# Sediment Yield along an Actively Managed Streamside Management Zone

by

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A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
August 9, 2010

Keywords: Sediment, Best Management Practices,Water quality
Streamside Management Zones, Silviculture, Partial Cut



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Abstract

In this study, we aim to regenerate a mature streamside management zone (SMZ) and create an uneven-aged forest with multiple canopy tiers and a dense understory using single tree selection (based on the Proportional-B method). We observed the effects of this partial cutting on sedimentation by comparing a treatment watershed with an unharvested reference site. In addition to determining partial cutting effects on sediment yield, we also evaluated the effects of different land uses and a recent clearcut on sedimentation, quantifying the effects of forest cover on sediment, and determining the efficacy of the SMZ at reducing sediment yield from the clearcut.

The study was conducted on the Mary Olive Thomas Demonstration Forest which is owned and managed by the School of Forestry and Wildlife Sciences. Sediment water quality data were sampled from April 2009 to April 2010. Water stage measurements were monitored using pressure transducers installed at each monitoring station. In addition to continuous water stage measurements by transducers, stream discharge measurements were recorded, and water samples collected during storm events. Continuous discharge data were created using rating curves between water levels and discharge data. Total suspended sediment (TSS) was determined from water samples and continuous sediment data were estimated using the LOADEST software. Pre-harvest data from two watersheds were calibrated to determine the effects of the partial cutting on sedimentation.

During the calibration period, forest cover caused a decrease in sediment yield while the current clearcut and forest road increased sediment yield because the SMZ was not sufficient to

trap all of the sediment originating from these disturbances. During the treatment period, in comparison to the reference watershed, the partial cut within the SMZ caused an increase in both water and sediment yield on the harvested sections. During pre-harvest period, upstream sections (pasture and urban on the treatment and control watersheds, respectively) generated much more sediment yield than downstream sections. However, following harvest there was a significant increase in sediment load from downstream sections of the treatment.

Our data suggest that undisturbed forest cover seems to be effective at reducing sediment yield. It may be suggested that forest operations can cause an increase in sediment load if forest roads and SMZs are not managed properly. If effective forest road best management practices (BMPs) are not in place, then simply focusing on SMZs to reduce sediment yield is not sufficient. The study also shows the importance factoring in upstream land use/cover conditions in designing SMZs for sediment trapping as well as the importance management of a watershed as a whole to increase the efficacy of BMP's.

## Acknowledgments

The author would like to thank Drs. Edward F Loewenstein, Latif Kalin and Tom Gallagher for their instruction, guidance, patience, and commitment, with special consideration to Dr. Loewenstein serving as the author's major professor. The author would also like to recognize and thank Dr. Sabahattin Isik, Andrew Morrison, and James Ransom for their help. The author would also like to thank his parents, Nizamettin and Aliye Kara, for their dedicated support and encouragement.

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# Chapter 1

# Introduction

## 1.1. Background

One of nature's most important gifts to living beings is water. It is a vital resource that we rely on every day. With increasing pollution, human population and global warming, clean water is becoming one of the most precious natural resources for the future. Thus, protection of water quality has become very important to the public. In the last two decades, there has been growing concern over the impact of human activities such as land conversion, deforestation, urbanization, and forest management on water quality (Amatya, 2007).

Forested watersheds are generally associated with high quality water compared to watersheds with other major land use/cover types (Chang, 2006). They are the main sources of clean water. Because surface runoff and erosion are negligible in undisturbed forests, they generate relatively low sediment yields (Elliot et al., 2000). In addition to low sediment yield, dissolved nutrients and stream temperature are also low; and oxygen content is high in streams draining undisturbed forests (Swank et al., 2001). Erosion rates from undisturbed forest lands are actually less than the background rate of soil formation caused by geological processes (Beasley, 1979). Both trees and understory provide effective surface cover in undisturbed forests. Minimal erosion and sedimentation occurs because this cover protects the soil surface from damaging storm energy (Grace, 2002). Given the benefits derived from undisturbed forests on water quality, we must be particularly aware of site disturbance during the conduct of forestry operations.

In addition to protecting water quality, forests provide many other benefits such as oxygen production, wind control, animal habitat, aesthetics, recreation, and timber production. To ensure the sustainability of these benefits, some management practices may be required. For example, intensive forest management operations such as timber harvesting, residue removal, and road construction are necessary to increase timber production from the forest. But these operations can affect Nonpoint Source Pollution (NPS) pollution leaving a forested watershed (Saleh, 2004). Forest management and harvesting practices may cause multiple effects such as modification of watershed hydrology, increase in erosion and sedimentation, habitat change, and chemical contamination of the stream (Binkley and Brown, 1993). The effects of such operations are not independent but are related (Thornton et al., 2000). Most of the harvest impacts that cause sedimentation are induced by the access and movement of vehicles and machinery, including the skidding and loading of trees and logs (Fulton and West, 2001).

Recently, many environmental communities have focused on NPS (Brannen et al., 2000) as being the biggest threat to the nation's water quality (USEPA, 2003). It was estimated that the damage from NPS pollution to streams, lakes and estuaries was $7 to $9 billion a year in the mid-1980s (Klapproth and Johnson, 1999). Higher levels of NPS pollution are created by more frequent or intense disturbances (Catts and Chescheir, 2006). Swank (2001) states that the closer a disturbance is to a stream, the greater the risk of its impacting water quality. Forestry, agriculture, construction, and urban activities are all considered potential sources of NPS pollution. Sediment and nutrients are the most common NPS pollutants from forestry activities (Borah et al., 2006)

Over the past 30 years, the need to protect water quality has gained recognition, and best management practices (BMPs) such as streamside management zones (SMZs) were developed. These practices are designed to be at or above the minimum standards necessary to protect and maintain water quality during forestry activities (AL Forestry Commission, 1999). Many studies have shown that without BMPs, forest management practices can have negative effects on water quality (Fulton and West, 2001; Wynn et al., 2000; Arthur et al., 1998; McBroom et al., 2007). These negative effects can be reduced by the implementation of BMPs as part of forest management (Norris, 1993), and BMPs have proven to be a cost effective means for controlling NPS pollution in forested watersheds (McBroom et al., 2007).

In most situations (in Alabama), BMPs are recommendations only, and are not mandated by law (AL Forestry Commission, 1999). However, full compliance with the U.S. Clean Water Act requires BMPs in one of the enforcement exemptions. Site-specific factors such as soil, slope, and land use may change the effectiveness of BMPs (Shukla and Mostaghimi, 2002), so to determine the effectiveness of BMPs, monitoring data under various hydrologic and weather conditions should be collected (Santhi et al., 2006). There are several categories of BMPs: SMZs, stream crossings, forest roads, timber harvesting, stand management, and wetland management. While SMZs are one of the most effective BMPs to protect water quality, the total BMP objective cannot be accomplished by a single practice (AL Forestry Commission, 1999).

Streamside Management Zones are one of the most commonly employed nonstructural BMP types. A SMZ is a strip of land immediately adjacent to a water body where soils, organic matter and vegetation are managed to protect the physical, chemical and biological integrity of the surface water adjacent to and downstream from forestry operations (AL Forestry Commission, 1999) (Figure 1.1). A SMZ consists mostly of riparian habitat area and provides a variety of functions and values. The most important function of SMZs is maintaining water quality. They filter sediment, nutrients, pollutants, and they help maintain stream temperatures; they stabilize stream banks, and they provide food and shelter for wildlife. Cooper et al. (1987) have shown that a riparian buffer can trap 84 to 90 percent of the sediment loading.

Figure 1.1: A streamside management zone (AL Forestry Commission publication, 1999).

Even though the width of a SMZ is determined according to type of stream, management objectives, or width of stream, it should not be less than 10 meters from a definable bank (AL Forestry Commission, 1999). A SMZ should be wide enough to protect water quality, but unnecessarily wide SMZs will cause economic loss of valuable timber resources (NCASI, 2000). Streamside management zones with greater canopy cover may increase the ability of trees to reduce the effects of direct rainfall on erosion. The intent is to maintain sufficient overstory and understory cover to provide shade, maintain bank stability, and protect water quality.

There are many factors that influence the effectiveness of streamside buffers to trap sediment including slope, hydrology, type and density of riparian vegetation, surface litter layer, soil structure, and frequency and force of storm events (Klapproth and Johnson, 1999). These factors should be taken into account when designing SMZs. Riparian vegetation is very important for the water quality because it creates roughness on the ground, decreases water velocity and allows water to infiltrate the soil, and trap sediments (Daniels and Gilliam, 1996). Riparian vegetation also protects the surface of the soil from wind and water erosion that cause sedimentation.

Although silvicultural activities need not be excluded from SMZ's, any silvicultural activity within them must be closely supervised and managed. Careful management within a SMZ may increase its effectiveness. Timber harvesting within a SMZ must be done using selection, and with special care (AL Forestry Commission, 1999). In order to reduce fire and insect hazards, to provide some economic return, and to improve the effectiveness of SMZs, forested SMZs are often thinned (McBroom et al., 2007). Complete removal of the streamside or riparian vegetation during harvesting might increase: sediment and slash delivery to the stream, sediment accumulation in the streambed, stream temperature, and nutrient concentration (Thornton et al., 2000). Higher roughness with many small stems within a SMZ increases infiltration and decreases runoff, thus reducing transport of detached soil particles (Grace, 2002).

Thus, we decided to examine the potential for active management in a SMZ while evaluating their effectiveness as a sediment filter. By developing a SMZ with multiple canopy tiers and a denser understory, using single tree selection based on the Proportional-B method, our intent is to develop a more efficient filtration buffer by generating a higher roughness and denser understory. We also intend to increase the potential for production of high value trees within a SMZ by actively managing the allocation of growing space. The effects of a partial cutting on sedimentation will be observed within a SMZ. In addition, the effects of different land uses, a recent clearcut, and undisturbed forest cover on sediment yield as well as determining the efficacy of the SMZ at filtering sediment from a clearcut will be evaluated.

## 1.2. Objectives

The overall objective of this research is to examine the effects of forestry treatments on sediment yield from two small adjacent watersheds.

Specific objectives of this study are:

1) Bring a mature SMZ under active management and create an uneven-aged stand by developing multiple canopy tiers and a dense understory using single tree selection based on the Proportional-B method
2) Determine the effect of partial cutting on sediment yield within a SMZ
3) Determine the effects of different land uses on sediment yield
4) Quantify the effect of forest cover on sediment yield after a stream enters a forested area
5) Determine the efficacy of a streamside management zone at reducing sediment yield adjacent to a clearcut.

As a further objective, it will be seen if a vertically stratified SMZ with denser understory can serve as a better filter in comparison to a mature even-aged SMZ when sediment rate is examined in the future.

# Chapter 2
# Literature Review

## 2.1. Water Quality

The quality of water and aquatic systems are affected by alterations in the chemical, physical and biological characteristics of streams (Brooks et al., 2003). However, the term 'water quality" is relative to any specific use (Scherer and Pike, 2003), for instance, the standards for drinking water may be much more stringent than for recreation use. If human activities foul natural water to the point where it can no longer meet a specific use, it is said to be polluted (Hewlett, 1969). There are many characteristics of water used to define its quality such as: suspended sediment, turbidity, total dissolved solids, dissolved gases, alkalinity, hardness, total conductivity, immiscible liquids, dissolved oxygen, toxic chemicals, water temperature, or pH.

The Clean Water Act (CWA), which is the primary federal law in the United States dealing with water pollution, is very important for surface water quality protection. It establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters (EPA, 2008). As mentioned, water quality standards vary by use since the quality of water suitable for recreation, drinking, or habitat is different in each situation. For example, water quality standards of irrigation water are not acceptable for drinkable water.

Erosion, climate, season, soil and rock mineralogy, vegetation, wildfire, and mass wasting can affect quality of water as well (Scherer and Pike, 2003). Each year in the U.S.A., about 3.9 billion metric tons of soils are lost through the processes of wind and water erosion; about 70% of this total is eroded from agricultural lands (National Resources Inventory, USDA SCS, 1987). Pimental et al. (1995) state that the cost of off-site and on-site soil erosion from agricultural lands is about $44 billion per year in the United States.

Water quality characteristics most affected by human activities are sediment, dissolved nutrients, and water temperature (Swank et. al, 1989). Runoff is considered a major agent of erosion since sediment, which is a NPS pollution, is carried to streams, lakes or any other body of water by runoff (USEPA, 1995). Suspended sediment concentrations, thermal pollution, and the level of dissolved oxygen are the more important physical characteristics of surface water (Brooks et al., 2003). Suspended sediment is an indicator used to determine the physical quality of surface water, and can restrict sunlight, smother benthic communities, and carry many nutrients and heavy metals that affect water quality (Brooks et al., 2003).

Research specific to forestry operations has been conducted on water quality and NPS pollution associated with land use. Some studies have only focused on sediment yield while some studies have evaluated water quality in terms of various parameters such as K, Cl, Ca, and Mg. Crignan et al. (2000) monitored water quality for three years following clearcut logging and wildfire. In comparison to the reference sites, they concluded that clearcut logging and wildfire increased dissolved organic carbon, concentrations of total phosphorous, total organic nitrogen, $K^+$, $Cl^-$, $Ca^2$, $NO_3$, and $SO_4$.

## 2.2. Sediment

Sediment refers to soil particles that pollute streams or other bodies of water having originated from eroding lands such as agricultural areas, construction, logging sites, and urban areas (U.S.EPA, 1995). It is a product of erosion. Suspended sediment specifically refers to particulate matter suspended in and carried by moving water. On average, suspended sediment is less than 3% of the total mass of streamflow (Hewlett, 1969). Transportation and deposition of materials in water refers to a sedimentation process. Coarse particles in the water move relatively short distances while finer particles move longer distances (Hewlett, 1969). Concentration (dry weight per unit volume) is the best way to measure sediment (Ursic and Douglass, 1978).

Sediment poses the biggest risk to water quality (Grace, 2005). In addition to its effect on water quality, sediment effects stream biota as well (Callender and Rice, 2000). For example, fish gills are blocked, fish eggs and aquatic insect larvae are destroyed, or fish are forced to change their feeding and reproductive behaviors because of sedimentation (Klapproth and Johnson, 1999). Excessive amounts of Total Suspended Solids (TSS) cause damage to water quality and habitat degradation in streams. Suspended sediment may degrade water quality by changing light penetration (Kirk, 1994). Visual clarity that affects aquatic ecosystems and influences aesthetics may also be reduced with increased turbidity because of sedimentation (Davies-Colley and Smith, 2001).

Disturbance of the soil or vegetation cover, climatic variation, or catastrophic events may change the runoff characteristics of a watershed. Such disturbances may change the particle size distribution and total amount of sediment that a stream carries (Ursic and Douglass, 1978).When the soil is disturbed by harvest and/or site preparation techniques, it is exposed to the erosional effects of raindrops allowing the movement of sediment down slope when rain events occur (Fulton and West, 2001). Bare soil on steep slopes, debris flows, streambank erosion, and roads are main sources of sediment (Fulton and West, 2001). Forestry operations and urbanization may become a source of excessive sediment to downstream reaches and result in degradation of water and biotic quality (Paul and Meyer, 2001).

### 2.3. Forested Watersheds and Forest Operations

Canopy and surface cover reduce raindrop impact and soil detachment by intercepting part of the precipitation in forested watersheds. When harvesting occurs in forested watersheds, it affects water quantity and quality by reducing transpiration and interception, and increasing surface evaporation. Harvesting primarily affects water quality in terms of sediment, dissolved nutrients and water temperature. Clearcutting in particular, causes a large decrease in evapotranspiration and a large increase in streamflow (Douglass, 1980). Although clearcutting is considered to have the biggest impact on water quality, silvicultural systems that include more frequent entries into the forest may actually cause greater impact than clearcutting (Ursic and Douglass, 1978). As the vegetation reestablishes following harvest, the evapotranspiration rate will eventually return to previous conditions. Of all of the disturbances associated with timber harvest, skidding is considered to cause the most serious disturbance during forest operations because of the high potential for exposing mineral soil by dragging trees along the ground. However, as long as careful logging practices are followed, logging can be conducted without increasing risk of sediment input to streams (Kreutzweiser et al., 2009). When a forested watershed is exposed to minimal soil disturbance by these careful logging practices, the watershed will generally continue to provide high water quality (Colson, 2008).

Walling and Gregory (1970) compared impacts of building activity upon suspended sediment concentrations with two small adjacent watersheds, one of which served as a control. Building activity caused an increase in suspended sediment concentration between two and ten times, and occasionally up to hundred times compared to that of undisturbed conditions (Walling and Gregory, 1970). A similar study conducted in urban and suburban areas found that sediment yield was between 80–200 ton/km$^2$/yr on wooded watersheds while intensive farming caused yields up to 400 ton/km$^2$/yr. They also estimated sediment yields of 700-1800 ton/km$^2$/yr on construction sites (Wolman and Schick, 1967).

Site disturbances such as clearcutting or road construction can increase surface runoff and erosion potential (Binkley, 1999). McBroom et al. (2007) observed sediment losses associated with the degree of watershed disturbances resulting from a forest clearcutting and site preparation in nine small watersheds with no BMPs. They reinstrumented the same nine watersheds after 19 years with BMPs, and concluded that sediment losses were generally reduced with decreasing intensity of site disturbances (McBroom et al., 2007).

The effects of thinning on the hydrology and water quality of a watershed with no-SMZs were evaluated over a 3-year study period on an artificially drained pine plantation watershed by Grace et al. (2006). The treatment watershed received a fifth-row with selection thinning while the other subwatershed served as an un-thinned control. They concluded that total suspended sediment (TSS) loads increased following the thinning. Thinning also doubled mean daily outflow and increased peak flow rates about 40%. In addition to an increase in sediment, phosphorous and Total Kjeldahl Nitrogen (TKN) also increased following the thinning operations (Grace et al., 2006).

Beasley (1979) evaluated three methods of intensive site preparation (brush chopping, shearing and windrowing, and bedding on contour) against a control in terms of their effects on sediment loss on four small watersheds. The three treated watersheds were fertilized, limed, sown with clover, and planted with loblolly pine (*Pinus taeda L.*). Sediment losses were 12.5 tons/ha on the chopped watershed, 12.8 tons/ha on the sheared watershed, 14.2 tons/ha on the bedded watershed, and 0.6 tons/ha on the control watershed during the first year. Second year, sediment losses decreased on all four watershed to 2.4, 2.2, 5.5, and 0.1 metric tons/ha respectively (Beasley, 1979).

### 2.4. BMPs and Water Quality

Water quality in streams is related to upland disturbance or management activities, and BMPs are implemented to protect water quality. They represent a balance between natural resource protection and forest resource use. Three small watersheds (clearcut with BMP, clearcut with no-BMP and a no treatment control) were monitored to evaluate the impacts of forest clearcutting on water quality and to evaluate the effectiveness of BMPs for minimizing timber harvesting effects on water quality. Forest clearcutting without BMP implementation reduced storm runoff volume, but did not change peak flow rate. Storm flow volume and peak flow rate declined significantly following site preparation. On the BMP site, storm flow volume decreased and peak flow increased after harvest. Loadings of sediment increased significantly following clearcut and site prep on the No-BMP watershed. On the other two watersheds, there were few changes (Wynn et al., 2000).

Since southern forests are some of the most productive forests in the U.S.A, they are often exposed to intensive management practices (Grace, 2005). To increase site productivity and reduce rotation time, silvicultural prescriptions often include site preparation, fertilization, and thinning, as well as harvesting. These intensive management practices may affect NPS pollution because they disturb the natural environment. Grace (2005) investigated the effects of forestry operations on water quality in the 13 southern states. He concluded that forestry best management practices help protect and maintain water quality of the region following forest operations (Grace, 2005). However, he also found that it is not possible to accurately estimate the overall effectiveness of BMPs since their benefits on different scales are relatively unknown.

Stream water quality of three watersheds was compared by Arthur et al. (1998). One watershed was harvested with BMPs, one was harvested with no-BMPs and third watershed was kept as control. In comparison to the uncut watershed, sediment rates were 14 times higher on the BMP watershed, and 30 times higher on no-BMP watershed during the treatment. After 17 months following treatment, sediment was 4 times higher on the BMP watershed and 6.5 times higher on the no-BMP watershed than on the control (Arthur et al., 1998). Concentrations of nitrate, and other nutrients also increased on the treatment watersheds following harvest. They found that the strip buffer was effective in reducing the effects of clearcutting on water yield and sediment rate (Arthur et al., 1998).

### 2.4.1. SMZs and Water Quality

The width of a SMZ is important for its effectiveness at protecting water quality. Ensign and Mallin (2001) monitored water quality before harvest for 2.5 years, during the clearcut, and following the clearcut for two years. In comparison with neighboring control watershed, post-clearcut water quality measurements showed significantly higher levels of suspended solids, even though a 10 m uncut buffer zone was left streamside. The authors concluded that a 10 m buffer zone was not sufficient to prevent impacts from a clearcut on water quality.

In order to protect water quality during and after forest harvesting, SMZs are usually recommended (Blinn and Kilgore, 2001). Lakel et al. (2006) clearcut, applied site preparation using prescribed fire, and planted loblolly pine on sixteen watersheds. SMZs were maintained on all of the watersheds, but half of them were thinned. The SMZs varied in width from 7.6 m to 30.5 m. Results indicated that harvesting did not damage water quality and all SMZ widths were equally effective at protecting water quality in the first year after the harvest (Lakel et al., 2006).

Kreutzweiser et al. (2009) also examined the effects of partial harvest in SMZs, Three logged and three reference stream reaches were compared in terms of sediment deposition before and after logging. At the three logged sites adjacent to upland clearcut areas, partial-harvest logging was done in the riparian buffer zone. No significant differences were found in comparison with pre-logging and reference-site sedimentation patterns for two of the three logged sites. The third site was treated with the most intensive riparian logging; in this case, sediment yield was 3-5 times higher than pre-logging or reference levels. The authors concluded that careful logging practices, including winter harvesting, in riparian areas mitigated logging impacts on fine sedimentation in streams (Kreutzweiser et al., 2009).

After examining the effects of silvicultural operations on streamflow for 20 years, Patric (1980) concluded that the greatest impact of forest operations on water quality occurs in first year following harvest. Within this time period, the area was clearcut, a 40 m buffer zone was left, and streamflow was observed. No effect on stormflow or stream temperature was found, but the treatment increased water yield about 38% during the first year. A slight increase was observed in concentration of sediment, nitrate, calcium, magnesium, potassium, and sodium. The potential impacts of the treatment were mitigated by the buffer zone and well-managed logging roads (Patric, 1980). Within two years after the harvest, all treatment effects were reduced over the entire watershed because of revegetation. After a few years, no effects from the treatment were measurable (Patric, 1980).

### 2.4.2. Forest Roads

Sediment from forest roads, skid trails, and log landings has been a major factor affecting water quality (Ursic and Douglas, 1978) since the most of sediment yield is contributed by forest roads and skid trails (Appelboom et al, 2002; Grace, 2002). Runoff and seepage from forest roads can contain increased levels of suspended sediment (Brooks et al, 2003). Saturation of road beds and subsequent soil mass movement can be caused by poor drainage (Brooks et al, 2003). Proper planning and location of forest roads minimize deposition of sediment into water (AL Forestry Commission, 1999). Disturbances of roadbeds are the main cause of sediment from forest roads. Sediment originating from forest roads can flow directly to streams (Packer, 1967)

Road management is an important component of forestry best management practices. Surfaces should be graveled to minimize sediment yield. Techniques such as turnout ditches, water bars, or broad-base dips can also be installed to further reduce the effects of forest roads on sedimentation. Stream crossings by roads, skid trails or firebreaks should be avoided because these crossings cause a break in the canopy and SMZs (AL Forestry Commission, 1999). If they are necessary, special methods of stream crossings such as log crossing, culverts, fords or bridges must be installed. Vegetation establishment can be used to control erosion from forest roads as well (Grace, 2002). Appelboom et al. (2002) examined the effectiveness of seven road management practices at reducing sediment production from forest roads. They found that the construction of a continuous berm along the edge of forest road, gravelling the road surface, and maintenance of a roadside vegetation strip appeared to reduce the total loss of sediment from roads (Appelboom et al, 2002).

### 2.5. Summary

Many studies have been conducted to examine the effects of forestry operations, effectiveness of best management practices, effects of forest roads, effects of urbanization, or the effectiveness of SMZs on water quality and aquatic life. Most of them have revealed that BMPs, especially stream buffer zones have the potential to protect and maintain water quality and quantity during and after management activities. Many studies have proven that SMZs are very effective at trapping sediment yield from forest operations. Most studies in the literature have focused on the effect of one particular treatment such as clearcutting, thinning or SMZs on soil erosion and/or sediment. In this study, we intend to explore the effects of both different land use types and forest operations on sediment on the same watershed.

Most watersheds contain more than one land use. Generally one land use is considered dominant in each watershed and the watershed is categorized as forested, urban, or pastoral according to this dominant land use. It is often difficult to isolate the effects of dominant land use from other land uses on a watershed. Thus, most of the studies in the literature have not been able to isolate the amount of sediment originating within each land use on the same watershed. In this study, monitoring sediment yield at different locations along a watershed allowed us to isolate these effects.

# Chapter 3

# Methods

### 3.1. Study Area

The study was conducted on the Mary Olive Thomas Demonstration Forest which is owned and managed by the School of Forestry and Wildlife Sciences, Auburn University. The property is located near Auburn, Alabama (Figure 3.1) and consists of a 162 hectare tract of land within Sections 34 and 35 of T19N R25E and Sections 2 and 3 of T18N R25E. The study area is located at the toe of an upland area. It is a transition zone from a Piedmont upland to a bottomland. The average annual rainfall is 148 cm, and 50% of the rainfall occurs during the growing season from April to September (Dubois et al., 2000). The average daily temperature is 7 °C in winter and 27 °C in summer. The average relative humidity is about 50% in mid-afternoon, and is higher at night (McNutt et al, 1981).

Most of the area has slopes of less than 6%; however, steep slopes are present on some parts of the tract. Pacolet series is the predominant soil type on the property except for narrow bands of Taccoa sandy loam along streams and main drainages. These soils are considered typical soils of the Piedmont plateau, and are fairly productive for forests (McNutt et al, 1981). Average site index for loblolly pine is about 26 m (base age 50 years) on the property. Lower slopes along the creeks are quite rocky. Aerial photos from 1939 show that almost the entire tract was in row crops. All of the A Horizon and much of the B horizon have been lost to erosion.

However, the more level ground still retains topsoil since portions of unit were abandoned early. The lower slopes along the stream also retain much of their original soil since these areas were probably never cleared due to rocky formations in these zones (Anonymous, 2009).

Figure 3.1: Locator Map of Auburn, and Mary Olive Thomas Demonstration Forest

The timber on the property is primarily loblolly pine. However, the SMZs (including the study area) are dominated by deciduous species such as white oak (*Quercus alba*), water oak (*Q. palustris Muenchh.*), sweetgum (*Liquidambar styraciflua L.*), yellow poplar (*Lirodendron tulipifera L.*), red maple (*Acer rubrum L.*), Hickory (*Carya sp.*), and flowering dogwood (*Cornus florida L*). The SMZ stands are well stocked, and are typically wider than required (20 m) by the State of Alabama guidelines (AL Forestry Commission, 1999). The area in hardwood is about 22% of the property (36 ha) while openings including roads, permanent fields, power line all cover 8% of the tract. Currently, 92% (149 ha) of the tract is in woodland of which 14% (21 ha) is in regeneration, 1% (2 ha) in small trees, 31% (46 ha) in small poles, 10% (15 ha) in large poles, and 44% (65 ha) in saw timber (Anonymous, 2009).

In order to demonstrate BMPs for road construction, about five kilometers of road was constructed on the area in 1991. Additional gravel was applied to the road system, and some portions were re-graded in 2002 (Anonymous, 2009).

Two small adjacent watersheds, treatment (Tw) and control (Cw), were chosen for the study (Figure 3.2). The treatment watershed has an area of 37 ha while the control watershed has an area of 50 ha. Each watershed was divided into three sections (Tw1-Tw2-Tw3, and Cw1-Cw2-Cw3 respectively) based on land use or forestry treatment. Direction of flow is generally from north to south. An intact SMZ borders the stream the entire length of the watershed from point T1 south to T3, and from point C1 south to point C3. North of T1 on the treatment watershed is an open area, mostly pasture with a pond in the middle of the section. The central portion of the study area, Tw2, is entirely forested. On the control watershed (Cw), section Cw1 (north of C1) is mostly residential area with a pond in the middle of the section. The mid- portion of the study area, Cw2, is entirely forested. The property north of T1 and C1 is not owned by Auburn University and no sampling or data collection was conducted in these areas. In Tw3 and Cw3, there is a clearcut area between the two SMZs that was harvested in early 2008, site prepared with herbicide in late summer, windrowed with a root rake in the fall 2008 and planted during 2008-09 dormant season (Figure 3.2).

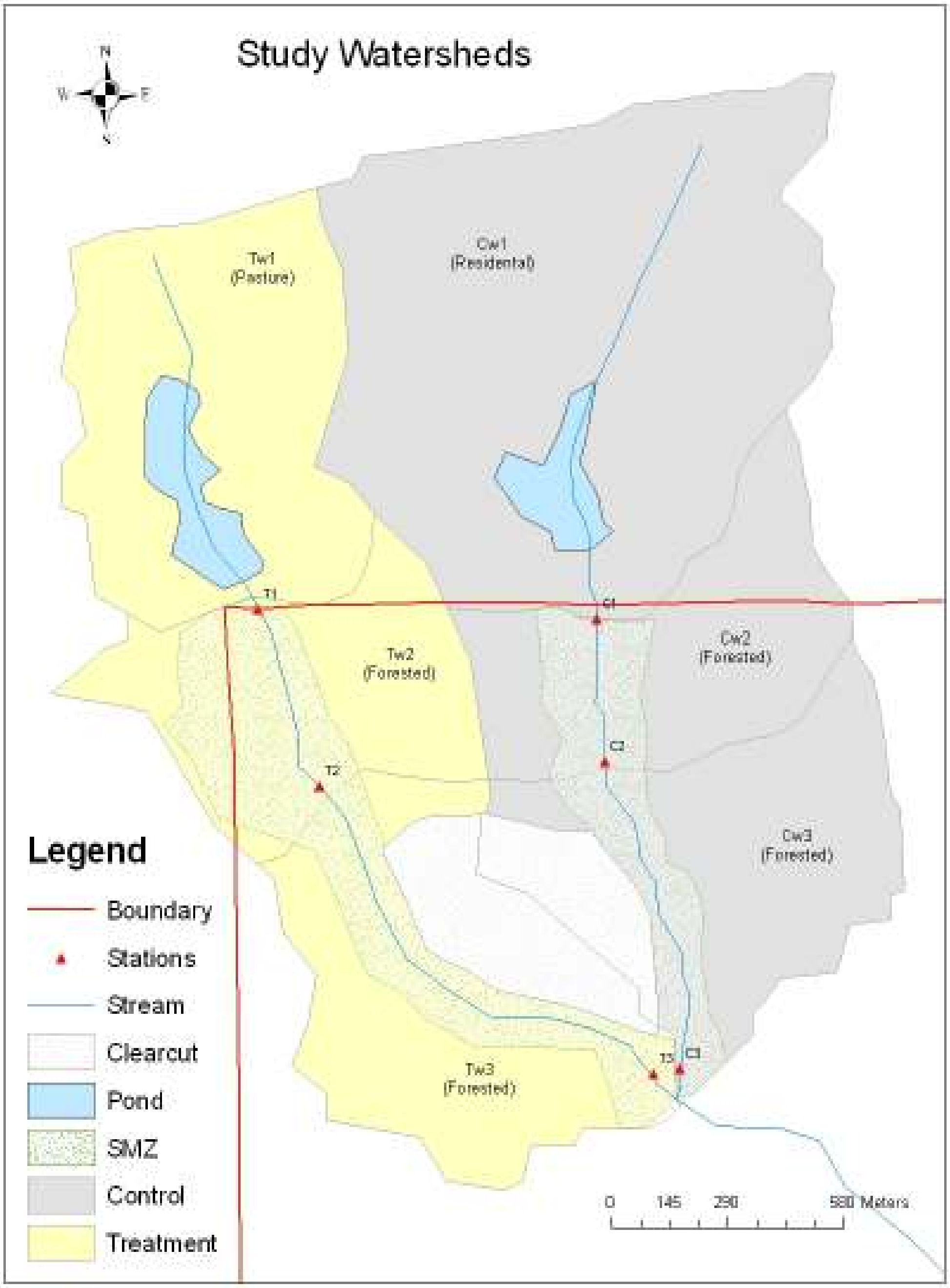



Figure 3.2: Map of the study watersheds

### 3.2. Watershed Boundaries and Monitoring Stations

ArcSWAT was used to delineate the watersheds and stream network in the study area (Neitsch et al, 2005) based on 10 m Digital Elevation Model (DEM) data (Figure 3.3). The watershed outlet was identified and the watershed delineated based on this outlet (Figure 3.4).

