PREHARVEST CALIBRATION OF THE LITTLE CREEK WATERSHED

A PAIRED AND NESTED WATERSHED ANALYSIS

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By

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TITLE: Preharvest Calibration of the Little Creek Watershed – A Paired and Nested Watershed Analysis

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ABSTRACT

Preharvest Calibration of the Little Creek Watershed – A Paired and Nested Watershed Analysis

Michael Gaedeke

The Little Creek watershed is an experimental watershed in the Santa Cruz Mountains of Central California. Stream monitoring stations are located to enable a paired and nested watershed analysis of a timber harvest scheduled for Summer 2007. Five years of water quality data that include flow, turbidity and suspended sediment have been collected and analyzed as part of a six-year calibration period. Individual storm events are analyzed to determine suspended sediment transport at each monitoring station. A dataset of event loads is built to enable a regression analysis of the existing conditions in the watershed. Theoretical increases at the treatment station are compared to existing conditions via regression analysis to determine the detectable magnitude of change in suspended sediment export. A smaller magnitude of change in suspended sediment export will be detectable using the nested design. Based on regression analysis, changes in storm event suspended sediment loads approximately 30% above background levels may be detected for the nested watershed design, while changes of approximately 90% may be needed to detect change in the paired watershed design. One additional year of data will be collected before the harvest and data will continue to be collected for at least four years after the harvest.

ACKNOWLEDGEMENTS

I thank my advisor, Brian Dietterick, for his guidance and encouragement in the thesis development process. The opportunity to work in the Little Creek watershed and collect information that can benefit future environments is a great gift and responsibility, and Brian has trusted me with this responsibility.

The credit for all that I do belongs to my wife, Jessica. Love and support (and an occasional push) have enabled me to continue my studies and always remember what is important in life.

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CHAPTER 1

Introduction

Water quality measurements and monitoring programs are used for a variety of applications. Metrics associated with water quality and water monitoring in urban areas often include various chemical or biological constituents. In forested lands, the most important pollutant is sediment (Douglass, 1975; EPA, 1980; Phillips, 1989). The source of sediments and the amounts that are naturally occurring compared to the amounts associated with management activities have been researched yet are still widely debated. In particular, establishing a level of sediment expected to be transported from a watershed based on prior research becomes very difficult in differing physiographic regions.

While management activities, such as timber harvesting, have become increasingly regulated, the common logic is that the extensive regulations are maintaining the level of sediment delivered to a stream system at a pre-harvest level. However, sediment data are often collected after a harvest has occurred and the pre-harvest levels of sediment transport are left to speculation. Or, data that are collected for short periods of time before and after a harvest are assumed to be representative of the longer term. Longer term studies often indicate a significant amount of annual variability in the sediment response of a stream system and point to the need for more extensive monitoring.

The analysis contained herein seeks to assist the broader goals of the Little Creek paired and nested watershed study by assessing the calibration phase. There is a significant amount of uncertainty regarding the ability to successfully calibrate a watershed study in the Santa Cruz Mountains. The climatic variability and physiographic dynamics of this tectonically active area result in a strong potential for highly variable background conditions. Given such potential variability, the duration of time needed to characterize the background conditions is uncertain. The present analysis encompasses the first five years of a six-year calibration.

Purpose and Need

The purpose of the Little Creek study is to evaluate the ability of the current California Forest Practice Rules to maintain water quality during and after timber harvests. These rules encompass both state and local regulations that dictate the practices and procedures for conducting a timber harvest. The evaluation for this study will be based on water quality samples that are collected during storm events and analyzed for turbidity and suspended sediment concentration (SSC). The samples are collected before and after the timber harvest and changes in the water quality parameters will be used as the basis for determining whether the timber harvest activities are causing adverse changes in water quality.

The ultimate results of the Little Creek study may contribute information to those mandating regulatory requirements for planning timber harvests. The current understanding that regulations are providing for the maintenance of pre-harvest water quality levels during and after the harvest may be tested by the Little Creek study. The study results may also be used to provide information to aid in setting appropriate reporting standards for timber companies operating in this region. Because the data collected thus far in the Little Creek study have been during pre-harvest conditions, sediment export quantities may be used to aid the understanding of typical pre-harvest levels in this region. Or, at least, for watersheds sharing similar topography, soils, and underlying geology.

Water quality data have been collected during winter 2001/2002, 2002/2003, 2003/2004, 2004/2005, and 2005/2006. One additional year of pre-harvest data will be collected during winter 2006/2007, with the harvest occurring in summer 2007. Data will continue to be collected after the harvest to detect change. However, the ability to detect change, and the magnitude of change detectable, is largely determined by the amount of variability found in the data collected prior to the harvest. In other words, a larger amount of variability means a larger magnitude of change must occur to be detected. The current purpose is to accomplish a calibration by building a statistical model that describes the variability of the relationship in sediment loads between stations.

CHAPTER 2

Literature Review

Studies documenting the impacts of timber harvesting have been performed in different physiographic regions in the U.S, and many of them have been sediment related. In California, the Caspar Creek watershed, a coastal mountain watershed located in northern California has undergone intensive studies of the impacts of timber harvesting practices (Ziemer, 1998, Keppeler et al., 1994, Wright et al., 1990, Ziemer, 1981). Though studies to date have produced many findings and relationships, many questions remain on the applicability of these finding to different geographic regions. In part, this can be attributed to the factors that control sediment production and export from a watershed such as geologic structure, soil properties, topography, land use, management strategies, vegetation, temporal and spatial distribution of rainfall, and streamflow generation mechanisms (Lopes and Ffolliott, 1992, 1993a). Further, it is very difficult to combine all these factors into a single formula that predicts a parameter such as sediment discharge from a watershed, or to isolate the single factors and determine the effects on sedimentation processes (Lopes and Pfolliott, 1992). Over a broad region, land management activities that cause turbidity increases in one watershed may not affect turbidity in another watershed (Campbell and Doeg, 1989; Macdonald et al., 1991). With such difficulties in consideration, methods have still emerged that use water quality data, such as suspended sediment concentration and turbidity, to quantify the effects of land management activities on sediment production. The outcome of studies, such as those at Caspar Creek, and a number of other watershed-scale studies, has been to provide scientific documentation that aids policy-making decisions as land management practices change.

Current forest practice rules are expected to provide greater protection to watersheds and the beneficial uses of water. Cumulative Watershed Effects (CWE) are specified in the 2006 California Forest Practice Rules to identify individual impacts that combine to produce a greater effect than the individual impacts acting alone. The intent of the article defining Watercourse and Lake Protection Zones within the 2006 California Forest Practice Rules is “to ensure that the beneficial uses of water, native aquatic and riparian species, and the beneficial functions of riparian zones are protected from potentially significant adverse site-specific and cumulative impacts associated with timber operations”. The watershed effects associated with timber harvesting or other activities may include; sediment, water temperature, organic debris, chemical contamination, and/or peak flow (CA FPR, 2006). Sediment, as well as the other watershed effects, has received considerable attention in the literature. In the Caspar Creek watershed, logging practices in the 1970’s resulted in a 212% increase in suspended sediment loads over predicted for a six-year period after logging. Also at Caspar Creek, an evaluation of harvesting practices under the California Forest Practice Rules in the 1990’s found no significant increase in annual suspended loads (Lewis, 1998). An extreme case of the effects of forest harvesting on sediment production was shown at the Alsea watershed in coastal Oregon. Sediment loads exiting a watershed increased more than 10-fold in the first year following a complete clear-cut and burning to mineral soil (Harris, 1977). An important factor in the Caspar Creek and Alsea studies is that even-aged (clearcutting) timber management techniques were applied.

Fish and other aquatic organisms are specified for protection under current forest practice rules (CA FPR, 2006). The protection is elevated when the fish species have been identified as threatened or endangered. The 2006 California Forest Practice Rules Cumulative Watershed Effects addendum targets increased sediment delivery, among others, due to the potentially negative effects of sediment on fish and other aquatic organisms. The gills of salmonids and macroinvertebrates may be damaged by high sediment concentrations (Bozek and Young, 1994, Newcombe and Macdonald, 1991), the ability for fish to locate food may be impaired by high turbidity (Gregory and Northcote, 1993), and fine sediments that settle and infiltrate into spawning gravels reduces the transport of oxygen to incubating eggs (Lisle, 1989). In addition, fish rearing habitat may be lost if the increased sediment fills pools or results in a wider or shallower channel (Lewis, 1998).

The importance of long-term monitoring to be able to assess and measure the response to change has been recommended (Reid, 1993, Ziemer, 1998). An important factor to long-term monitoring is the existence of a period of pre-treatment measurements (Lewis et al., 2001). Many studies have been conducted that do not use any pretreatment data (Plamondon, 1981; O'Loughlin et al., 1980; Leaf, 1970). A difficulty encountered in such studies is that unproven assumptions must be made about the relationship between control and treatment watersheds (Lewis et al., 2001). The Little Creek studies employ control and treatment watersheds as part of a paired watershed design. Paired watershed studies have been used successfully to evaluate and document impacts on water quality and quantity associated with various land use activities. Historically, many of the paired watershed studies have focused on impacts related to forest management activities (Hibbert, 1967; Reinhart, 1967; Harr, 1976; Troendle and King, 1985; Dietterick and Lynch, 1989; Ziemer, 1998).

Multiple studies have occurred in the Western United States using changes in peak flows as a measurement of forest management effects. These studies have occurred at the H.J. Andrews Experimental Forest (Rothacher, 1971, 1973) and Coyote Creek watershed (Harr, 1976) in the Oregon Cascades, the Fox Creek watershed in the Oregon Coast Range (Harr et al., 1975), and Caspar Creek in the Coast Range of Northern California (Ziemer, 1981; Wright et al., 1990). These studies did not detect significant changes in the largest floods after harvesting. However, smaller peak flows in the fall were found to increase on average. Moving beyond peak flows, the variability and increased costs of measuring sediment loads can make change even more difficult to detect than with peak flows (Lewis et al., 2001). Interpretation difficulties arise when a study is dominated by a single extreme event (Grant and Wolff, 1991; Rice et al., 1979, Olive and Reiger, 1991). Despite such difficulties, studies on suspended sediment changes due to forest management have been conducted in addition to the Caspar Creek study. Lopes et al. (2001) used sediment rating curves to evaluate harvesting effects in ponderosa pine and pinon-juniper dominated watersheds in Arizona. Higher levels of suspended sediment were found in watersheds where harvesting resulted in the greatest amount of soil disturbance and removal of understory vegetation. A paired watershed study at the H.J. Andrews Experimental Forest showed significantly higher suspended sediment after harvesting, though the study was confounded by a debris flow (Grant and Wolff, 1991). Deer Creek and Needle Branch in the Alsea watershed both showed significant increases (Harris, 1977). However, an important factor in the above studies is the implementation of clearcut harvesting and, in some cases, broadcast burning after the harvest.

Sediment may enter channel systems from a variety of sources. In the Pacific Northwest, mass movements such as slumps, earthflows, landslides and debris flows are the major sources of external sediment in steep, forested terrain. At any given time, slumps and earthflows may constitute 10-30% of the mountainous areas in the Pacific Northwest (Swanston et al., 1988). However, the actual delivery to streams varies based on the width and incision of the valley (Roberts and Church, 1986). Surface erosion processes such as sheet erosion, rain splash, dry ravel, freeze/thaw, and animal activities may provide chronic sources of sediment (Macdonald and Ritland, 1989). Once sediment has entered the stream channel system it may be stored or transported. In the Oregon Coast Range, first and second order channels may store 90 percent of the sediment delivered from hillsides, while the remaining 10% is flushed from the system as suspended sediment or bed load (Benda and Dunne, 1987). The particle size of the flushed particles largely determines whether it is considered suspended sediment or bed load. The clay and silt particles (≤0.05 mm) are typically transported in suspension while the gravel, cobble, and boulder particles (>2 mm) are transported as bed load. Sand-sized particles (0.05-2 mm) may be alternately transported in suspension or as a component of the bed load, depending on the local hydraulic and channel conditions (Beschta, 1978). The suspended portion of the sediment fraction is targeted for the Little Creek study due to the high mobility and potential for far-reaching negative effects on fish and other aquatic organisms.

There is a continuous cycle of sediment source depletion and new sediment source availability. The sediment sources are of particular concern when management practices are causing an elevated amount of available sediment for transport. Forest management practices can alter both fine and course sediment supply to channels. New pathways can be created by roads and drainage systems that can transport fine sediments (Wemple et al., 2001). Studies in the Northwest have placed sediment yield increases due to roads at a level <2 to 50 times background yields (Gomi et al., 2005). Effects from roads are due to both the cut and fill areas that may contribute significant amounts of fine sediments from rain splash, frost, dry ravel, and mass erosions. Megahan et al. (2001) demonstrated these effects are most severe within a year of construction. Other potential effects of management practices include rising water tables and increases in pore water pressure that cause slope failures. Failures may also occur due to lowered internal soil cohesion, which may not occur until 3 to 15 years after harvesting due to decaying roots (Zeimer, 1981; Sidle et al., 2000).

The dynamics of suspended sediment transport are apparent at varying time scales. On an event basis, suspended sediment transport is often dependent on placement in the hydrograph. There is often more sediment transported at a given flow rate on the rising limb of the hydrograph than the same flow rate on the falling limb. This phenomenon, commonly referred to as the hysterisis effect, occurs when the available sediment for transport is exhausted during the rising limb of the hydrograph. The available sediment may be exhausted when the finer materials are flushed from the channel bed substrate (Kurashige, 1996). This same phenomenon could be carried out further when a series of storms successively deplete the sediment supply so each storm transports less than the previous storm (Paustian and Beschta, 1979). Extended seasonally, a similar process of supply depletion is reflected in lowered SSC amounts when an event occurs after the annual peak discharge (Beschta, 1978). In contrast to these findings, a study on northern Vancouver Island showed that if flows exceeded a certain threshold value, then SSC would continue to increase, regardless of position on the hydrograph. However, smaller flows exhibited the sediment supply depletion effect on SSC. The theory in this situation was that sediment supply was significantly replenished during the summer and possibly during cold periods in the winter due to dry ravel and frost (Nistor and Church, 2005). Patterns of clockwise hysteresis have also been observed during spring snowmelt events. Macdonald et al. (2003) documented SSC six times greater on the rising limb than on the falling limb for snow runoff events in three catchments.

