accounted for 35% of the watershed's annual sediment budget, while occupying a mere 1.3% of the total watershed area. Properly installing BMPs, such as crowns for road drainage and applying geotextile fabric and gravel to the road surface can reduce sediment yields by as much as 80% (Turton et al., 2009). In the comparison of standardized TSS yields by rainfall among the sites, the trend was similar: baseflow sediment yields decreased at all sites, but with the exception of site E5, which is located downstream of the No-BMP-harvest site in the headwaters of Big Creek.

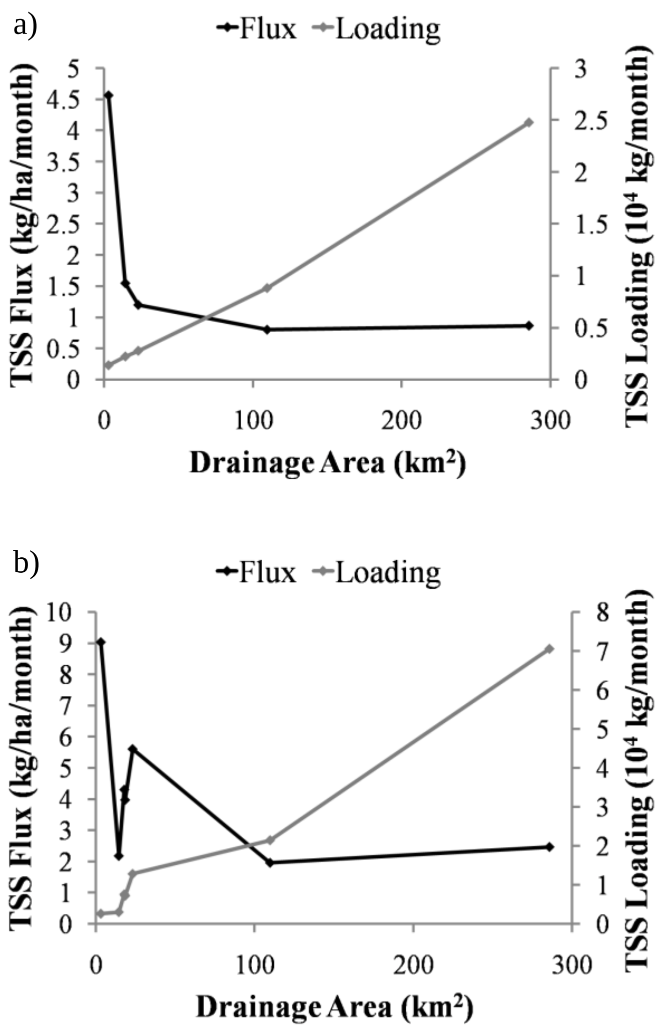

Figure 4.9. Pre-harvest (a) and post-harvest (b) TSS flux (kg ha^{-1} mo.$^{-1}$) and loading (10^4 kg mo.$^{-1}$). Values are means of monthly flux and loading.

Figure 4.10. Soil erosion (a) and logging trail (b) leading to the stream channel at the No-BMP harvest site (9Up/9Down). This intermittent stream is a tributary to Big Creek sampling site E5.

The decreases in standardized baseflow sediment yield are harmonious with decreases in baseflow in the post-harvest period (Brown and Xu, *In Review*), which were attributed to seasonal rainfall differences between treatment periods. A two-sample t-test showed that the decreases in standardized baseflow sediment yield were significant for intensive sites I1 and E4, but that baseflow TSS yields were not different for sites I4, E1, and E5 (Table 4.6). When yields were standardized with the full range of flow conditions, an increase in sediment yield was detected at site E5 during the post-harvest period as well. This result strongly suggests that even small-scale clearcutting adjacent to the stream without BMP implementation can increase downstream sediment transport

Table 4.6. Comparison of standardized yields (kg ha^{-1} $mo.^{-1}$ mm^{-1}) of total suspended solids and total dissolved solids by treatment period for the entire range of flow conditions and during baseflow conditions only (in *italics*) for sites I1, I4, E1, E4, and E5.