Using the CLIP option in GIS, watershed boundaries and streams within the property were determined. The highest elevation is 230 m on the north boundary of the watershed while the lowest elevation is 180 m at the outlet of the watershed.

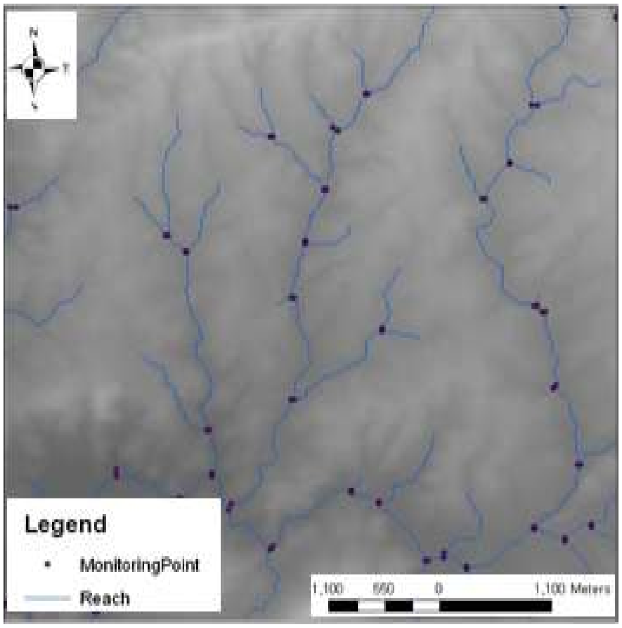



Figure 3.3: Stream processing


Figure 3.4: Watershed delineation

A digital map of the property was created by ArcGIS. An aerial photo was used as the base layer for digitizing. The clearcut area did not appear in the most recent photos, so the boundary was mapped using a Trimble GeoXM 2005 handheld GPS. This data was transferred to a computer and overlaid on the base using ArcMap. (Figure 3.2)

One monitoring station was established on each section (T1, T2, T3, C1, C2, and C3) to sample stream stage and sediment. The first stations (T1and C1) were located on the north boundary of the forested area to observe how much sediment entered the forested area from the pasture and residential area. The second group of stations (T2 and C2) was located at the upstream edge of the clearcut area so that in comparison with T1, it would be possible to evaluate the effect of intact forest cover on sediment rate changes in the stream. The third stations (T3 and C3) were located at the downstream end of the watershed to evaluate the effects of a clearcut area on sedimentation through an intact SMZ (Figure 3.2).

### 3.3. Sediment and Hydrologic Sampling

Water stage and water quality data (defined as sediment load) were sampled from April 5, 2009 until April 5, 2010. Water stage measurements were monitored using Solinst Levelogger Gold Model 3001 pressure transducers installed at each monitoring station (Figure 3.5). Calm sections of the streams were chosen for the installation of transducers. The transducers were set to collect stream stage levels every 15 minutes. Leveloggers record the combined barometric pressure and water pressure. This total pressure reading is logged as a water level equivalent. The actual water level is obtained by compensating for variation in barometric pressure (Levelogger User Guide, 2009). Barometric pressure was obtained from the http://weather.noaa.gov/weather/current/KAUO.html website each day.

Figure 3.5: Levelogger Gold transducers

In addition to continuous water stage measurements by transducers, stream discharge was measured and water quality samples were collected during storm events (whenever possible, while it was still raining) at each monitoring station. Stream discharge was measured at each station using a Marsh-McBirney Inc., Model 2000 portable flowmeter during each site visit. The standard stream cross-sectional velocity profile method was used to obtain discharge (Hewlett, 1969). The cross-sectional area of the stream was determined by measuring the stream depth every 10, 20 or 30 cm (depending upon stream width), and recording the velocity of water at 0.6 depth at each sampling point When water depth was deeper than 0.3 m at any monitoring station, flow measurements were also taken at 0.8 and 0.2, and averaged to obtain more accurate results (Figure 3.6). Total discharge (Q) was calculated using the following equation:

$$Q=\Sigma \text{ (width of each increment*mean depth of each increment*velocity of each increment)}$$

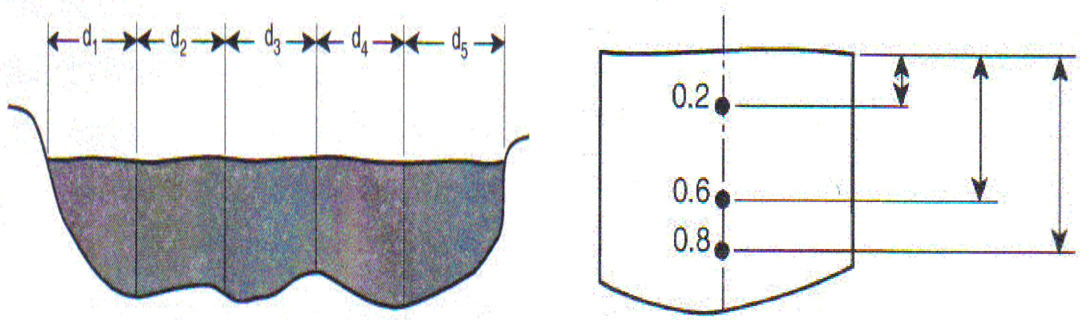



Figure 3.6: Cross-sectional area stream profile for measuring discharge at 0.6 depths (left), and at 0.6, 0.8 and 0.2 depths (right)

Water levels were associated with discharge measurements taken during each site visit to determine water level-discharge relationships. These relationships were used to calculate the total discharge for each 15 minute period by creating rating curves between water levels and discharge data from each station (Figure 3.7)

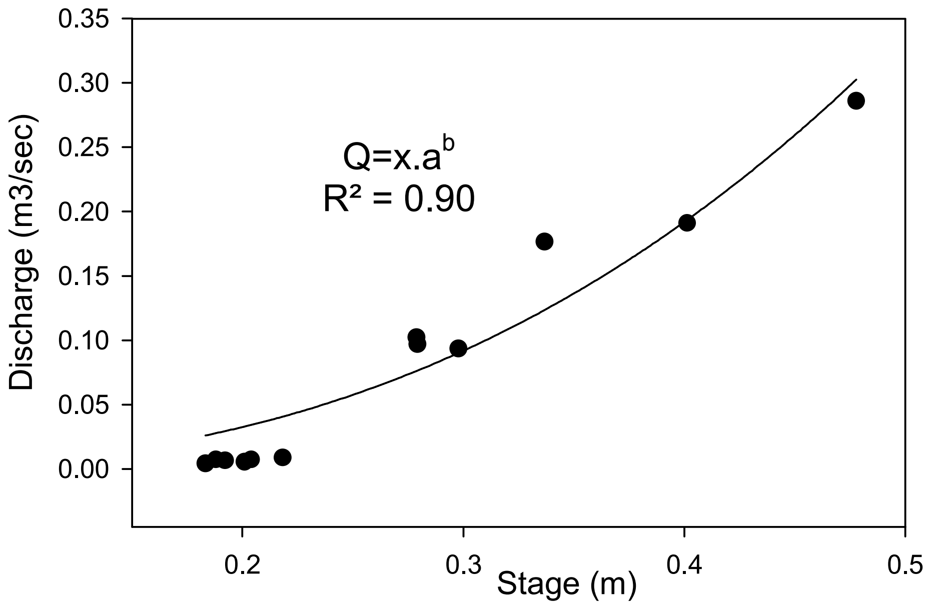



Figure 3.7: An example of a Rating Curve

Grab samples were taken prior to flow measurements to ensure that particles dislodged by persons wading in the stream would not contaminate the samples. Polypropylene bottles were rinsed with stream water before water samples were collected. Samples were stored in a cooler at 4°C until they were analyzed. Sediment analyses were done at the School of Forestry and Wildlife Sciences (SFWS) Laboratory.

Total suspended sediment (TSS) concentrations were determined from water samples using the 2540 total suspended solids dried at 103-105 °C method. In this approach, a standard glass-fiber filter is washed with 100ml distilled water, dried in a 103-105 °C oven for one hour, and then weighed. The process is then repeated two more times to ensure accurate results. After the filters are washed, 100 ml of well-mixed water sample is filtered through the pre-washed and weighed filters, dried at least one hour in a 103-105 °C oven, cooled for 15 minutes, and weighed. The heating, cooling and weighing is repeated two more times. TSS concentrations are then calculated using the following equation:

TSS (mg/L): [(mass filter + dried residue) – (mass filter)] / sample volume 100 ml x 1000

Calculated TSS concentrations were used to estimate the sediment load for each 15 minute period using LOADEST software, a FORTRAN program designed to estimate constituent loads in streams and rivers. LOADEST requires a time series of streamflow, and constituent concentration (such as sediment) to develop a regression model for the estimation of constituent load (calibration) (Loadest Manual, 2004), (Appendix H).

Hydrographs and sediment graphs at each location were developed using 15-minute discharge (Figure 3.8) and sediment data. Discharge and sediment data were analyzed for each of the six stream sections.

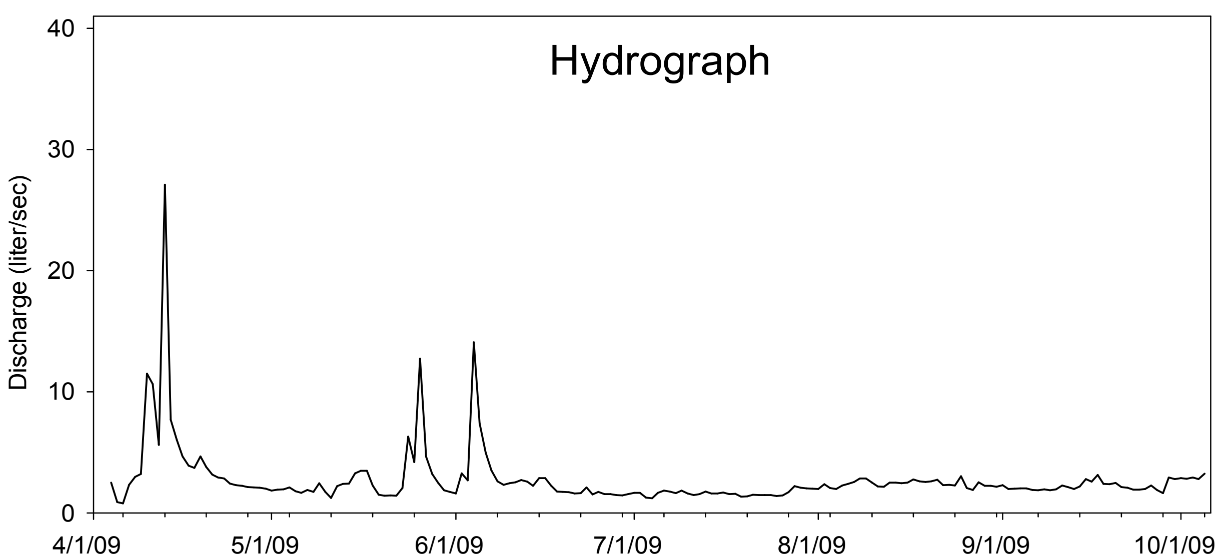


Figure 3.8: An example of hydrograph

Baseflow of each section was determined using the WHAT model[1] (Muthukrishnan, 2005), a web-based hydrograph separation model (Figure 3.9). This model estimates baseflow (separating out peakflow) from observed flowdata. The hydrograph separation was used to observe change in baseflow and runoff after harvesting.

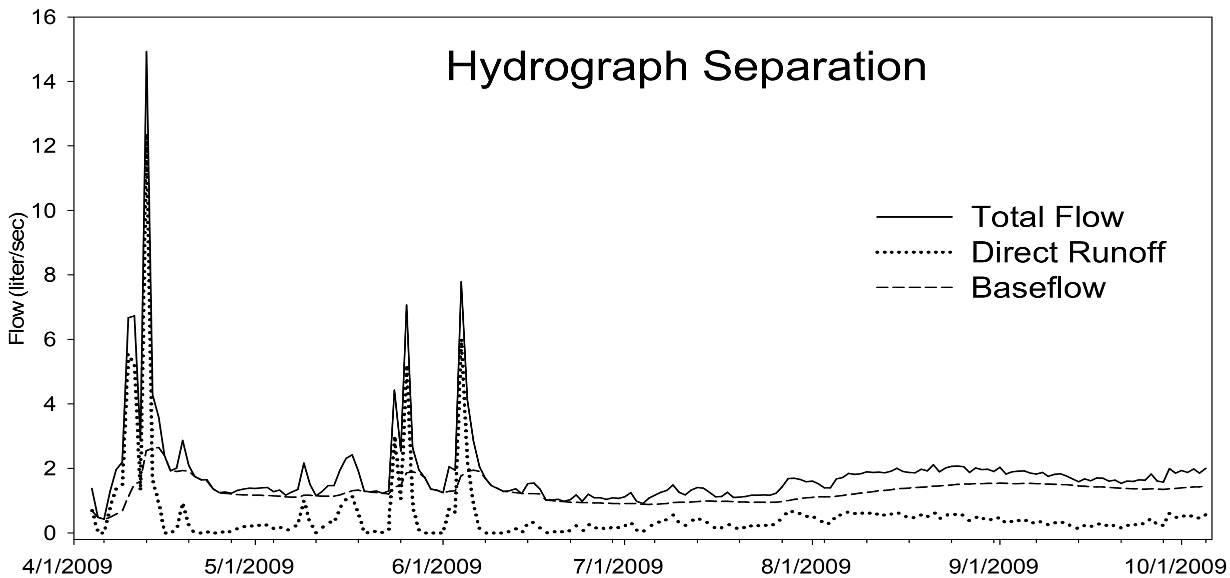


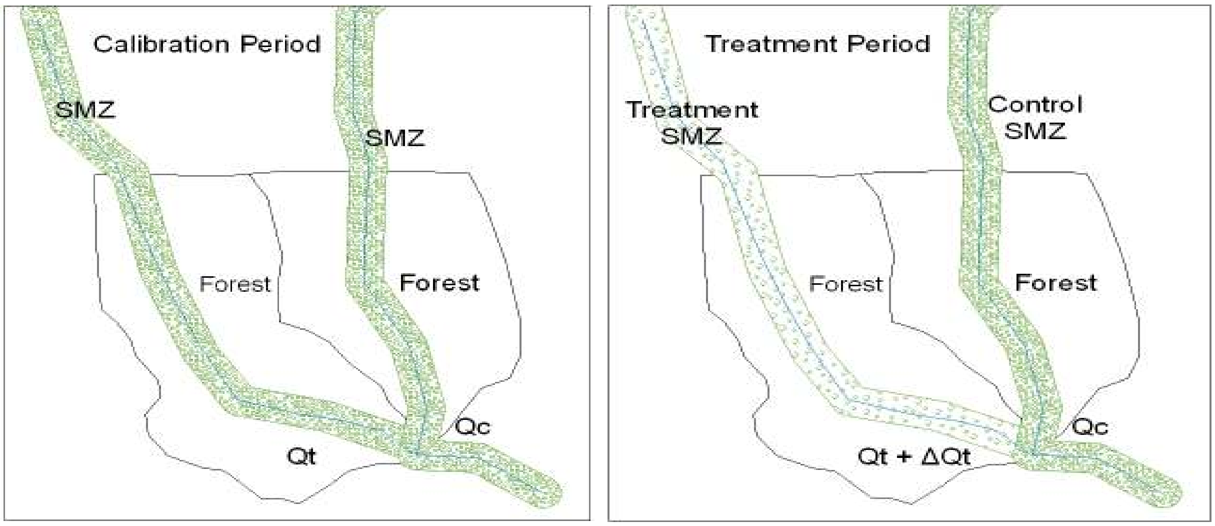

Figure 3.9: An example of baseflow separation

### 3.4. Statistical Analysis

The east watershed served as a control for comparison with the west watershed which was scheduled for partial cutting within the SMZ. Treatment effects for watersheds were determined using the paired watershed approach based on streamflow (Figure 3.10) (Hewlett, 1969). Six-months of pre-harvest data were used as a basis for developing calibration regression equations between the treatment and control watersheds using paired monitoring stations (e.g. T1 with C1, T2 with C2, and T3 with C3).

[1] The software is provided by the Purdue University, and is available at; http://cobweb.ecn.purdue.edu/~what/

Post-treatment comparison relies on the high correlation that normally exists between sediment rates from treatment watersheds and control watersheds when there is no harvest on either watershed. Given this relationship, the change in water yield attributable to the harvest operation could be determined.




Calibration Period Streamflow (cm/yr)

| Qt | Qc |
|---|---|
| 50.8 | 63.5 |
| 30.9 | 40.6 |
| 59.7 | 73.7 |

[ $Qt(x) = -5.3 + 0.88\ Qc$ ]

Treatment Period Streamflow (cm/yr)

| Qt | Qc | Qtx | Qt-Qtx |
|---|---|---|---|
| 61.0 | 50.8 | 39.4 | 21.6 |
| 48.3 | 40.6 | 30.5 | 17.8 |
| 61.0 | 61.0 | 48.3 | 12.7 |

Figure 3.10: A simple example of a paired watershed experiment to determine the effects of partial cut within the SMZ on discharge and sediment.

After post-harvest discharge data were predicted using the regression models produced during calibration, post-harvest sediment yield was predicted based on the pre-harvest relationships between discharge and sediment yield provided by the LOADEST.

PASW Statistics 18.0 software was used to determine significant differences between observed and predicted means on the treatment watershed by the Independent-Samples T Test for all mean comparisons.

### 3.5. Harvest

The harvest operation was designed to create an uneven-aged SMZ with multiple canopy layers by allocating growing space among three canopy tiers (overstory, midstory, and understory) based on the Proportional-B method. This method is well suited for use within a SMZ as it ensures a continuous canopy cover, maintains full site utilization with approximately 80% of stand basal area allocated to the sawtimber size classes, and allows sufficient growing space for the recruitment of new cohorts as needed (Loewenstein, 2005)

#### 3.5.1. Inventory

A standard 10% Fixed Radius Timber Cruise was used for the inventory of the SMZ's (Figure 3.11).

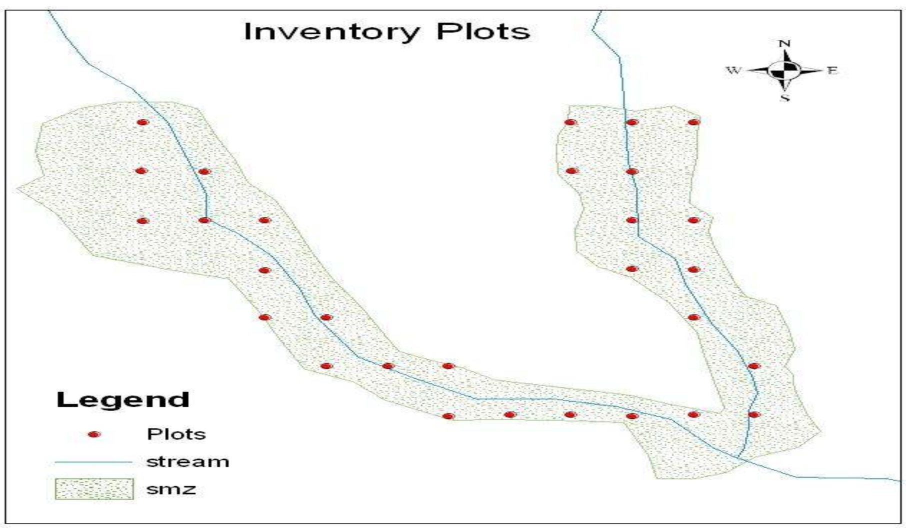



Figure 3.11: Inventory plots on the treatment watershed

Overstory plots were 500 $m^2$ (12.62 m radius) and all trees that were larger than 10 cm were tallied by species and tree-diameter at breast height (dbh). Nested understory plots used the same plot center, were 50 $m^2$ (4 m radius), and tallied all trees that were smaller than 10 cm but

>1.3m tall, by species and dbh. Seedlings <1.3m tall were recorded by height class 0-25 cm, 25-50 cm, 50-75 cm, 75-100 cm, 100-125 cm, and >125 DBH.

On the treatment watershed, overstory basal area was 18.17 $m^2ha^{-1}$. Basal area (94 %) was dominated by white oak, sweetgum, maple, and hickory. Understory basal area was 2.03 $m^2ha^{-1}$, and with 7666 seedlings per hectare.

### 3.5.2. Tree Marking

As previously mentioned, the harvest was marked using the Proportional- B method. This method is an uneven-aged system loosely based on structural control and is fairly simple to apply because a standard 'target structure' defined by a q-value of 1.3 and a largest diameter tree (LDT) of 50cm has its basal area distributed among 3 product classes (<15cm; 15-30cm; >30cm) in a ratio of 1:2:3 (Loewenstein, 2005). Loewenstein (2009) outlines the following steps to create a marking guide using this method (Table 3.1).

- Conduct current inventory and sum BA by size class
- Decide on a residual basal area. Target is based on proportions
- Subtract target BA from current inventory
- Calculate proportion to cut (1 – Target BA/ Current Inventory)
- Record 'simplified' marking guide

| Diameter (DBH) | Inventory | Target | Harvest | Proportion | Guide |
|---|---|---|---|---|---|
| < 15 cm | 11 $m^2h^{-1}$ | 10 | 1 | 0.09 | None |
| 15-30 cm | 45 $m^2h^{-1}$ | 20 | 25 | 0.56 | 3 of 5 |
| >30 cm | 50 $m^2h^{-1}$ | 30 | 20 | 0.4 | 2 of 5 |

Table 3.1: An example of obtaining a marking guide.

Based on our calculations (Table 3.2), trees were marked based on the idea of "Take the worst and leave the best". Undesirable species and trees with poor form or damage were discriminated against during the marking process.

| Diameter (DBH) | Inventory | Target | Harvest | Proportion | Guide |
|---|---|---|---|---|---|
| < 15 cm | 3.5 $m^2h^{-1}$ | 1.9 | 1.6 | 0.46 | 1 of 2 |
| 15-30 cm | 5.7 $m^2h^{-1}$ | 3.8 | 1.9 | 0.33 | 1 of 3 |
| >30 cm | 11 $m^2h^{-1}$ | 5.8 | 5.2 | 0.47 | 1 of 2 |

Table 3.2: Marking guide for the harvest within the treatment SMZ

### 3.5.3. Cutting and Skidding

Cutting and skidding operations were completed during about two weeks, in October, 2009. A rubber-tired Hydro-AX 411EX model Feller Buncher was used to cut the marked-trees (Figure 3.12). The harvest was conducted in dry weather to avoid compaction and rutting of the soils. Trees were removed from the SMZ with a rubber-tired John Deere 540 GIII Model Skidder (Figure 3.12).

Figure 3.12: Rubber-tired Hydro-AX 411EX model Feller Buncher and John Deere 540 GIII Model Skidder

### 3.6. Post-Harvest Data Collection

Collection of hydrologic and sediment load data continued across treated and untreated watersheds following harvest operations for an additional six months. Using the pre-harvest regression model, the sediment rate for a "No-harvest" scenario was projected and the effects of the partial cut within the SMZ on sedimentation were determined. Sediment yield was compared between land uses classes based on the mitigating effects of the two SMZ implementations.

# Chapter 4

# Results and Discussions

### 4.1. Pre-Harvest Results

Pre-harvest results deal with the calibration period. This period is a collection of baseline data. Pre-harvest data were sampled during 183 days (from April 5, 2009 to October 5, 2009). Flow and sediment data are associated with the rainfall events during this time period (Figure 4.1). The naming conventions used (i.e. treatment and control watersheds), refer to the post-harvest conditions.

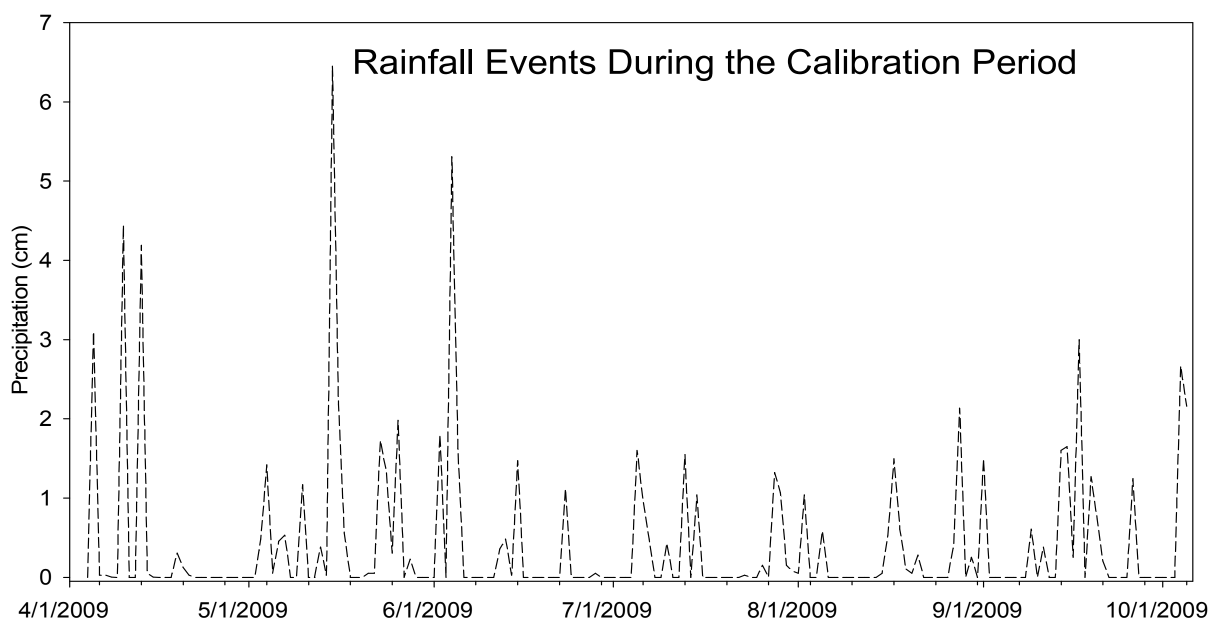



Figure 4.1: Rainfall events during the calibration period

### 4.1.1. Water Yield

Hydrology can have substantial impact on water quality within a watershed. As commonly occurs, flow increases downstream on both watersheds (Appendix K), and the hydrographs peaked during rainfall events but exhibited little or no flashiness[2]. Increases in streamflow due to rain events are more prominent during wet periods compared to dry periods. Flows are distinctly higher at downstream monitoring stations (T3 and C3) suggesting that the downstream sections (Tw3 and Cw3) have much higher baseflow rates than upstream sections. In comparison to flows of the treatment watershed, flows were higher on the control watershed. This is likely due to the larger drainage area of the control watershed (Appendix K).

We examined flow contributions of each section by subtracting T1 from T2 and T2 from T3 on the treatment watershed (C1 from C2 and C2 from C3 on the control watershed). Since the area drained by each section differs in size, discharge per unit area for each section is shown in figures 4.2 and 4.3. In general, during storm events, section Tw1 generates more water per unit area followed by Tw2, with Tw3 generating the least (Figure 4.2). However, Tw3 yields more water than either of the two upstream sections when baseflow is the predominant input into the system.

On the control watershed, section Cw3 generates the most water, and Cw2, which is forested, yields the least water per unit area during storm events (Figure 4.3). We expect that Cw3 is substantially affected by both the clearcut and the forest road that goes through section Cw3. This road was not constructed parallel to the contour lines, thus increasing water flow from this section (Figure 3.2).

[2] Streams that rise and fall quickly are considered flashier than those that maintain a firmer flow.

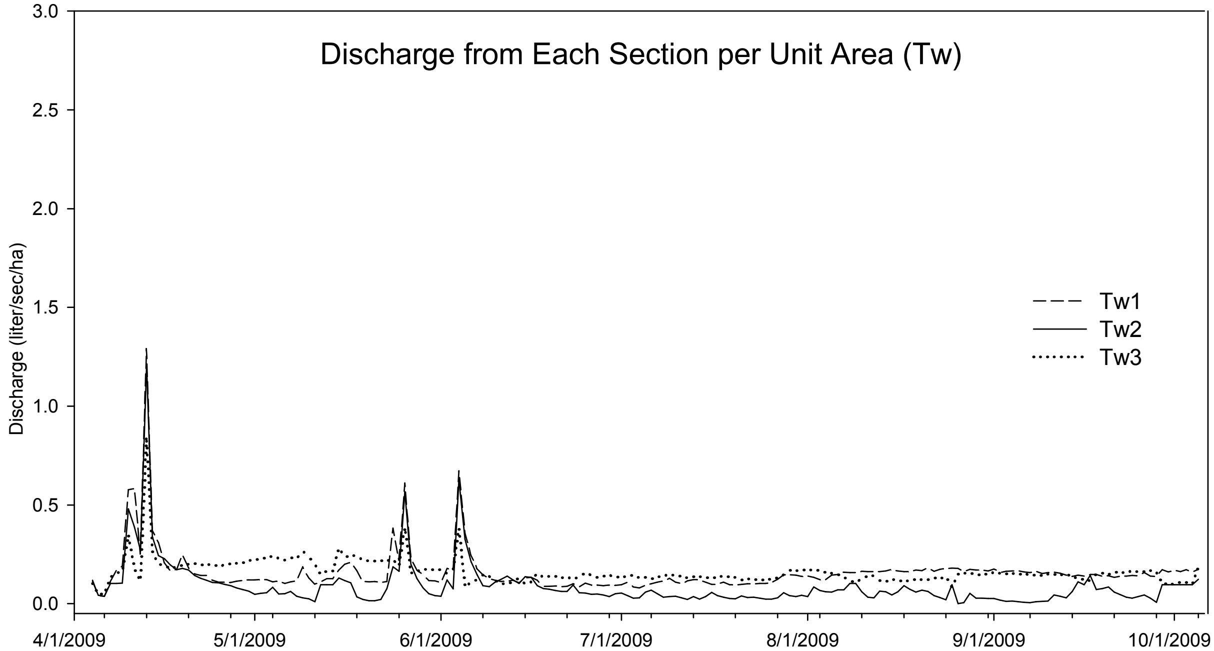



Figure 4.2: Discharge per unit area on the treatment watershed for pre-harvest conditions

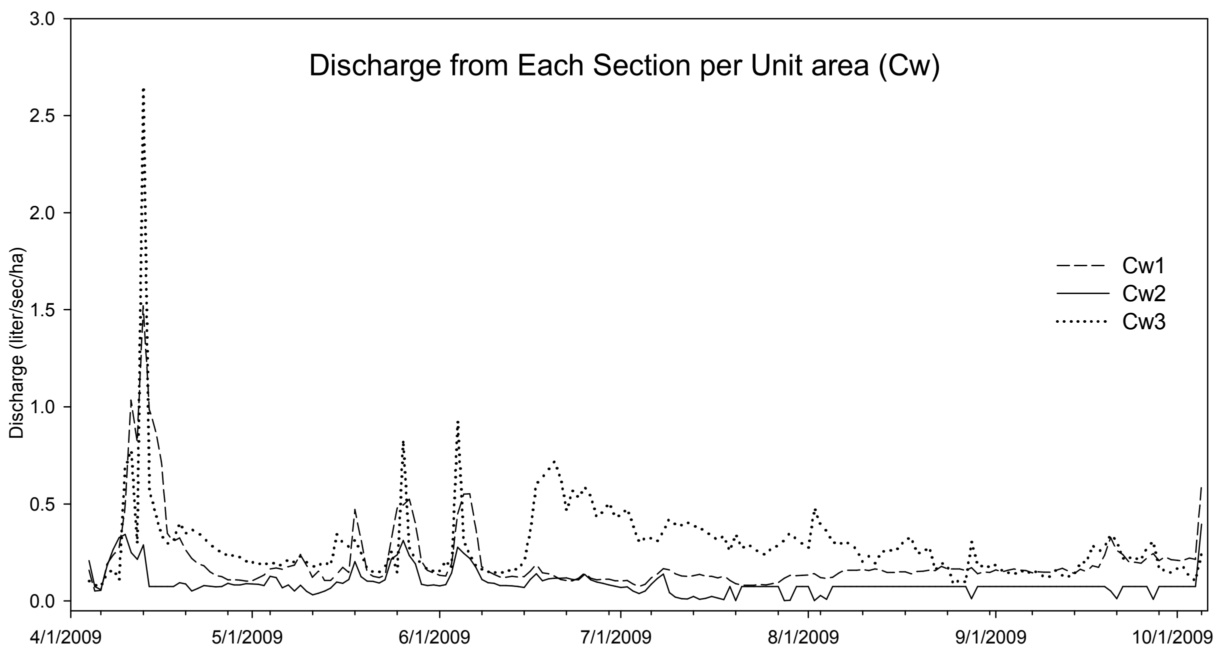



Figure 4.3: Discharge per unit area on the control watershed for pre-harvest conditions

### 4.1.2. Hydrograph Separation (Direct runoff- Baseflow Separation)

Both direct runoff and total baseflow are components of total flow at each station. Total baseflow consists of baseflow and subsurface storm flow. During rain events, direct runoff peaks at all three stations. Most of the flow comes from direct runoff during rainfall events. During dry periods there is little or no direct runoff, and total flow was contributed by baseflow.