Rapidly changing suspended sediment concentrations at different points on the hydrograph would seem to necessitate frequent suspended sediment sampling. However, laboratory analysis of high-frequency suspended sediment sampling can become extremely time-consuming and expensive. A high-frequency sampling scheme for SSC typically becomes impractical, and as an option, a simpler surrogate variable is monitored (Gilvear and Petts, 1985; Hasholt, 1992; Jansson, 1992; Lawler et al., 1992). Turbidity can be used as a surrogate for suspended sediment concentration and can provide a method of obtaining closely spaced SSC values.

However, the SSC versus turbidity relationship is typically unique within a particular period of time (Gippel, 1989) and thus important to establish on an event-basis for accurate sediment estimation (Sun et al., 2001). Though the event-based SSC versus turbidity relationship is typically very efficient (Lewis, 1996), the relationship may still be variable at the event level. The variability in the SSC versus turbidity relationship arises from the temporal variations in the suspended solids (Gippel, 1995). During storm events, the particle size distribution may vary (Bogen, 1992; Pearl and Walling, 1992) as can the amount and types of organic material (Walling and Kane, 1982; Hadley et al., 1985). Such changes have a greater relative influence on turbidity or SSC and can thereby change the SSC versus turbidity relationship.

Researchers have employed several methods of estimating suspended sediment concentration using either turbidity or flow. Concentrations of suspended sediment at a given flow rate may vary by several orders of magnitude (Beschta, 1978). This variability is not necessarily due to physical laws based on hydraulic parameters, but rather the factors that affect the varying sediment supply (Sharma et al., 1984). While turbidity is the preferred method, flow interpolations and regressions have been employed. Storm loads in the Caspar Creek watersheds have been estimated by filling in concentrations between pump samples using interpolations that relate concentrations to time or stage (Lewis, 1998). Linear regressions of concentrations on turbidity were also used for prediction with results having better accuracy than the time or stage interpolations. The interpolations were still used during periods when turbidity data were not available (Lewis, 1996).

Sediment rating curves may be used that relate suspended sediment concentration to stream discharge. The relationship is established so annual loads can be quantified and used to estimate future sediment loads. The feasibility of using annual loads is difficult given the often limited sample size compared to the variability in response. Even when control and treatment watersheds are utilized, it is rare to find a study with more than 5 years of pretreatment measurements (Lewis et al., 2001). An option to using annual loads for analysis is the use of all hydrologically-significant storm events. Based on an 11-year record (1986-1996) at Caspar Creek, on average, seven hydrologically-significant storm events occurred each year (Lewis et al., 2001). The larger sample size provided by such events enables more robust statistical analysis that can include confidence limits. However, studies based on loads are rare and peak concentrations are difficult to capture in flashy watersheds without very short time interval samples (Lewis et al., 2001).

Given the potential benefits of a high-frequency dataset of suspended sediment, the Little Creek watershed has been instrumented to provide short time interval samples. These samples are intended to provide an accurate quantification of suspended sediment transport before and after a harvest. Thus far, five years of data have been collected as part of a six-year calibration period.

CHAPTER 3

Study Location and Site Description

Located roughly twelve miles north of Santa Cruz, California and four miles north of Davenport, Little Creek is one of seven subwatersheds that combine to form Scotts Creek watershed (Figure 3-1). The lower half of the 526-hectare Little Creek watershed is within Swanton Pacific Ranch, a coastal property that is owned by California Polytechnic State University Corporation and managed by the Cal Poly College of Agriculture, Food and Environmental Sciences. Little Creek is typical among smaller coastal mountain watersheds found along the central and northern California coast. It includes first, second and third-order tributaries, as defined by Strahler (1964), as well as Class 1, 2, and 3 streams, as defined by the California Forest Practice Rules (CDF, 2006).

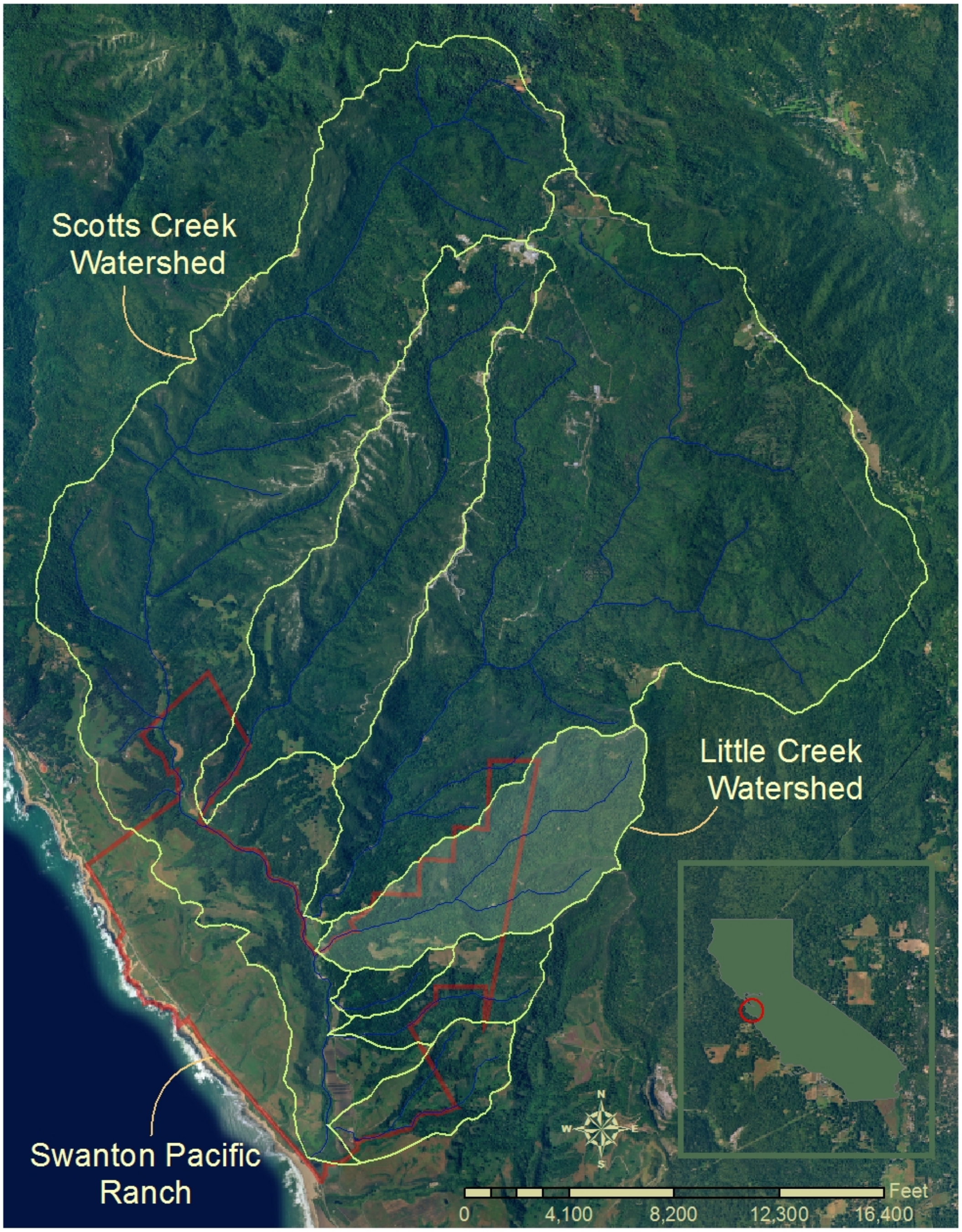

Figure 3-1. The Scotts Creek watershed.

The watershed is dominated by second-growth redwood (*Sequoia sempervirens* (D. Don) Endl.) that characterize the redwood vegetation series (Sawyer and Keeler-Wolf, 1995). Common species found in association with the redwood vegetation series are listed in Table 3-1.

Table 3-1. Common species associated with redwood vegetation series (Hickman 1993, Sawyer and Keeler-Wolf 1995)

Latin name and author	**Common name**
Abies grandis (D. Don) Lindl.	Grand fir
Acer macrophyllum Pursh	Bigleaf maple
Arbutus menziesii Pursh	Madrone
Berberis nervosa Pursh	Little Oregon-grape
Blechnum spicant (L.) Sm.	Deer fern
Carex globosa Boott	Round-fruited sedge
Gaultheria shallon Pursh	Salal
Iris douglasiana Herb.	Douglas iris
Lithocarpus densiflora (Hook. & Arn.) Rehder	Tanoak
Marah fabaceus (Naudin) Greene	Man root
Oxalis oregana Nutt.	Redwood oxalis
Polypodium californicum Kaulf.	California polypody
Polystichum munitum (Kaulf.) C. Presl	Sword fern
Pseudotsuga menziesii (Mirbel) Franco *var. menziesii*	Douglas-fir
Pteridium aquilinum (L.) Kuhn	Bracken
Sequoia sempervirens (D. Don) Endl.	Redwood
Trillium ovatum (Pursh)	Trillium
Tsuga heterophylla (Raf.) Sarg.	Western hemlock
Umbellularia californica (Hook & Arn) Nutt.	California bay
Vaccinium ovatum Pursh	Black huckleberry
Woodwardia fimbriata Sm.	Chain fern

Most species listed in Table 3-1 can be found in the Little Creek watershed. Though not included in Table 3-1, knobcone pine (*Pinus attenuata* Lemm.) and hairy manzanita (*Arcostaphylos tomentosa* (Pursh) Lindl. ssp. *crinita* (Mcminn) Gankin) also exist but are limited to portions of the ridgelines. The riparian corridor, from the confluence with Scotts Creek to the North and South fork confluence, is dominated by red alder (*Alnus rubra* Bong.). The riparian corridor above the confluence of the forks contains a mixture of the dominant conifers and hardwoods of the watershed. Topographic elevations range from approximately 40 to 1600 feet, with an average ground surface slope of 42%. Mean annual precipitation ranges from approximately 40 inches at the watershed outlet to 55 inches on the ridgelines. The stream network within the watershed includes the Main Stem and the North and South forks (Figure 3-2). Included on Figure 3-2 are the monitoring stations (flumes) that comprise the data collection network for the water quality samples. For the purpose of the analysis described herein, data from the North Fork, South Fork, and Upper North Fork stations are utilized.

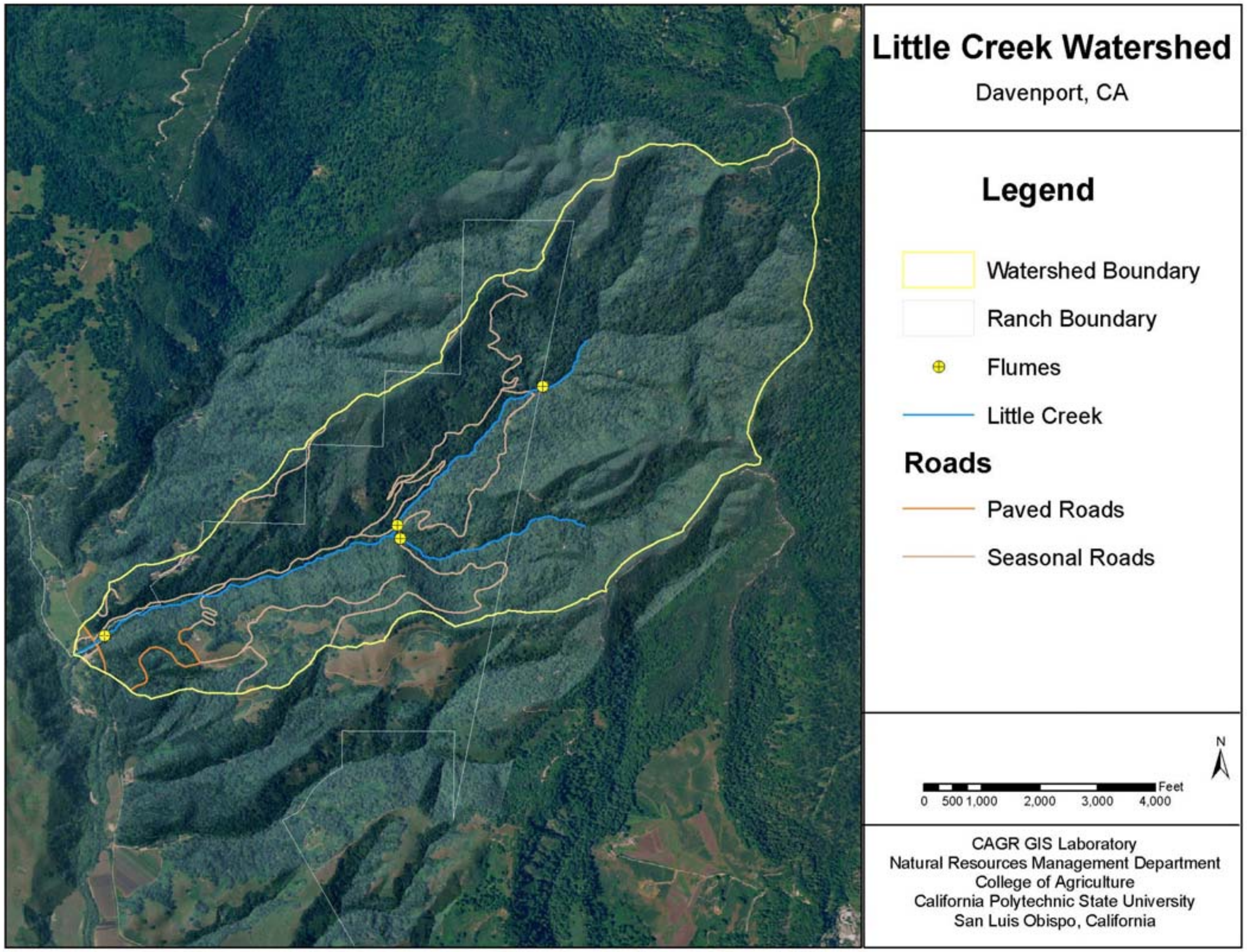

Figure 3-2. The Little Creek watershed.