	TSS Yield (kg ha^{-1} $mo.^{-1}$ mm^{-1})		**TDS Yield (kg ha^{-1} $mo.^{-1}$ mm^{-1})**	
Site	Pre-harvest	Post-harvest	Pre-harvest	Post-harvest
I1	0.04 ± 0.05[a]	0.04 ± 0.10[a]	0.19 ± 0.15[a]	0.10 ± 0.11[b]
	0.05 ± 0.07[a]	*0.01 ± 0.02[b]*	*0.29 ± 0.35[a]*	*0.11 ± 0.15[b]*
I4	0.02 ± 0.02[a]	0.02 ± 0.03[a]	0.10 ± 0.08[a]	0.09 ± 0.13[a]
	0.03 ± 0.03[a]	*0.02 ± 0.05[a]*	*0.13 ± 0.13[a]*	*0.10 ± 0.26[a]*
E1	0.01 ± 0.01[a]	0.02 ± 0.03[a]	0.10 ± 0.08[a]	0.18 ± 0.24[a]
	0.02 ± 0.01[a]	*0.01 ± 0.01[a]*	*0.14 ± 0.12[a]*	*0.08 ± 0.12[a]*
E4	0.01 ± 0.01[a]	0.02 ± 0.03[a]	0.13 ± 0.10[a]	0.20 ± 0.24[a]
	0.02 ± 0.03[a]	*0.01 ± 0.01[b]*	*0.23 ± 0.25[a]*	*0.05 ± 0.07[b]*
E5	0.02 ± 0.02[a]	0.04 ± 0.05[b]	0.11 ± 0.13[a]	0.25 ± 0.22[b]
	0.02 ± 0.02[a]	*0.02 ± 0.02[a]*	*0.13 ± 0.13[a]*	*0.17 ± 0.18[a]*

*Means followed by the same letter within a row are not significantly different at the 0.05 level.

Collectively, these results demonstrate that low-intensity clearcut harvesting adjacent to streams and with BMP implementation did not increase sediment transport in these low-gradient headwaters (sites I1 and I4) or at the larger watershed-scale (i.e., site E4). The plot- and watershed-scale effectiveness of timber harvesting BMPs in minimizing sediment yield was

likely enhanced in this study by natural landscape and hydrologic conditions, such as flat topography, low streamflow velocity, and pooling created by beaver and debris dams (Figure 4.11).

High flow TSS yield could not be compared between treatment periods due to differences in the abilities of rating curves to predict discharge from stream stage height during bankfull and flood stage conditions. During the pre-harvest period, bankfull and flood events were conservative estimates because these high flows could not be measured. Measurement of bankfull and flood conditions was challenging because wading was unsafe and ADCP towing was not easily applicable to remote forested headwaters.

Figure 4.11. Beaver dams are abundant in this flat terrain watershed. They complicate flow and serve as filters as shown by the photo taken at site I4 on Turkey Creek in December 2009.

Flood stage discharge measurements were conducted during the post-harvest period only and are conservative streamflow measurements because extensive overland flow could not be measured (Figure 4.12). Flood stage flow conditions occurred several times during the pre-harvest period (Philip Saksa, PhD student, University of California, Merced, personal

communication) and at least five times during the post-harvest period. Flooding is not rare due to slowly permeable soils, high stream meander, and beaver dams, which can increase surface runoff by forcing streamflow to overtop and/or flow around the dam (Westbrook et al., 2006). These high flow events can account for a large portion of annual measured discharge and sediment loading (McBroom et al., 2008), which makes quantification of these events critical for Total Maximum Daily Loading (TMDL) development. For example, a 107-mm rain event on October 30, 2009 generated a 49,294 kg TSS load at headwater site I1. This represented 47% of the total load quantified for this site during the entire four-year study period.

Figure 4.12. a) Flood event at effective Flat Creek watershed outlet site E4 on October 31, 2009. b) Streamflow measurement by way of ADCP towing from the Highway 127 Bridge.