Total rainfall during the six-month pre-harvest calibration period was 780 mm in the study area. Four discrete storm events resulted in direct runoff at each station during this time period. Direct runoff results from precipitation occurring on the watershed in excess of the amount that can percolate into the soil. Whether direct runoff occurs, and how much, is a function of topography, vegetation, intensity of the storm event, and existing soil saturation. Average direct runoff per unit area is typically higher on Tw1 than downstream sections (Tw2 and Tw3) on the treatment watershed (Figure 4.4). This exhibits the effect of forest cover at reducing direct runoff by increasing both interception and evapotranspiration. Direct runoff from Tw2 is higher than from Tw3. This is likely due to decreasing slope on section Tw3.

On the control watershed, rainfall events generate much more runoff on Cw3 than on upstream sections, while the least direct runoff is generated on the forested middle section, Cw2 (Figure 4.5). During dry periods, there is little or no direct runoff at all stations.

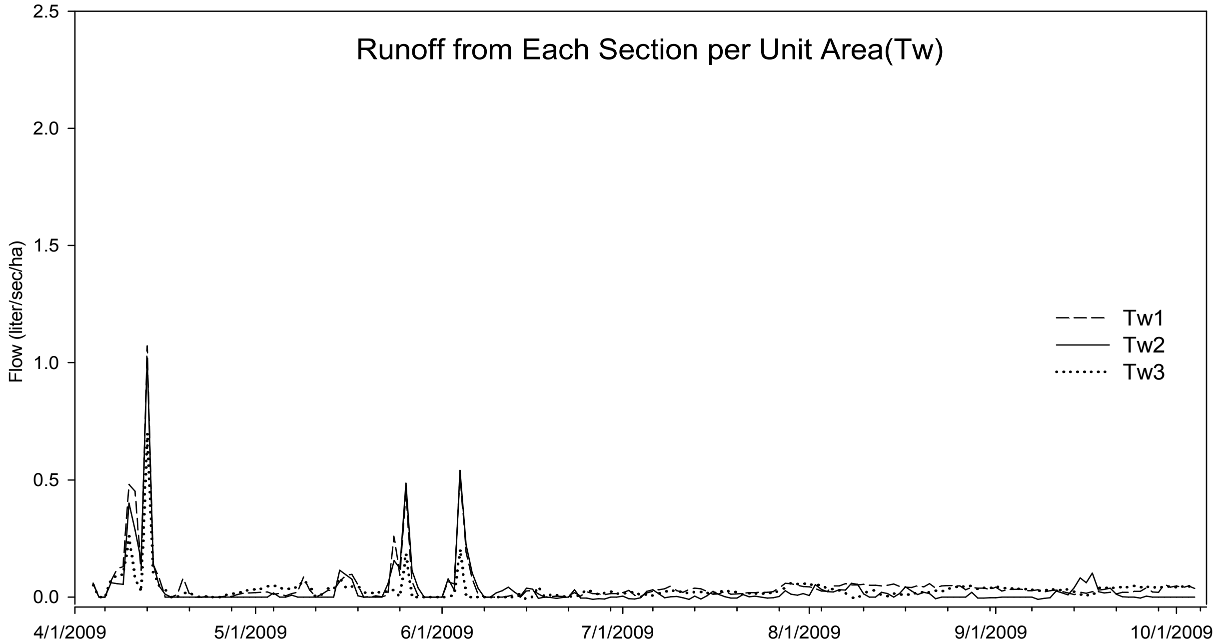



Figure 4.4: Runoff per unit area on the treatment watershed for pre-harvest conditions

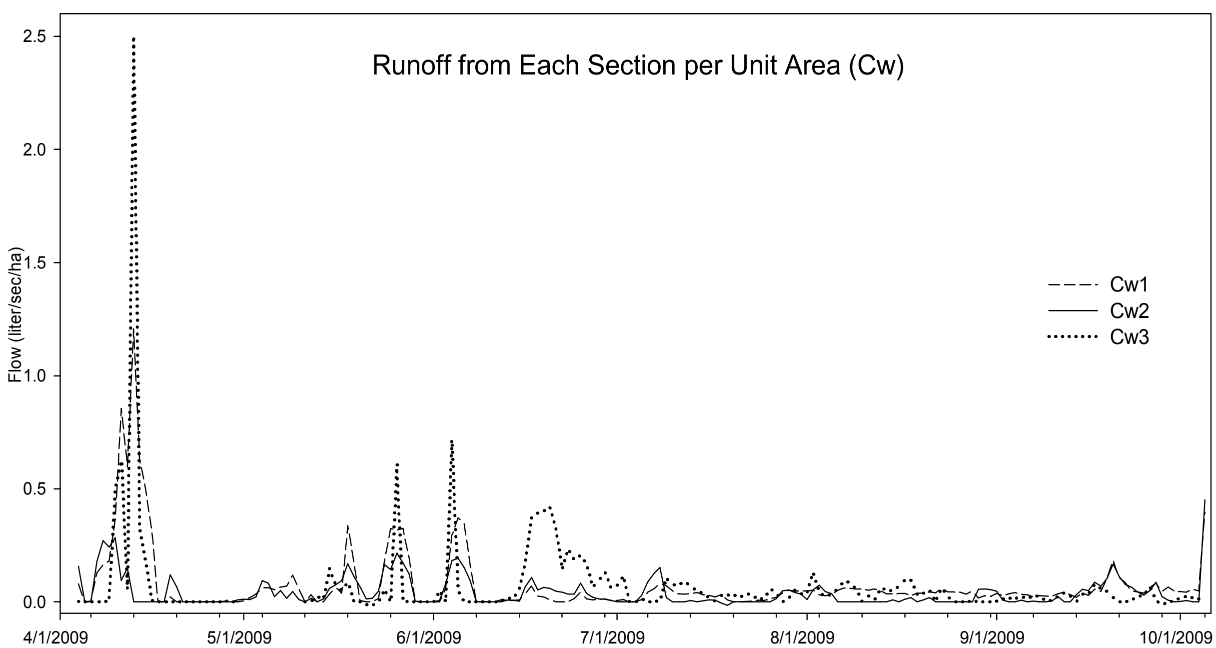



Figure 4.5: Runoff per unit area on the control watershed for pre-harvest conditions

Baseflow is the flow of water entering stream channels from ground water sources and is not attributable to direct runoff from precipitation. The baseflow rate per unit area is higher from Tw3 than from Tw2 on the treatment watershed (Figure 4.6). Although baseflow from Tw1 was typically less than Tw3 and greater than Tw2, there were periods where it exceeded that of Tw3. Decreasing slope downstream seems to be the biggest factor for increasing baseflow on Tw3. As they move downstream, streams usually get closer to water table, and generate more baseflow (Hewlett, 1969). During dry periods, total flow is equal to baseflow at all stations. The forested middle section has the lowest baseflow contribution on the study watershed.

Baseflow rates are variable during the six-month pre-harvest period on the control watershed. From early April to early July, baseflow from section Cw2 is higher than other sections while section Cw3 is the highest between early July and early October (Figure 4.7). Section Cw1 has the highest baseflow rate during large rainfall events.

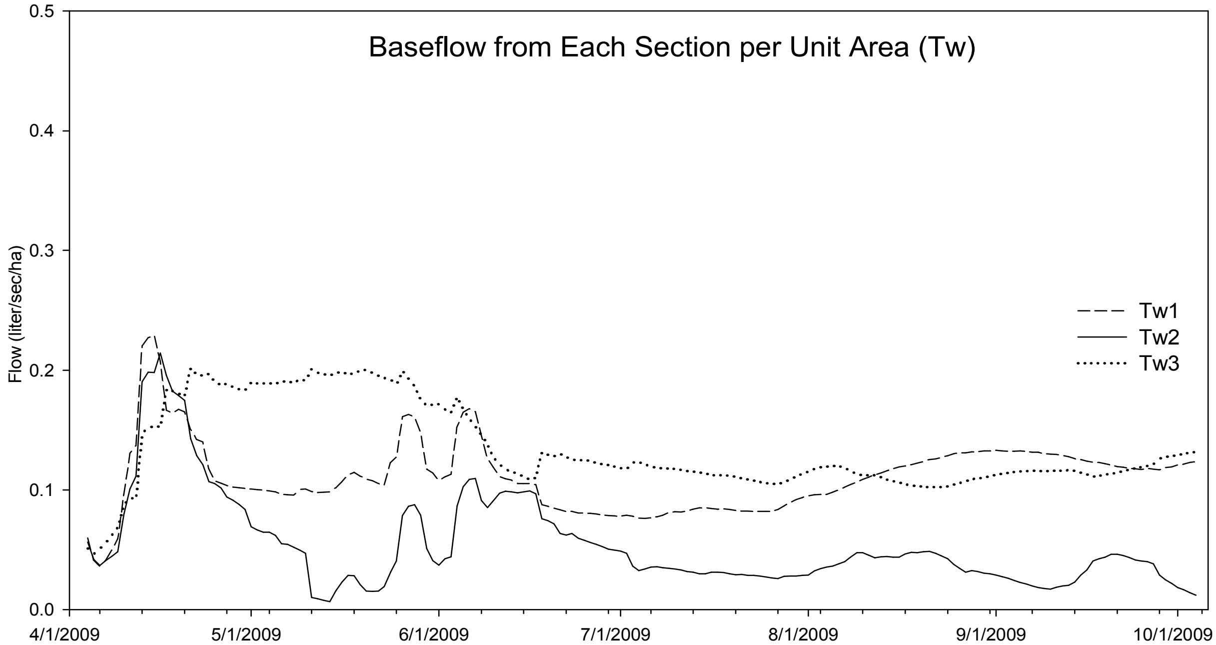



Figure 4.6: Baseflow per unit area on the treatment watershed for pre-harvest conditions

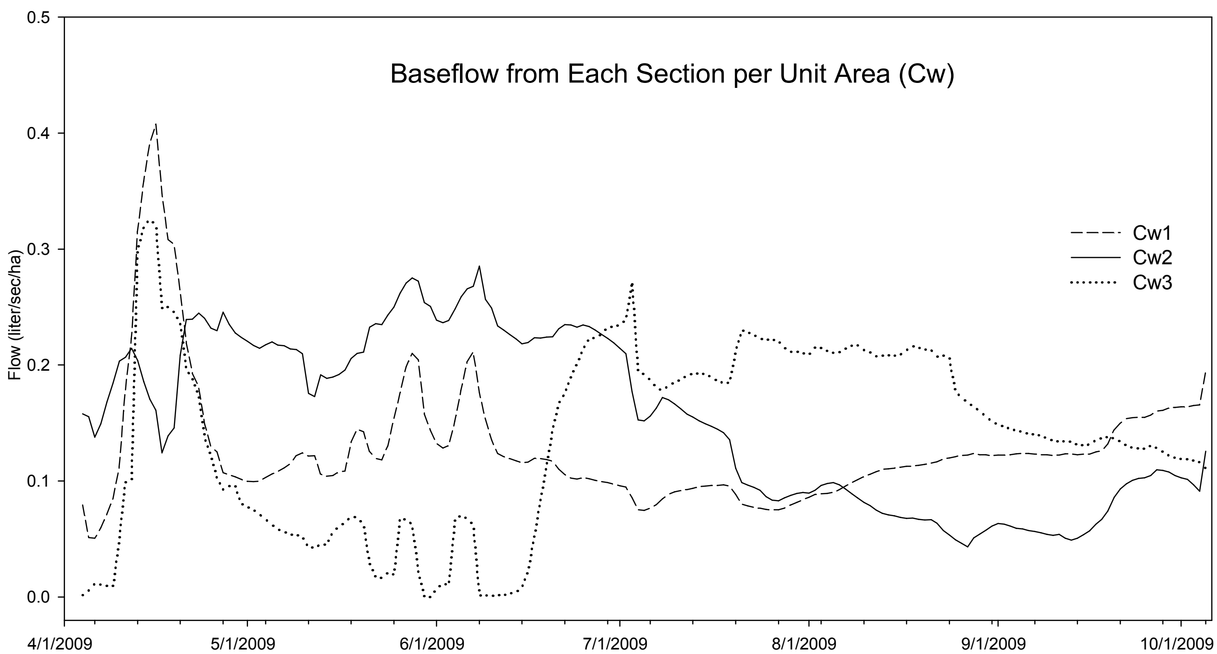



Figure 4.7: Baseflow per unit area on the control watershed for pre-harvest conditions

### 4.1.3. Sediment Load

As water yield increases downstream, sediment load increases as well (Appendix L). Sediment load is mainly created by the biggest rain events. About thirty percent of the total sediment load was created by the four biggest storm events during a six month period. On the control watershed, sediment load also increased downstream during the biggest rain event (Appendix L). However, during other rainfall events, higher amount of sediment was measured at C1 in comparison with C2 suggesting that there was probably some deposition between these two stations on the control watershed (Appendix L). Like the treatment watershed, approximately thirty percent of the total sediment load was created by the biggest storm events during the pre-harvest period. During the same rain events, however, sediment yield measurements on the control watershed were higher than that of the treatment watershed (Appendix L). This is probably because of the differences in land uses and size of areas.

The sediment rate at each station does not give complete information about the sediment yield generated by each section. Thus, we determined sediment yield from each section on a per unit area basis which provides more information about the relative amount of sediment generated by each section. When comparing each section in terms of sediment yield per unit area, pasture covered Tw1 generates much more sediment than the downstream forested sections on the treatment watershed during rain events as this section generates higher amount of water per unit area in comparison with the other two sections (Figure 4. 8). Because sediment yield from the pasture is higher, this suggests that open areas generate more sediment yield than forested areas during storm events. It is possible that sediment yield is affected by the pond in the middle of section Tw1, which may allow settlement of sediment before it reaches the forested area.

However, during rainfall events the capacity of the pond to retain sediment may be overwhelmed.

The forested middle section generated the least sediment per unit area showing the importance of forested areas at reducing sediment yield on the treatment watershed. The sediment rate from section Tw2, which is intact forest, is lower than Tw3, which contains the clearcut and road crossing (Figure 4.8). We expected that sediment yield from the clearcut would be mitigated by the existing SMZ, but it appears that it was not sufficient to trap all of the sediment yield from both the clearcut area and the roads. It should be noted that we were unable to separate the sediment yield of the road from that of the clearcut. During dry periods, sediment load from section Tw3 is higher than upstream sections. Higher baseflow seems to be the major factor increasing sediment yield during dry periods from Tw3 by causing channel erosion (Figure 4.8).

On the control watershed a similar situation was observed; sediment yield per unit area during rainfall events is higher from Cw1 than from further downstream (Figure 4.9). However, during some storms, sediment yield from Cw3 is nearly as high as section Cw1. On section Cw3, again the clearcut and the road seem to be the biggest factors for increasing sediment yield. The negative values on the y-axis of Figure 4.9 illustrates that there is significant deposition of sediment occurring between C1 and C2. The deposition could be observed when the site was visited during dry periods.

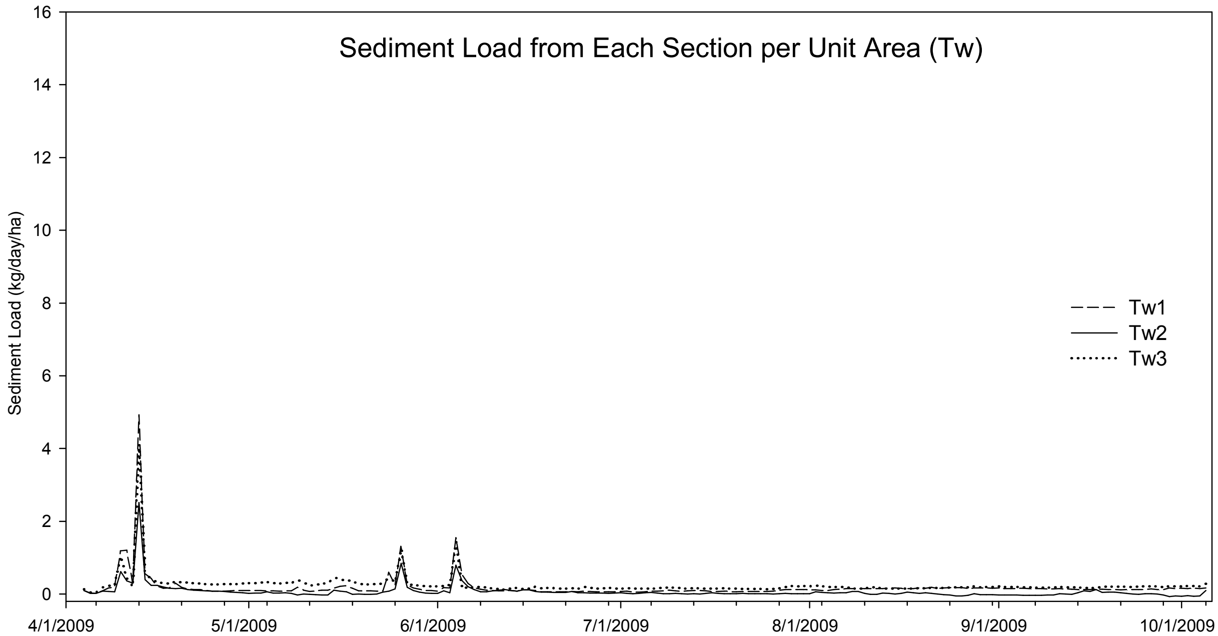



Figure 4.8: Sediment yield on the treatment watershed for pre-harvest conditions

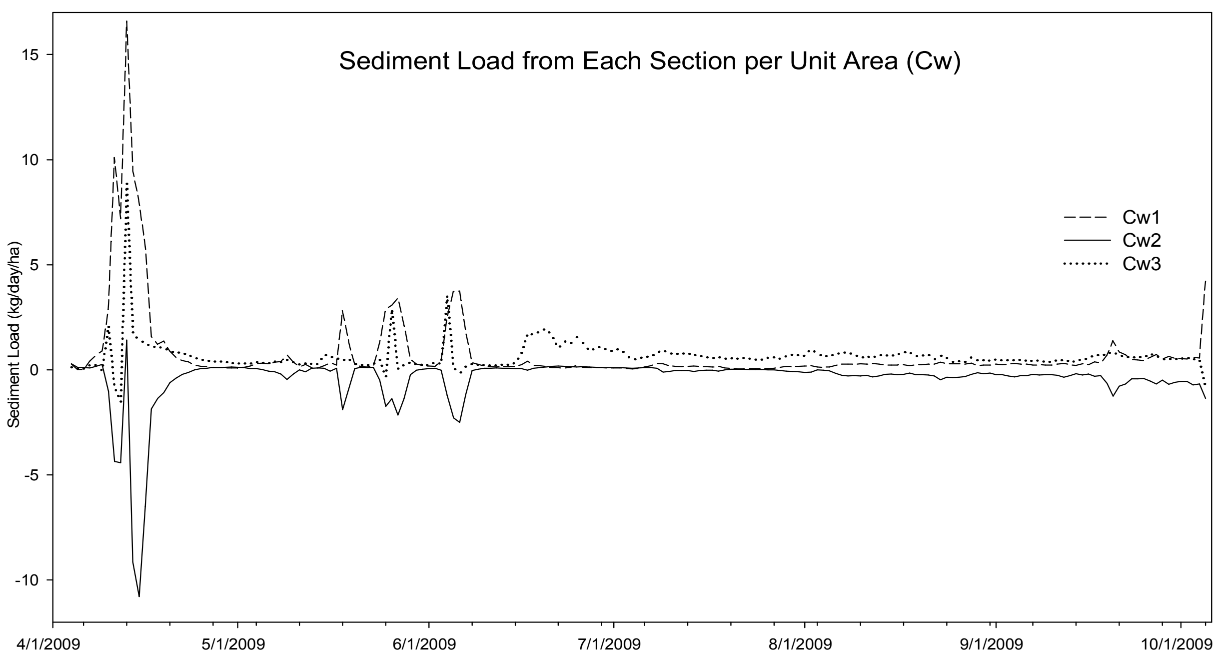



Figure 4.9: Sediment yield on the control watershed for pre-harvest conditions

#### 4.1.4. Sediment Concentration

Sediment concentration gives the ratio of the dry weight of the sediment in a water-sediment mixture to the total weight of the mixture. Sediment concentration is highest at T3 (Figure 4.10) and the forested middle section (Tw2) has lower sediment concentration levels than the other sections during both storm events and dry periods. Concentration generally decreases downstream on the control watershed during rainfall events (Figure 4.11). During dry periods, section Cw2 has the least sediment concentration. During dry periods, sediment concentration at C3 is similar to C1.

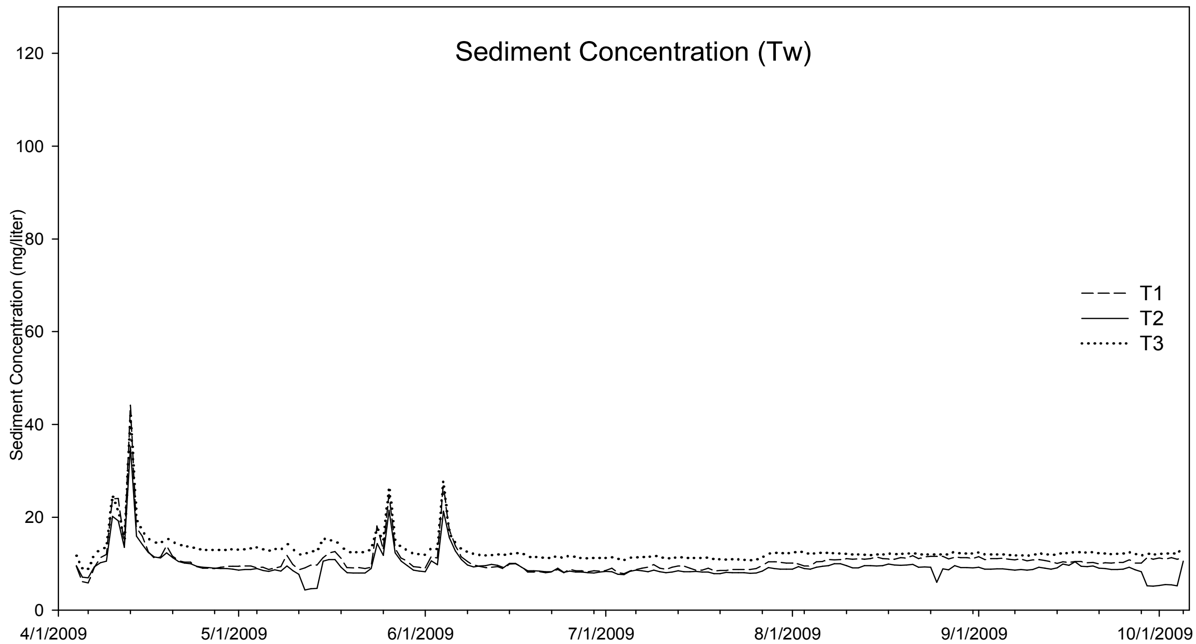



Figure 4.10: Sediment concentration on the treatment watershed for pre-harvest conditions

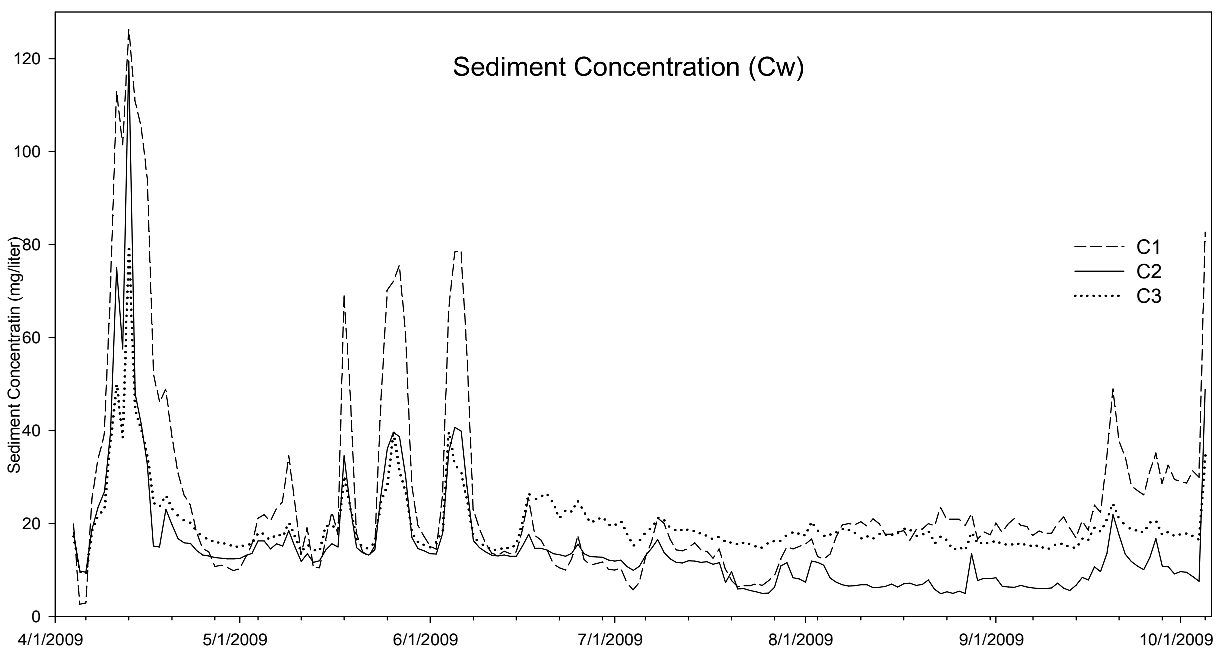



Figure 4.11: Sediment concentration on the control watershed for pre-harvest conditions

Table 4.1 gives a summary for the hydrology and sediment yield of each stream section pre-treatment. As should be expected, forested sections (Tw2 and Cw2) convert a smaller percentage of precipitation to streamflow on both watersheds because these sections are completely forested with corresponding high evapotranspiration rates.

The flashiness of a system can be described with the Richard-Baker Index (RB), which is a measure of the stream flow response to storms (Baker et al, 2004). Flashiness is mostly affected by vegetation, soil, watershed size and amount of impervious surface; forested watersheds generally show less flashy characteristics than open areas (Fongers et al, 2007). Although the middle sections Tw2 and Cw2 are covered with forest, they still exhibit flashy characteristics. We attribute this to low baseflow coming from areas. During a rain event, the subsurface flow (also called interflow) is the primary input in these subwatersheds. Groundwater in these sections seems to be flowing horizontally and most of it does not enter the stream before it reaches Tw3 and Cw3 (Hewlett, 1969). Also, specifically, smaller watersheds tend to have flashier flows (Fongers et al, 2007). Thus, another reason for the high flashiness on these sections may be that these sections have smaller areas. Although Tw2 and Cw2 do not behave similarly in flashiness, this should not affect our ability to directly compare the two subwatersheds because flashiness can be affected by many factors.

Even though a larger amount of sediment is generated from Tw1 during rainfall events (Figure 4.18) section Tw3 generated more sediment in total during the 6-month pre-harvest period on the treatment watershed. On the control site, the most of the sediment was generated by section Cw1 during the calibration period. By far, the least amount of sediment comes from the forested sections on both watersheds.

Table 4.1: Summary of pre-harvest results. SF: Streamflow, P: Precipitation, RB: Flashiness

| Sections | SF/P (%)[1] | RB (%)[2] | Sediment Load kg/ha) |
|---|---|---|---|
| Tw1 | 33 | 26 | 34 |
| Tw2 | 17 | 20 | 13 |
| Tw3 | 34 | 17 | 46 |
| Cw1 | 41 | 21 | 140 |
| Cw2 | 19 | 28 | 8 |
| Cw3 | 60 | 15 | 120 |

[1] The proportion of precipitation on the watershed that is converted to streamflow
[2] Streams that rise and fall quickly are considered flashier than those that maintain a more consistent flow

### 4.2. Calibration

Discharge data of the treatment watersheds were calibrated with that of the control watershed using calculated daily discharges from April 2009 to October 2009 (Figure 4.12). T1 was paired with C1, T2 with C2, and T3 with C3 for calibration (Figure 3.2). Discharge data were validated using post-harvest data from October 2009 to April 2010. The regression models indicate strong relationship between the third stations' streamflow (T3-C3) ($p<0001$). However, correlations between T1 and C1 ($p<0001$), and between T2 and C2 ($p<0001$) during the calibration period is lower, but are still significant ($\alpha=0.05$). All coefficients were statistically significant except the intercept for the T2-C2 model ($p=0.07$) (Appendix M). Since removing this coefficient of the T2-C2 model weakens the $R^2$, we retained the intercept term. We also wanted to maintain consistency across all of the models.

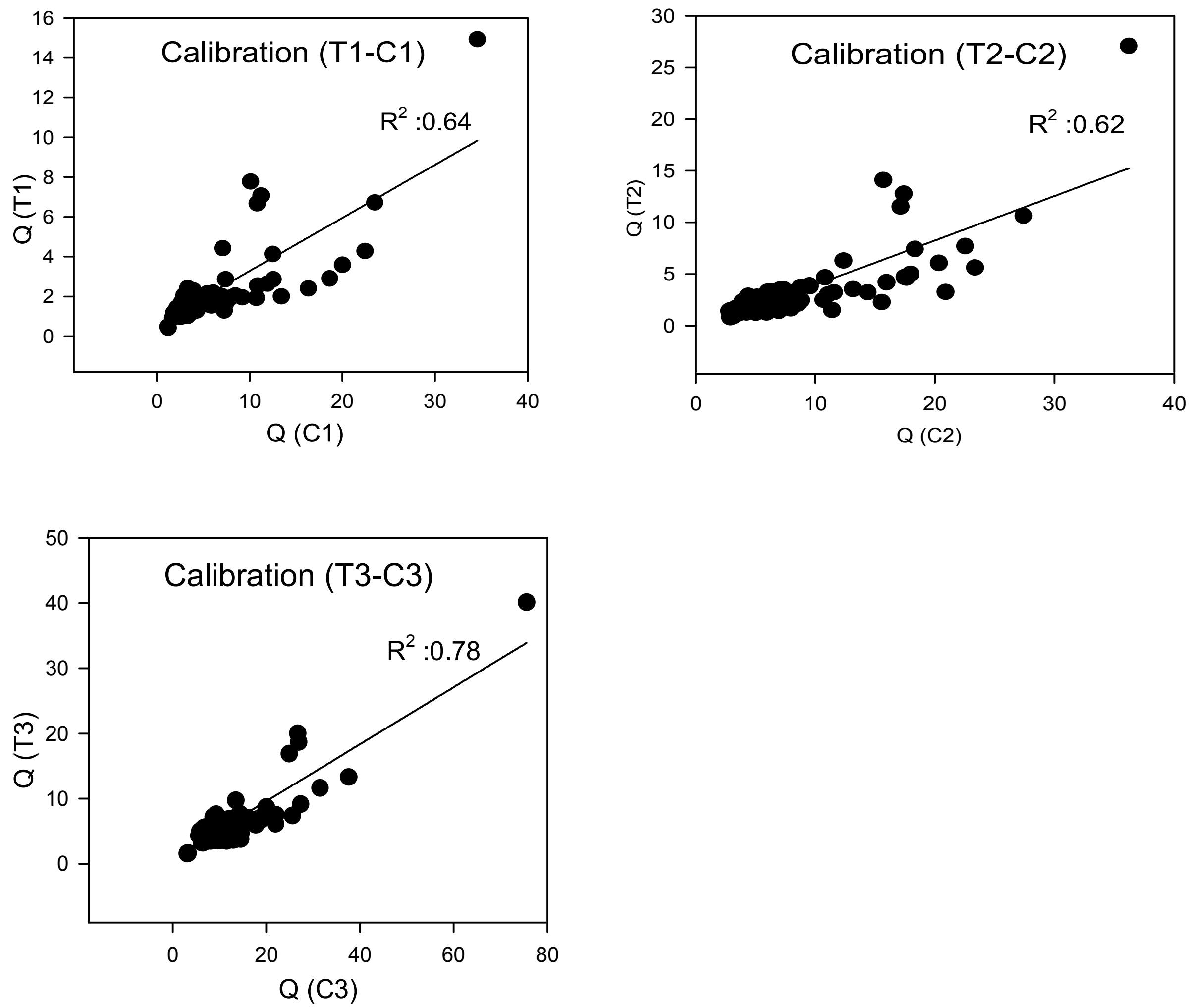



Figure 4.12: Calibration

### 4.3. Post-Harvest Results

Post-harvest data were collected from October 6, 2009 to April 5, 2010. Flow and sediment data are associated with the rainfall events during this time period (Figure 4.13).