The underlying geologic structure is composed of Santa Cruz Mudstone (upper Miocene, Tsc), Santa Margarita Sandstone (upper Miocene, Tsm), Quartz diorite (Cretaceous, qd), and Metasedimentary rocks (Mesozoic or Paleozoic, sch), mainly pelitic schist and quartzite (Brabb et al., 1997). The soil in and around the stream channel and dominating most of the watershed is the Ben Lomond-Catelli-Sur complex (NRCS, 2004). This complex is about 30 percent Ben Lomond (taxonomic class: coarse-loamy, mixed, superactive, mesic Pachic Ultic Haploxerolls) sandy loam (deep, well drained, rapid to very rapid runoff, high to very high erosion hazard), 30 percent Catelli (taxonomic class: coarse-loamy, mixed, superactive, mesic Ultic Haploxerolls) sandy loam (moderately deep, well drained, rapid to very rapid runoff, high to very high erosion hazard), and 20 percent Sur (taxonomic class: loamy-skeletal, mixed, superactive, mesic Entic Haploxerolls) stony sandy loam (moderately deep, somewhat excessively drained, rapid to very rapid runoff, high to very high erosion hazard). The remaining 20 percent includes small areas of Aptos (taxonomic class: fine-loamy, mixed, active, mesic Pachic Ultic Argixerolls) sandy loam, Felton (taxonomic class: fine-loamy, mixed, superactive, mesic Ultic Argixerolls) sandy loam, Lompico (taxonomic class: fine-loamy, mixed, superactive, mesic Ultic Argixerolls) loam, Maymen (taxonomic class: loamy, mixed, active, mesic Lithic Dystroxerepts) stony loam, Nisene (taxonomic class: fine-loamy, mixed, superactive, mesic Pachic Ultic Argixerolls) loam, and Zayante (taxonomic class: sandy, mixed, mesic Humic Dystroxerepts) coarse sand (NRCS, 2004). Complete soils series descriptions and a map can be found in Appendix A.

Management history of the watershed includes three timber harvesting entries. The San Vicente Lumber Company began clearcut harvesting following the 1906 San Francisco earthquake and fire, and continued until 1911. A few residual trees were left following this harvest, due to either defect or difficulty of removal. Timber was ground skidded and then transported out of the watershed via a railroad near the mainstream channel. A few railroad ties are still visible on some roads and in the stream channel. An even-aged stand of second growth redwood and Douglas-fir regenerated after the logging in the early 1900's. Portions of the second growth stand of redwood and Douglas-fir were then harvested in a second entry during the 1950's. This entry utilized a partial cut method where only the higher-grade trees were selected for removal. Numerous skid trails were established in the stand to support the tractor yarding operations for this entry. Portions of the stand were burned following the logging operations to remove slash (SPR Management Plan, 2004). The third entry occurred in 1992 in a portion of the North Fork. This was a single tree and small group selection harvest that removed a mixture of size classes of both redwood and Douglas-fir. The selection was intended to start a sustainable harvesting cycle in which the stand would be re-entered approximately every 15 years.

CHAPTER 4

Methodology

Field Data Collection

Streamflow data and water quality samples are collected to determine total suspended sediment transport at each monitoring station. Stage monitoring equipment enables a quantification of streamflow volumes while automated pump samples allow a quantification of suspended sediment concentration. The product of streamflow volumes and suspended sediment concentrations over the course of storm events are calculated to determine suspended sediment loads.

Stage and Streamflow

Stage is monitored using four different measurements (Figure 4-1). A manual stage measurement is taken by reading a staff gage on the flume wall each time a station is visited. The other three measurements are automated within stilling wells; an Isco® bubbler flow meter determines water depth using a differential pressure transducer and a flow of bubbles, a Wescor® Datapod monitors depth using a pressure transducer, and a Belfort® FW-1 stage recorder utilizes a float and pulley system to make a pen tracing on a revolving drum (Note: use of product names does not imply endorsement by Cal Poly). The FW-1 recorder is primarily used to verify bubbler and transducer data if any discrepancies arise.

A


B


C


D


Figure 4-1. Stage measurement equipment. A - Staff gage, B - Isco bubbler flow meter, C - Wescor Datapod with pressure transducer, D - Belfort FW-1. (Note: Use of product names does not imply endorsement by Cal Poly)

Though the Little Creek flumes are rated-section flumes, these flumes do not meet the physical attributes of standard flumes that function according to empirically-derived rating curves. In particular, the Upper North Fork station utilizes the natural stream channel rather than a flume. Thereby, rating curves specific to each monitoring site have been developed for each site by field measurements (Figures 4-2, 4-3, and 4-4).

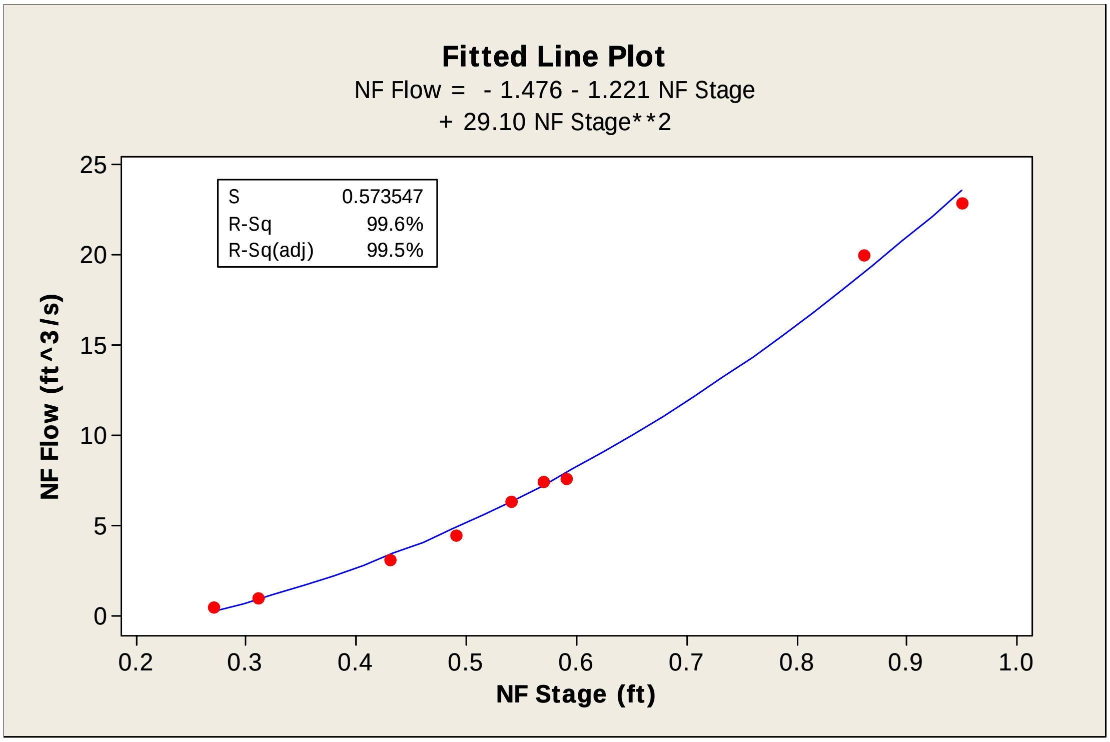

Figure 4-2. North Fork rating curve

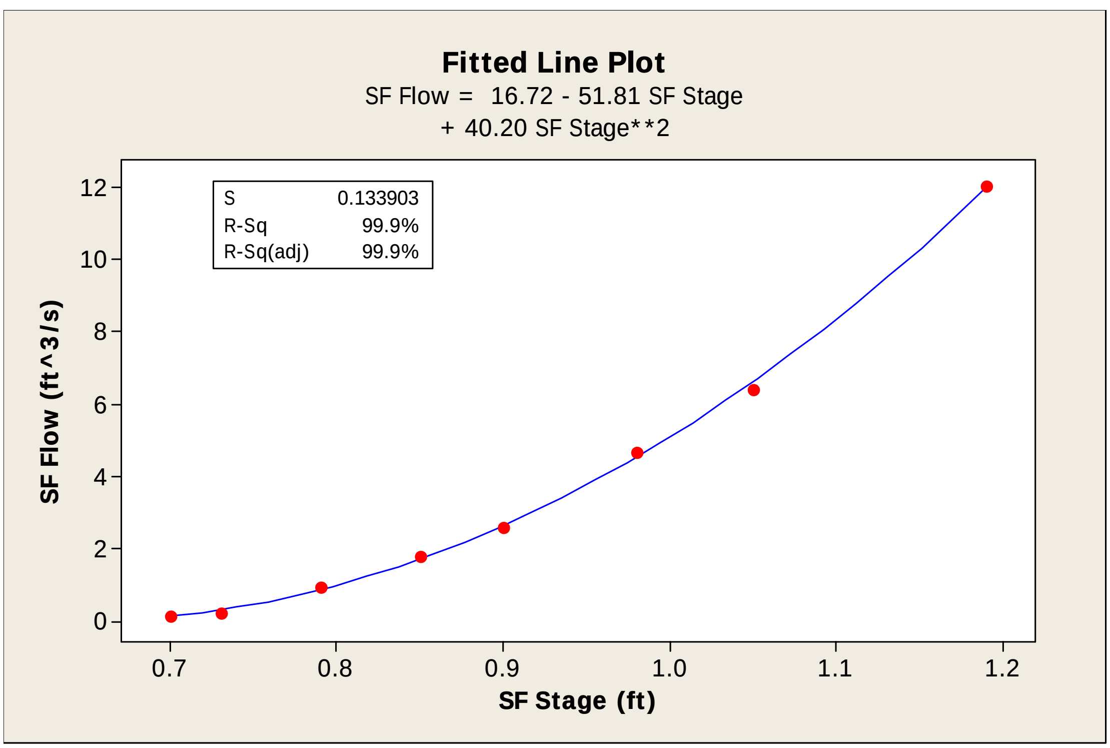

Figure 4-3. South Fork rating curve

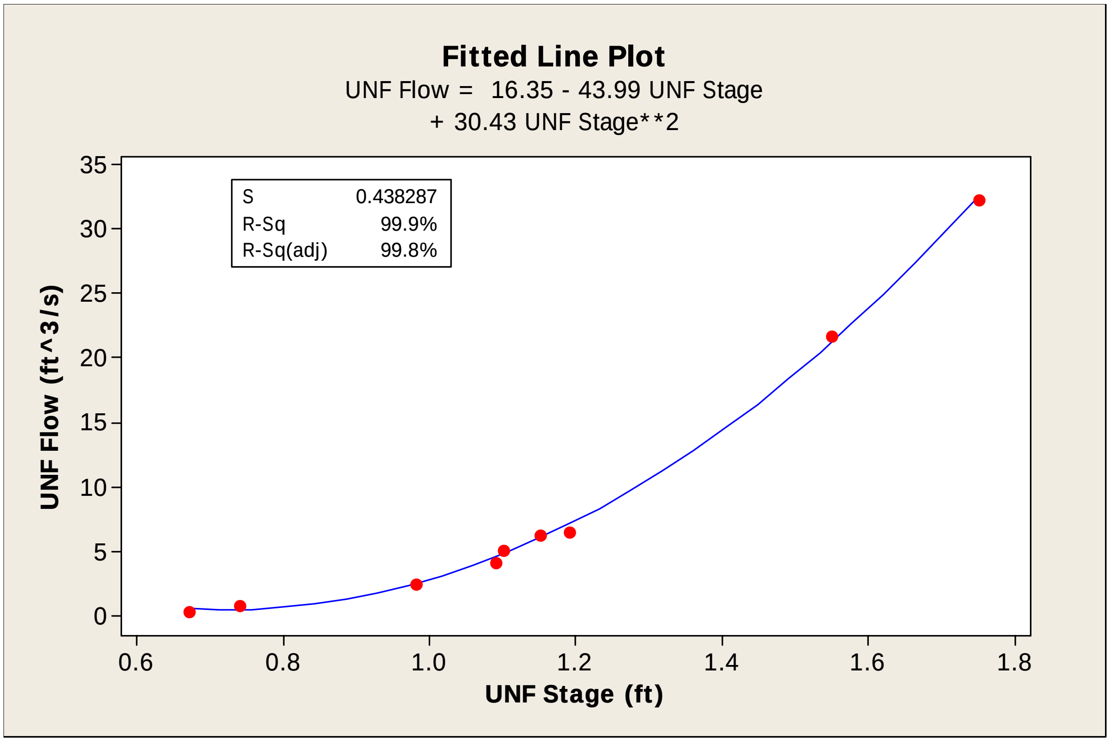

Figure 4-4. Upper North Fork rating curve

Velocity readings taken at various stage levels are used to develop the rating curves that directly relate stage to discharge. Velocity measurements are taken within the walls of a flume, when possible, to take advantage of the permanent, consistent width and uniform depth of water across the channel. Thus far, each rating curve contains from 8 to 9 data points, with an effort made to distribute the data collection throughout a range of flow levels. Each rating curve is created by fitting a quadratic regression line to the dataset. The R^2 values depicted in Figures 4-2, 4-3, and 4-4 indicate a highly significant flow versus stage correlative relationship at each station, and provide good confidence in the created rating curves.