4.4 Conclusions

Based on analyses of post-harvest TSS concentrations during baseflow and stormflow conditions and TSS yield, low-intensity clearcut harvesting adjacent to streams with BMP implementation did not increase sediment runoff at the plot- or the watershed scale. No difference was found between treatment periods for monthly baseflow or stormflow sediment concentrations. Sediment concentrations during the first two years following timber harvesting were toward the lower end of published results for the Gulf Coastal Plain. TSS flux (kg/ha/yr) for all monitoring locations was well within the range for undisturbed forested watersheds of the Southeast. TSS yields during baseflow conditions did not increase post-harvest. TSS yields calculated with the full range of flows increased significantly in the post-harvest period downstream close to the No-BMP-harvest location, which indicates that without BMPs, even small-scale clearcutting adjacent to streams can increase downstream sediment transport. Natural conditions such as beaver dams, low streamflow velocities, and frequent periods of intermittency of these low-gradient headwaters may have also aided BMP implementation in minimizing NPS sediment runoff from timber harvesting. High flow events can represent a substantial portion of annual and, in this case, entire study period totals for sediment loading. Overall, as intensive forest management is ubiquitous throughout the Flat Creek Watershed, findings of this study indicate a high resiliency of the flat terrain landscape to forest management effects on sediment runoff and yield at the plot- and watershed-scale.

CHAPTER 5: SUMMARY

A research project with paired-watershed and Before-After-Control-Impact (BACI) designs was initiated in 2005 in the low-gradient headwaters of the Flat Creek Watershed in north-central Louisiana. The research monitored changes in streamflow, water quality conditions, and benthic macroinvertebrate communities from December 2005 to December 2009, during which timber harvest with and without BMPs was conducted in the summer of 2007. The primary goal of the study was to determine whether or not Louisiana's current forestry BMPs are effective in water quality protection. This thesis study is part of the interdisciplinary research and it focused on the project's major findings in streamflow, stream sediment concentration, and yield and discussed the effectiveness of timber harvesting BMPs in these unique flat terrain conditions.

Based on analyses of post-harvest baseflow, stormflow, and stage-discharge relationships, clearcut harvesting adjacent to streams at a rate of less than two percent of the total drainage area and with the BMP implementation did not impact streamflow at the plot- or watershed-scale. No difference was found in monthly baseflow measurements at any site or in peak water level response to winter storm events for the intensive monitoring locations. Flow duration curve analysis showed that baseflow decreased post-harvest, possibly due to differences in the timing of precipitation between treatment periods. Timber harvesting without BMPs, such as maintaining SMZs and improving stream crossings, increased the slope of the stage discharge relationship during the 27-month post-harvest period. Secondary findings include a highly variable, stormflow-dominated flow regime in the low-gradient headwaters of the Flat Creek watershed. In addition, beaver dams impacted hydrology in this low-gradient landscape.

Potential exists for future studies to determine long-term cumulative impacts of intensive forest management to headwater streamflow, as forest disturbance increases throughout the watershed.

Based on analyses of post-harvest TSS concentrations during baseflow and stormflow conditions and TSS yield, low-intensity clearcut harvesting adjacent to streams with BMP implementation did not increase sediment runoff at the plot- or the watershed scale. No difference was found between treatment periods for monthly baseflow or stormflow sediment concentrations. Sediment concentrations during the first two years following timber harvesting were toward the lower end of published results for the Gulf Coastal Plain. TSS flux (kg/ha/yr) for all monitoring locations was well within the range for undisturbed forested watersheds of the Southeast. TSS yields during baseflow conditions did not increase post-harvest. TSS yields calculated with the full range of flows increased significantly in the post-harvest period downstream close to the No-BMP-harvest location, which indicates that without BMPs, even small-scale clearcutting adjacent to streams can increase downstream sediment transport. Natural conditions such as beaver dams, low streamflow velocities, and frequent periods of intermittency of these low-gradient headwaters may have also aided BMP implementation in minimizing NPS sediment runoff from timber harvesting. High flow events can represent a substantial portion of annual and, in this case, entire study period totals for sediment loading. Overall, as intensive forest management is ubiquitous throughout the Flat Creek Watershed, findings of this study indicate a high resiliency of the flat terrain landscape to forest management effects on sediment runoff and yield at the plot- and watershed-scale.

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