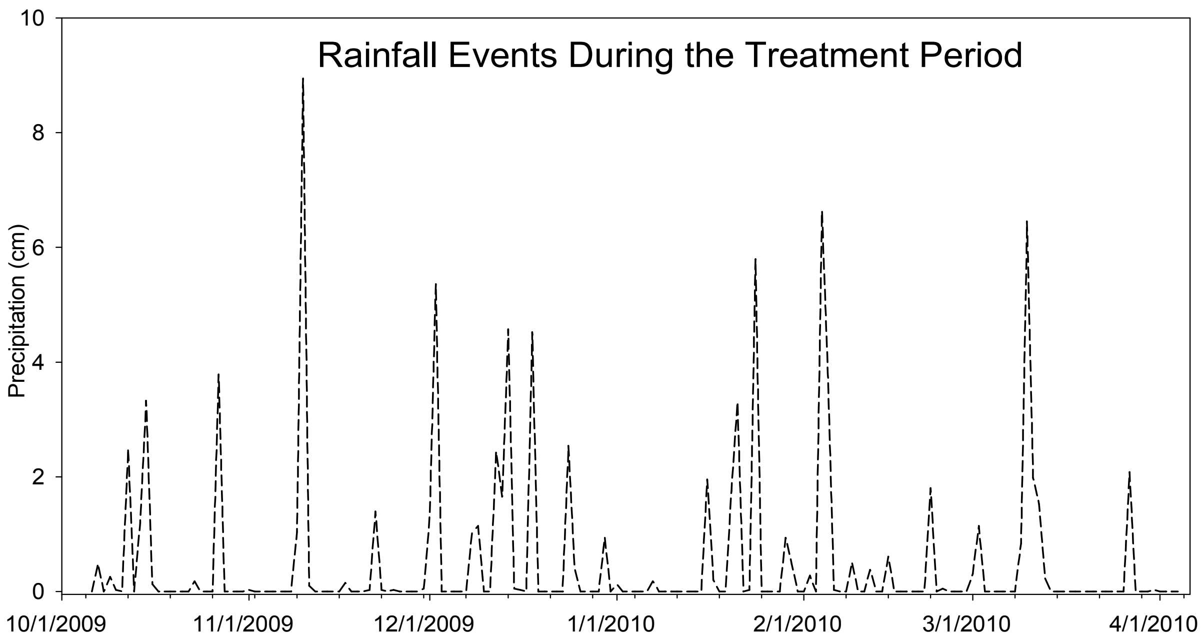



Figure 4.13: Rainfall events during the treatment watershed

### 4.3.1. Water Yield

Post-harvest hydrographs illustrate similar relationships as pre-harvest patterns (Appendix K). Flow rates increased downstream on both treatment and control watersheds (Appendix N). High peak flows correspond to rainfall events, and during dry periods flow rates are still higher at the third stations T3 and C3.

Flow contribution of each section per unit area was determined after harvest as well. In contrast with the pre-harvest results (Figure 4.2), the hydrologic pattern of the treatment watershed changed; downstream sections generated much more water per ha than the upstream section (Tw1). During large rainfall events, either Tw3 or Tw2 generated more water per unit area while Tw1 always generated the least (Figure 4.14). On the other hand, as should be expected, on the control watershed, there was no change in the hydrologic pattern since this watershed was not affected by harvesting (Figure 4.15). It is likely that the harvest in the SMZ has changed the hydrologic pattern of the treatment watershed. However, the harvest is not the only factor affecting water yield on these sections. During this season, more rainfall events occurred (Figure 4.1 and 4.13). In addition, the post-treatment period overlaps the dormant season and the lack of foliage would cause the evapotranspiration rate to decrease thus increasing direct runoff in comparison to pre-treatment period. Streamsflow was predicted based on the pre-harvest period evapotranspiration rates; we were able to determine that about 50% of the increase was caused by the dormant season and the marked reduction in evapotranspiration, and 50% by the harvest.

Although the patterns did not change on the control site, the amount of water discharged did change because total rainfall during post-treatment period was higher in comparison with pre-treatment period.

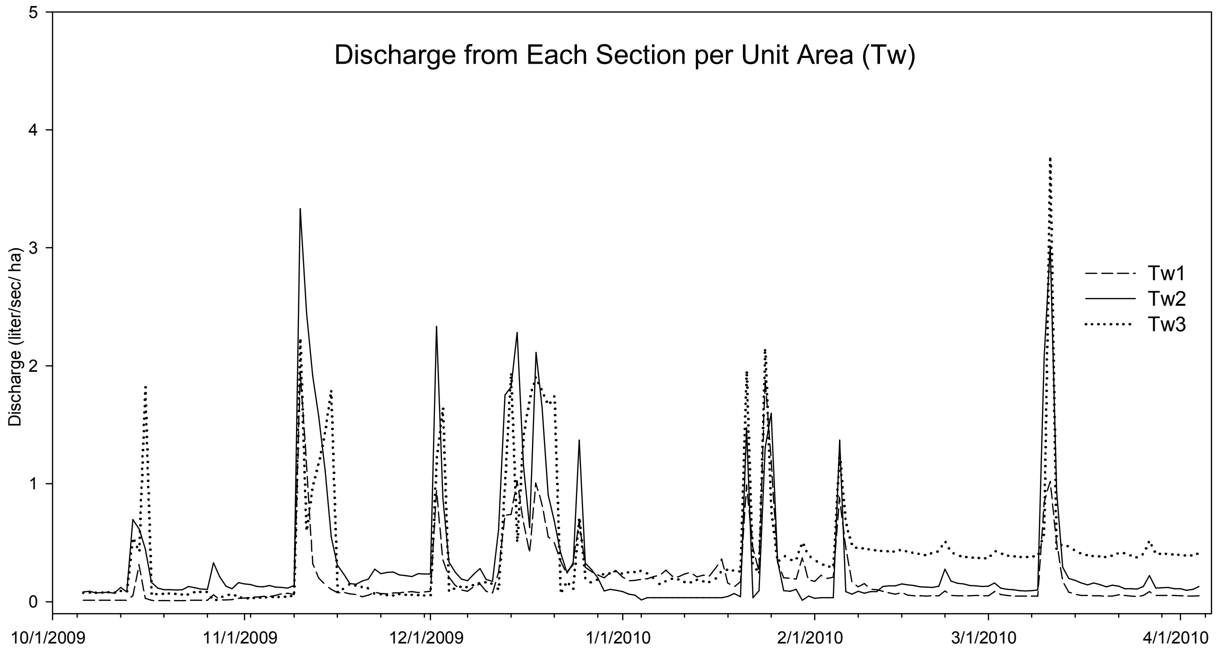



Figure 4.14: Discharge per unit area on the treatment watershed for post-harvest conditions

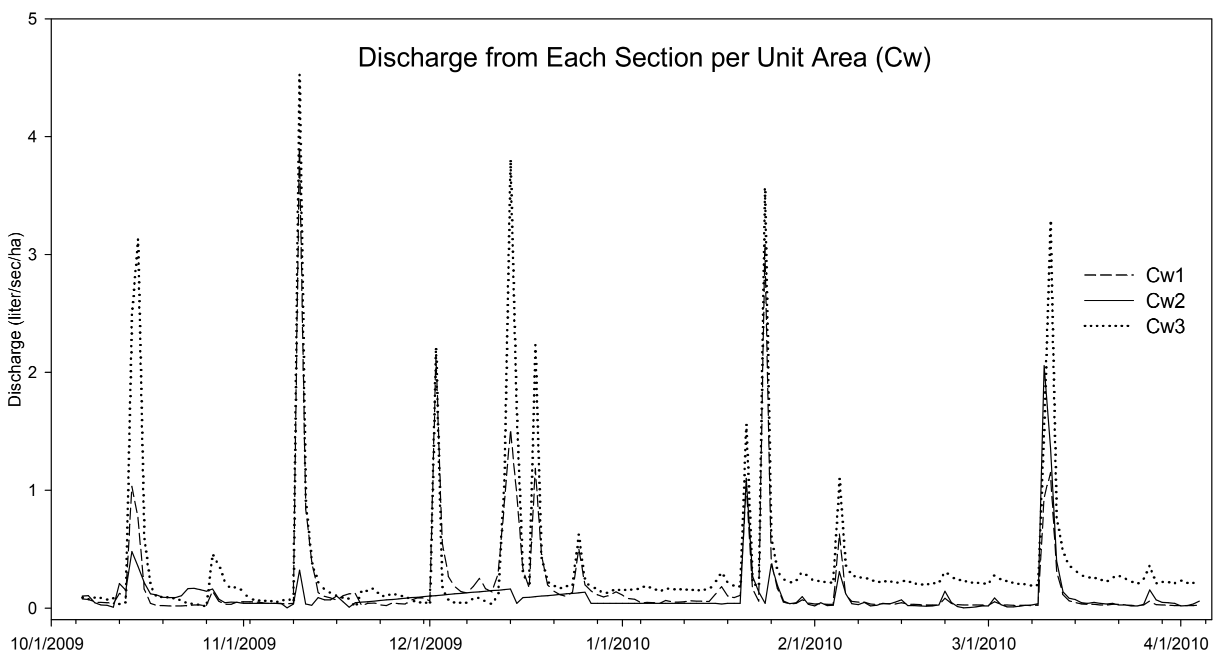



Figure 4.15: Discharge per unit area on the control watershed for post-harvest conditions

### 4.3.2. Hydrograph Separation (Direct runoff- Baseflow Separation)

Total rainfall for the post-harvest period was 930 mm on the study watersheds. Eleven storm events resulted in runoff at each station during the six-month period after harvest. Examination of direct runoff from each section per unit area reveals that it is generally higher from Tw3 during the three biggest rain events on the treatment watershed for the post-harvest conditions (Figure 4.16). On the control watershed, section Cw3 generated much more runoff than upstream sections during rainfall events (Figure 4.17) as occurred during the pre-harvest period (Figure 4.6). The forested sections Tw2 and Cw2 tended to produce less direct runoff although it is similar to other sections during moderate rainfall events. There is little or no direct runoff during dry periods from any section on either watershed.

Trends in runoff are substantially the same as they were during the pre-treatment period on the control site, but they are changed post-harvest on the treatment watershed. It is likely that the harvest increased runoff rates on the treated sections. However, the difference in the magnitude of flow is also partially attributable to two other factors: more total rainfall (930 mm vs. 780 mm), and lower evapotranspiration rates during the dormant season.

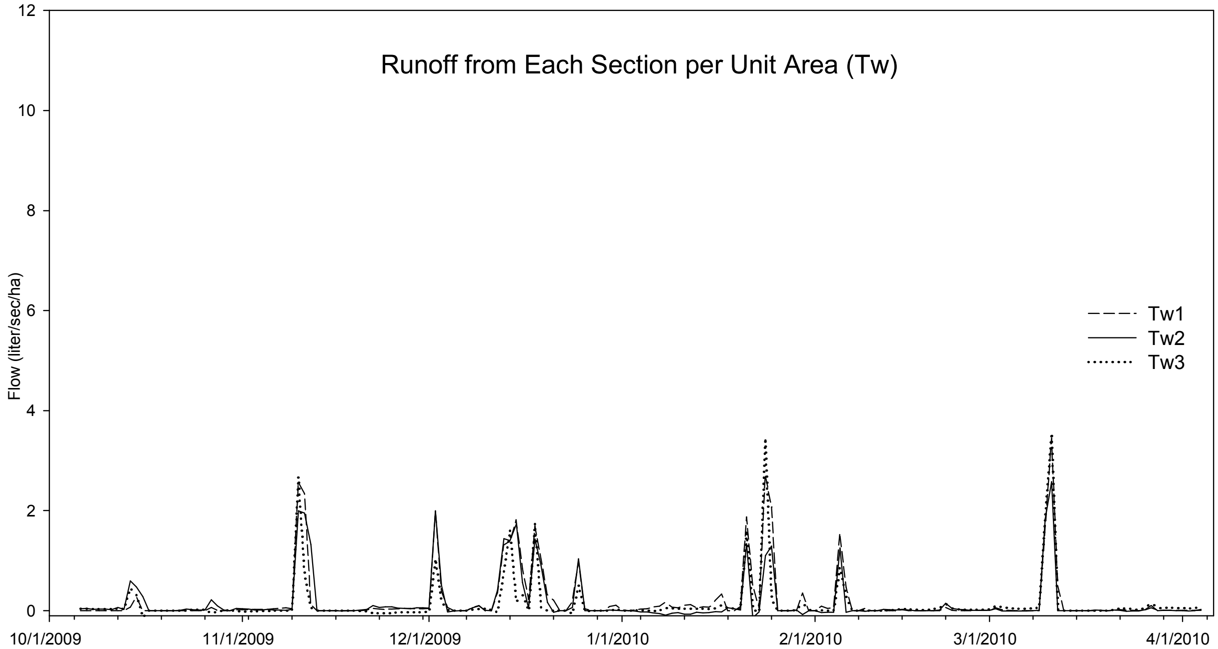



Figure 4.16: Runoff per unit area on the treatment watershed for post-harvest conditions

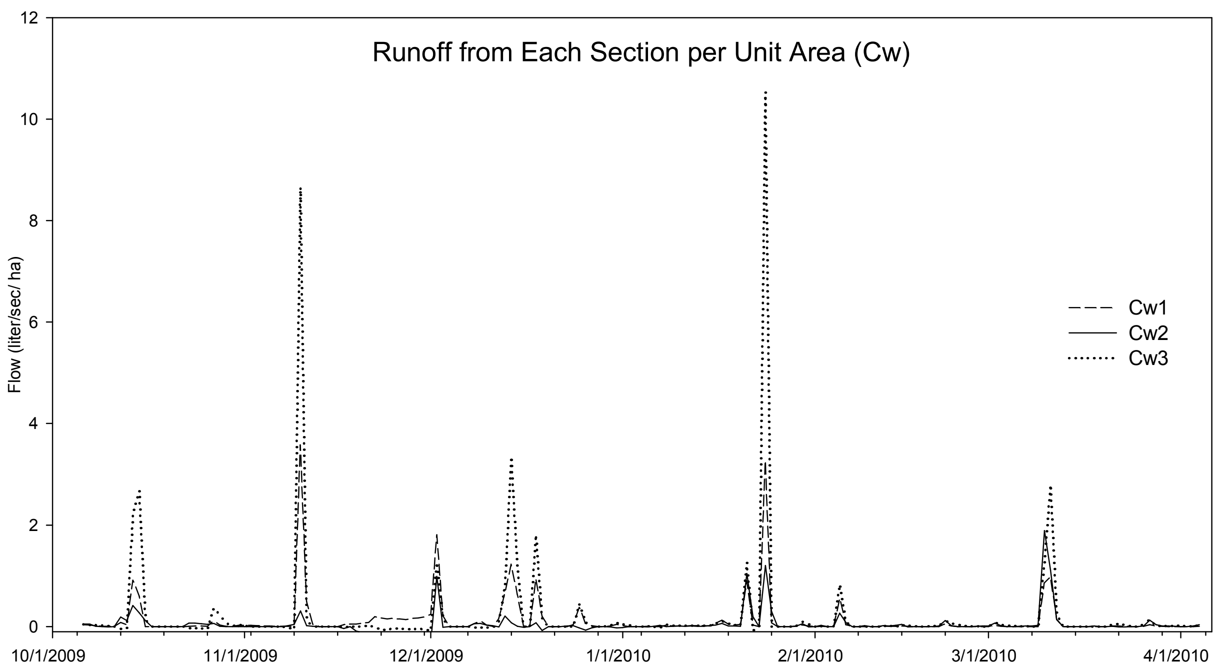



Figure 4.17: Runoff per unit area on the control watershed for post-harvest conditions

Baseflow rate per unit area from the downstream sections, Tw3 and Tw2, is higher than from the upstream section, Tw1, following harvest (Figure 4.18). Tw2 generated a higher baseflow rate than Tw3 from early October to early January, however, there were prolonged periods when baseflow from Tw3 was higher than from Tw2. The baseflow rate from section Cw3 is mostly higher than from upstream sections on the control watershed during rainfall events as it was during the pre-harvest period (Figure 4.19). During dry periods, total flows are contributed only by baseflow at all stations. Again, trends in baseflows are substantially the same as they were during the pre-treatment period on the control site while they changed on the treatment watershed.

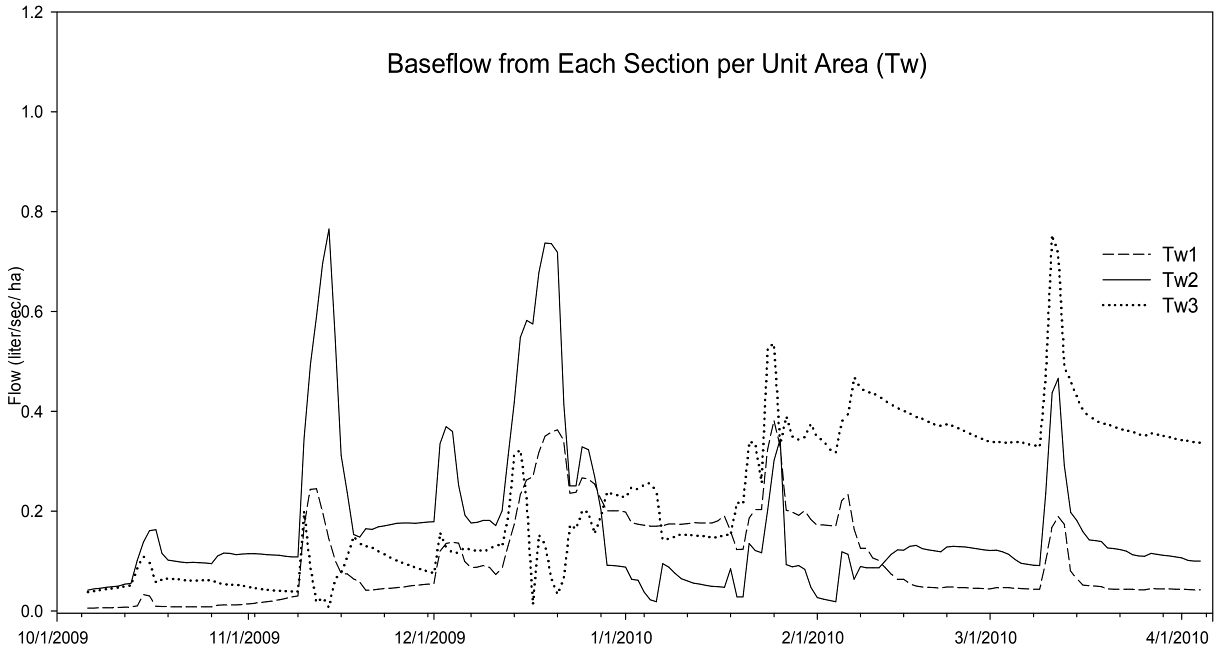



Figure 4.18: Baseflow per unit area on the treatment watershed for post-harvest conditions

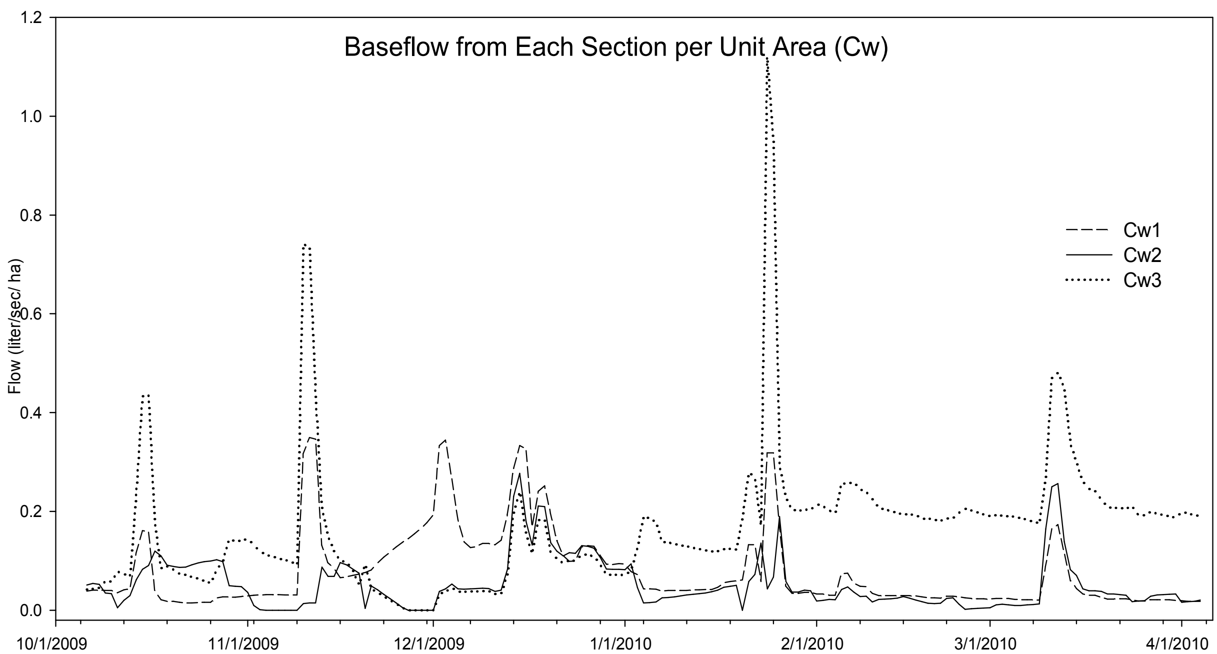



Figure 4.19: Baseflow per unit area on the control watershed for post-harvest conditions

#### 4.3.3. Sediment Load

Similar to pre-harvest trends (Appendix L), sediment yield increased downstream on both the treatment and control watersheds during the post-harvest period (Appendix O). Sediment yield significantly increased at downstream stations (T2 and T3) on the treatment watershed during rain events. About 90 percent of the sediment load was created by the biggest rainfall events in comparison with about 30 percent before harvest. On the control watershed, about 70 percent of the total sediment load was created by the biggest rain events post-treatment. Little or no sediment was created during other events. In comparison to the pre-treatment period, the magnitude of sediment yield created during rainfall events increased on both watersheds.

Figure 4.20 and 4.21 show sediment yield from each section on a per unit area basis and provides more insight on the relative amount of sediment generated by each section. On the treatment watershed, post-treatment data shows that the sediment pattern changed after the harvest (Figure 4.20). Section Tw3 generated significantly higher amounts of sediment per hectare than did the upstream sections. Section Tw2 generated remarkably higher amounts of sediment per hectare after harvest. Section Tw1 produced the least sediment yield per unit area, a complete reversal of the pre-harvest trends (Figure 4.8). This relationship was maintained during both storm events and dry periods (Figure 4.20). Although there was still little or no sediment movement during dry periods, and the amount of sediment only increased by about 40% on average off of the untreated pasture site (increase attributed to the lack of active growth during the dormant season, and increase in number of rainfall events), the amount of sediment load originating from the treated sections Tw2 and Tw3 increased by approximately 900% on Tw2 and 400% on Tw3. This difference is primarily attributed to the immediate post treatment effects caused by exposed soil from skidding operations. Although some of this increase is explained by the reduced canopy cover during dormant season as evidenced by the approximately 140% increase in sediment yield from the forested section of the control watershed.

Ursic and Douglass suggest that 70 mg/liter of sediment concentration is the average annual natural back-ground yield from undisturbed southern pine forests. According to their report mean sediment concentration can be increased up to 1200 mg/liter by forestry operations during the first year after treatment. Based on these data, the effects observed following the partial cut on sediment yield seem reasonable.

On the control watershed, the sediment pattern did not change (as expected) since this watershed was not affected by harvesting. Sediment yield per unit area generated by section Cw1 is higher than from the downstream sections during the two biggest storm events (Figure 4.21). During milder rainfall events, section Cw3 contributed higher sediment per unit area than other sections as occurred during the pre-harvest period. Section Cw2 continued to generate the least sediment.

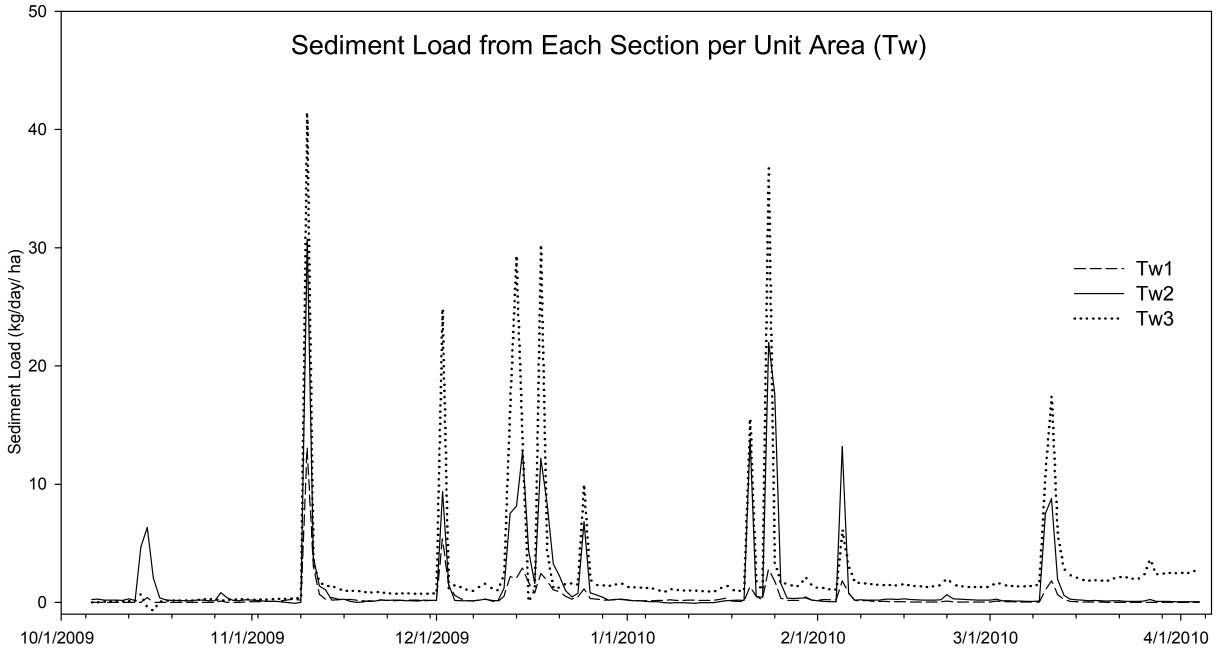



Figure 4.20: Sediment yield per unit area on the treatment watershed for post-harvest conditions

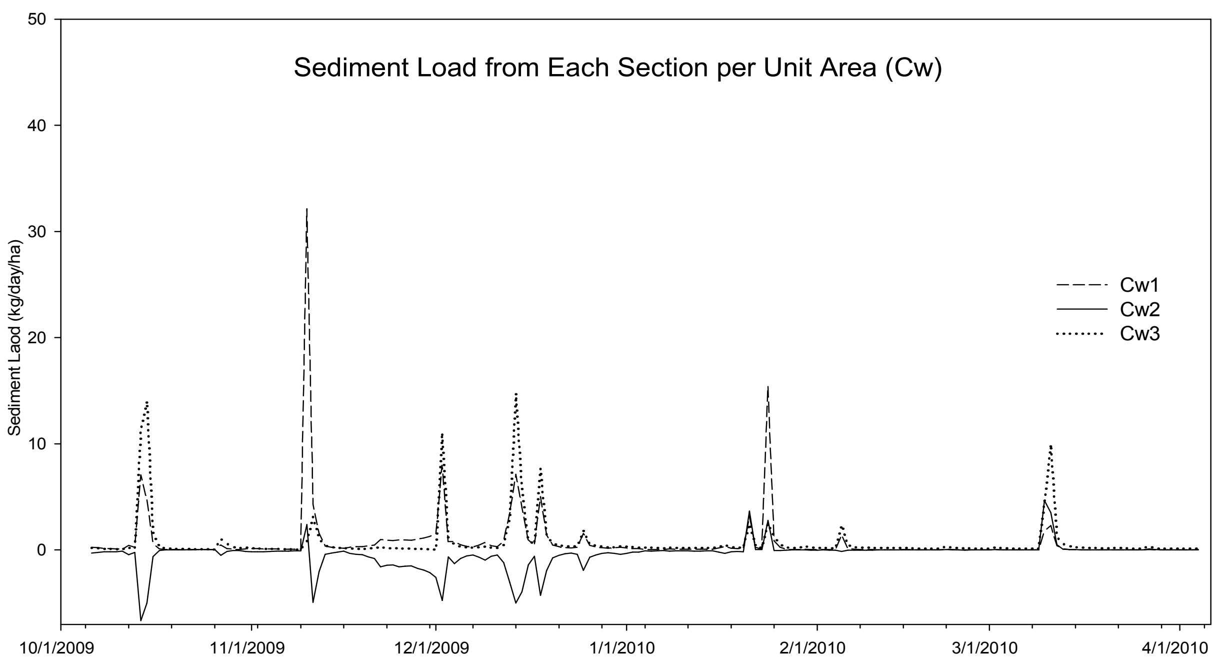



Figure 4.21: Sediment yield per unit area on the control watershed for post-harvest conditions

#### 4.3.4. Sediment Concentration

Sediment concentration increased downstream on the treatment watershed during rainfall events (Figure 4.22). It was higher at T3 and lower at T1 during both rainfall events and dry periods. In comparison to pre-harvest conditions (Figure 4.10), T2 had inversely higher sediment concentrations than T1. In comparison with the pre-harvest data, the magnitude of increase in concentration was in very high at T3 after the harvest.  Sediment trends on the control watershed (Figure 4.23) did not change in comparison with the pre-harvest period (Figure 4.11).