The Upper North Fork rating curve is not used to determine flow for stage values less than 0.99 feet. A comparison of predicted flow values to actual flow values when the stage is less than 0.99 feet reveals an overestimate in the predicted values. Additionally, as the stage drops below approximately 0.80 feet the predicted flow approximates a flat line and no longer decreases with decreasing stage. Fortunately, the stage versus flow relationship behaves more linearly at these lower values and thereby linear interpolation can be used to predict values. This is preferable to using a separate stage versus flow linear regression for the lower values because there are only three datapoints available.

The interpolation used is:

$\left(\frac{A}{B} = \frac{C}{D}\right)$ where A= unknown flow, B= stage at unknown flow, C = known flow, D = stage at known flow

All stage readings over 0.98 feet have the quadratic regression equation applied to determine stage.

<u>Water Quality Samples</u>

Stream samples used for suspended sediment concentration and turbidity analysis are collected from the Little Creek monitoring sites using automated water quality samplers (Figure 4-5).

Figure 4-5. Pump sampler.

When the beginning of a storm event is forecasted, the Isco® 6700 pump samplers are manually turned on and samples drawn at 1-hour intervals. Samples are pumped through polyvinyl tubing housed in a keel suspended in the streamflow (Figure 4-6). The samplers hold 24 bottles that are collected and replaced with an empty set within 24 hours. The samplers continue to collect after a storm event until turbidity levels are relatively low in the streamflow, preferably below 20 NTUs. Though the samplers only require bottle changing once every 24 hours, practical experience has shown the need to visit the monitoring stations more frequently during storm events. Issues that need attention for proper sample collection include debris removal from the pump tube intake, keel adjustment if the streambed is aggrading and

Figure 4-6. Keel with pump intake tube

potentially contributing bed load to the pumped samples, and battery replacement for proper power supply to the samplers.

Laboratory Analysis

All data collected in the field must be processed in the laboratory to ensure quality control of measurements. Water quality samples are processed on-site to determine turbidity values and suspended sediment concentrations.

Streamflow Data Quality Control

All potential sources of stage data must be extensively screened to ensure the most accurate source is being used to calculate streamflow. Each of the four potential sources of stage data (staff gage readings, FW-1 charts, pressure transducer datapods, and flow meters), if available, are compared to construct the final streamflow record.

The datapods and flow meters both electronically log stage data at 15-minute intervals. Electronically logged data are the preferred source of stage readings, so that the data can be automatically paired with lab SSC and turbidity readings. Before automatically pairing such datapoints, though, the pressure transducer and flow meter records must be examined for 1) the existence of data at the desired time intervals and 2) if data are present, the expected accuracy of such data. Data may not exist due to equipment failure, missing equipment that has been sent out for repairs, and power failure. The accuracy of the electronic data is determined by comparison to staff gage and FW-1 chart readings.

Staff gage readings are taken by field personnel when visiting a site and entered into a log book. Though much less frequent than the other three methods of recording stage data, these visual readings form the basis for stage recording equipment verification.

The mechanical FW-1 charts provide a continuous stage record that is first verified by staff gage readings and then used to help validate datapod and flow meter readings. The charts may also provide a source of backup data, if needed.

The FW-1 charts are changed after one week of recording and data from the datapods and flow meters are downloaded at this same time to enable accuracy checks. At such times, the staff gage readings are compared to the current chart, datapod, and flow meter readings and any variations are recorded in a log book. If a log book entry reveals a problem with either the datapod or flow meter data, then the dataset from the malfunctioning device is flagged to not be used in the event analysis. An FW-1 chart, if noted as functioning properly, is further used to make checks of the electronic data at various times during an event when staff gage readings are not available. If both electronic devices are malfunctioning or missing then stage readings can be manually read from the FW-1 charts.

Water Quality Sample Analysis

Sample bottles are transported from the field to the Al Smith Water Quality Laboratory for analysis of turbidity and suspended sediment concentration. Turbidity is “an expression of the optical properties of a liquid that causes light rays to be scattered and absorbed rather than transmitted in straight lines through a sample” (ASTM, 2003a). Turbidity also becomes a measurement of the amount of suspended particles in the water that affect clarity. The measurement units are in Nephelometric Turbidity Units (NTUs), which measure the scattering of light passed through a water sample.

Suspended Sediment Concentration (SSC) measures the total amount of suspended material in a water sample collected, in this case, from the flow in open channels. The SSC analytical method used is based on the ASTM D 3977-97, Standard Test Method for Determining Sediment Concentration in Water Samples, which is used by all USGS sediment laboratories, the Agriculture Research Service, National Resources Conservation Service, and the Bureau of Reclamation, among other agencies. However, the method has been modified in accordance with procedures established by the Redwood Sciences Laboratory (USDA Forest Service) by eliminating the sample settling period and the decanting procedure.

The SSC analysis is time-intensive and is desirable to perform on a minimum number of bottles in a sample set while still adequately estimating the total suspended sediment load of an event. The Caspar Creek Study has used turbidity as a predictor of significant changes in SSC to determine how often stream samples need to be taken during an event (Lewis, 1996). The protocol, referred to as Turbidity Threshold Sampling (TTS), was developed to reduce costly laboratory analysis and partly out of convenience, to limit the collection of masses of sample bottles from remote locations. A modified version of this turbidity threshold sampling process was initially applied to the Little Creek samples during 2002/2003. Bottles that meet the following specific turbidity thresholds were analyzed for SSC:

20-50 NTU, sample every 12 hours
50-200 NTU, sample every 6 hours
200-500 NTU, sample every 3 hours
500-2000 NTU, sample every 2 hours
Greater than 2000 NTU, sample every hour

Samples with turbidity lower than 20 NTUs were not analyzed for SSC based on communication with Jack Lewis of the USDA Pacific Southwest Research Station in 2001. At that time, the turbidity threshold sampling protocol implemented at Caspar Creek did not draw samples when instream turbidity was below 20 NTUs. This threshold was set to ensure a turbidity value that is above the typical inter-storm level. Thus far, an increase in stream turbidity above 20 NTUs does not appear to have occurred outside of a storm event. Also, an initial rise in turbidity above 20 NTUs is necessary at the beginning of a storm to ensure sampling intakes and instream turbidimeters are submerged. The threshold for the number of samples processed for SSC when the turbidity is above 20 NTUs was adjusted in 2003/2004 and thereafter. The thresholds were modified to provide more SSC values from each storm event. Analysis was performed on all bottles over 100 NTUs due to potential increased variability in the SSC versus turbidity relationship and the large influence these samples have on total event load determination. The more frequent analysis interval was desirable for an increased level of accuracy in the event-based regressions of SSC and turbidity.

CHAPTER 5

Data Analysis

Statistical Equations

Regression analysis is used to generate single event loads and establish the calibration of event loads between treatment and control stations. The following equations are found in Helsel and Hirsch (2002).

A regression line is given by the equation:

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i \qquad i=1,2,\ldots,n$$

Where:

- y_i = the ith observation of the response variable
- x_i = the ith observation of the explanatory variable
- β_0 = the intercept
- β_1 = the slope
- ε_i = the random error or residual for the ith observation
- n = the sample size

An important aspect of a regression line involves the confidence interval. The confidence interval is given by:

$$\hat{y} \pm ts\sqrt{\frac{1}{n} + \frac{(x_o - u_x)^2}{SS_x}}$$

Where:

- $\hat{y}$ = the estimate of the expected value of y at x_0 based on the regression equation $y = b_0+b_1x_0$
- t = the quantile of the students' t-distribution having n-2 degrees of freedom with exceedance probability $\alpha/2$
- s = the standard deviation for the regression
- n = the number of data points
- x_0 = a specified value of x

u_x = the mean of the sample population x
SS_x = the sum of squares for the sample population x

As indicated by the confidence interval formula, the confidence interval increases with increasing distance from the mean.

Prediction intervals can also be generated for a regression, but are considerably wider than a confidence interval. The prediction interval includes the unexplained variability of y in addition to any uncertainties involving the parameter estimates β_0 and β_1. The prediction interval is given by:

$$\hat{y} \pm ts\sqrt{1 + \frac{1}{n} + \frac{(x_o - \bar{x})^2}{SS_x}}$$

<u>Defining the Dataset</u>

The first step in organizing the dataset into storm events is to define an "event". The available stream data for defining an event are streamflow, turbidity, and SSC. An example plot of flow, turbidity, and SSC for the largest storm event sampled to date at the North Fork station is shown in Figure 5-1. A major feature in this example plot is the variability between SSC and turbidity values at the high points on the hydrograph. However, such variability is not always present, therefore an example plot from another event displaying less variability is shown for comparison purposes in Figure 5-2.

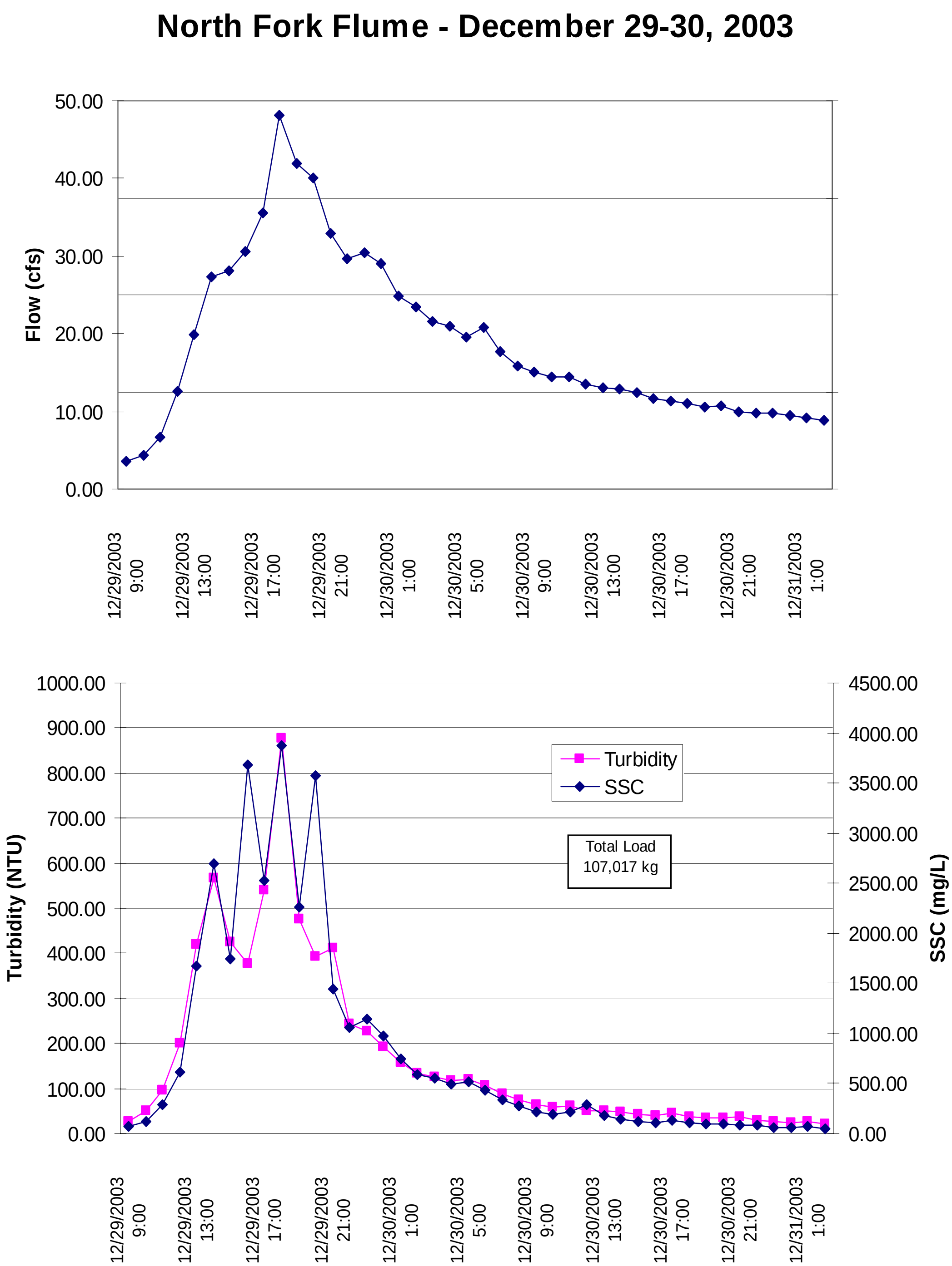

Figure 5-1. Example flow and water quality data from a large storm event, displaying a relatively high amount of SSC versus turbidity variability near hydrograph peak.

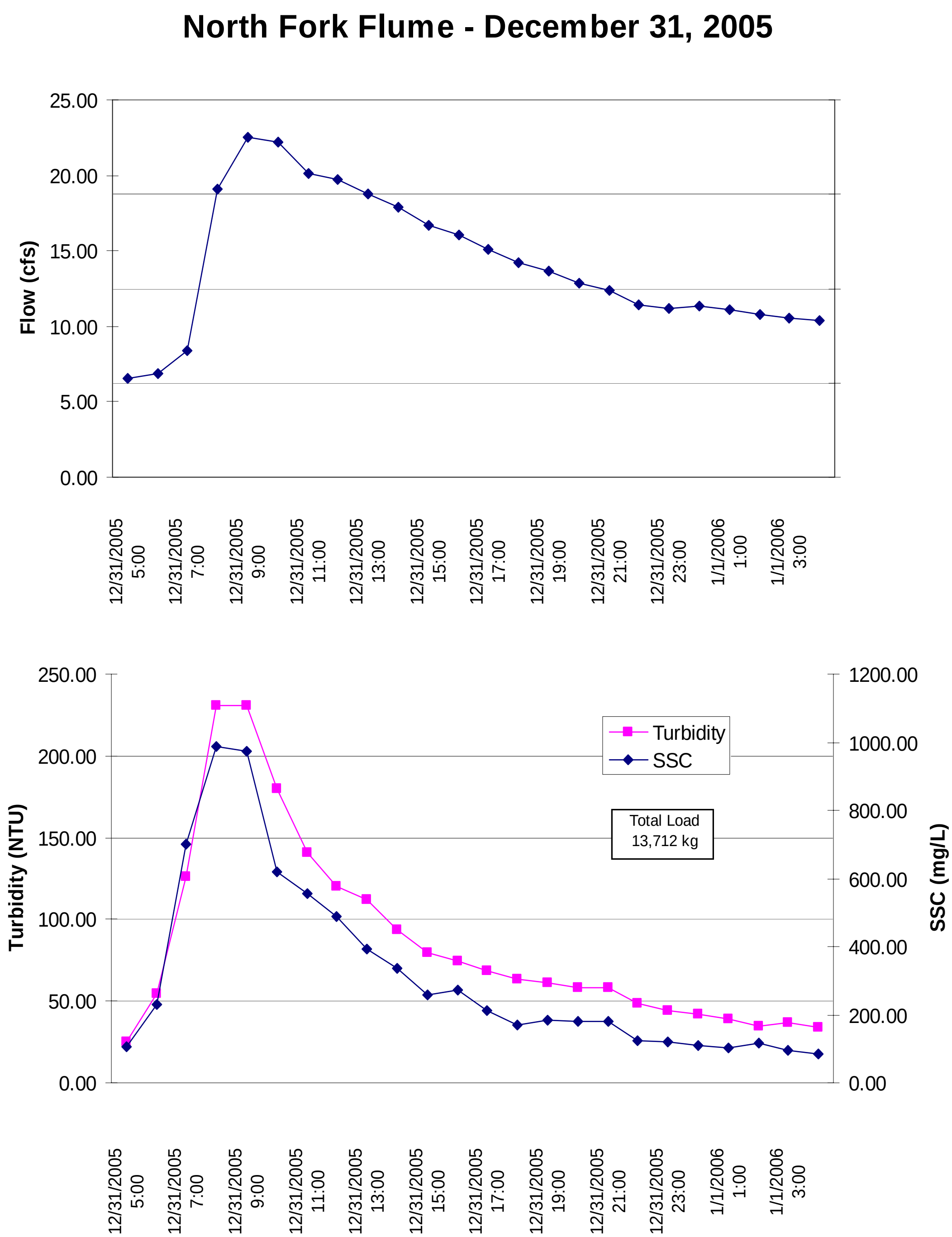

Figure 5-2. Example flow and water quality data from a storm event, displaying relatively little SSC versus turbidity variability near hydrograph peak.

Turbidity and SSC would be problematic to use for event definition due to the lack of complete data coverage prior to, during, and after most events. Streamflow records encompass most events and are utilized for event definition.

For some events, a station may not have stage data available from any of the recording methods throughout the duration of an event. In such a situation, the laboratory data cannot be paired with flow and, therefore, is omitted from the event analysis dataset.

When streamflow data are available, two situations must be considered in defining an event; 1) an event that begins during a baseflow condition, and 2) an event that begins during the receding hydrograph limb of a previous event. For an event encountered in the first situation, the beginning point is selected as that point on the hydrograph where an initial increase in flow is observed. The increase must be subsequently sustained so that it does not fall below a 0.05 cubic feet per second (cfs)/mi^2/hour separation slope line extending from the beginning point, as described by Hewlett and Hibbert (1967) for small watersheds. Given the increase is sufficient, the event is continued until the hydrograph intersects the 0.05 cfs/mi^2/hr separation slope line. If, before the separation slope line intersects the hydrograph, one or more additional hydrograph peaks occur these peaks may define separate events (situation #2) based on certain characteristics. These characteristics are if two peaks on the hydrograph are at least 24 hours apart and the hydrograph has fallen to at least ½ the level of the lesser of the two peaks. This method was used to define events for the Caspar Creek study (Lewis et al., 2001).

An additional consideration is that a minimum event size must be established, so that any increases in flow are not considered potential events. Other research projects, such as Caspar Creek, have defined an event by setting a minimum value of flow per watershed unit area that must be reached to signify the occurrence of an event (Lewis et al., 2001). The minimum value was set at such a level that seven events would occur in a normal year. For very dry years, the minimum value may be adjusted down to provide for more events in a yearly analysis.

For the Little Creek study, a similar minimum value technique is used to determine whether an event has occurred, but the value depends on turbidity. Turbidity is chosen because the water quality sampling strategy for the project has been based on samples greater than 20 NTUs. Samples that are tested in the laboratory at less than 20 NTUs are typically not analyzed for SSC. This presents a potential problem in event analysis in that the duration of an event defined by flow typically extends beyond the point where turbidity drops below 20 NTUs. Thereby, to fully utilize the Little Creek dataset, only those portions of a flow-defined event when turbidity is greater than 20 NTUs are included in the event analysis. However, events are not continued beyond the 0.05 separation slope, even if turbidity is still above 20 NTUs. An example of a hydrograph and turbidity plot shown with the respective 0.05 separation slope and 20 NTU threshold is provided in Figure 5-2. Using a 20 NTU minimum acts to alleviate the need for a flow minimum since very small hydrograph-based events rarely exceed 20 NTUs.

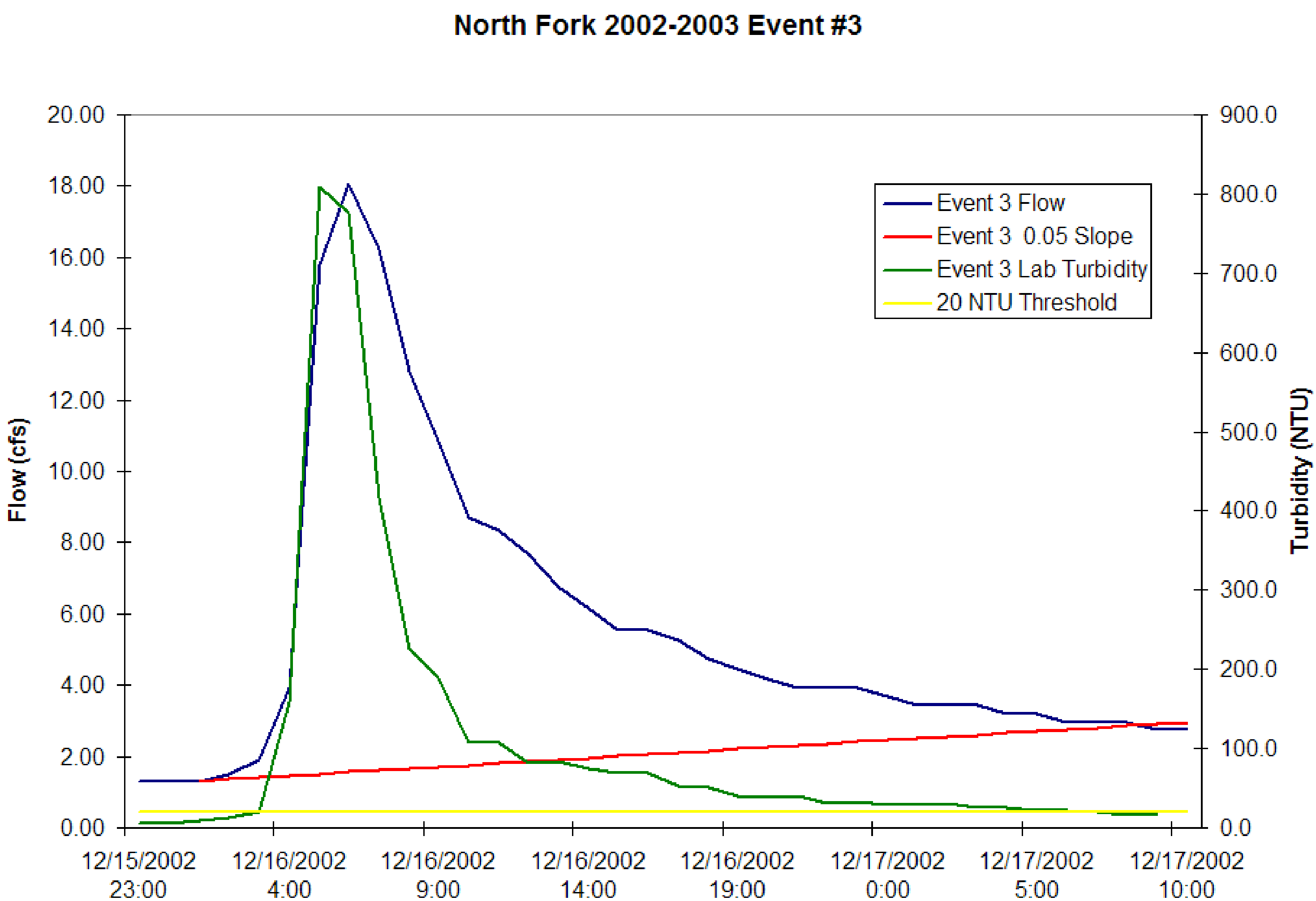

Figure 5-3. North Fork event showing flow, tubidity, 0.05 slope line, and 20 NTU threshold

Each identified event must also be assigned an event number. To do so, a candidate event must occur during a period of time for which water quality samples consisting of laboratory turbidity and/or SSC exist for the North Fork Station. This period of time is specified because the current analysis is focused on the NF versus UNF (nested) and NF versus SF (paired) load relationships. Events occurring at the North Fork station are assigned sequential numbers within each sampling season. Once events have been defined at the NF station, matching events at the UNF and SF stations are defined based on data availability. Event data for the North Fork, South Fork, and Upper North Fork are listed in Appendix B-1, B-2, and B-3, respectively.

Explanation of data tables in Appendix B-1, B-2, and B-3

The necessary data and calculated values for determining event loads are presented in Appendix B-1, B-2, and B-3. Data is organized by station and by year and displays the hourly water quality and flow data. Each listing for the North Fork begins with a summary table of the number of hydrologically significant events as defined by the North Fork flow. Also displayed in this table are the event loads from the South Fork and Upper North Fork stations available for the paired or nested analysis. Following the table, data is organized by column (see Figure 5-4 for an example of the appendix display). Following Figure 5-4, the column headings and a basic description of the content are provided. An expanded description of the measured data can be found in Chapter 3.

2003-2004 Little Creek North Fork Flow, Turbidity, SSC, and Event Summary

Event #:	1	2		3	4	5	6	7	8
NF Load (kg):	546	6250		2168	105052	49411	387	1872	486
NF load (kg/ha):	2.0	22.4		7.8	376.3	177.0	1.4	6.7	1.7
SF Load (kg):	26	78		35	6971	3761	n/a	n/a	n/a
SF load (kg/ha):	0.2	0.7		0.3	63.8	34.4	n/a	n/a	n/a
UNF Load (kg):	377	3567		n/a	56554	30225	79	719	195
UNF load (kg/ha):	2.0	18.7		n/a	296.1	158.2	0.4	3.8	1.0

Time	Turbidity (NTU)	SSC (mg/L)	Regression	Lab SSC or Regr. SSC (mg/L)	Stage (ft)	Flow (cfs)	Hourly Load (kg)	Event #	Event Load (kg)	0.05 $cfs/mi^2/hr$ Slope	Hydrograph Event Definition
11/8/2003 15:00					0.23	0.27					
11/8/2003 16:00					0.22	0.22					
11/8/2003 17:00					0.23	0.30					
11/8/2003 18:00	8.2				0.22	0.24				0.24	START
11/8/2003 19:00	21.9	58		58	0.26	0.79	5	1		0.29	GO
11/8/2003 20:00	121.0	246		246	0.31	1.76	44	1		0.35	GO
11/8/2003 21:00	227.0	498		498	0.38	3.19	162	1		0.40	GO
11/8/2003 22:00	245.0	456		456	0.45	4.97	231	1		0.46	GO
11/8/2003 23:00	102.0	163		163	0.42	4.14	69	1		0.51	GO
11/9/2003 0:00	47.3	90		90	0.36	2.82	26	1		0.56	GO
11/9/2003 1:00	27.6	46		46	0.32	1.97	9	1	**546**	0.62	GO

Figure 5-4. Data display from Appendix B-1.

Time: The date and time of a water quality sample in "mm/dd/yyyy hh:mm" format.

Turbidity (NTU): A laboratory-measured turbidity value in nephelometric turbidity units (NTU) for each hourly water quality sample.

SSC (mg/L): A laboratory-measured suspended sediment concentration value in milligrams per liter (mg/L) for each hourly water quality sample.

Regression: The range of event data used in a regression to predict missing SSC values is indicated by a double-ended vertical arrow. A few events have two double-ended vertical arrows to signify that two separate regressions were used. This occurred for long-duration events where better fits were achieved using separate parts of the hydrograph, such as the rising limb and falling limb. A subset may also be used if autocorrelation is detected when using the entire dataset. Additionally, a regression may not utilize data from the entire event if only a portion of the event requires estimated SSC values and better fits are achieved using that portion of the event. For example, if only values on the rising limb require estimation then the regression will only utilize the rising limb, assuming a sufficient number of data points are available and fits are improved using the subset. Event-specific regression equations developed for the North Fork, South Fork, and Upper North Fork stations are shown in Tables 5-4, 5-5, and 5-6, respectively.