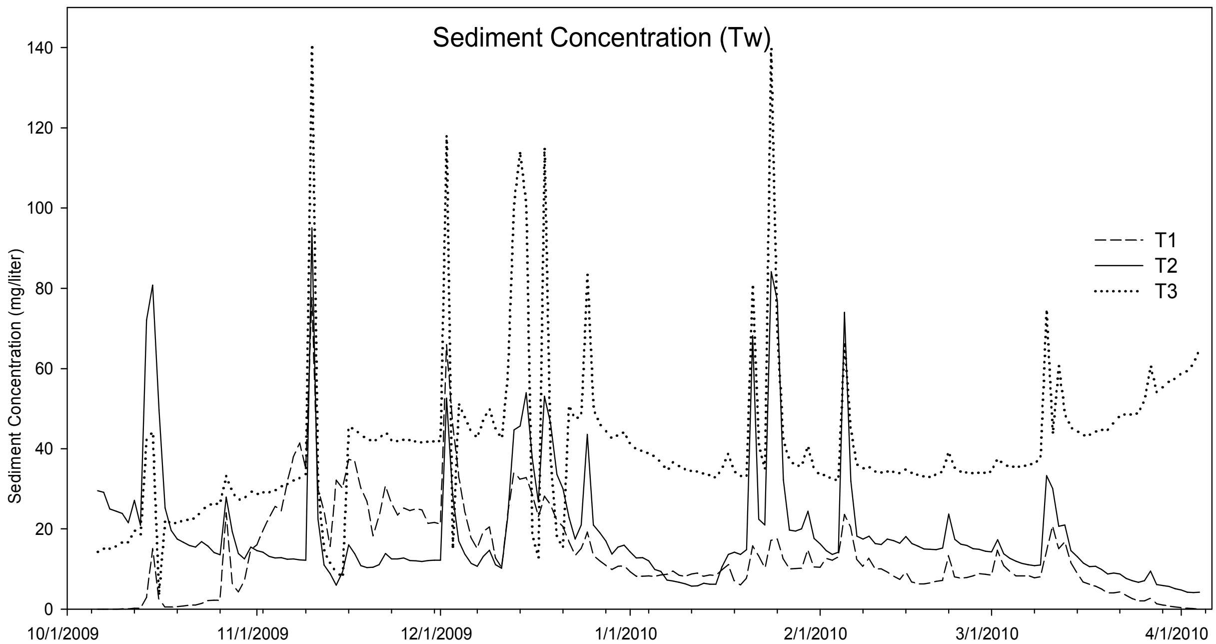



Figure 4.22: Sediment concentration on the treatment watershed for post-harvest conditions

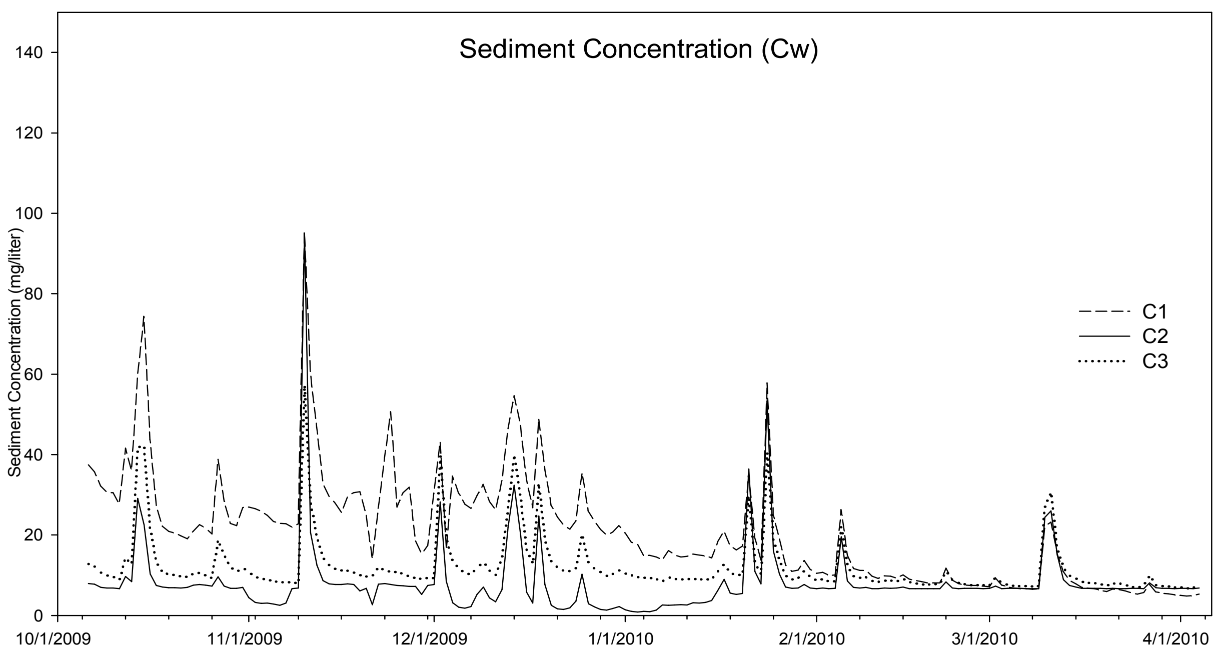



Figure 4.23: Sediment concentration on the control watershed for post-harvest conditions

During the post-harvest period, forested section Cw2 converted a smaller percentage of precipitation to streamflow (Table 4.2) as was the case pre-harvest (Table 4.1) on the control watershed. However, on the treatment watershed, the pattern changed; forested section Tw2 converted a higher percentage of precipitation to streamflow than section Tw1 as a result of the harvest and dormant season. Although upstream sections on both watersheds were the flashiest during the calibration period, following treatment, section Tw2 is the flashiest section while Cw3 is flashiest on the control watershed. Again, this is attributed to the lack of foliage in the remaining canopy during the dormant season.

Downstream sections (Tw3 and Tw2) generate higher amounts of sediment than upstream sections on the treatment watershed after harvest operation due to the reasons mentioned previously. Sediment yield significantly increased post-harvest on Tw2 and Tw3 suggesting that the harvest operation affected soil stability in these sections. Trends on the control watershed were unchanged with Cw2 generating very little sediment. RB values are lower during the post-harvest period compared to pre-harvest period. This is attributed to the more steady rains during post-treatment period.

Table 4.2: Summary of post-harvest results. SF: Streamflow, P: Precipitation, RB: Flashiness

| **Stations/ Sections** | **SF/P[1] (%)** | **RB[2] (%)** | **Sediment(kg/ha)** |
|---|---|---|---|
| Tw1 | 34 | 3 | 72 |
| Tw2 | 59 | 13 | 246 |
| Tw3 | 70 | 11 | 464 |
| Cw1 | 51 | 10 | 138 |
| Cw2 | 12 | 13 | 19 |
| Cw3 | 70 | 14 | 137 |

[1]The proportion of precipitation on the watershed that is converted to streamflow
[2] Streams that rise and fall quickly are considered flashier than those that maintain a more consistent flow.

### 4.4. Post-Harvest Validation (Harvest Effects)

Post-harvest validation results deal with the harvest effects on hydrology and sedimentation. Models derived from the calibration data were used to predict response on both treatment and control watersheds for the post-harvest period from October 6, 2009 to April 5, 2010. Observed and predicted discharge data were compared to determine harvest effects on hydrology.

### 4.4.1. Discharge

The pasture was not affected by the partial cut and because this was the most upstream section of the watershed, one would not expect there to be any post-treatment difference in any of the monitored parameters. There was no change in discharge per unit area of Tw1 ($p=0.059$) (Figure 4.24). Discharge from Tw1 on a unit area basis was observed at 0.20 liter/sec/ha while the predicted discharge was 0.14 liter/sec/ha on this section during the six-month post-harvest period (Figure 4.25)

During major rainfall events, Tw2 generated 7-10 times more water than predicted following harvest (Figure 4.26). Section Tw2 was expected to create about 0.09 liter/sec/ha water during the six-month period, while 0.38 liter/sec/ha, almost four times more than predicted, was measured (Figure 4.25). Observed rates were also higher than predicted during dry periods as well.

On a unit area basis, observed water yield from Tw3 was 3-5 times higher than predicted during rainfall events (Figure 4.27) and approximately 2.5 times higher than average predicted discharge rates(0.42 liter/sec/ha vs. 0.17 liter/sec/ha) over the entire post-harvest monitoring period (Figure 4.25).

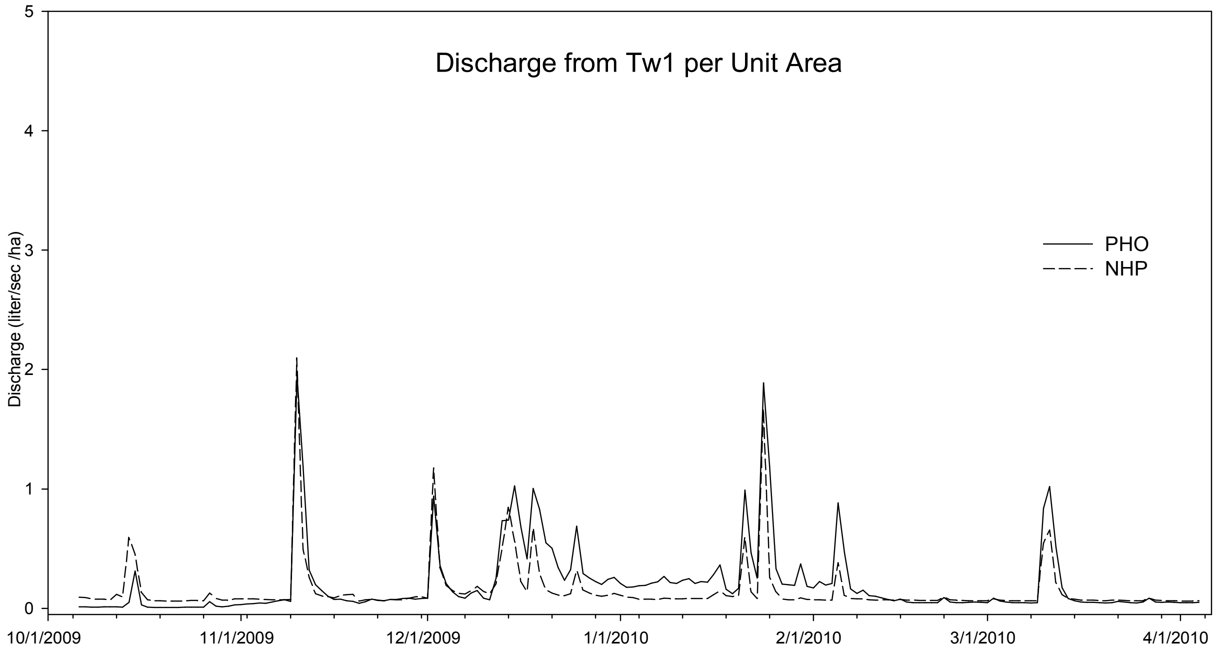



Figure 4.24: Harvest effects on hydrology from Tw1 (PHO: Post-harvest observation, NHP: No-harvest prediction)

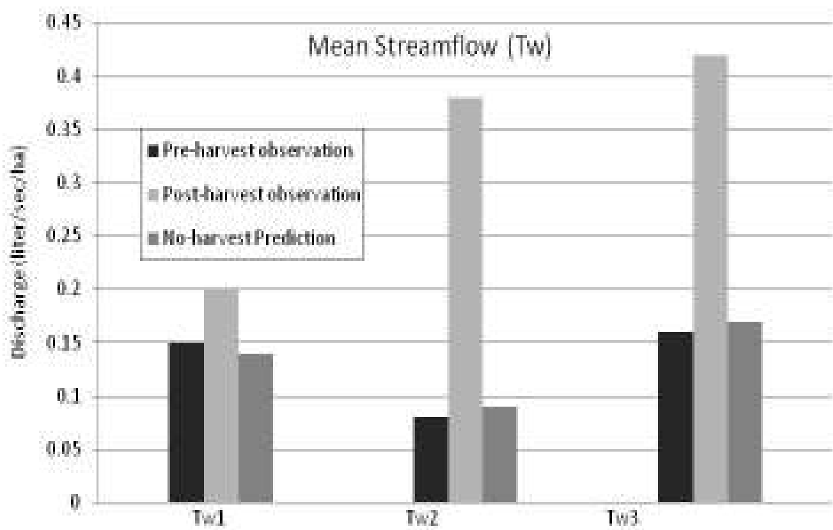



Figure 4.25: Mean streamflow values

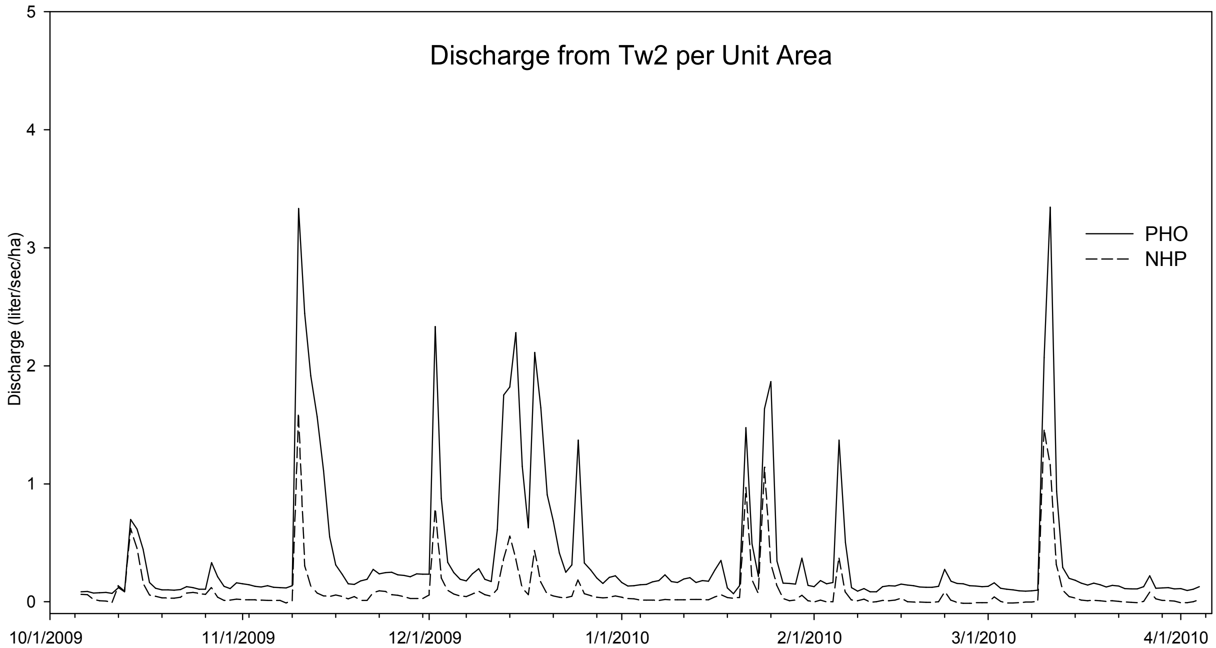



Figure 4.26: Harvest effects on hydrology from Tw2 (PHO: Post-harvest observation, NHP: No-harvest prediction)

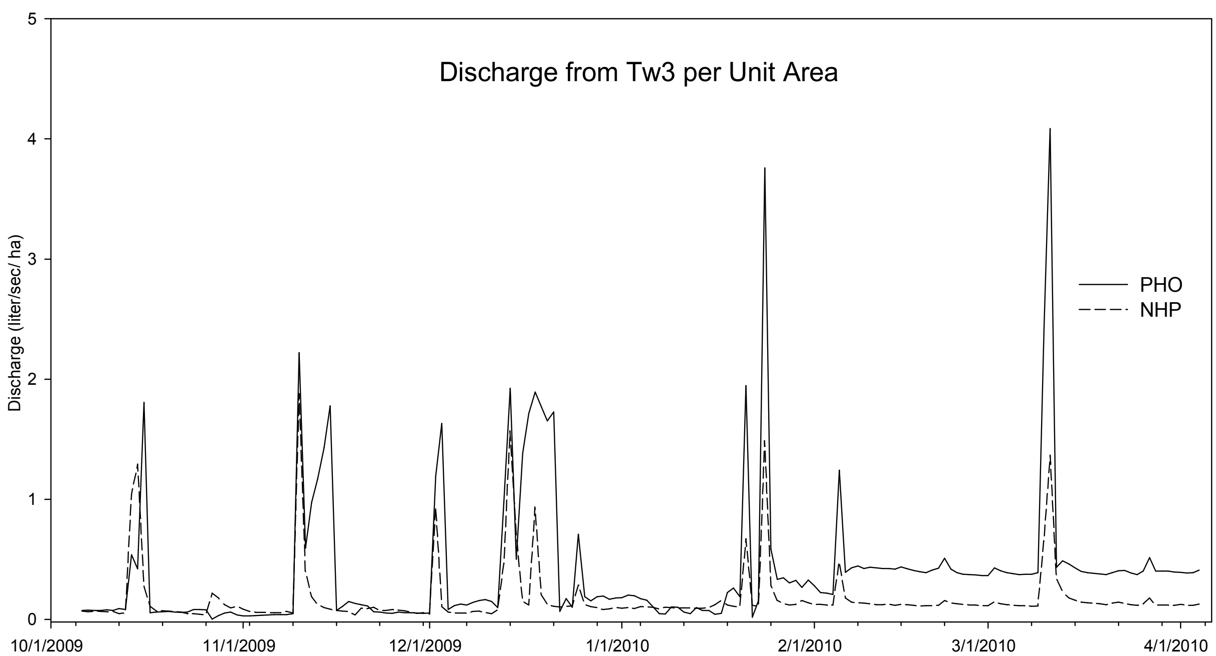



Figure 4.27: Harvest effects on hydrology from Tw3 (PHO: Post-harvest observation, NHP: No-harvest prediction)

### 4.4.2. Direct Runoff & Baseflow

Total rainfall for the post-harvest study period was 930 mm on the study watershed. Eleven storm events resulted in runoff at each station during the six-month period after harvest: during the pre-treatment period, there were four discrete storm events and 780 mm rainfall in total. Little or no change in runoff occurred at station T1 (Figures 4.4 and 4.28). However, at downstream stations T2 and T3, there were marked increases in direct runoff after treatment (Figure 4.4, 4.29, and 4.30). Observed direct runoff rates are about two times higher than predicted direct runoff rates during rainfall effects on these sections. No significant changes were observed during dry periods at any of the stations (p=0.37 for T1, p=0.24 for T2, and p=0.42 for T3). The harvest and the dormant season caused a 34% increase in runoff at T2 and 58% at T3 in comparison with the pre-harvest period. Again, about 50% of this increase was caused by the harvest at T2, and 84% at T3.

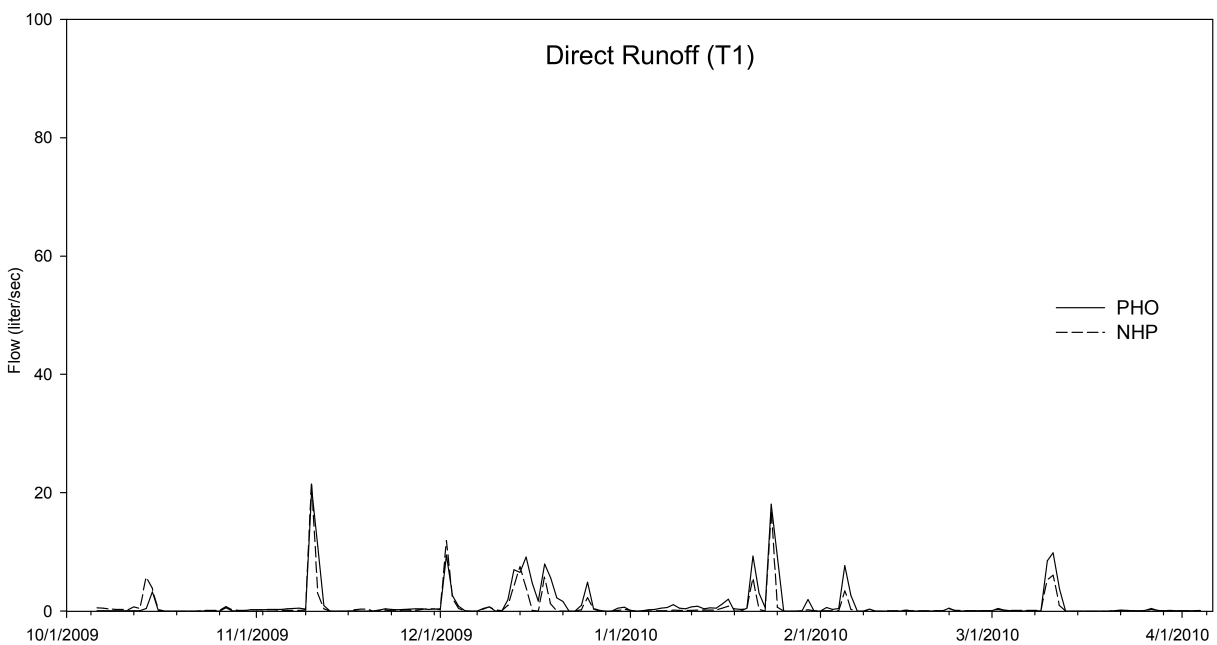



Figure 4.28: Harvest effects on direct runoff at T1 (PHO: Post-harvest observation, NHP: No-harvest prediction)

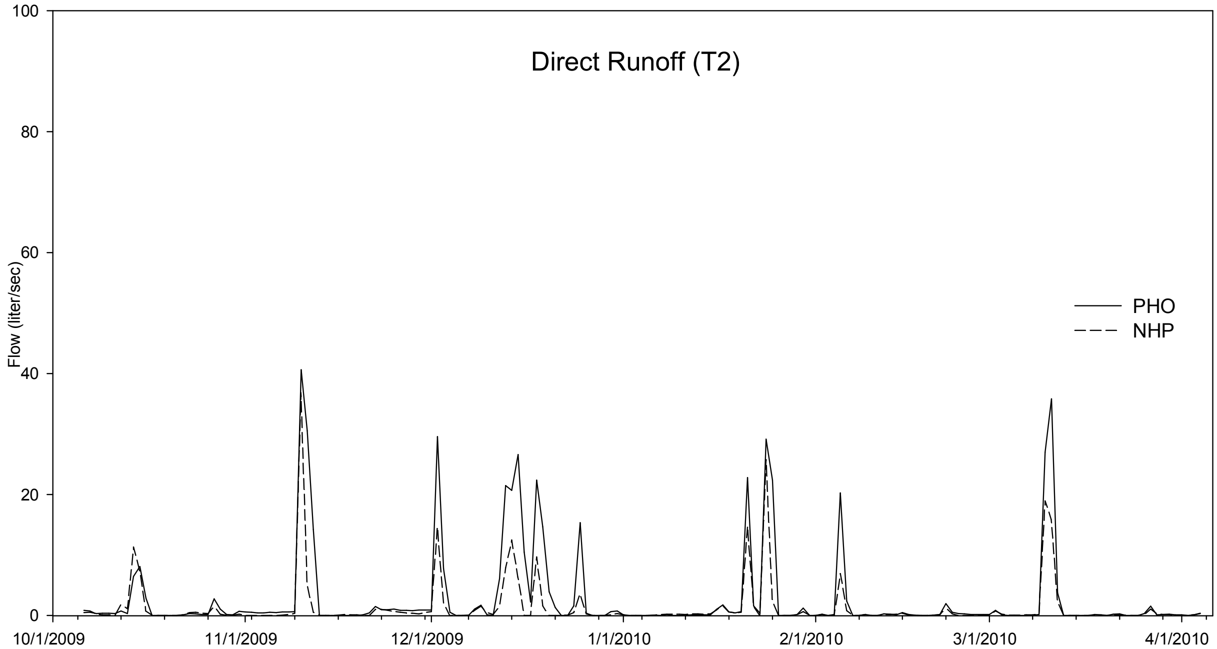



Figure 4.29: Harvest effects on direct runoff at T2 (PHO: Post-harvest observation, NHP: No-harvest prediction)

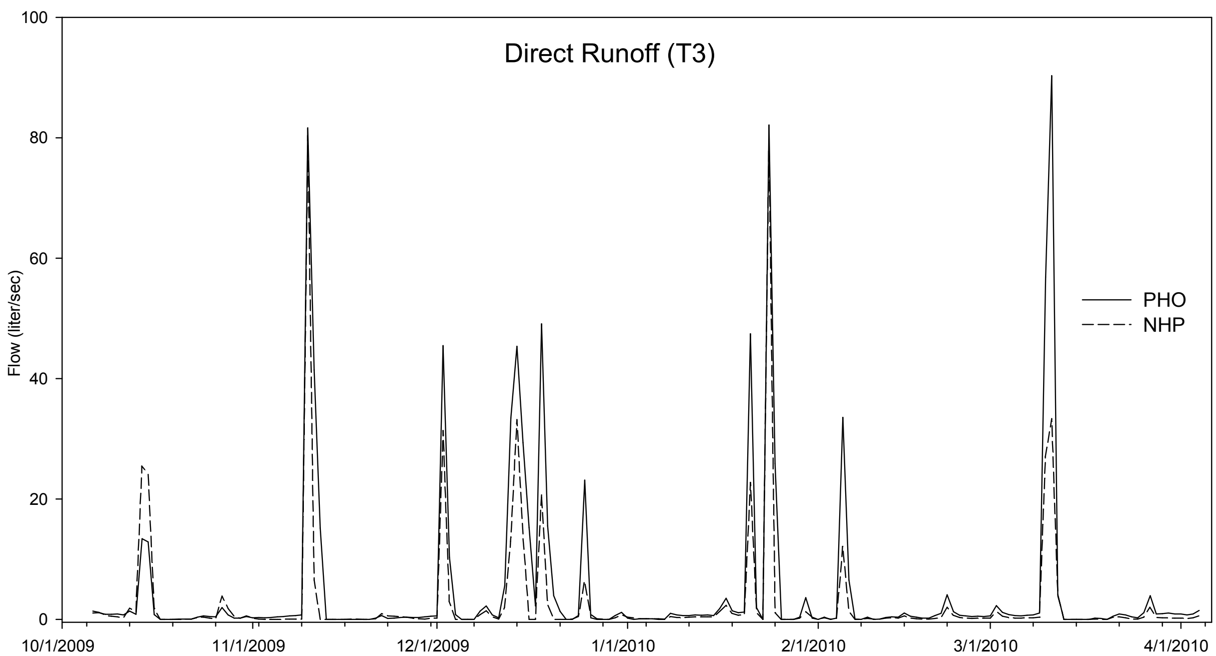



Figure 4.30: Harvest effects on direct runoff at T3 (PHO: Post-harvest observation, NHP: No-harvest prediction)

Even though observed and predicted baseflow rates show variation during the post-harvest period at T1, there was no significant difference between average-observed (1.22 liter/sec/ha) and average-predicted (0.98 liter/sec/ha) on a unit area basis during the six-month post-treatment period (Figure 4.31). However, there were increases at T2 and T3 in baseflow rates following harvest (Figure 4.32 and Figure 4.33). At T2, average baseflow per hectare was measured at 2.94 liter/sec/ha while it was predicted to be 1.07 liter/sec/ha; a nearly three-fold increase. At T3, average observed baseflow per unit area was 6.40 liter/sec/ha while the average predicted rate was 2.97 liter/sec/ha. These data suggest that baseflow patters are affected by the harvest and dormant season.

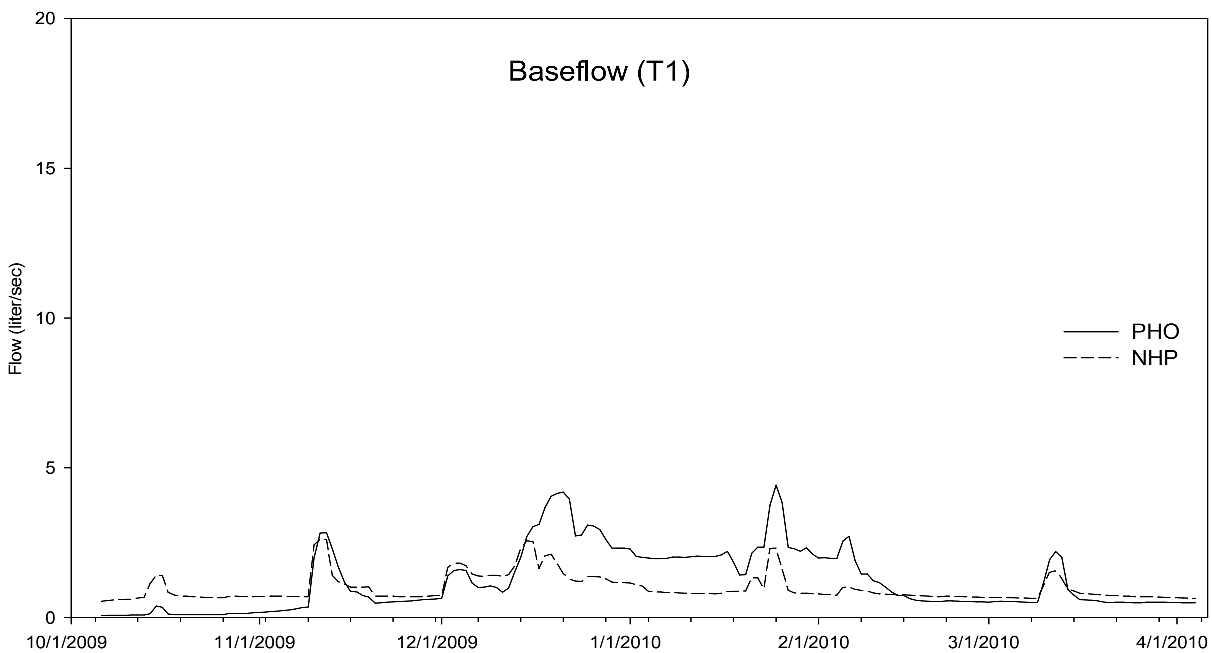



Figure 4.31: Harvest effects on baseflow at T1 (PHO: Post-harvest observation, NHP: No-harvest prediction)

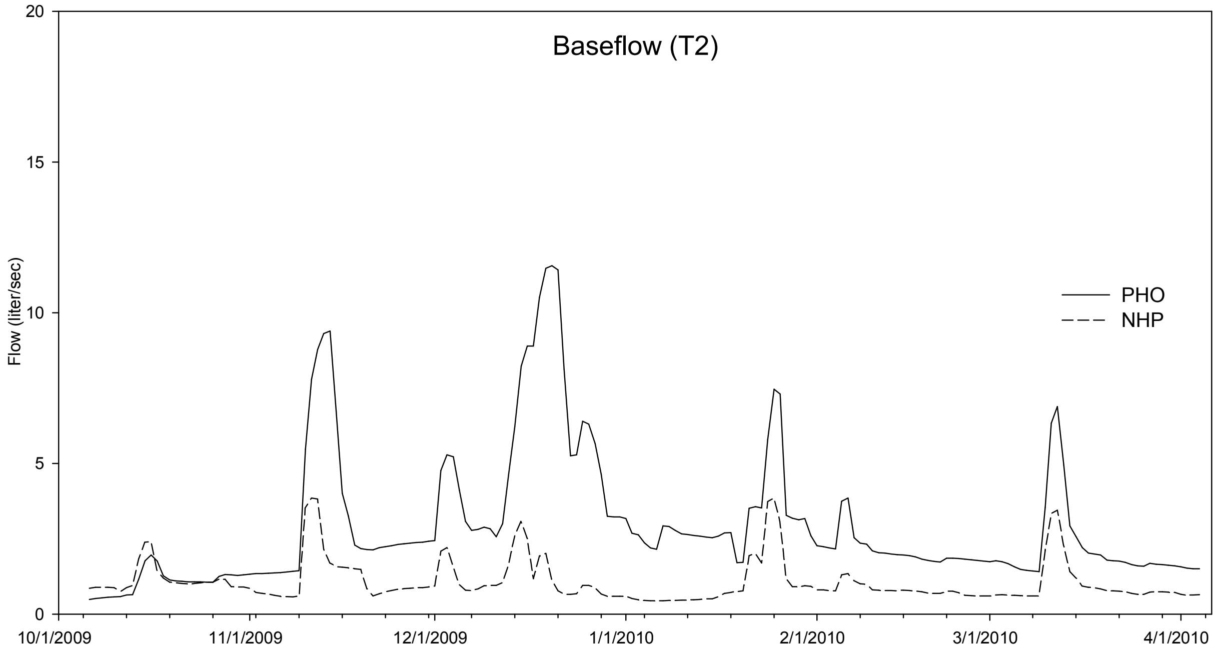



Figure 4.32: Harvest effects on baseflow at T2 (PHO: Post-harvest observation, NHP: No-harvest prediction)

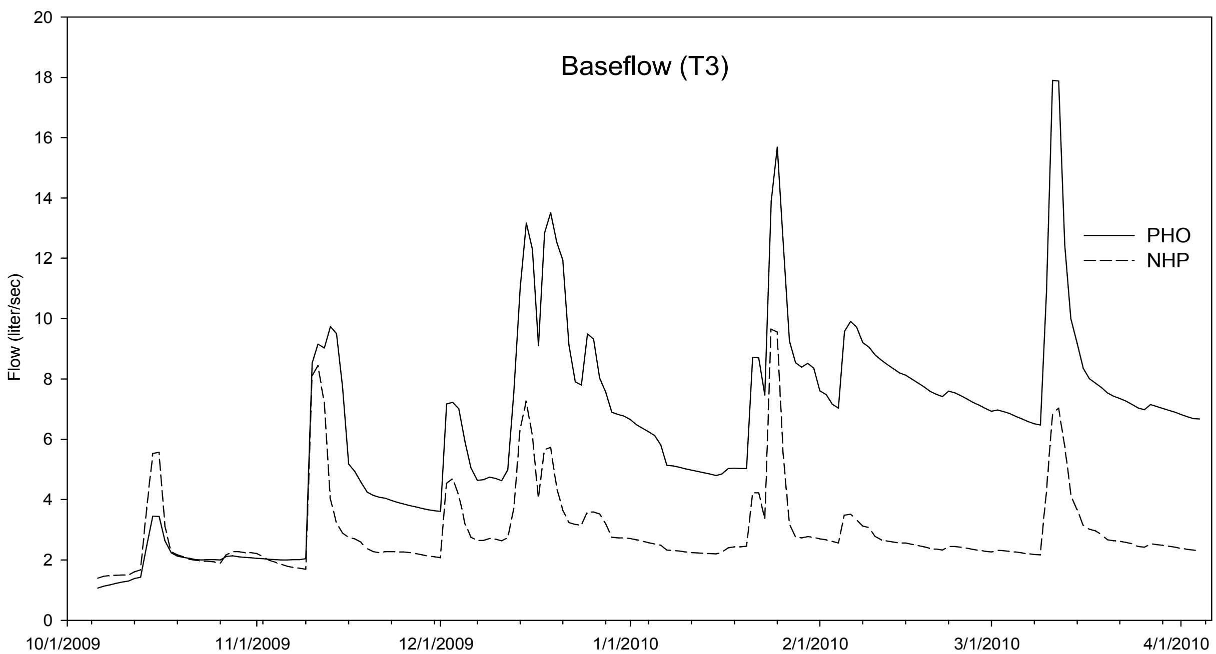



Figure 4.33: Harvest effects on baseflow at T3 (PHO: Post-harvest observation, NHP: No-harvest prediction)

#### 4.4.3. Sediment Yield

During the pre-harvest period, sediment loads from the pasture were higher than from downstream sections during rainfall events on the treatment watershed. However, downstream sections Tw2 and Tw3 generated much more sediment than the pasture after the harvest operation.