Lab SSC or Regr. SSC (mg/L): SSC values that come from laboratory-determined values when available or regression-predicted values as needed.

Stage (ft): A depth of water equivalent to a staff plate reading.

Flow (cfs): A calculated value based on a station-specific rating curve.

Hourly load (kg): The product of the "Lab SSC or Regr. SSC" and "Flow" columns.

Event #: A sequentially designated event number as defined by the North Fork station and specific to each storm season.

Event load (kg): The sum of the hourly loads during the defined storm event.

0.05 cfs/mi^2/hr Slope: Used to define each event using Hewlett and Hibbert's (1967) method. The beginning value in each storm event represents the incipient rise on the hydrograph. Subsequent values trace a 0.05 cfs/mi^2/hr separation slope on the hydrograph.

Hydrograph Event Definition: "Start" at the first rise in the hydrograph for a given event. "Go" when the hydrograph is above the 0.05 separation slope. "Stop" when the 0.05 separation slope has intersected the hydrograph. "Stop" may not be shown for all events due to the lack of water quality data coverage for the entire hydrograph.

Event sampling summaries for the North Fork, South Fork, and Upper North Fork are shown in Tables 5-1, 5-2, and 5-3. These summaries describe the event data as "good" if the event can be used for the final analysis or describe the circumstances of data loss if the event is not useable for the final analysis.

Table 5-1. Storm event sampling summary for North Fork monitoring station.

North Fork monitoring station

Year	Yearly event #	Sampling status
2001-2002	1	Sampler started late, rising limb of hydrograph missing
	2	Good
	3	No samples for portion of recession due to program error
	4	Good
	5	Good
	6	Sampling stopped during rising limb of hydrograph
	7	Good
	8	Good
2002-2003	1	Good
	2	Good
	3	Good
	4	No samples after rising limb, unknown error
	5	Good
2003-2004	1	Good
	2	Good
	3	Good
	4	Good
	5	Good
	6	Good
	7	Good
	8	Good
2004-2005	1	Sampler started late, rising limb of hydrograph missing
	2	Good
	3	Good
	4	Good
	5	Good
	6	Good
	7	No samples, unknown error
	8	Good
	9	Good
	10	Event peak <20 NTU
	11	Event peak <20 NTU
	12	Good
	13	Rising limb and peak missed due to lab error
	14	Good
	15	Event peak <20 NTU
2005-2006	1	Good
	2	Event peak and portion of falling limb missing due to pumping errors
	3	Good
	4	Good
	5	Good
	6	Streambed enrichment of samples on falling limb
	7	Good
	8	No samples, pump tube disconnected
	9	Good
	10	Good
	11	Good
	12	Good

Table 5-2. Storm event sampling summary for South Fork monitoring station.

South Fork monitoring station

Year	Yearly event #	Sampling status
2001-2002	1	Sampler started late, rising limb of hydrograph missing
	2	Good
	3	Good
	4	Good
	5	Good
	6	Sampling stopped during rising limb of hydrograph
	7	Good
	8	Sample streambed enrichment
2002-2003	1	Good
	2	Good
	3	Good
	4	No samples after rising limb, unknown error
	5	No samples due to power failure
2003-2004	1	Good
	2	Good
	3	Good
	4	Good
	5	Good
	6	No samples due to programming error
	7	No samples from recession limb of hydrograph
	8	Major portion of recession limb not sampled
2004-2005	1	Sampler started late, rising limb of hydrograph missing
	2	Event peak <20 NTU
	3	Good
	4	Good
	5	Good
	6	Good
	7	No samples, unknown error
	8	Good
	9	Good
	10	Event peak <20 NTU
	11	Event peak <20 NTU
	12	Event peak <20 NTU
	13	Good
	14	Event peak <20 NTU
	15	Event peak <20 NTU
2005-2006	1	Good
	2	Good
	3	Good
	4	Good
	5	Good
	6	Good
	7	No samples, distributor arm jam on pump sampler
	8	Good
	9	Good
	10	Missing samples, distributor arm jam on pump sampler
	11	Missing samples, distributor arm jam on pump sampler
	12	Good

Table 5-3. Storm event sampling summary for Upper North Fork monitoring station.

Upper North Fork monitoring station

Year	Yearly event #	Sampling status
2001-2002	1	Missing stage data due to equipment malfunction
	2	Missing stage data due to equipment malfunction
	3	Missing stage data due to equipment malfunction
	4	Missing stage data due to equipment malfunction
	5	Missing stage data due to equipment malfunction
	6	Missing stage data due to equipment malfunction
	7	Missing stage data due to equipment malfunction
	8	Missing stage data due to equipment malfunction
2002-2003	1	Good
	2	Streambed enrichment of samples on falling limb, pump tube clog
	3	Good
	4	No samples after rising limb, unknown error
	5	Missing samples due to clogged pump tube
2003-2004	1	Good
	2	Good
	3	Sampler started late, rising limb of hydrograph missing
	4	Good
	5	Good
	6	Good
	7	Good
	8	Good
2004-2005	1	Sampler started late, rising limb of hydrograph missing
	2	No sample data due to lab error
	3	No samples due to power failure
	4	Good
	5	Good
	6	Event peak <20 NTU
	7	No samples, unknown error
	8	Good
	9	No sample data due to lab error
	10	Event peak <20 NTU
	11	Event peak <20 NTU
	12	No samples due to power failure
	13	Good
	14	Good
	15	Event peak <20 NTU
2005-2006	1	Good
	2	Event peak and portion of falling limb missing due to pumping errors
	3	Good
	4	Good
	5	Good
	6	Good
	7	Good
	8	Good
	9	Good
	10	Good
	11	Good
	12	Good

Qualitative Summary of Water Quality Collection by Year

2001-2002

Significant events occurred primarily in December and early January. Very large events in late December and early January were successfully sampled though sample enrichment from the streambed at the North Fork and South Fork stations was a recurring difficulty. Equipment problems prevented the collection of flow data at the UNF station. Pressure transducer units were installed in April 2002, but the major recorded events for the year occurred prior to January 4, 2002. Electronic data logged using older bubbler technology were problematic and FW-1 charts were relied upon for reconstruction of a significant amount of stage data. Unfortunately, an FW-1 recorder was not installed until the following season on the Upper North Fork and therefore, no events are available from the UNF for the 2001-2002 sampling season.

2002-2003

The largest events occurred in mid-December. Sampling coverage and data integrity are good for a significant portion of the period. Samples from a significant event in February are not available from the Upper North Fork and South Fork stations due to a clogged pump tube and a power failure, respectively.

2003-2004

Significant events occurred in late December and early January and again in February. Two of the largest events, thus far in the calibration period, were successfully captured in late December and early January. For the other significant events, data collection was successful at the North Fork. A programming error at the South Fork and missing samples for the rising limb at the Upper North Fork were problematic for two events.

2004-2005

Significant events occurred throughout the rain season from late October to late March. The relatively large number of events during this high precipitation year yielded multiple useable events for analysis. However, occasional errors such as stilling well clogging, streambed enrichment, and power failure resulted in the omission of a few events. Several small events were sampled but not useable due to peak turbidity levels less than the 20 NTU threshold for event analysis.

2005-2006

This year was another active hydrologic year for obtaining stream samples. Extremely wet conditions prevailed during late December/early January and late March/early April. Multiple events were successfully sampled and included in the final analysis. Data collection at the Upper North Fork was successful throughout the season. Problems encountered at the North Fork included stilling well clogging during one storm event and bed enrichment and sampling errors for two subsequent events. Only two sampling events were lost at the South Fork, both due to a pump sampler distributor arm failure.

Event-based SSC versus Turbidity Regressions.

Suspended sediment concentrations need to be estimated for certain hourly water quality samples. As previously mentioned in Chapter 4, turbidity values do exist for all hourly samples and the strong correlation between turbidity and SSC, at least on a per event basis, allows for regressions that enable non-measured SSC values to be predicted (Lewis, 1996). The relatively high cost of performing an SSC analysis as compared to turbidity often necessitates the use of some threshold logic. For the Little Creek dataset, however, there are several events that have measured SSC values for all hourly samples and do not require any regressions to predict SSC as a function of turbidity.

SSC versus turbidity regressions are performed as necessary for each event that is used in the load analysis dataset. Occasionally, SSC versus flow regressions are necessary as well. Event-specific regression equations and associated test statistics are summarized for the North Fork (Table 5-4), the South Fork (Table 5-5), and the Upper North Fork (Table 5-6).

Table 5-4. North Fork event-based regressions.

Little Creek North Fork Event-based SSC v. Turbidity* Regressions							
(*Flow used for portion of four events)							
Year	**Event #**	**Number of data pairs (n)**	**Transfor-mation applied**	**Hydrograph area used for regression**	**Regression equation SSC=Susp.Sed.Conc.(mg/L) T=turbidity(NTU) F=flow(cfs)**	**R^2**	**P-value of the F test**
2001-2002	2	6	none	Rising + Recession	SSC = -13.1 + 2.76T	0.982	<0.001
	7	17	ln	Recession	lnSSC = 0.467 + 1.24lnT	0.686	<0.001
	7	17	ln	Recession	lnSSC = 0.01 + 0.486F	0.614	<0.001
	8	13	ln	Rising	lnSSC = 3.27 + 0.725lnT	0.858	<0.001
	8	26	ln	Recession	lnSSC = 2.42 + 0.83lnT	0.734	<0.001
2002-2003	1	8	none	All	SSC = 16.6 + 2.14T	0.984	<0.001
	2	7	ln	Event 1 Recession + All Event 2	lnSSC = -0.41 + 1.26lnT	0.815	0.003
	3	8	ln	All	lnSSC = 1.29 + 1.01lnT	0.860	0.001
	5	4	ln	All	lnSSC = 1.17 + 0.907lnT	0.839	0.05
2003-2004	4	9	ln	Rising	lnSSC = 0.163 + 1.22lnT	0.948	<0.001
	4	7	ln	Recession	lnSSC = -0.266 + 1.36lnT	0.943	<0.001
	4	7	ln	Recession	lnSSC=3.52 + 0.109F	0.916	<0.001
	5	8	none	Recession	SSC = 84.5 + 3.76T	0.952	<0.001
	5	8	none	Recession	SSC = -29.5 + 3.40T	0.957	<0.001
	5	8	ln	Recession	lnSSC= 5.27 + 0.0434F	0.847	0.001
2004-2005	4	16	ln	All	lnSSC = 0.934 + 1.01lnT	0.856	<0.001
	5	7	none	Recession	SSC = -48.9 + 3.61T	0.992	<0.001
	6	6	ln	All	lnSSC = 1.72 + 0.652lnT	0.591	0.046
	8	14	ln	All	lnSSC = 1.57 + 0.865lnT	0.586	0.001
	9	6	none	All	SSC = 5.2 + 2.47T	0.937	0.001
	14	17	none	Event 13 Recession	SSC = 2.3 + 2.49T	0.630	<0.001
2005-2006	1	6	none	Recession	SSC = - 13.8 + 3.49T	0.917	0.002
	3	8	none	All	SSC = - 48.8 + 5.07lnT	0.737	0.004
	4	14	none	Recession	SSC = -47.1 + 4.00T	0.974	<0.001
	6	9	none	All	SSC = - 27.4 + 2.99T	0.938	<0.001
	8	9	none	Event 7 Recession	SSC = -27.6 + 2.85T	0.964	<0.001
	9	12	none	All	SSC = 40.3 + 2.33T	0.616	0.002
	9	9	none	Rising	SSC = -755 + 93.4F	0.688	0.004
	10	22	ln	All	lnSSC = 2.45 + 0.663lnT	0.920	<0.001
	11	11	none	Recession	SSC = 92.5 + 1.51T	0.845	<0.001
	12	7	ln	Rising	lnSSC = 0.633 + 1.07lnT	0.977	<0.001
	12	13	none	Middle	SSC = 72.8 + 2.49T	0.977	<0.001
	12	13	none	Recession	SSC = 50.5 + 2.67T	0.778	<0.001

Table 5-5. South Fork event-based regressions.