There was no change in the sediment yield from section Tw1 on a unit area basis (Figure 4.34). Average sediment yield per hectare was measured at 0.37 kg/day/ha while the average predicted sediment per hectare was 0.27 kg/day/ha during the six-month post-harvest period (Figure 4.35).

When looking at the sediment yield on a per unit area basis, the post-harvest effect is quite distinct on Tw2 (Figure 4.36), suggesting that the partial cut within the SMZ caused disturbance of the duff layer and/or vegetation therefore allowing soil movement (erosion) and an increase in sediment yield during rainfall events. During rainfall events, between 10-15 times more sediment than predicted was generated in Tw2. There was little or no change during dry periods suggesting that the increase in sediment yield is due to surface erosion and soil movement in overland flow. Average observed sediment yield was 1.36 kg/day/ha versus a predicted rate of 0.14 kg/day/ha (Figure 4.35).

Sediment yield significantly increased following harvest from Tw3 ($p=0.012$) (Figure 4.37). As on section Tw2, differences were most notable during rainfall events with sediment yields of 3-4 times what was predicted. Although less obvious, the magnitude of increased sediment yield during dry periods is greater than during storm events. In terms of sediment yield from section Tw3 per hectare, observed sediment yield generated by this section (2.56

kg/day/ha) is significantly higher (p=0.012) than average predicted sediment yield per unit area (0.54 kg/day/ha) (Figures 4.35)

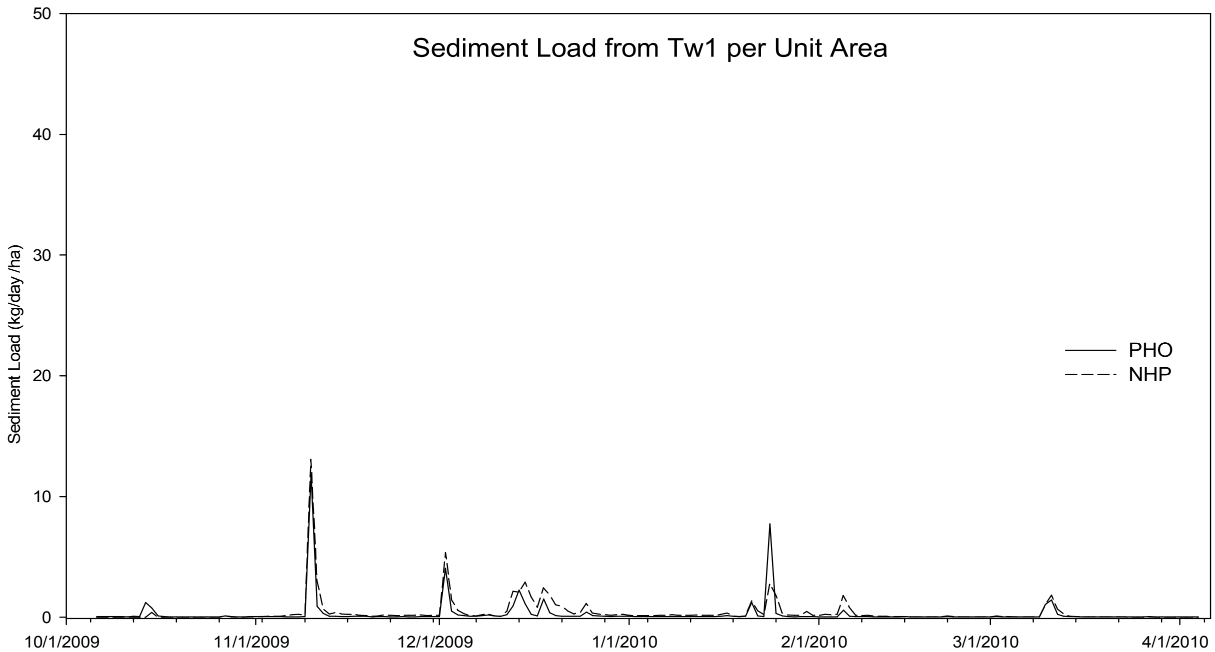



Figure 4.34: Harvest effects on sediment yield from Tw1 (PHO: Post-harvest observation, NHP: No-harvest prediction)

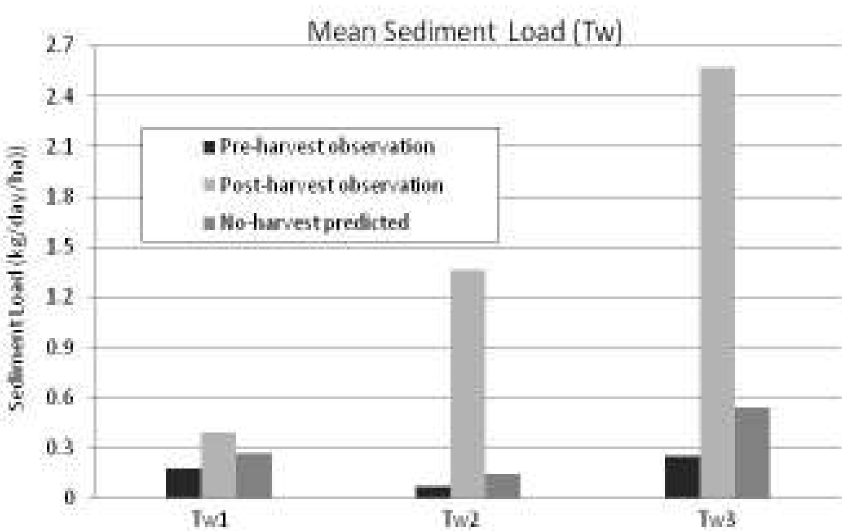



Figure 4.35: Mean sediment yield before and after harvest

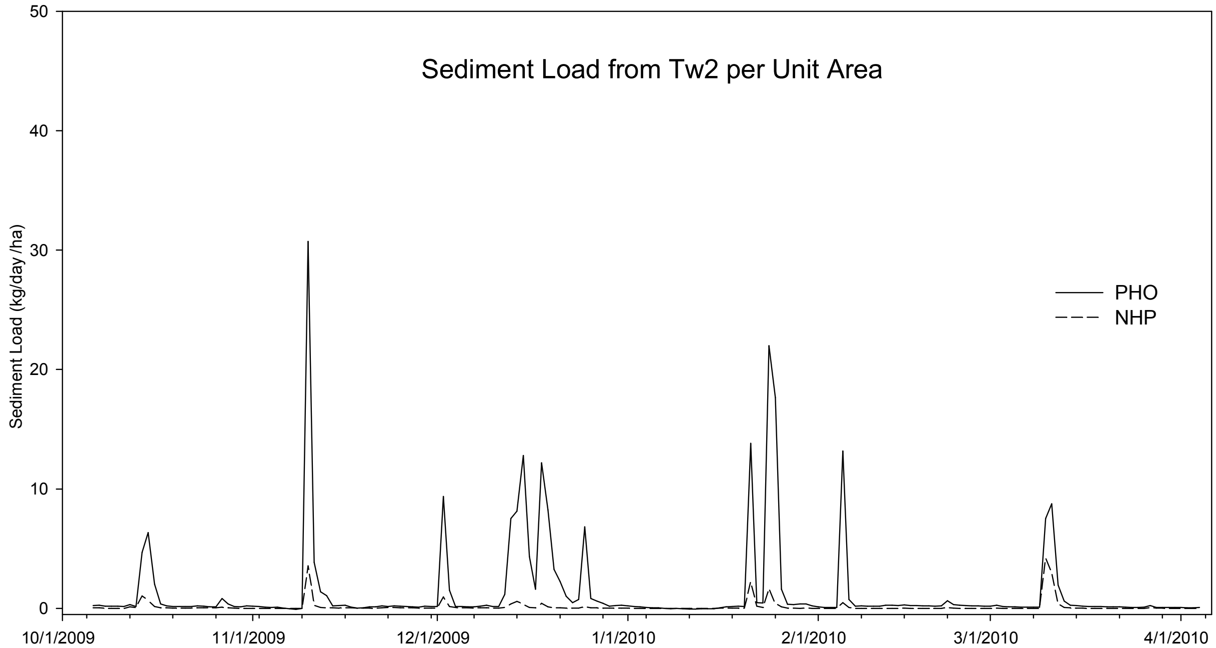



Figure 4.36: Harvest effects on sediment yield from Tw2 (PHO: Post-harvest observation, NHP: No-harvest prediction)

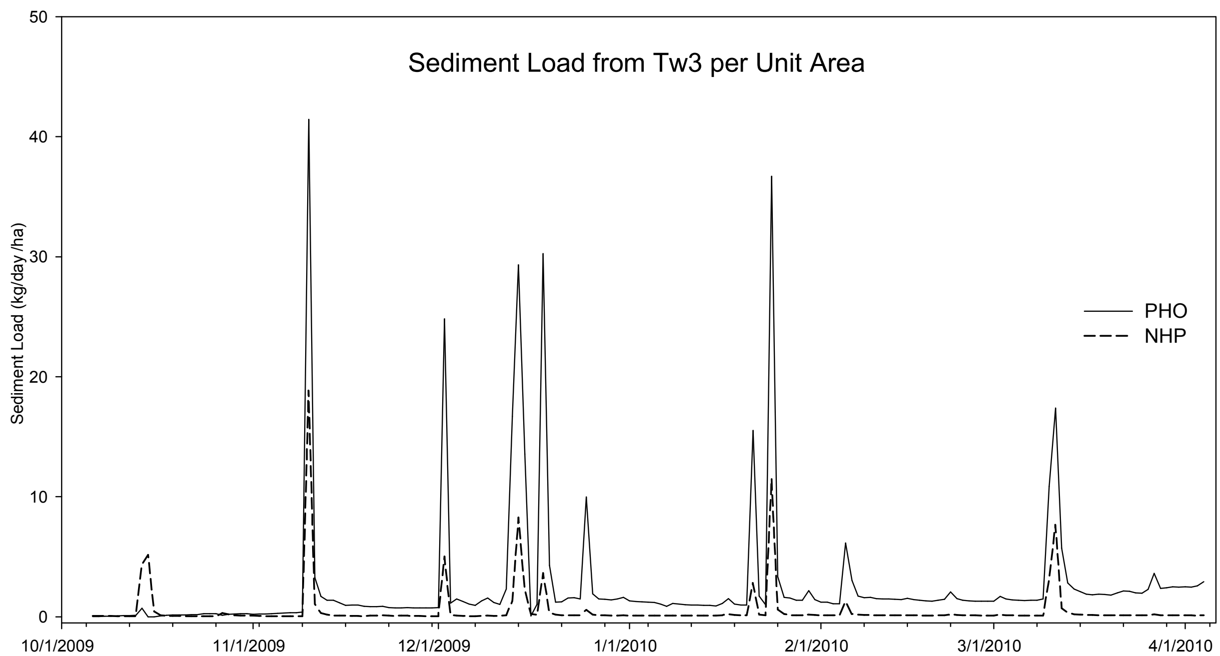



Figure 4.37: Harvest effects on sediment yield from Tw3 (PHO: Post-harvest observation, NHP: No-harvest prediction)

### 4.4.4. Sediment Concentration

Similar to water and sediment yield, sediment concentration did not significantly change following harvest at T1 (Figure 4.38). Average predicted sediment concentration was 9.9 mg/liter vs. 13.6 mg/liter observed on the treatment watershed (Figure 4.39). As might be expected because post-harvest sediment yield increased at downstream stations T2 and T3, sediment concentrations were also found to be significantly higher than predicted (p=0.0001) (Figures 4.40 and 4.41). Average observed sediment concentration (19.02 mg/liter) was about two times higher than average predicted sediment concentration (9.27 mg/liter) at station T2 (Figure 4.39). At the station T3, the effect of the harvest on sediment concentration was even greater (p=0.0001). Average sediment concentration was measured at 40.70 mg/liter while it was predicted to be about 12.78 mg/liter at this station (Figure 4.39).

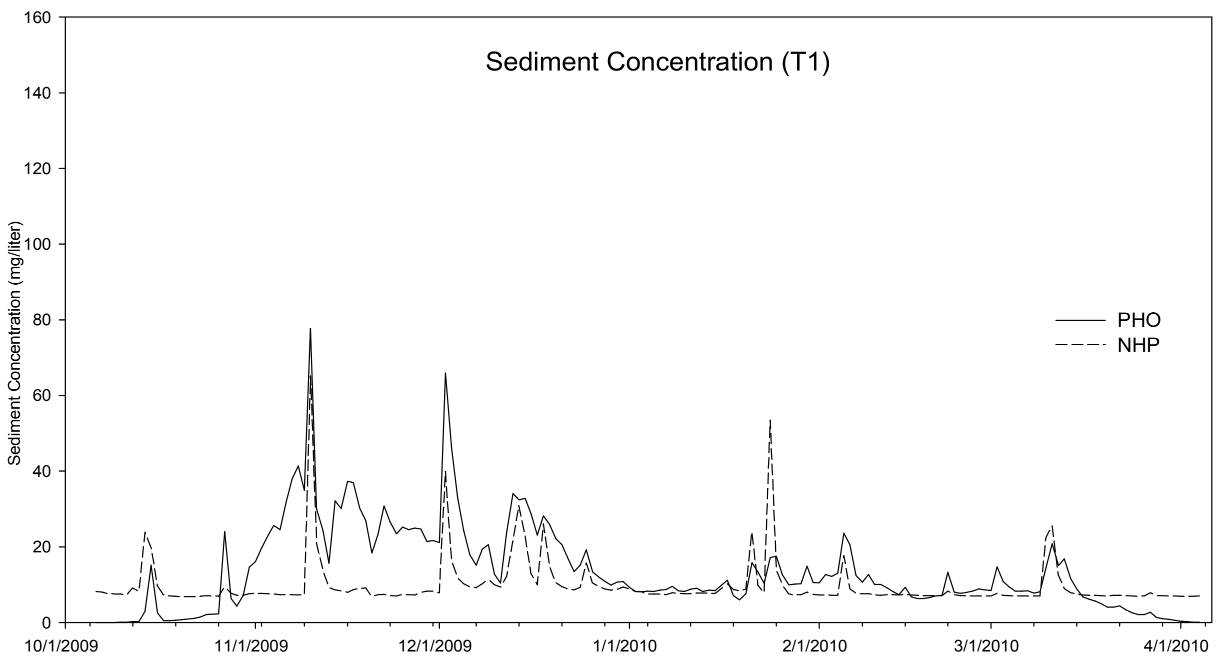



Figure 4.38: Harvest effects on sediment concentration at T1 (PHO: Post-harvest observation, NHP: No-harvest prediction)

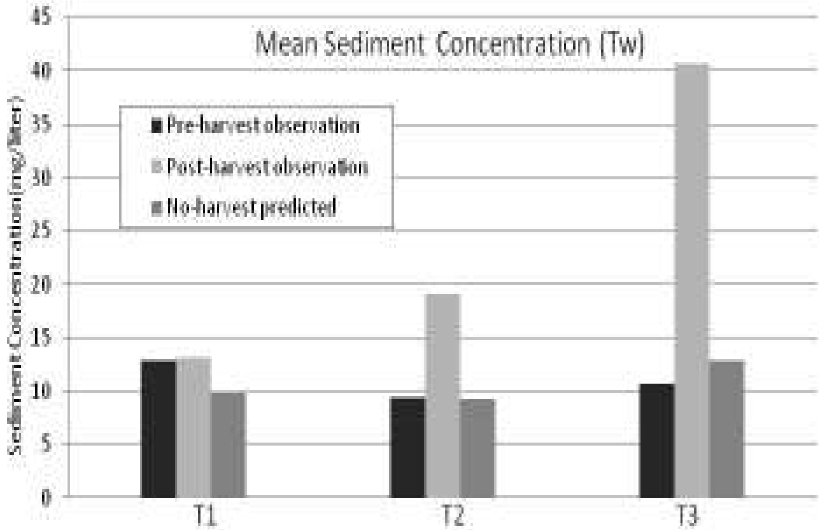


Figure 4.39: Mean sediment concentration before and after harvest

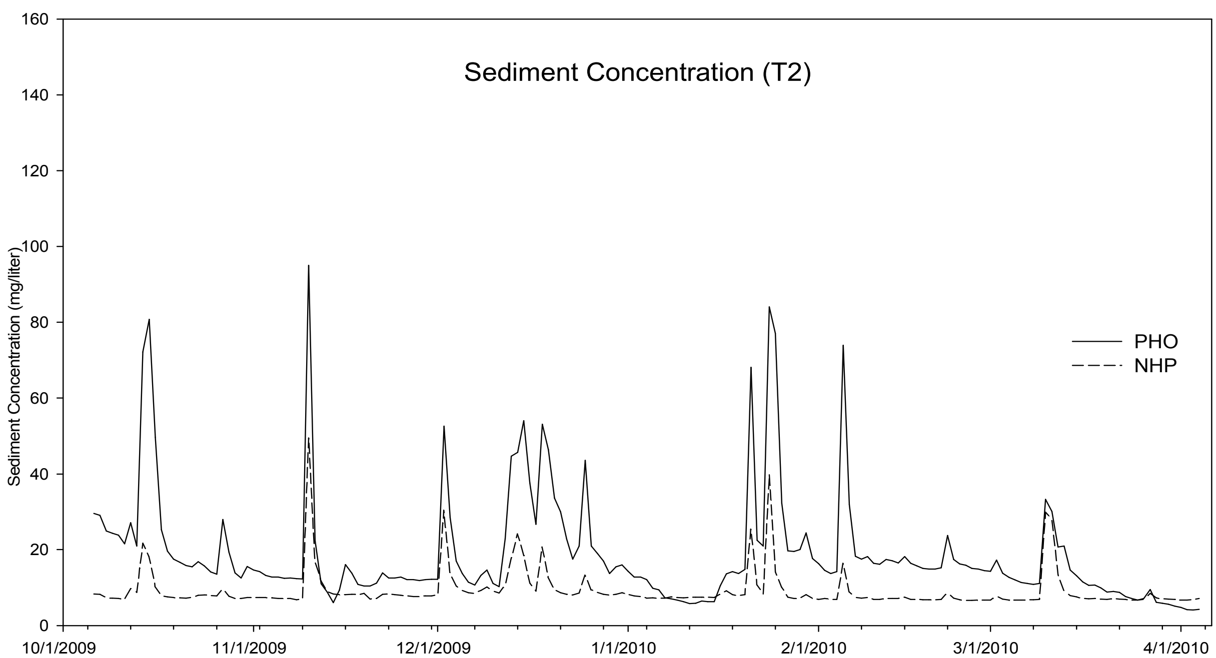


Figure 4.40: Harvest effects on sediment concentration at T2 (PHO: Post-harvest observation, NHP: No-harvest prediction)

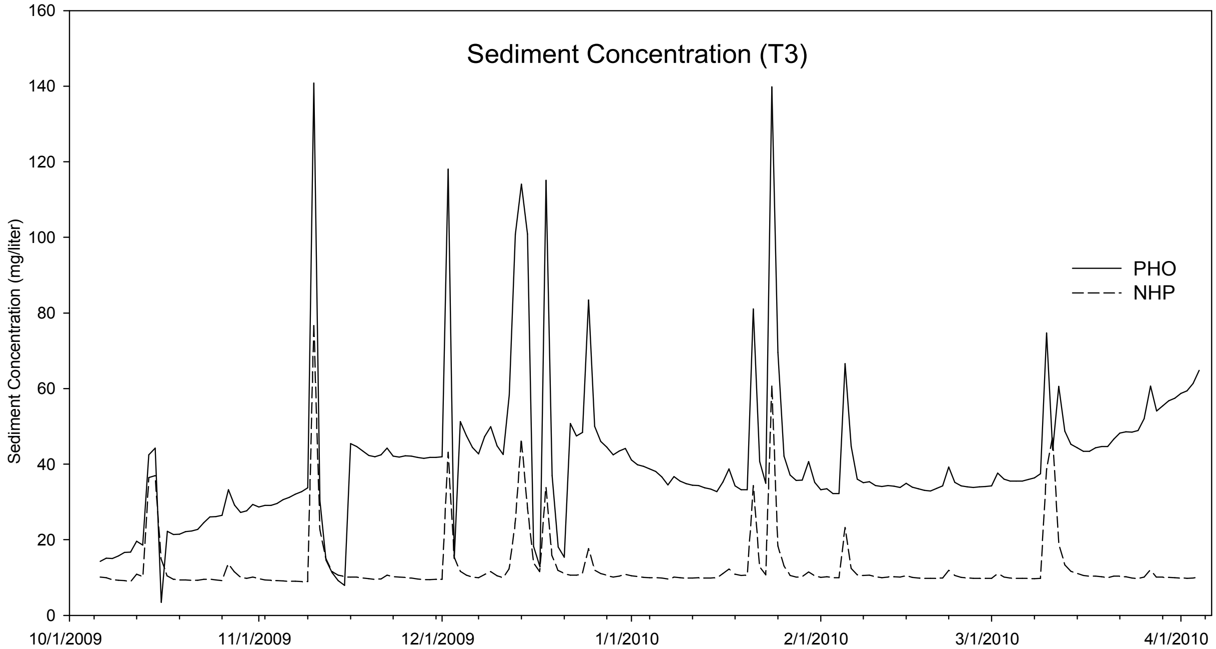



Figure 4.41: Harvest effects on sediment concentration at T3 (PHO: Post-harvest observation, NHP: No-harvest prediction)

Over the six-month pre-harvest period, section Tw2 converted the smallest percentage of precipitation (SF/P) to streamflow because this section was undisturbed forest which has associated with it, a high rate of evapotranspiration (Table 4.1). After the harvest, this section was still predicted to convert the smallest percentage (Table 4.3). However, it converted nearly twice that of section Tw1. We attribute this to a decrease in evapotranspiration on sections Tw2 and Tw3 because of the harvest. As has been mentioned previously, a confounding variable is the fact that the six-month post-harvest period spans the dormant season during which time evapotranspiration rates in deciduous forests decline dramatically. Generally forested areas show less flashy characteristics. However, after the harvest operation, sections Tw3 and Tw2 became flashier than section Tw1 due to the effects of harvest and dormant season. Total sediment yield didn't significantly change on Tw1 during the post-harvest period. However, sections Tw2 and Tw3 generated much more sediment yield than predicted during the six-month post-treatment period. Section Tw2 created about ten times more sediment yield than predicted yield while it was about five times higher than predicted rates on Tw3. Some of these increases are explained by the reduced canopy cover during the dormant season.

Table 4.3: Effects of the harvest on each section. SF: Streamflow, P: Precipitation, RB: Flashiness

| | | SF/P[1] (%) | RB[2] value | Sediment(kg/ha) |
|---|---|---|---|---|
| Tw1 | Pre-harvest Observed | 33 | 26 | 34 |
| | Post-harvest Observed | 34 | 3 | 72 |
| | Post-harvest Predicted | 25 | 7 | 49 |
| Tw2 | Pre-harvest Observed | 17 | 20 | 13 |
| | Post-harvest Observed | 59 | 13 | 246 |
| | Post-harvest Predicted | 16 | 3 | 24 |
| Tw3 | Pre-harvest Observed | 34 | 17 | 46 |
| | Post-harvest Observed | 70 | 11 | 464 |
| | Post-harvest Predicted | 30 | 12 | 97 |

[1] The proportion of precipitation on the watershed that is converted to streamflow
[2] Streams that rise and fall quickly are considered flashier than those that maintain a more consistent flow.

# Chapter 5
# Conclusions and Recommendations

### 5.1. Conclusions

Forested watersheds and forested areas on a watershed both play important roles in protecting and maintaining both water quality and quantity. However, any silvicultural operations in forested watersheds must be carefully managed and supervised in order to protect and maintain water quality. During a one year period, we observed sediment and water yield on discrete sections of two small watersheds. Effects of different land use and forestry treatments on sediment and water yield were evaluated.

Most watersheds contain more than one land use. Generally one land use is considered dominant in each and the watershed is categorized by that dominant land use as forested, urban, or pastoral. It is often difficult to isolate the effects of the dominant land use from other land uses on a watershed. Monitoring sediment yield at different locations on the watershed allowed us to isolate the effects of each discrete land use on sedimentation.

It has been shown that stream water increases according to the percentage of trees removed from a watershed (Patric, 1978). Clearcutting generally causes the maximum increase in water yield because all trees are removed during the harvest operation (Douglass, 1980). In this study, we confirm that streamflow is increased on the sections exposed to partial cutting.

Discharges from these sections were observed to be 3-4 times higher than expected. However, approximately 50% of these changes can be attributed to seasonal effects due to reduction in evapotranspiration.

During the pre-harvest period, upstream sections (pastoral and urban landuse on watersheds Tw and Cw, respectively) generated much more sediment yield than downstream forested sections on both watersheds. The least amount of sediment was created by the forested middle sections which differed from the downstream forested sections in that they were intact forest. The furthest downstream sections Tw3 and Cw3, which contained a stream crossing and a two year old clearcut, created much more sediment than forested sections Tw2 and Cw2. This suggests that the SMZs were not sufficient to trap all of the sediment from the clearcut area and forest road, even though the SMZs were often much wider than the minimum guidelines. It may be also suggested that a SMZ may not function at desired level under certain conditions no matter how wide it is.

Following the partial cutting treatment of the SMZ in watershed Tw, it was observed that during the first six months following harvest, there was a significant increase in sediment load from the treated sections (Tw2 and Tw3) caused by increased erosion from exposed soil from skidding operations. Higher amounts of sediment were observed on these sections in comparison to the pre-harvest calibration period. Some of this increase is explained by the reduced canopy cover due to the dormant season, and by increased number of rain events. However, no significant change was observed between the pre-harvest and post-harvest period on the section Tw1. Sediment trends did not differ from the calibration period following harvest on the control watershed.

On the treatment watershed, sediment concentration was higher at T1 than at T2 during the calibration period. On the control watershed, sediment concentration was higher at C1 than at C2 during both pre-harvest and post-harvest periods. Pre-harvest results showed the forests effect at reducing sediment concentration on both watersheds. However, on the treatment watershed, sediment concentration was lower at T1, and significantly higher sediment concentration was observed at T3 and T2 after the harvest illustrating the effect of partial cutting in a SMZ on sediment concentration from the harvested area.

This study shows the importance of forest cover at reducing sediment yield. Forest cover also shows evidence of being effective at reducing direct runoff on a watershed. The study also shows the season effects sediment and water yield as well. It may be suggested that clearcutting causes at least a temporary increase in sediment load, even with properly managed BMP's and SMZ's. If effective forest road BMPs are not in place then simply focusing on SMZs to reduce sediment yield may not be sufficient. This study also shows the importance factoring in upstream land use and land cover conditions when designing SMZs for sediment trapping. Based on results from this study, it is suggested that best management practices could provide better protection if a watershed were managed and supervised as a whole.

## 5.2. Limitations

Timing of logging operations is very important. To reduce soil compaction, timber harvesting operation should be limited to the dry periods since compaction will increase surface runoff and consequently surface erosion. Soils are also unable to support the machines when they are saturated. In this study, the harvesting operation was conducted in early October. This harvesting time may affect sediment rate on the watershed. Summer harvesting may have caused less sedimentation.

Another issue with winter logging is the decrease in evapotranspiration due to loss of leaves in the dormant season. Because much of our post-harvest period was during the dormant season, it partially confounded our observed sediment and water yield data.

Before the harvest operation, there were increases in sediment load from downstream sections (Tw3 and Cw3) in comparison to forested middle sections (Tw2 and Cw2). We cannot be sure if these increases were caused by the clearcut or road because our placement of the monitoring stations does not allow us to separate the sediment of the road from that of the clearcut. The separation of the sediment of the road from that of clearcut may have given a better idea about the effectiveness of streamside management zone at trapping sediment from the clearcut.

It is also likely that sediment yields were affected by the ponds in the middle of sections Tw1 and Cw1. We cannot determine the actual sediment yield from the upstream sections (Tw1 and Cw1) because during all times except rain events, the pond acts as a settling basin. Also, during a rain event, we cannot know how much of the sediment generated from these sections is from that particular event or how much is stored sediment from previous erosion.

### 5.3. Suggestions for future work

Silvicultural activities generally have only a short-term effect on water quality in comparison to other land uses. Study streams should continue to be monitored to determine the longevity of this effect. Determination of whether an uneven-aged SMZ will be more effective than the existing mature even-aged riparian zone can also only be determined following conversion in the future.

For the harvesting and logging operations, the timing should be chosen to assure the soil protection. Sediment yield from the road and the clearcut should be also separated out for better understanding of SMZs.

# References


Alabama Forestry Commission, 1999.Alabama's Best Management Practices for Forestry Publication. Available at: http://www.forestry.alabama.gov/Publications/BMPs/2007_BMP_Manual.pdf

Amatya, D., Harrison, C., Trattin, C. 2007. Water quality of two order watersheds in Coastal South Carolina. Watershed Management to meet water quality standards and TMDLS proceedings of the fourth conferences.

Anonymous. 2009. Management planning for the Mary Olive Thomas Demonstration Forest 2010-2015. School of Forestry and Wildlife Sciences. Alabama Cooperative Extension System. Auburn University, AL. 35p.

Appelboom, T. W., G. M. Chescheir, R. W. Skaggs, and D. L. Hesterberg. 2002. Management practices for sediment reduction from forest roads in the coastal plains. Transactions of the ASAE Vol. 45(2): 337–344. Available at: http://asae.frymulti.com/azdez.asp?JID=3&AID=8529&CID=t2002&v=45&i=2&T=2

Arthur, M. A., Coltharp, G. B., Brown, D. L. 1998. Effects of best management practices on forest streamwater quality in eastern Kentucky. Journal of the American water resources association. Vol 34, no.3

Baker, D.B., P. Richards, T.L. Loftus, and J.W. Kramer. 2004. A New Flashiness Index: Characteristics and Applications to Midwestern Rivers and Streams. Journal of the American Water Resources Association 40(2):503 – 522. http://web.epa.ohio.gov/dsw/nps/NPSMP/docs/JAWRA_03095_Baker.pdf

Beasley, R. S. 1979. Intensive site preparation and sediment losses on steep watersheds in the Gulf Coastal Plain. Soil Sci. Soc.Am. J. 43(2): 412-417.