Little Creek South Fork Event-based SSC v. Turbidity* Regressions							
(*Flow used for portion of two events)							
Year	Event #	Number of data pairs (n)	Transfor-mation applied	Hydrograph area used for regression	Regression equation SSC=Susp.Sed.Conc.(mg/L) T=turbidity(NTU) F=flow(cfs)	R^2	P-value of the F test
2001-2002	3	33	none	All	SSC = - 92.3 + 3.54T	0.740	<0.001
	4	39	ln	All	lnSSC = - 11.9 + 4.48 lnT	0.404	<0.001
	7	11	none	Rising	SSC = - 41 + 4.93T	0.402	0.012
	7	10	none	Recession	SSC = -216 + 7.93T	0.796	0.005
	7	10	ln	Recession	lnSSC = 1.68 + 0.563F	0.899	<0.001
2002-2003	1	14	none	All from events 1, 2, 3	SSC = - 44.5 + 2.51T	0.961	<0.001
	2	14	none		SSC = - 44.5 + 2.51T	0.961	<0.001
	3	14	none		SSC = - 44.5 + 2.51T	0.961	<0.001
2003-2004	4	13	ln	Recession	lnSSC = - 2.82 + 1.68T	0.868	<0.001
	5	7	none	Rising	SSC = - 49.5 + 2.94T	0.954	<0.001
	5	9	none	Recession	SSC = - 82.3 + 3.50T	0.952	<0.001
2004-2005	4	10	ln	All	lnSSC = - 4.53 + 2.33 lnT	0.628	0.004
	5	13	none	All	SSC = -14.9 + 0.770T	0.782	<0.001
	6	8	none	All	SSC = - 45.0 + 2.40T	0.520	0.017
	8	20	ln	All	lnSSC = - 5.31 + 2.69 lnT	0.649	<0.001
	9	14	ln	All	lnSSC = - 6.34 + 2.60 lnT	0.922	<0.001
	13	20	ln	All	lnSSC = - 0.689 + 1.46 lnT	0.742	<0.001
2005-2006	1	15	none	All	lnSSC = - 7.05 + 2.83 lnT	0.801	<0.001
	2	16	ln	All	lnSSC = - 2.51 + 1.68 lnT	0.949	<0.001
	3	5	none	Rising	SSC = - 20.6 + 1.25T	0.754	0.036
	3	6	none	Peak+Rising	SSC = - 36.8 + 1.49T	0.744	0.017
	4	12	ln	All	lnSSC = - 8.08 + 3.28 lnT	0.892	<0.001
	5	9	ln	Rising	lnSSC = -3.31 + 2.06lnT	0.828	<0.001
	5	18	ln	Recession	lnSSC = 0.323 + 1.12lnT	0.904	<0.001
	5	18	ln	Recession	lnSSC = 2.62 + 0.422F	0.871	<0.001
	7	29	ln	All	lnSSC = - 3.02 + 1.81 lnT	0.816	<0.001
	8	29	ln	Event 7 regression	lnSSC = - 3.02 + 1.81 lnT	0.816	<0.001
	9	11	ln	All	lnSSC = - 3.67 + 2.09 lnT	0.852	<0.001
	12	20	ln	All	lnSSC = - 1.70 + 1.53 lnT	0.886	<0.001

Table 5-6. Upper North Fork event-based regressions.

Little Creek Upper North Fork Event-based SSC v. Turbidity* Regressions							
(*Flow used for portion of two events)							
Year	**Event #**	**Number of data pairs (n)**	**Transfor-mation applied**	**Hydrograph area used for regression**	**Regression equation SSC=Susp.Sed.Conc.(mg/L) T=turbidity(NTU) F=flow(cfs)**	**R^2**	**P-value of the F test**
2001-2002	4	36	ln	All	lnSSC = 2.78 + 0.789 lnT	0.616	<0.001
2002-2003	1	9	ln	All	lnSSC = 1.40 + 0.943 lnT	0.803	0.001
	1	9	ln	All	lnSSC = 5.30 + 0.130F	0.497	0.02
	3	10	ln	All	lnSSC = - 0.215 + 1.26 lnT	0.877	<0.001
2003-2004	1	7	none	All	SSC = - 3.2 + 2.36T	0.918	<0.001
	2	10	none	All	lnSSC = 4.40 + 0.185F	0.485	0.015
	4	20	ln	All	lnSSC = 0.135 + 1.24 lnT	0.968	<0.001
	5	18	ln	All	lnSSC = 0.491 + 1.12 lnT	0.954	<0.001
	8	7	none	All	SSC = - 31.1 + 3.53T	0.572	0.030
2004-2005	4	12	none	All	SSC = -30.0 + 3.28T	0.935	<0.001
	5	9	none	All	SSC = -13.1 + 2.69T	0.971	<0.001
	8	13	none	All	SSC = - 9.7 + 2.42T	0.818	<0.001
	13,14	23	none	Event 13 regression	SSC = - 21.6 + 2.78T	0.927	<0.001
2005-2006	1	16	ln	All	lnSSC = 0.454 + 1.09 lnT	0.936	<0.001
	3	6	none	All	SSC = - 29.0 + 3.23T	0.909	0.002
	4	21	ln	All	lnSSC = - 0.349 + 1.33 lnT	0.974	<0.001
	5	29	ln	All	lnSSC = - 0.535 + 1.42 lnT	0.975	<0.001
	6	7	ln	All	SSC = - 3.96 + 2.27T	0.965	<0.001
	7	11	ln	All	lnSSC = 0.359 + 1.21 lnT	0.922	<0.001
	9	15	ln	All	lnSSC = 1.59 + 0.856 lnT	0.947	<0.001
	10	15	ln	Rising	lnSSC = 1.93 + 0.846 lnT	0.765	<0.001
	10	10	none	Recession	SSC = -18.5 + 5.14T	0.736	0.001
	11	26	none	All	SSC = -32.9 + 4.02T	0.710	<0.001
	12	8	none	Rising	SSC = -31.6 + 3.28T	0.996	<0.001
	12	9	none	Middle	SSC = 85.8 + 3.17T	0.984	<0.001
	12	14	none	Recession	SSC = 53.6 + 2.74T	0.866	<0.001

The regression statistics demonstrate an SSC versus turbidity relationship that justifies turbidity being used as a predictor of SSC in the Little Creek watershed, if used on an event basis and if a sufficient number of data points are available. In addition, only events where data is available for rising, peak, and recession portions of the hydrograph are used to estimate event loads. A total of two SSC versus turbidity regressions at the South Fork and two SSC versus flow regressions at the Upper North Fork produced R^2 coefficients less than 0.5, indicating over 50% of the variability in these regressions cannot be explained by the regression equation. Any event regression displaying an R^2 value less than 50% was permissible if 1) a relatively small number of points were being estimated, or 2) the estimated points contributed a small portion of the total event load, or 3) a visual assessment confirmed reasonable predicted values. For example, the 2001/2002 event #4 regression for the South Fork displays an R^2 of 0.404, but only one SSC value in an extended event required estimation, with the estimated point contributing 3% of the total event load. Similarly, estimated loads for the South Fork 2001/2002 event #7 rising limb (R^2 = 0.402) and the Upper North Fork 2002/2003 event #1 rising limb contributed 2% and <1% of the total event loads, respectively. The performance of all regression equations, regardless of associated R^2, were visually assessed by comparing fits to existing values to ensure proper estimation of missing SSC values.

Occasionally, using the turbidity threshold sampling logic, there may be too few SSC points to enable a valid turbidity versus SSC regression. In such situations, the regression equations from surrounding events may be used to estimate the small events (Lewis et al., 2001). This situation arose in a total of two events for the North

Fork, five events for the South Fork, and one event for the Upper North Fork (Tables 5-4, 5-5, and 5-6). In no case was the surrounding event separated by more than a few days time.

Additionally, there are a few larger events missing hourly water quality samples. For these events, samples are missing for a relatively small period in an otherwise extended event. There is the potential to predict SSC based on flow, though this is not as desirable because SSC versus flow can contain up to 100 times greater variability than SSC versus turbidity (Lewis, 1998). However, for those events when a very small number of hourly samples (e.g. <3) do not have turbidity and are preventing a complete event load calculation, then the SSC versus flow relationship is utilized. To ensure the greater variability of the SSC versus flow relationship is not strongly affecting an event load calculation, missing SSC values based on flow are not filled in for highly influential portions of an event, such as within 2 hours of the peak. If turbidity data are missing during the peak of an event then the event is omitted from the final analysis. Flow was used to predict missing SSC values for four events at the NF, two events at the SF, and two events at the UNF.

In tables 5-4, 5-5, and 5-6, some events required a natural log transformation of the SSC and turbidity data. This transformation is performed after each SSC versus turbidity dataset is tested for conformity to the basic assumptions of a regression. A regression is performed using the raw (non-transformed) datapoints and several plots are generated to evaluate three basic assumptions of a regression: 1) Homogeneity of variance, 2) normality of error, and 3) linearity/additivity (Grafen and Hails, 2002). If any of these regression assumptions are violated, test statistics such as the correlation coefficient (R^2) and the p-value of the F-test may not be valid to assess the confidence of the correlation.

Homogeneity of variance is assessed by first determining the residuals of the regression and then plotting the residuals versus the fitted values of the regression line. This scatter plot should display approximately equal variance throughout the range of fitted values. Unequal variance indicates heterogeneity of variance and some transformation is needed.

Normality of error can be assessed by examining a histogram of the residuals. The histogram should be symmetric to indicate a normal distribution of residuals. A dataset with relatively few large values will often display non-normality of error evidenced by a right-skew of the distribution. An additional method to assess normality is by normal probability plots. A normal probability plot compares the standardized residuals to their Normal scores. If the assumption of normality is valid, the plot should approximate a straight line. A concave downward plot would indicate left-skewed data while a convex upward plot would indicate right-skewed data. Transformations of the variables can correct for non-normality.

Linearity/additivity can be assessed plotting residuals against the fitted values. If the residuals show a pattern of being consistently positive or consistently negative for lower or higher fitted values, then there is likely a problem with linearity.

For the Little Creek dataset, some events required transformations while others did not. Regressions were first performed on the raw data for each event. The residual plots were then examined for potential violations of the regression assumptions. If any assumptions were violated then natural log transformations were performed and assumptions were improved. Events with a large number of low turbidity/SSC datapoints relative to the number of high datapoints were more likely to violate the regression assumptions and require some transformation. Heterogeneity of variance was a common violation for these datasets that was evident by residual variance that increased with the fitted values.

An additional consideration in assessing the validity of a regression is to ensure the residuals are independent. If the residuals are not independent then the dataset exhibits autocorrelation, which often can be an issue with time series data. The effect of autocorrelation is that regression coefficient estimates are no longer the most efficient possible and that the sample variance may significantly underestimate the population variance (Helsel and Hirsch, 2002). A method of testing for the presence of autocorrelation is the Durban-Watson statistic. The statistic is compared to two values, d_L and d_U, to determine if autocorrelation exists. If the statistic is below d_L then there is evidence autocorrelation exists, if the statistic is above d_U then there is evidence autocorrelation does not exist, and if the statistic is between d_L and d_U then the test is inconclusive (Durbin and Watson, 1951). The presence of autocorrelation based on the Durbin-Watson statistic was only detected in a few of the larger events for the event-based SSC versus turbidity regressions. Partitioning a single event and performing separate regressions for the rising and falling limbs of the hydrograph removed the presence of autocorrelation based on the Durbin-Watson statistic.

Event Load Calculation

Events that have complete SSC and flow datasets are analyzed to determine event loads. The total event load is the sum of hourly loads during the defined event. Each hourly load is an extrapolated product of SSC and flow, given by:

$$Load\left({kg}/{hr} \right) = \left(Flow\left(\frac{ft^3}{\sec} \right)\left(\frac{60\sec}{1\min} \right)\left(\frac{60\min}{1hr} \right) \right) \times \left(SSC\left(\frac{mg}{L} \right)\left(\frac{1kg}{1000000mg} \right)\left(\frac{28.3168L}{1\,ft^3} \right) \right)$$

Total event loads for the North Fork, South Fork, and Upper North Fork stations are tabulated in Appendix B-1, B-2, and B-3, respectively.

Event Load Analysis

Event loads tabulated for the North Fork station are paired with event loads from the South Fork and Upper North Fork stations, when available. As referenced in Chapter 2, utilizing event loads improves the number of data points available for analysis. This method is preferred over analyzing annual loads when the number of years of data is limited (Lewis, 2001). The North Fork versus South Fork data (Table 5-7) constitute the paired watershed analysis and the North Fork versus Upper North Fork data (Table 5-8) constitute the nested watershed analysis.

Table 5-7. North Fork versus South Fork event loads for paired watershed comparison.

			NF (279 ha)		SF (109 ha)	
Year	Yearly Event #	Analysis Event #	Load (kg)	Load (kg/ha)	Load (kg)	Load (kg/ha)
2001-2002	2	1	12438	44.5	151	1.4
	4	2	4587	16.4	854	7.8
	5	3	3429	12.3	748	6.8
	7	4	21934	78.6	3975	36.4
2002-2003	1	5	14068	50.4	212	1.9
	2	6	1287	4.6	66	0.6
	3	7	19374	69.4	360	3.3
2003-2004	1	8	546	2.0	26	0.2
	2	9	6250	22.4	78	0.7
	3	10	2168	7.8	35	0.3
	4	11	107017	383.3	6971	63.8
	5	12	49214	176.3	3761	34.4
2004-2005	3	13	159	0.6	11	0.1
	4	14	10411	37.3	1157	10.6
	5	15	3436	12.3	160	1.5
	6	16	791	2.8	114	1.0
	8	17	4102	14.7	1512	13.8
	9	18	911	3.3	289	2.6
2005-2006	1	19	5914	21.2	218	2.0
	3	20	1414	5.1	80	0.7
	4	21	13799	49.4	1946	17.8
	8	22	143	0.5	47	0.4
	9	23	4783	17.1	53	0.5
	12	24	24526	87.8	496	4.5

Table 5-8. North Fork versus Upper North Fork event loads for paired watershed comparison

			NF (279 ha)		UNF (191 ha)	
Year	Yearly Event #	Analysis Event #	Load (kg)	Load (kg/ha)	Load (kg)	Load (kg/ha)
2002 - 2003	1	1	14068	50.4	25337	132.7
	3	2	19374	69.4	18837	98.6
2003-2004	1	3	546	2.0	377	2.0
	2	4	6250	22.4	3567	18.7
	4	5	105052	376.3	56554	296.1
	5	6	49411	177.0	30225	158.2
	6	7	387	1.4	79	0.4
	7	8	1872	6.7	719	3.8
	8	9	486	1.7	195	1.0
2004-2005	4	10	10411	37.3	9568	50.1
	5	11	3436	12.3	2497	13.1
	8	12	4102	14.7	1554	8.1
	14	13	352	1.3	201	1.1
2005-2006	1	14	5914	21.2	7283	38.1
	3	15	1414	5.1	922	4.8
	4	16	13799	49.4	11619	60.8
	6	17	514	1.8	365	1.9
	8	18	143	0.5	54	0.3
	9	19	4783	17.1	2497	13.1
	10	20	13461	48.2	10318	54.0
	11	21	24848	89.0	15226	79.7
	12	22	24526	87.8	19846	103.9

The event loads in the tables have also been unitized on a per unit area (hectare) basis. The per unit area loads (kg/ha) are used for analysis, and are plotted with regression lines in Figure 5-5 (North Fork versus South Fork) and Figure 5-7 (North Fork versus Upper North Fork). This analysis performed using per unit area loads yields regression results identical to using total event loads. Residual plots associated with each regression are plotted in Figure 5-6 (North Fork versus South Fork) and Figure 5-8 (North Fork versus Upper North Fork). The residual plots indicate problems with the regressions of the non-transformed data.