Binkley, D., Brown, T. C. 1993. Forest practices as nonpoint source of pollution in North America. Water resources bulletin 29(8), 729-740. Available at http://warnercnr.colostate.edu/~dan/papers/WaterResourcesBulletin_29_5_1993.pdf

Binkley, D., H. L. Allen, and H. Burnham 1999. Water quality effects of forest fertilization. NCASI Technical Bulletin No. 782. National Council of the Paper Industry for Air and Stream Improvement, Inc.: Research Triangle Park, NC, USA: 53.

Blinn C.R. and M.A. Kilgore. 2001. Riparian management practices, a summary of state guidelines. Journal of Forestry, August 2001.

Borah, D.K., G. Yagow, A. Saleh, P.L. Barnes, W. Rosenthal, E.C. Krug, and L.M. Hauck. 2006. Sediment and nutrient modeling for TMDL development and implementation. Transactions of the ASABE. 49(4) 967-986.

Brannan, K.M., S. Mostaghimi, P.W. McClellan, and S. Inamdar. 2000. Animal waste BMP impacts on sediment and nutrient losses in runoff from the Owl Run watershed. Transactions of the ASAE. 43(5):1155-1166.

Brooks, N. B., Ffolliott, P. F., Gregerson, H. M., DeBano, L. F. 2003. Hydrology and the management of watersheds. Third edition. Iowa State Press. ISBN-13: 978-0-8138-2985-2

Callender, E., and K. C. Rice. 2000. The urban environmental gradient: anthropogenic influences on the spatial and temporal distributions of lead and zinc in sediments. Environmental Science & Technology 34:232-238.

Carignan, R., D'Arcy, P., Lamontagne, S. 2000. Comparative impact of fire and forest harvesting on water quality in Boreal Shield lakes.Can. J. Fish. Aquat. Sci. 57 (Suppl.2):105-117

Catts, G. P., Chescheir, G. M. 2006. Water quality from undisturbed, forested, inter-stream wetlands: An empirical approach for land management. ASABE Publication Number 701P0406.

Chang, M. 2006. Forest Hydrology: An introduction to water and forests (second edition). Published by CRC Press Taylor and Francis Group: Boca Raton, FL. ISBN:0-8493-5332-7

Colson, C. G. 2008. Biogeochemical effects of silvicultural management on intermittent streamside management zones in the Coastal plain of Alabama. Auburn University. Master thesis, 2008

Cooper, J.R., Gilliam J. W., Daniels, R. B., Robarge, W. P., 1987. Riparian areas as filters for agricultural sediment. Soil science society of America journal 51: 416-420.

Daniels, R. B., Gilliam, J. W. 1996. Sediment and chemical load reduction by grass and riparian filters. Soil science of America journal 60: 246-251.

Davies-Colley, R. J., Smith, D. G. 2001. Turbidity, suspended sediment and water clarity. American water resource assoc. 37(5): 1085-1101.

Douglass, James E., 1980. Silviculture for Water Yield. In: Town Meeting Forestry - Issues for the 1980's. Proceedings of the 1979 Convention of the Society of American Foresters, pp. 90-96.

Dubois, M. R., Chappelka, A. H., Robbins, E., Somers, G., Baker, K. 2000. Tree shelters and weed control: Effects on protection, survival and growth of sherrbark oak seedlings planted on a cutover site. New Forests 20: 105–118

Elliot, W. J., D. E. Hall, and D. L. Scheele. 2000. Disturbed WEPP (Draft 02/2000) WEPP interface for disturbed forest and range runoff, erosion and sediment delivery, Available at http://forest.moscowfsl.wsu.edu/fswepp/docs/distweppdoc.html. (11/2005)

Ensign, S. H., Mallin, M. A., 2001. Stream water quality changes following timber harvest in a coastal plain swamp forest. Wat. Res. Vol. 35. No. 14. Pp. 3381-3390

EPA. 2008. Introduction to the Clean Water Act. Available at http://www.epa.gov/watertrain/cwa/

Fongers, D., Manning, K., Rathbun, J. 2007. Application of the Richard-Baker flashiness index to Gaged Michigan rivers and streams. Available at: http://www.michigan.gov/documents/deq/lwm-hsu-rb-flashiness_204776_7.pdf

Fulton, S., West, B. 2001. Aqua-3: Forestry impacts on water quality. Southern forest resource assessment draft report. Available at: www.srs.fs.fed.us.sustain

Grace, J.M. III. 2002. Effectiveness of vegetation in erosion control from forest road sideslopes. Trans. ASAE 45(3): 681-685. 2002 American Society of Agricultural Engineers ISSN 0001–2351

Grace III, J. M. 2005. Forest operations and water quality in the south. American society of agriculture engineers ISSN 000-235.

Grace III, J. M., Skaggs, R. W., Chescheir, G. M. 2006. Hydrologic and water quality effects of thinning loblolly pine. Transaction of the ASAE. American society of agricultural and biological engineers ISSN 0001-2351

Hewlett, J. D. 1969. Principles of forest hydrology. University of Georgia press. ISBN: 0-8203-0608-8

S. Muthukrishnan, K.J. Lim, J. Harbor, and B.A. Engel. 2005. iSep: A Simple GIS Enabled, Internet-based Hydrog raph Separation Tool. In Revision: for Computers & Geoscience. http://cobweb.ecn.purdue.edu/~kjlim/iSep/

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Williams, J. R. 2005. Soil and water assessment tool theoretical documentation. Available at: ftp://ftp.brc.tamus.edu/pub/swat/doc/swat2005/SWAT%202005%20theory%20final.pdf

Keppeler, E. T., Ziemer, R. R. 1990. Logging Effects on Streamflow: Water Yield and Summer Low Flows at Caspar Creek in Northwestern California. WATER RESOURCES RESEARCH, VOL. 26, NO. 7, PAGES 1669-1679, JULY 1990. Available at http://www.fs.fed.us/psw/publications/ziemer/Ziemer90a.PDF

Kirk, J. T. 1994. Light and photosynthesis in aquatic ecosystems. Second ed. Newyork, N. Y. : Cambridge University Press.

Klapproth, J. C., Johnson, J. E. 1999. Understanding the science behind riparian forest buffers: effects on water quality. Virginia Cooperative Extension. Publication 420-151.

Kreutzweiser, D., Capell, S., Good, K., Holmes, S. 2009. Sediment deposition in streams adjacent to uplant clearcuts and partially harvested riparian buffers in boreal forest catchments. Forest Ecol. Manage., doi:10.1016/j.foreco.2009.07.05

Lakel, W. A., Aust, W. M., Dolloff, C. A., 2006. Effects of forestry streamside management zone characteristics on soil erosion and water quality. ASABE publication number 701P0406

Loewenstein, E. F. 2005. Conversion of uniform broadleaved stands to an uneven-aged structure. Forest Ecology and Management. 215: 103.112

Loewenstein, E.F. 2009. Proportional-B: a simple but logical approach to marking single-tree selection. In: Proceedings of the SAF 2009 National Convention: Opportunities in a Forested World. Orlando, FL. September 30-October 4, 2009.

Marsh-McBirney, Inc. 1990. Flo-Mate Model 2000 Instruction and Operations Manual. Available at http://www.marsh-mcbirney.com/manuals/Model_2000_Manual.pdf

McBroom MW, Beasley RS, Chang M, Gowin B, Ice GG. 2007. Sediment losses associated with degree of watershed disturbance resulting from clearcut harvesting with best management practices. ASABE publication number 701P0207

McNutt, R. B., Tuck, M., Hoyum, R. A. 1981. Soil survey of Lee County, AL. United States Department of Agriculture and Soil Conservation Service. Available at: http://soildatamart.nrcs.usda.gov/Manuscripts/AL081/0/Lee.pdf

National Resource Inventory, USDA SCS. 1987. Soil erosion on non federal land in the United States. http://milford.nserl.purdue.edu/weppdocs/overview/ersn.html. Accesses on 29 October 2009.

NCASI. 2000. Handbook of control and mitigation measures for silvicultural operations. NCASI Draft Technical Bulletin. Research Triangle Park, N.C.: National Council for Air and Stream Improvement, Inc.

Norris, V. 1993. The use of buffer zones to protect water quality. Water resource mgt. 7(4), 257-272

Packer, P. E. 1967. Criteria for designing and locating logging roads to control sediment. Forest Science 13(1): 2-18.

Patric, J. H. 1978. Harvesting effects on soils and water in the eastern hardwood forest. Southern journal of applied forestry. 2(3): 66-73

Patric, J. H. 1980. Effects of wood products harvest on forest soil and water relations. Journal Environment Quality., vol.9, no.1.

Paul, M. J., and J. L. Meyer. 2001. Streams in the urban landscape. Annual Review of Ecology and Systematics 32:333-365.

Pimentel, D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri, and R. Blair. 1995. Environmental and Economic Costs of Soil Erosion and Conservation Benefits. Science. 267: 1117 – 1123.

Saleh, A., Williams, J. R., Wood, J. C., Hauck, L. M., Blackburn, W. H. 2004. Application of APEX for forestry: Transactions of the ASAE. American Society of Agricultural Engineers. Vol. 47(3): 751−765. Available at http://www.brc.tamus.edu/media/12987/apexfo.pdf

Santhi, C., R. Srinivasan, J.G. Arnold, and J.R. Williams. 2006. A modeling approach to evaluate the impacts of water quality management plans implemented in a watershed in Texas. Environmental Modeling & Software. 21:1141-1157.

Scherer, R. and R. Pike. 2003. Effects of forest management activities on streamflow in the Okanagan Basin, British Columbia: Outcomes of a literature review and a workshop. FORREX, Kamloops, B.C. FORREX Series 9.

Shukla, S. and S. Mostaghimi. 2002. Field and watershed scale N modeling to analyze lag time and BMP effects in a Mid-Atlantic Coastal Plain watershed. ASAE Paper No. 701P0102. St. Joseph, Mich.: ASAE.

Levelogger Gold Transducer User Guide. Solinst Canada Ltd. Available at: http://www.solinst.com/Downloads/LeveloggerGold-V3.pdf

Swank, W. T., Vose J. M., Elliott K. J. 2001. Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment

Swank, W. T., DeBano, L. F., Nelson, D. 1989. Effects of Timber Management Practices on Soil and Water. Available at http://coweeta.uga.edu/publications/424.pdf

Thornton, K.W., Holbrook, S. P., Stolte, K. L., Landy, R. B. 2000. Effects of forest management practices on mid-Atlantic streams. Environmental Monitoring and Assesment 63: 31-41

USEPA. 1995. National water quality inventory: 1994 report to congress. U.S. environmental protection agency office of water. E.P.A. Publication 841-R-95-005. Washington D.C. 497 pages

Ursic, S. J., Douglass J. E. 1978. The effects of forestry practices on water resources. The W. Kelly Mosley Environmental Forum, Proc. (Auburn University, May 1978), p. 33-49. Auburn University Press, Auburn, AL.

USDA Soil Conservation Service. 1981. Soil survey of Lee County, Alabama. USDA Soil Conservation Service. 100 pp.

USEPA. 2003. U.S. Environmental protection agency. Water Science. Available at http://www.epa.gov/waterscience/

Loadest Manual. USGS Load Estimator (Loadest) Program. 2004. Available at http://pubs.usgs.gov/tm/2005/tm4A5/pdf/508final.pdf

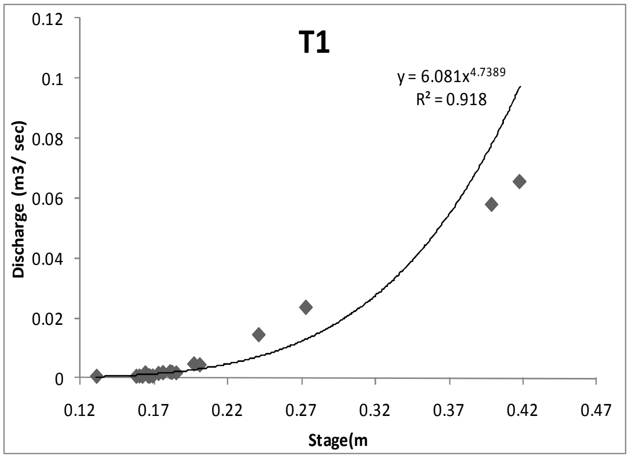
Walling, D. E., Gregory, K. J. 1970. The measurement of the effects of building construction on drainage basin dynamics. Journal of Hydrology. Volume 11, Issue 2, August 1970. Pages 129-144

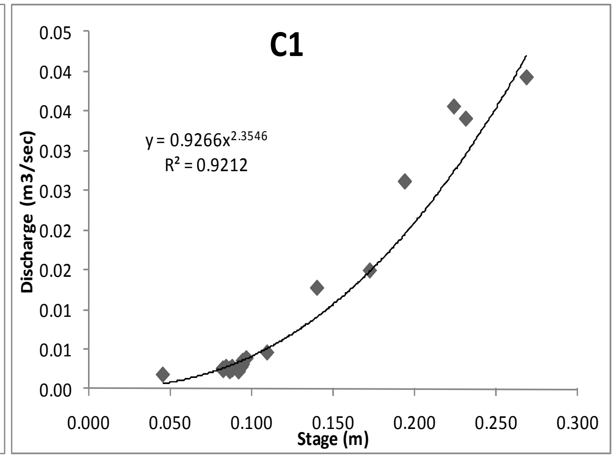
Wolman, M. G., Schick, A. P. 1967. Effects of Construction on Fluvial Sediment, Urban and Suburban Areas of Maryland. Water Resour. Res., 3(2), 451–464.

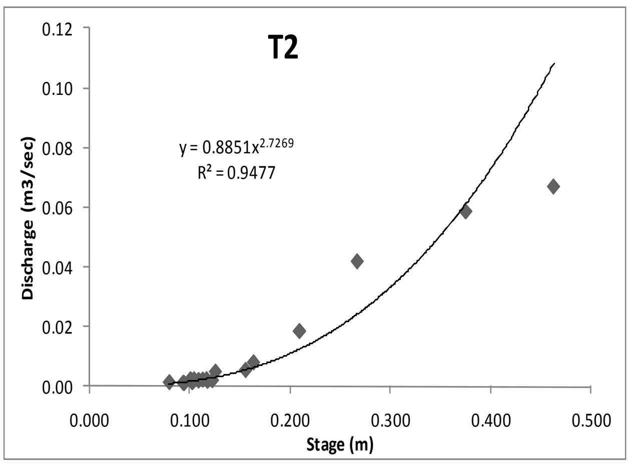
Wynn, T.M., Mostaghimi, S., Frazee, J. W., McClellan, P. W., Shaffer, R. M., Aust, W. M. 2000. Effects of Forest Harvesting Best Management Practices on Surface Water Quality in the Virginia Coastal Plain. Transaction of the ASAE. American society of agricultural engineers 0001-2351/00/4304-927

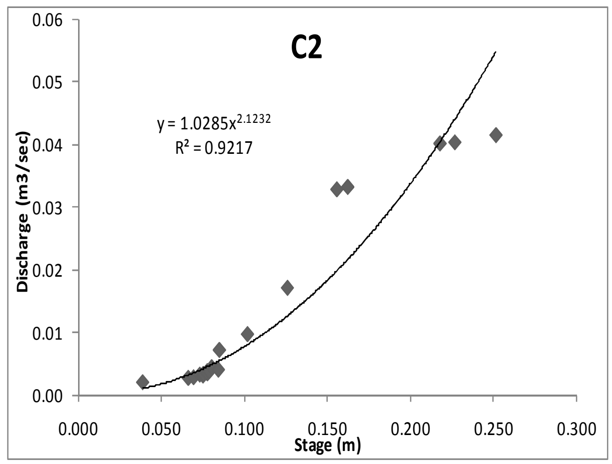
# Appendices

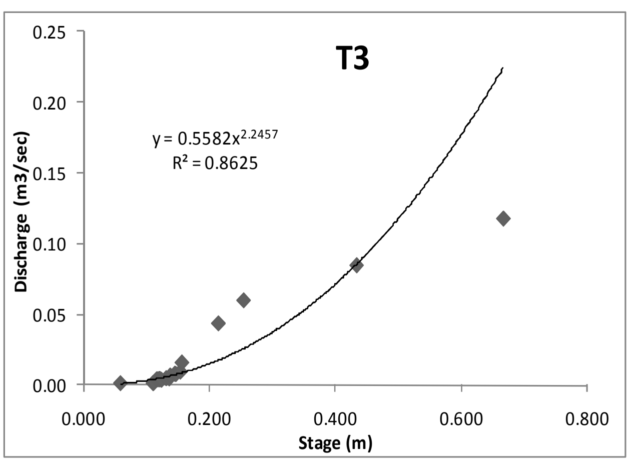
## Appendix A. Pre-Harvest Rating Curves between Water Stage and Discharges

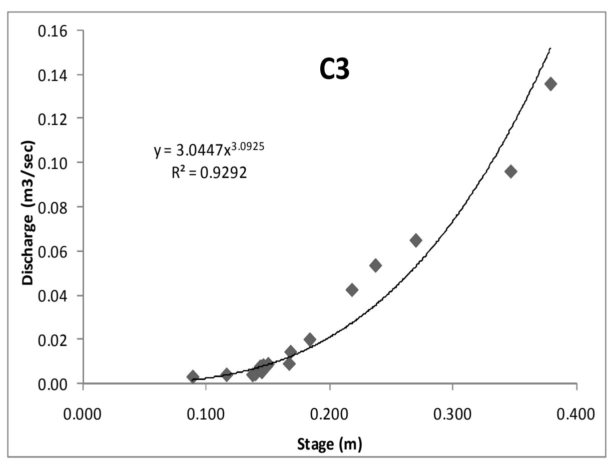


**Appendix B. Example Header File of Loadest**

```
############################################################################
#
#  LOADEST Header File
#
#  Mary Olive Thomas
#
############################################################################
Site9
1          |    PRTOPT (col.1-5)
1          |    SEOPT (col.1-5)
2          |    LDOPT (col. 1-5)
################################################################
#
# model number, MODNO (col.1-5)
#
################################################################
0
################################################################
#
# number of constituents, NCONST (col.1-5)
#
################################################################
1
################################################################
#
#  Unit flags and constituent names, for I=1,NCONST
#
#                                Unit Flags
#CNAME                                Conc Load
#                                |    |
################################################################
sediment                              1    1
```

**Appendix C. Example Control File of Loadest**

```
##########################################################################
#
#    LOADEST control file
#
#
#    line              name of the:
#    ----              --------------
#     1                header file
#     2                calibration file
#     3                estimation file
#
##########################################################################
header.inp
calib.inp
est.inp
```

**Appendix D. Example Calibration File of Loadest**

| Date | Time | Flow (cfs) | Load (mg/liter) |
|---|---|---|---|
| 20090405 | 1410 | 0.02355177 | 6.11 |
| 20090411 | 1633 | 0.1585419 | 13.64 |
| 20090413 | 1814 | 0.5127012 | 86.21 |
| 20090503 | 1709 | 0.02743587 | 8.47 |
| 20090505 | 1227 | 0.024717 | 7.11 |
| 20090506 | 1605 | 0.0278949 | 8.12 |
| 20090513 | 1019 | 0.063558 | 9.05 |
| 20090516 | 1700 | 0.02775366 | 6.96 |
| 20090517 | 1425 | 0.0695607 | 10.67 |
| 20090522 | 1711 | 0.02514072 | 6.64 |
| 20090523 | 1441 | 0.02923668 | 7.53 |
| 20090525 | 1642 | 0.16849932 | 12.41 |
| 20090526 | 1054 | 2.0391525 | 128.14 |
| 20090603 | 1023 | 0.061799562 | 9.76 |
| 20090604 | 1245 | 2.30983896 | 135.23 |
| 20090604 | 1645 | 0.83444592 | 83.62 |
| 20090613 | 1304 | 0.05808495 | 9.54 |
| 20090614 | 1357 | 0.06878388 | 10.33 |
| 20090706 | 1557 | 0.027675978 | 8.16 |
| 20090728 | 1621 | 0.076181325 | 11.84 |

**Appendix E. Example Estimation File of Loadest**

| Date | Time | Flow (cfs) |
|---|---|---|
| 20090404 | 0000 | 0.034781301 |
| 20090404 | 0100 | 0.035199138 |
| 20090404 | 0200 | 0.035620925 |
| 20090404 | 0300 | 0.035409536 |
| 20090404 | 0400 | 0.035726992 |
| 20090404 | 0500 | 0.035409536 |
| 20090404 | 0600 | 0.035409536 |
| 20090404 | 0700 | 0.036910262 |
| 20090404 | 0800 | 0.036801432 |
| 20090404 | 0900 | 0.038460727 |
| 20090404 | 1000 | 0.039714622 |
| 20090404 | 1100 | 0.037019346 |
| 20090404 | 1200 | 0.039140734 |
| 20090404 | 1300 | 0.039946027 |
| 20090404 | 1400 | 0.039830192 |
| 20090404 | 1500 | 0.040295128 |
| 20090404 | 1600 | 0.042684456 |
| 20090404 | 1700 | 0.040882308 |
| 20090404 | 1800 | 0.042197875 |
| 20090404 | 1900 | 0.042319108 |
| 20090404 | 2000 | 0.043175453 |
| 20090404 | 2100 | 0.044296496 |

**Appendix F. Example echo.out file of Loadest**

```
                    A Program to Estimate Constituent Loads
              U.S. Geological Survey, Version: MOD36 (Sep 2004)
                    ------------------------------------------------
Site9
-------------------------------------------------------------------
  Echo Output File Part I: Reading from the Header File, header.inp
-------------------------------------------------------------------
Estimated Values Print Option (PRTOPT):    1
Standard Error Option (SEOPT)          :    1
Load Option (LDOPT)                    :    2

Model Number 0 was selected. Regression model is selected based on
Akaike Information Criteria.

Number of Constituents (NCONST):    1
                                         Conc.         Load
Constituent                          Units (Flag)   Units (Flag)
-----------------------------------------------------------------------
sediment                             mg/L (1)       kg/d (1)
-------------------------------------------------------------------
                 Echo Output File Part II:
           Reading from the Calibration File, calib.inp
-------------------------------------------------------------------
Data Variables:
Date      Time   Streamflow
---------------------------------------------------
20090405  1410   2.3552E-02
20090411  1633   1.5854E-01
20090413  1814   5.1270E-01
20090503  1709   2.7436E-02
20090505  1227   2.4717E-02
20090506  1605   2.7895E-02
20090513  1019   6.3558E-02
20090516  1700   2.7754E-02
20090517  1425   6.9561E-02
20090522  1711   2.5141E-02
20090523  1441   2.9237E-02
20090525  1642   1.6850E-01
20090526  1054   2.0392E+00
20090603  1023   6.1800E-02
20090604  1245   2.3098E+00
20090604  1645   8.3445E-01
20090613  1304   5.8085E-02
20090614  1357   6.8784E-02
```

```
20090706  1557    2.7676E-02
20090728  1621    7.6181E-02

Constituent: sediment
                           Detection
Date      Time    Concentr.     Limit
-----------------------------------------------
20090405  1410    6.1100E+00    1.0000E-25
20090411  1633    1.3640E+01    1.0000E-25
20090413  1814    8.6210E+01    1.0000E-25
20090503  1709    8.4700E+00    1.0000E-25
20090505  1227    7.1100E+00    1.0000E-25
20090506  1605    8.1200E+00    1.0000E-25
20090513  1019    9.0500E+00    1.0000E-25
20090516  1700    6.9600E+00    1.0000E-25
20090517  1425    1.0670E+01    1.0000E-25
20090522  1711    6.6400E+00    1.0000E-25
20090523  1441    7.5300E+00    1.0000E-25
20090525  1642    1.2410E+01    1.0000E-25
20090526  1054    1.2814E+02    1.0000E-25
20090603  1023    9.7600E+00    1.0000E-25
20090604  1245    1.3523E+02    1.0000E-25
20090604  1645    8.3620E+01    1.0000E-25
20090613  1304    9.5400E+00    1.0000E-25
20090614  1357    1.0330E+01    1.0000E-25

* = Censored Observation
^ = Missing Observation
# = uncensored observation is less than the detection limit that
   was initially assigned (assigned detection limit makes it look
   as if the observation is censored, when in fact it is not).
   Assigned detection limit reset to 1.E-25.
---------------------------------------------------------------------
      Echo Output File Part III: Constituent Output Files
---------------------------------------------------------------------
Constituent                   File Name
-----------------------------------------------------------
sediment                      sediment.out
---------------------------------------------------------------------
                 Echo Output File Part IV:
         Reading from the Estimation File, est.inp
---------------------------------------------------------------------
No. of Observations of the Data Variables per Day (NOBSPD):    1
(The remaining lines in the Estimation File are not echoed unless
an error occurs)
```

## Appendix G. Example sediment.out file of Loadest

Individual Load Estimates

Loads Estimated by:

| Date | Time | Flow | AMLE | MLE | LAD |
|---|---|---|---|---|---|
| 20090404 | 0 | 4.870E-02 | 1.1225E+00 | 1.1225E+00 | 1.1476E+00 |
| 20090405 | 0 | 1.687E-02 | 2.5067E-01 | 2.5067E-01 | 2.8846E-01 |
| 20090406 | 0 | 1.483E-02 | 2.1078E-01 | 2.1078E-01 | 2.4708E-01 |
| 20090407 | 0 | 4.537E-02 | 1.0110E+00 | 1.0110E+00 | 1.0402E+00 |
| 20090408 | 0 | 6.935E-02 | 1.9109E+00 | 1.9109E+00 | 1.8981E+00 |
| 20090409 | 0 | 7.724E-02 | 2.2553E+00 | 2.2553E+00 | 2.2225E+00 |
| 20090410 | 0 | 2.356E-01 | 1.3785E+01 | 1.3785E+01 | 1.2771E+01 |
| 20090411 | 0 | 2.375E-01 | 1.3982E+01 | 1.3982E+01 | 1.2948E+01 |
| 20090412 | 0 | 1.025E-01 | 3.5109E+00 | 3.5110E+00 | 3.3945E+00 |
| 20090413 | 0 | 5.271E-01 | 5.6919E+01 | 5.6919E+01 | 5.1534E+01 |
| 20090414 | 0 | 1.509E-01 | 6.5503E+00 | 6.5503E+00 | 6.1936E+00 |
| 20090415 | 0 | 1.267E-01 | 4.9271E+00 | 4.9272E+00 | 4.7035E+00 |
| 20090416 | 0 | 8.468E-02 | 2.6009E+00 | 2.6009E+00 | 2.5465E+00 |
| 20090417 | 0 | 6.802E-02 | 1.8552E+00 | 1.8552E+00 | 1.8455E+00 |
| 20090418 | 0 | 7.096E-02 | 1.9795E+00 | 1.9795E+00 | 1.9628E+00 |
| 20090419 | 0 | 1.011E-01 | 3.4361E+00 | 3.4362E+00 | 3.3251E+00 |
| 20090420 | 0 | 7.404E-02 | 2.1128E+00 | 2.1128E+00 | 2.0885E+00 |
| 20090421 | 0 | 6.155E-02 | 1.5938E+00 | 1.5938E+00 | 1.5979E+00 |
| 20090422 | 0 | 5.815E-02 | 1.4627E+00 | 1.4627E+00 | 1.4731E+00 |
| 20090423 | 0 | 5.796E-02 | 1.4557E+00 | 1.4558E+00 | 1.4665E+00 |
| 20090424 | 0 | 4.806E-02 | 1.1007E+00 | 1.1007E+00 | 1.1266E+00 |
| 20090425 | 0 | 4.386E-02 | 9.6176E-01 | 9.6177E-01 | 9.9258E-01 |
| 20090426 | 0 | 4.458E-02 | 9.8522E-01 | 9.8523E-01 | 1.0153E+00 |
| 20090427 | 0 | 4.340E-02 | 9.4716E-01 | 9.4716E-01 | 9.7845E-01 |
| 20090428 | 0 | 4.636E-02 | 1.0435E+00 | 1.0435E+00 | 1.0715E+00 |
| 20090429 | 0 | 4.802E-02 | 1.0994E+00 | 1.0995E+00 | 1.1254E+00 |
| 20090430 | 0 | 4.876E-02 | 1.1245E+00 | 1.1245E+00 | 1.1495E+00 |
| 20090501 | 0 | 4.869E-02 | 1.1222E+00 | 1.1222E+00 | 1.1473E+00 |
| 20090502 | 0 | 4.940E-02 | 1.1463E+00 | 1.1463E+00 | 1.1705E+00 |
| 20090503 | 0 | 4.954E-02 | 1.1511E+00 | 1.1511E+00 | 1.1751E+00 |
| 20090504 | 0 | 4.504E-02 | 1.0000E+00 | 1.0000E+00 | 1.0296E+00 |
| 20090505 | 0 | 4.666E-02 | 1.0536E+00 | 1.0536E+00 | 1.0812E+00 |
| 20090506 | 0 | 4.121E-02 | 8.7792E-01 | 8.7792E-01 | 9.1134E-01 |
| 20090507 | 0 | 4.491E-02 | 9.9594E-01 | 9.9595E-01 | 1.0256E+00 |
| 20090508 | 0 | 4.756E-02 | 1.0838E+00 | 1.0838E+00 | 1.1103E+00 |
| 20090509 | 0 | 7.617E-02 | 2.2070E+00 | 2.2071E+00 | 2.1772E+00 |
| 20090510 | 0 | 5.318E-02 | 1.2794E+00 | 1.2794E+00 | 1.2981E+00 |
| 20090511 | 0 | 4.031E-02 | 8.5016E-01 | 8.5017E-01 | 8.8437E-01 |
| 20090512 | 0 | 4.510E-02 | 1.0022E+00 | 1.0022E+00 | 1.0316E+00 |

**Appendix H. Example Constituent Output File of Loadest**

```
                    A Program to Estimate Constituent Loads
                U.S. Geological Survey, Version: MOD36 (Sep 2004)
                    ----------------------------------------------
Site9
Constituent: sediment
------------------------------------------------------------------
   Constituent Output File Part Ia: Calibration (Load Regression)
------------------------------------------------------------------
Number of Observations          :    20
Number of Uncensored Observations:    20
"center" of Decimal Time        :   2009.404
"center" of Ln(Q)               :   -1.6054
Period of record                :    2009-2009
Model Evaluation Criteria Based on AMLE Results
--------------------------------------------
Model #     AIC          SPPC
--------------------------------
 1          0.325        -4.245
 2          0.155        -3.041
 3          0.415        -5.642
 4          0.516        -7.155
 5          0.253        -4.526
 6          0.315        -5.642
 7          0.627        -8.764
 8          0.428        -7.272
 9          0.338        -6.861
Model # 2 selected
Selected Model:
--------------
Ln(Load) = a0 + a1 LnQ + a2 LnQ^2
where:
    Load  = constituent load [kg/d]
    LnQ   = Ln(Q) - center of Ln(Q)
    Model Coefficients
     a0       a1       a2
    ----------------------------
AMLE   2.3294    1.6816    0.0703
MLE    2.3294    1.6816    0.0703
LAD    2.2077    1.6362    0.0857
AMLE Regression Statistics
------------------------
R-Squared [%]                : 99.16
Prob. Plot Corr. Coeff. (PPCC) : 0.9209
Serial Correlation of Residuals: -.0524
```

| Coeff. | Std.Dev. | t-ratio | P Value |
|---|---|---|---|
| a0 | 0.1030 | 22.61 | 1.132E-16 |
| a1 | 0.0376 | 44.67 | 1.499E-22 |
| a2 | 0.0301 | 2.33 | 1.851E-02 |

Correlation Between Explanatory Variables

---------------------------------------

Explanatory variable corresponding to:

| | a1 |
|---|---|
| a2 | 0.0000 |

Additional Regression Statistics

--------------------------------

| | Residual Variance | Turnbull-Weiss Stat | DF | PL |
|---|---|---|---|---|
| AMLE | 0.059 | 4.45 | 1 | 3.490E-02 |
| MLE | 0.059 | 4.45 | 1 | 3.490E-02 |

-------------------------------------------------------------------

Constituent Output File Part Ib: Calibration (Concentration Regression)

-------------------------------------------------------------------

AMLE Regression Statistics

--------------------------

Model # 2 was selected for the load regression (PART Ia) and is used here:
Ln(Conc) = a0 + a1 LnQ + a2 LnQ^2
where:
Conc = constituent concentration
LnQ = Ln(Q) - center of Ln(Q)

Concentration Regression Results

--------------------------------

R-Squared [%] : 95.15
Residual Variance : 0.0588

| Coeff. | Value | Std.Dev. | t-ratio | P Value |
|---|---|---|---|---|
| a0 | 3.0400 | 0.1030 | 29.51 | 5.882E-19 |
| a1 | 0.6816 | 0.0376 | 18.10 | 8.602E-15 |
| a2 | 0.0703 | 0.0301 | 2.33 | 1.851E-02 |

-------------------------------------------------------------------

Constituent Output File Part IIa: Estimation (test for extrapolation)
Load Estimates for 20090404-20091005

-------------------------------------------------------------------

Streamflow Summary Statistics [cfs]

-----------------------------------

| Data | Mean | Minimum | 10th Pct | 25th Pct | Median | 75th Pct | 90th Pct | Maximum |
|---|---|---|---|---|---|---|---|---|

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Cal. | 0. | 0. | 0. | 0. | 0. | 0. | 2. | 2. |
| Est. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 1. |

The maximum estimation data set steamflow does not exceed the maximum calibration data set streamflow. No extrapolation is required.

----------------------------------------------------------------------

Constituent Output File Part IIb: Estimation (Load Estimates)
Load Estimates for 20090404-20091005

----------------------------------------------------------------------

Load Estimates [KG/DAY]

------------------------

AMLE Load Estimates

-------------------

| | N | Mean Load | 95% Conf.Intervals Lower | Upper | Std Error Prediction | Standard Error |
|---|---|---|---|---|---|---|
| Est. Period | 185 | 2.12 | 1.81 | 2.48 | 0.17 | 0.14 |
| Apr. 2009 | 27 | 4.82 | 3.62 | 6.29 | 0.68 | 0.39 |
| May 2009 | 31 | 2.05 | 1.68 | 2.49 | 0.21 | 0.14 |
| June 2009 | 30 | 1.87 | 1.49 | 2.31 | 0.21 | 0.13 |
| July 2009 | 31 | 0.99 | 0.86 | 1.15 | 0.07 | 0.06 |
| Aug. 2009 | 31 | 1.77 | 1.51 | 2.06 | 0.14 | 0.12 |
| Sep. 2009 | 30 | 1.60 | 1.37 | 1.86 | 0.13 | 0.10 |
| Oct. 2009 | 5 | 1.86 | 1.43 | 2.37 | 0.24 | 0.13 |

Note: A linear approximation has been used to calculate the AMLE standard error (SEOPT equals 1). More accurate estimates of the standard error, standard error of prediction, and the confidence interval may be obtained with SEOPT equal to 3.

MLE Load Estimates

------------------

| | N | Mean Load |
|---|---|---|
| Est. Period | 185 | 2.12 |
| Apr. 2009 | 27 | 4.82 |
| May 2009 | 31 | 2.05 |
| June 2009 | 30 | 1.87 |
| July 2009 | 31 | 0.99 |
| Aug. 2009 | 31 | 1.77 |
| Sep. 2009 | 30 | 1.60 |
| Oct. 2009 | 5 | 1.86 |

LAD Load Estimates

| | N | Mean Load |
|---|---|---|
| Est. Period | 185 | 2.07 |
| Apr. 2009 | 27 | 4.52 |
| May 2009 | 31 | 2.01 |
| June 2009 | 30 | 1.83 |
| July 2009 | 31 | 1.02 |
| Aug. 2009 | 31 | 1.76 |
| Sep. 2009 | 30 | 1.60 |
| Oct. 2009 | 5 | 1.85 |

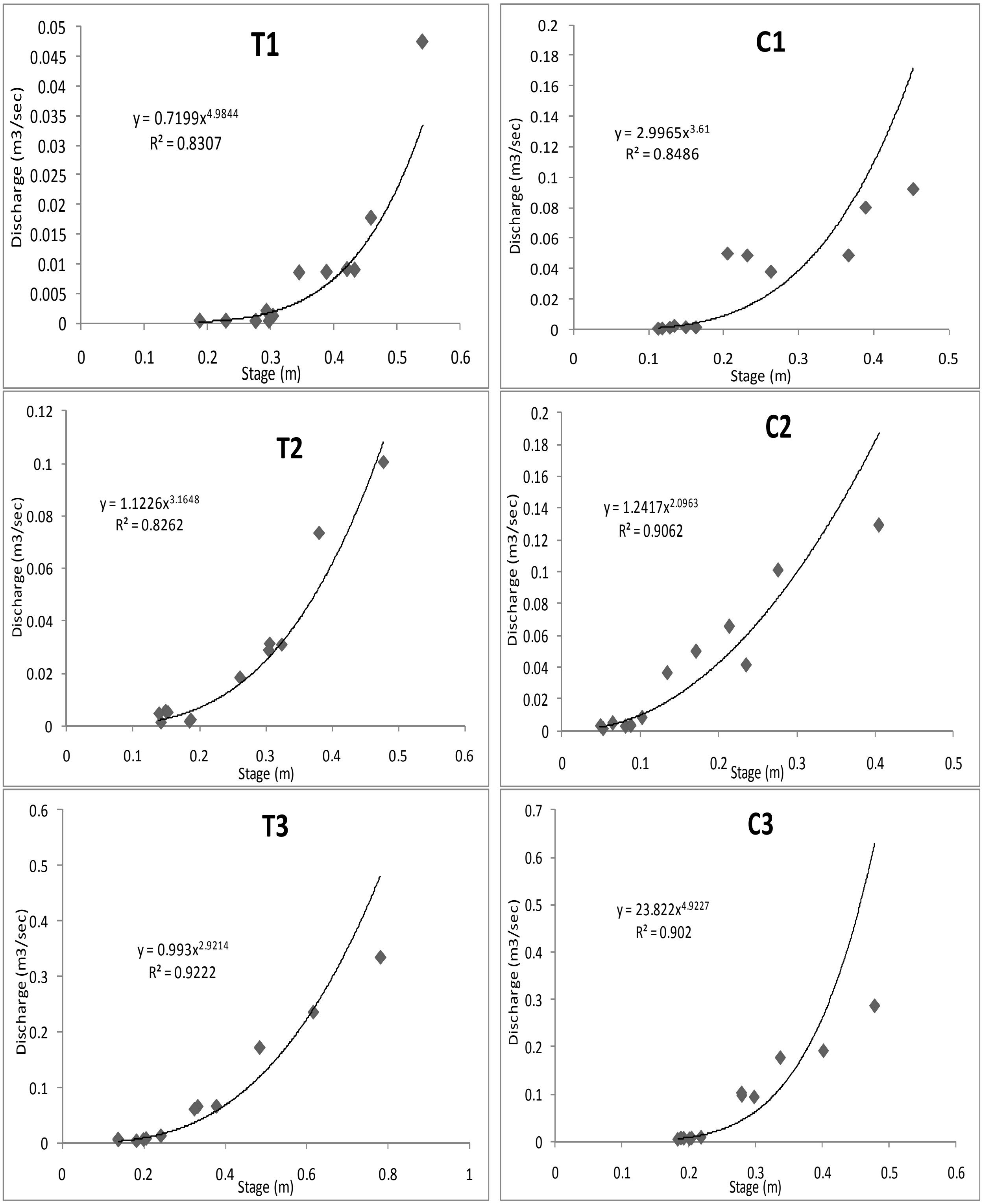
Summary Statistics - Estimated Loads [KG/DAY]

| | Min. | 25th Pct | Med. | 75th Pct | 90th Pct | 95th Pct | 99th Pct | Max. |
|---|---|---|---|---|---|---|---|---|
| AMLE | 0.21 | 1.00 | 1.41 | 1.84 | 2.23 | 4.50 | 23.39 | 56.92 |
| MLE | 0.21 | 1.00 | 1.41 | 1.84 | 2.23 | 4.50 | 23.39 | 56.92 |
| LAD | 0.25 | 1.03 | 1.42 | 1.83 | 2.20 | 4.31 | 21.42 | 51.53 |

Summary Statistics - Estimated Concentrations [MG/L]

| | Min. | 25th Pct | Med. | 75th Pct | 90th Pct | 95th Pct | 99th Pct | Max. |
|---|---|---|---|---|---|---|---|---|
| AMLE | 6. | 9. | 10. | 11. | 12. | 15. | 29. | 44. |
| MLE | 6. | 9. | 10. | 11. | 12. | 15. | 29. | 44. |
| LAD | 7. | 9. | 10. | 11. | 12. | 15. | 27. | 40. |

**Appendix I. Post-Harvest Rating Curves between Water Stage and Discharges**



## Appendix J. Inventory Results of the SMZ of the Treatment Watershed

Overstory basal area and percentage of basal area by diameter class on the treatment watershed

| | Within plots (0.9 ha) | | | Per hectare |
|---|---|---|---|---|
| Diameter Class | # of trees | Basal area ($m^2$/plots area) | % basal | Basal area ($m^2h^{-1}$) |
| 10-20 cm | 175 | 2.9682 | 18.15391 | 3.298003 |
| 20-30 cm | 70 | 3.4197 | 20.91534 | 3.799669 |
| 30-40 cm | 46 | 4.2646 | 26.08286 | 4.738447 |
| 40-50 cm | 26 | 4.1024 | 25.09082 | 4.558224 |
| 50-60 cm | 6 | 1.3107 | 8.016416 | 1.456334 |
| 60- + cm | 1 | 0.2846 | 1.740651 | 0.316222 |
| | 324 | 16.3502 | 100 | 18.1669 |

Understory basal area and percentage of basal area by diameter class on the treatment watershed

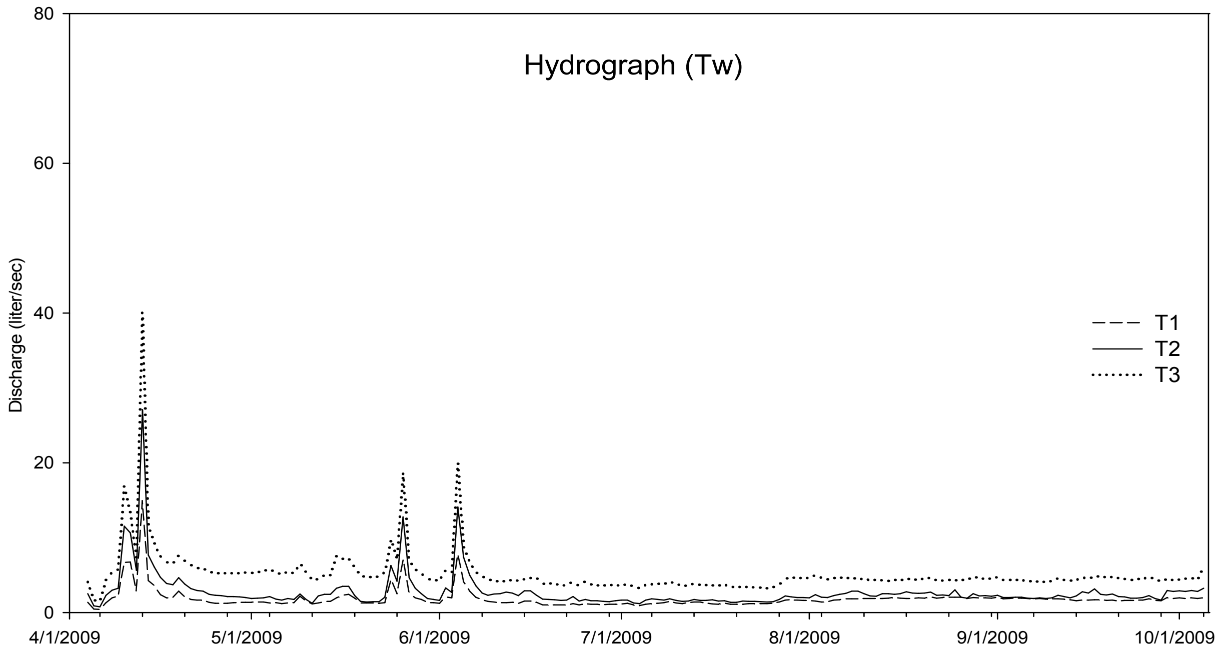
| Diameter class | # of trees | Basal area ($m^2$/plots area) | % basal | Basal area ($m^2h^{-1}$) |
|---|---|---|---|---|
| 0-10 cm | 88 | 0.182124 | 100 | 2.0233 |

Basal area of species by diameter classes on the treatment watershed ($m^2h^{-1}$)

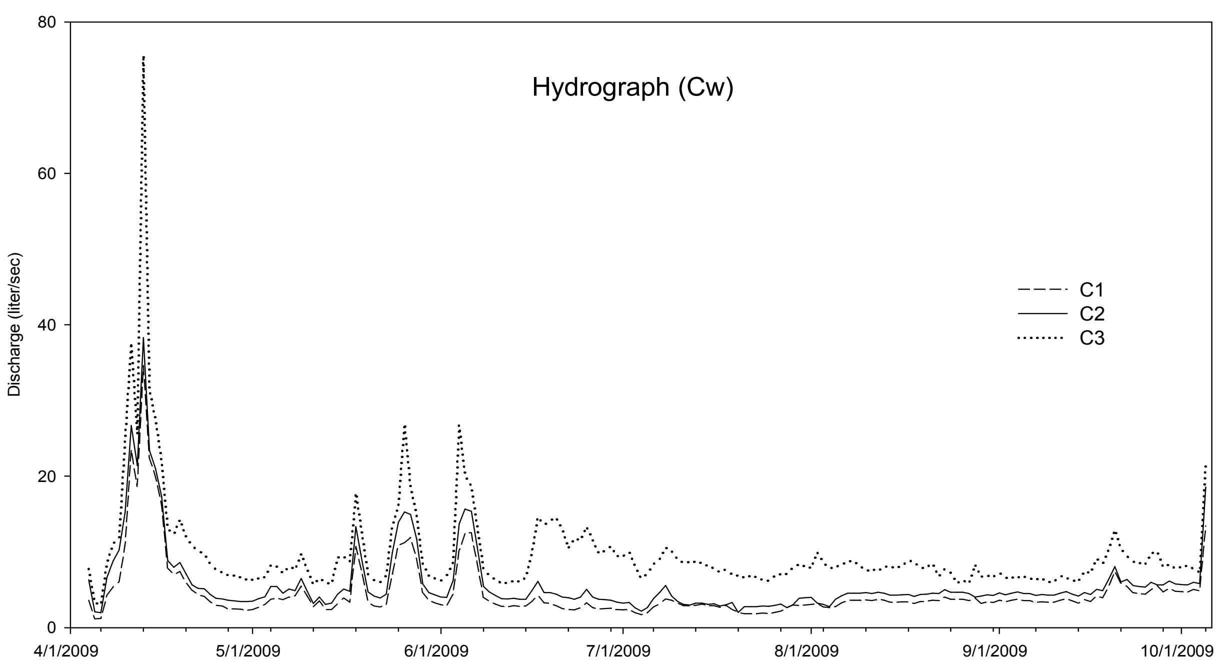
| Species | 10-20 cm | 20-30 cm | 30-40 cm | 40-50 cm | 50-60 cm | 60 cm-+ |
|---|---|---|---|---|---|---|
| Sweetgum | 1.312275 | 1.512268 | 1.816247 | 1.415329 | 0.243208 | 0.316222 |
| White aok | 0.62794 | 1.020211 | 1.465128 | 2.428166 | 0.767051 | 0 |
| Hickory | 0.308363 | 0.183904 | 0.399451 | 0 | 0 | 0 |
| Red maple | 0.193263 | 0.181244 | 0.294731 | 0 | 0.219906 | 0 |
| Tulip | 0.163911 | 0.202522 | 0.174849 | 0.369672 | 0.226023 | 0 |
| Wateroak | 0.11576 | 0.390606 | 0.310368 | 0.167287 | 0 | 0 |
| Beech | 0.19854 | 0.048636 | 0.159686 | 0 | 0 | 0 |
| Loblolly | 0.152368 | 0.176685 | 0 | 0 | 0 | 0 |
| other | 0.224924 | 0.083213 | 0.11704 | 0.176403 | 0 | 0 |

## Appendix K. Pre-Harvest Hydrographs

Pre-treatment (Calibration) hydrograph of the treatment watershed

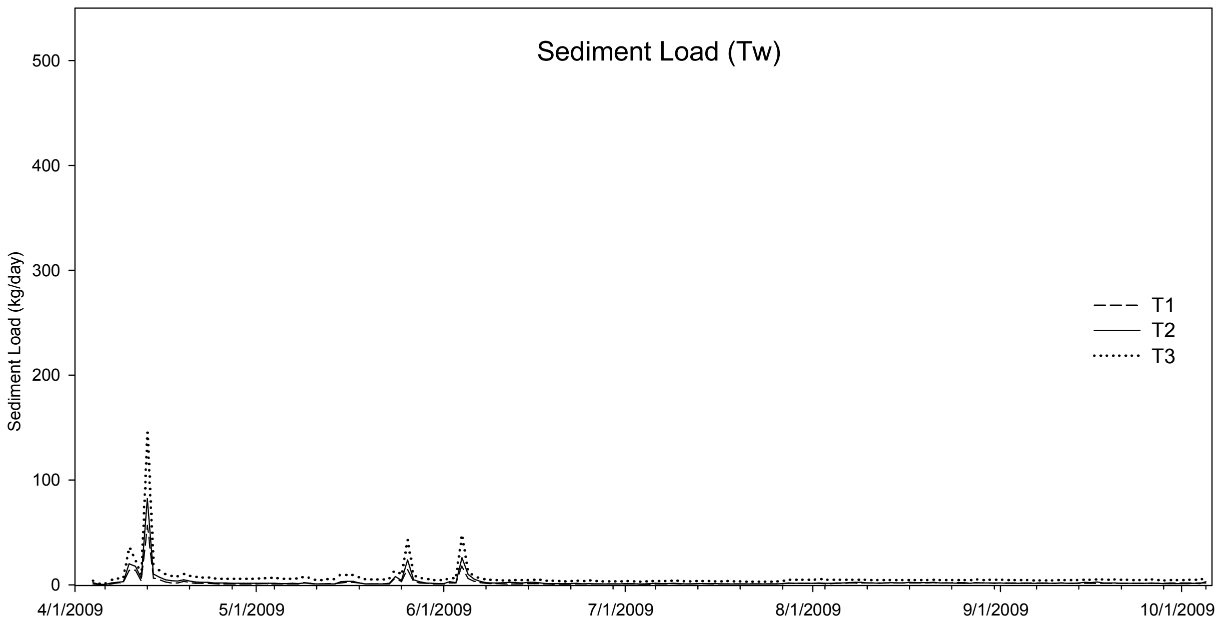



Pre-treatment (Calibration) hydrograph of the control watershed

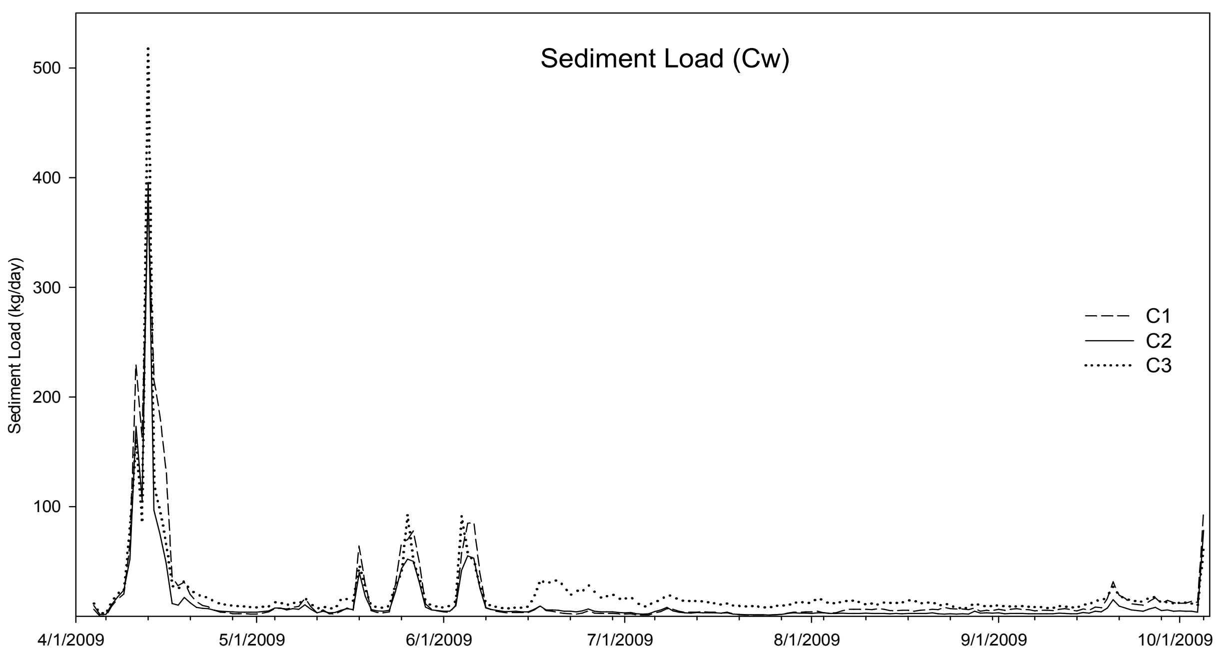


**Appendix L. Pre-Harvest Sediment Load Graphs**

Sediment yield on the treatment watershed for pre-harvest conditions




Sediment yield on the control watershed for pre-harvest conditions



## Appendix M. Calibration Models

**Nonlinear Regression (T1-C1)**

Equation: f = y0+a*x

| R | Rsqr | Adj Rsqr | Standard Error of Estimate |
|---|---|---|---|
| 0.7971 | 0.6353 | 0.6333 | 0.8271 |

| | Coefficient | Std. Error | t | P |
|---|---|---|---|---|
| y0 | 0.6091 | 0.0915 | 6.6562 | <0.0001 |
| a | 0.2668 | 0.0149 | 17.8547 | <0.0001 |

Analysis of Variance:

| | DF | SS | MS |
|---|---|---|---|
| Regression | 2 | 837.7121 | 418.8561 |
| Residual | 183 | 125.1810 | 0.6840 |
| Total | 185 | 962.8931 | 5.2048 |

Corrected for the mean of the observations:

| | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 1 | 218.0691 | 218.0691 | 318.7916 | <0.0001 |
| Residual | 183 | 125.1810 | 0.6840 | | |
| Total | 184 | 343.2500 | 1.8655 | | |

**Nonlinear Regression (T2-C2)**

Equation: f = y0+a*x

| R | Rsqr | Adj Rsqr | Standard Error of Estimate |
|---|---|---|---|
| 0.7890 | 0.6225 | 0.6204 | 1.5598 |

| | Coefficient | Std. Error | t | P |
|---|---|---|---|---|
| y0 | -0.3694 | 0.2086 | -1.7713 | 0.0782 |
| a | 0.4308 | 0.0248 | 17.3703 | <0.0001 |

Analysis of Variance:

| | DF | SS | MS |
|---|---|---|---|
| Regression | 2 | 2039.5965 | 1019.7983 |
| Residual | 183 | 445.2314 | 2.4330 |
| Total | 185 | 2484.8280 | 13.4315 |

Corrected for the mean of the observations:

| | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 1 | 734.0911 | 734.0911 | 301.7277 | <0.0001 |
| Residual | 183 | 445.2314 | 2.4330 | | |
| Total | 184 | 1179.3225 | 6.4094 | | |

**Nonlinear Regression (T3-C3)**

Equation: f = y0+a*x

| R | Rsqr | Adj Rsqr | Standard Error of Estimate |
|---|---|---|---|
| 0.8847 | 0.7826 | 0.7815 | 1.5930 |

| | Coefficient | Std. Error | t | P |
|---|---|---|---|---|
| y0 | 0.8869 | 0.2045 | 4.3375 | <0.0001 |
| a | 0.4366 | 0.0170 | 25.6695 | <0.0001 |

Analysis of Variance:

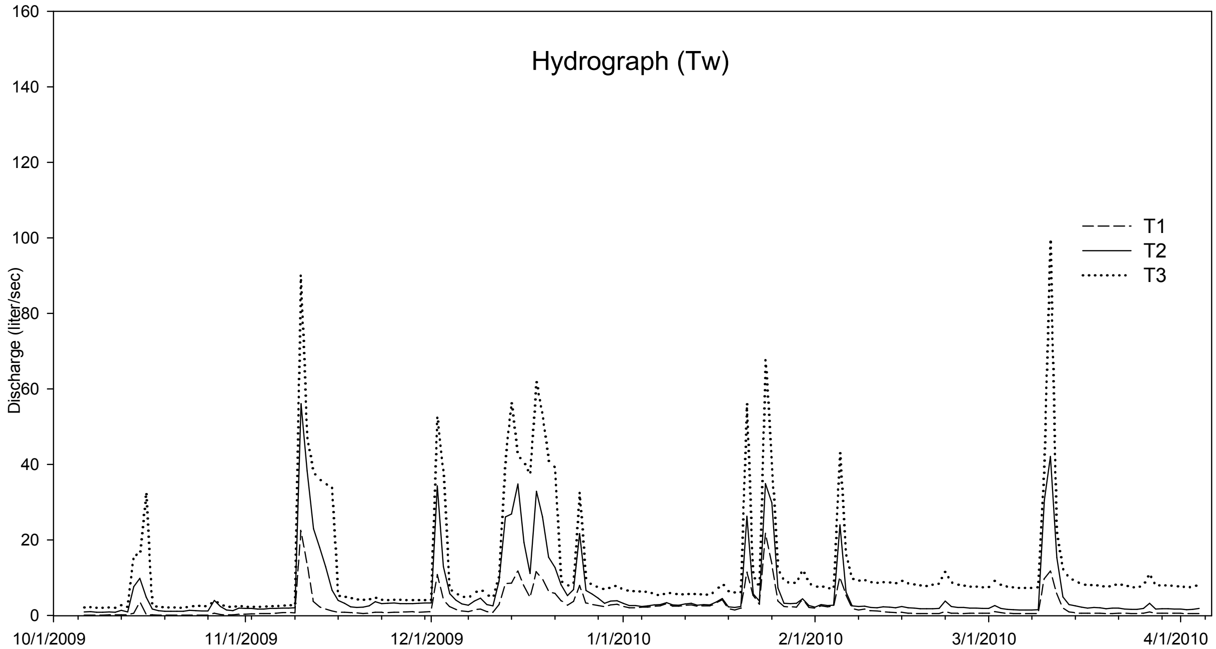
| | DF | SS | MS |
|---|---|---|---|
| Regression | 2 | 6654.8294 | 3327.4147 |
| Residual | 183 | 464.3989 | 2.5377 |
| Total | 185 | 7119.2283 | 38.4823 |

Corrected for the mean of the observations:

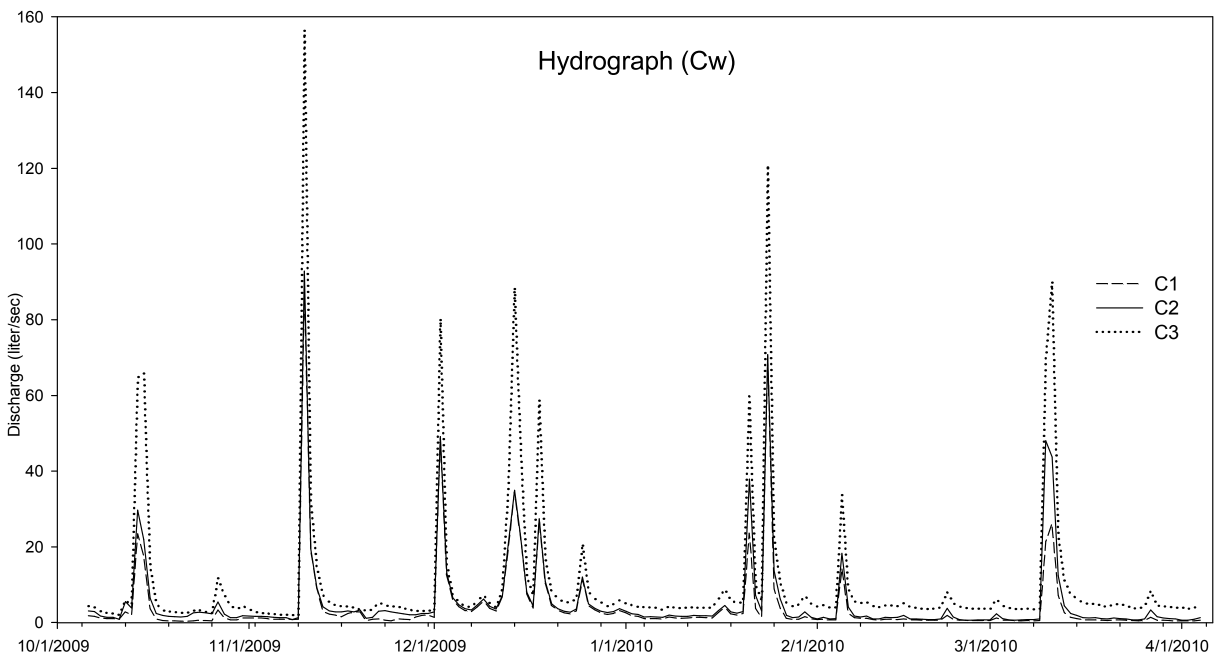
| | DF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 1 | 1672.1484 | 1672.1484 | 658.9231 | <0.0001 |
| Residual | 183 | 464.3989 | 2.5377 | | |
| Total | 184 | 2136.5473 | 11.6117 | | |

## Appendix N. Post-Harvest Hydrographs

Post-treatment hydrograph of the treatment watershed

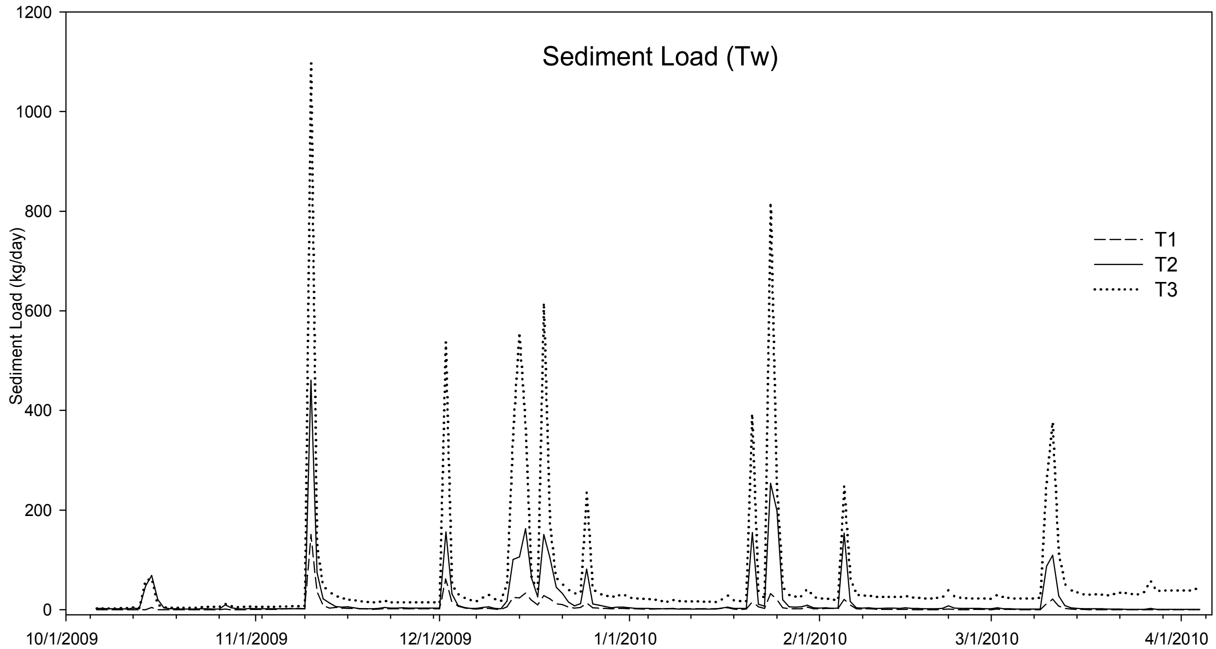



Post-treatment hydrograph of the control watershed



## Appendix O. Post-Harvest Sediment Load Graphs

Sediment yield on the treatment watershed for post-harvest conditions




Sediment yield on the control watershed for post-harvest conditions