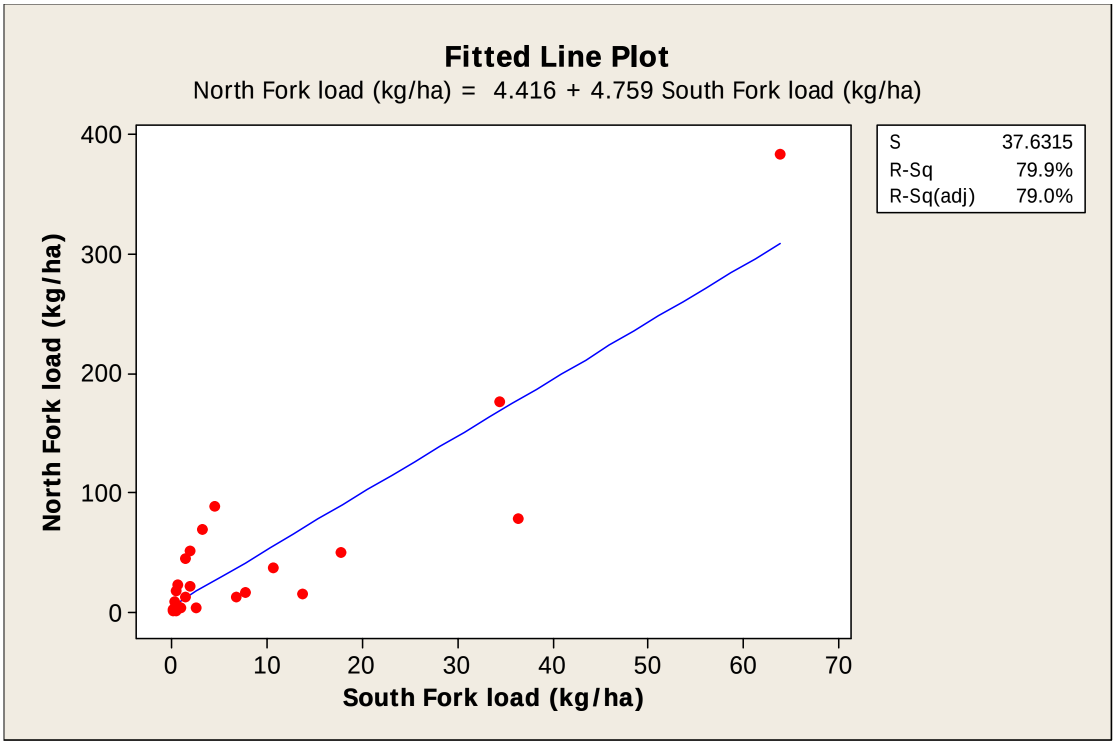

Figure 5-5. Regression plot of North Fork load versus South Fork load, using non-transformed data.

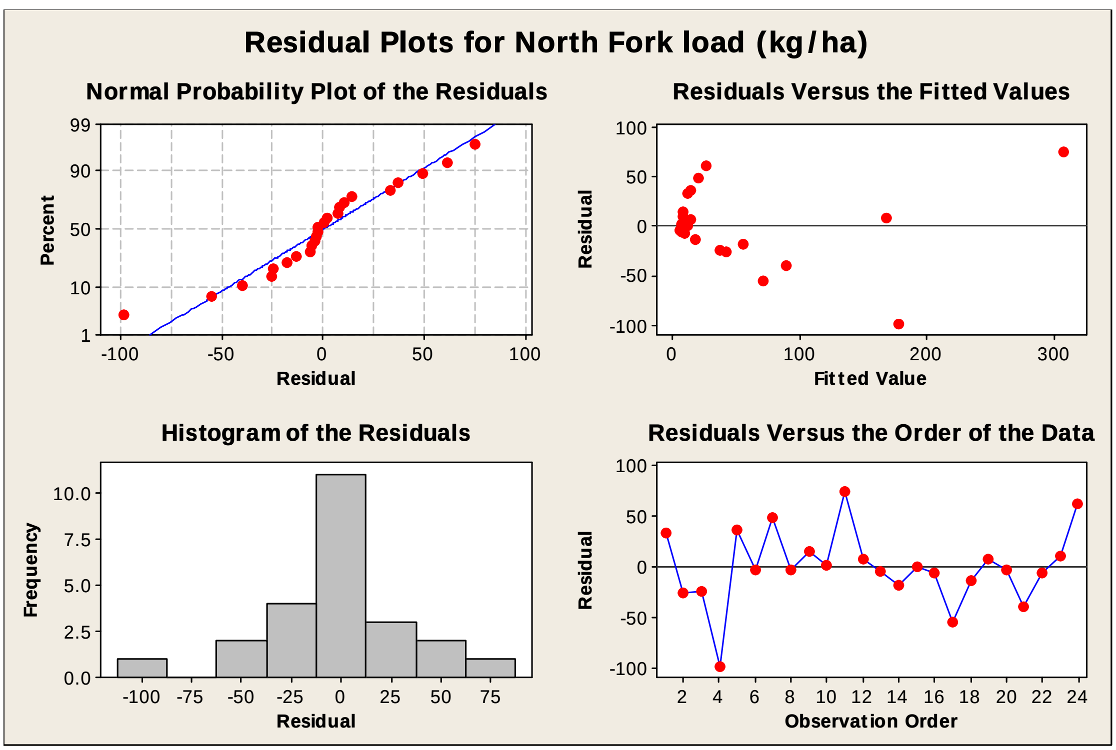

Figure 5-6. Residual plots from North Fork load versus South Fork load, using non-transformed data and indicating violations of regression assumptions.

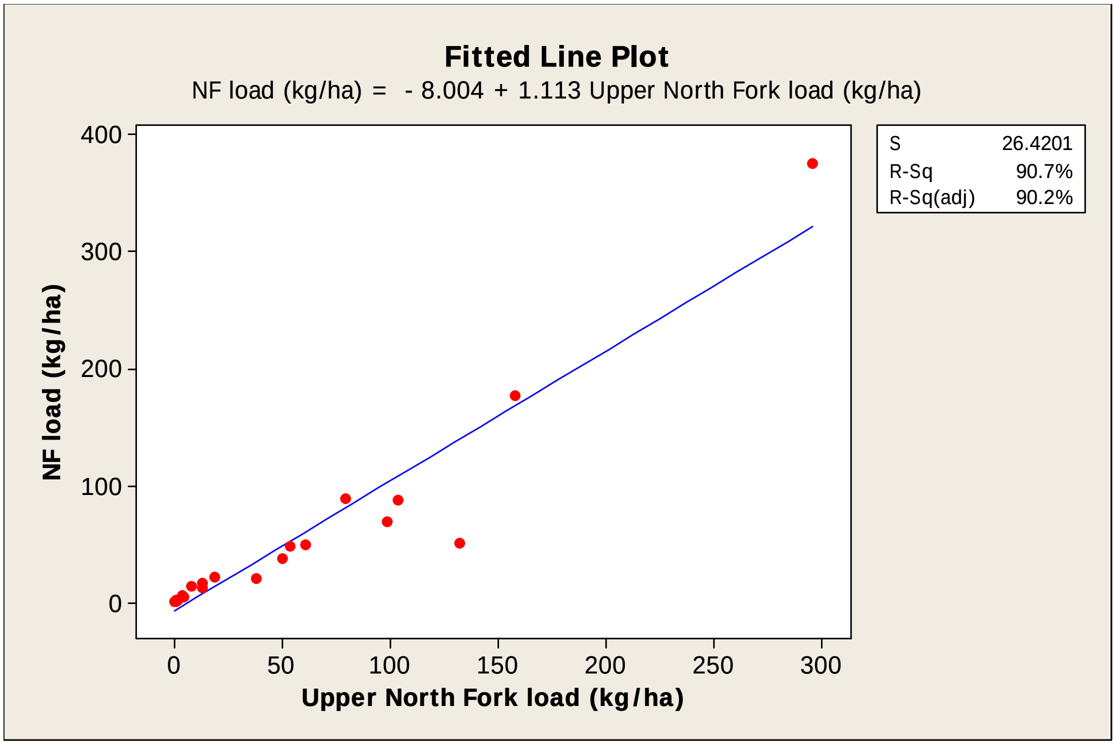

Figure 5-7. Regression plot of North Fork load versus Upper North Fork load, using non-transformed data.

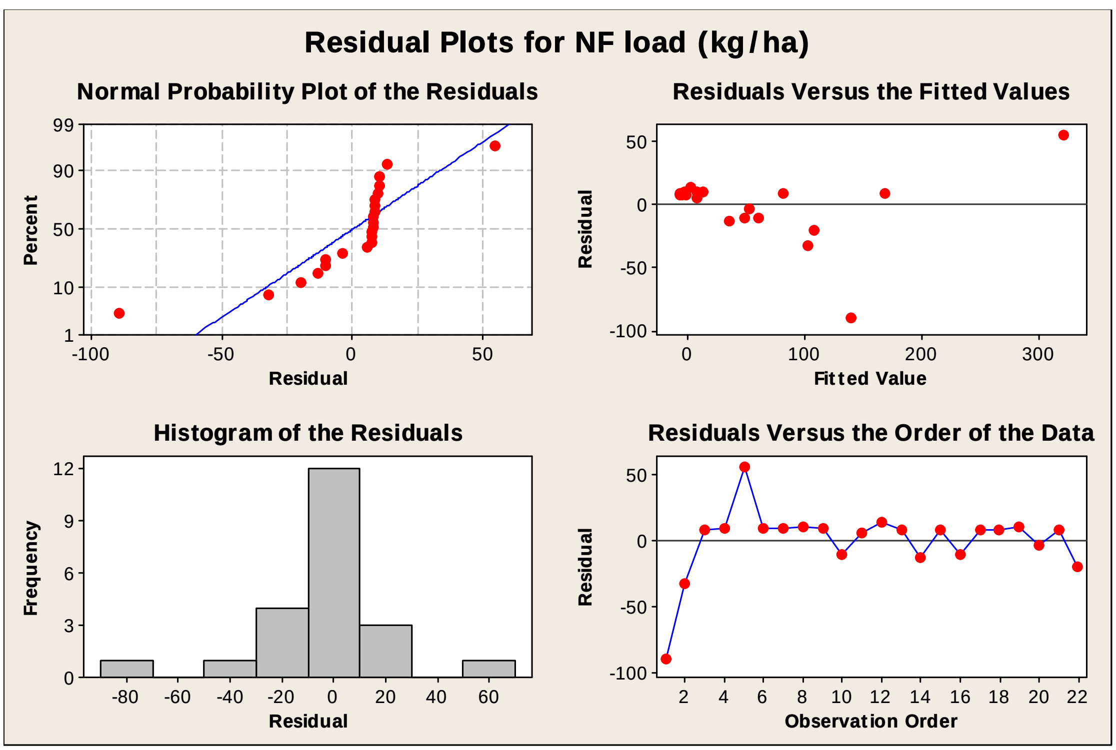

Figure 5-8. Residual plots from North Fork load versus Upper North Fork load, using non-transformed data and indicating violations of regression assumptions.

The fitted-line regression plots reveal the grouping of data points near the reduced load levels. This grouping is a result of a majority of the sampled events being more common smaller storms while only a few larger storms can be captured. An examination of the associated residual plots reveals that multiple regression assumptions are violated, thereby invalidating the correlation coefficients and any other regression statistics. The normal probability plot reveals the problem of non-Normality of error while the residuals versus fitted values plot reveals the problem of heterogeneity of variance. These issues can often be corrected by applying a transformation to both variables (Grafen and Hails, 2002).

<u>Transformations for the North Fork versus South Fork Analysis</u>

To select a transformation, it is recommended to start with the weakest transformation and re-analyze residual plots to determine if the transformation has corrected the regression violations (Grafen and Hails, 2002). The weakest transformation involves performing a square root transformation on only one variable. For the Little Creek dataset, transformations of both x and y variables may be necessary based on the problems revealed in the non-transformed residual plots. To correct for non-Normality and heterogeneity of variance the Y variable must be transformed, and the X variable may require transformation as well.

Transformations of the dataset are attempted to correct the regression violations found using the non-transformed data. An initial attempt is made to only transform the Y variable (North Fork) using a square root transformation. The regression plot is shown in Figure 5-9 and associated residual plots are shown in Figure 5-10. The residual plots reveal persistent non-Normality and heterogeneity of variance. Next, a square root transformation is also applied to the X variable (South Fork) and the new regression is shown in Figure 5-11, with associated residual plots in Figure 5-12. The residual plots indicate that Normality has been achieved while heterogeneity of variance continues to be problematic. Therefore, the stronger natural log transformation is next selected, with only the Y variable transformed initially. The regression and associated residual plots for natural log transformation of the Y variable are shown in Figures 5-13 and 5-14, respectively. Transformation of the Y variable successfully achieved Normality, but failed to achieve homogeneity of variance. Regression and residual plots for natural log transformation of both X and Y variables are shown in Figures 5-15 and 5-16, respectively. Transformations of both X and Y variables successfully achieved both Normality and homogeneity of variance. Therefore, the natural log transformation of both the North Fork event loads and the South Fork event loads is selected for final analysis.

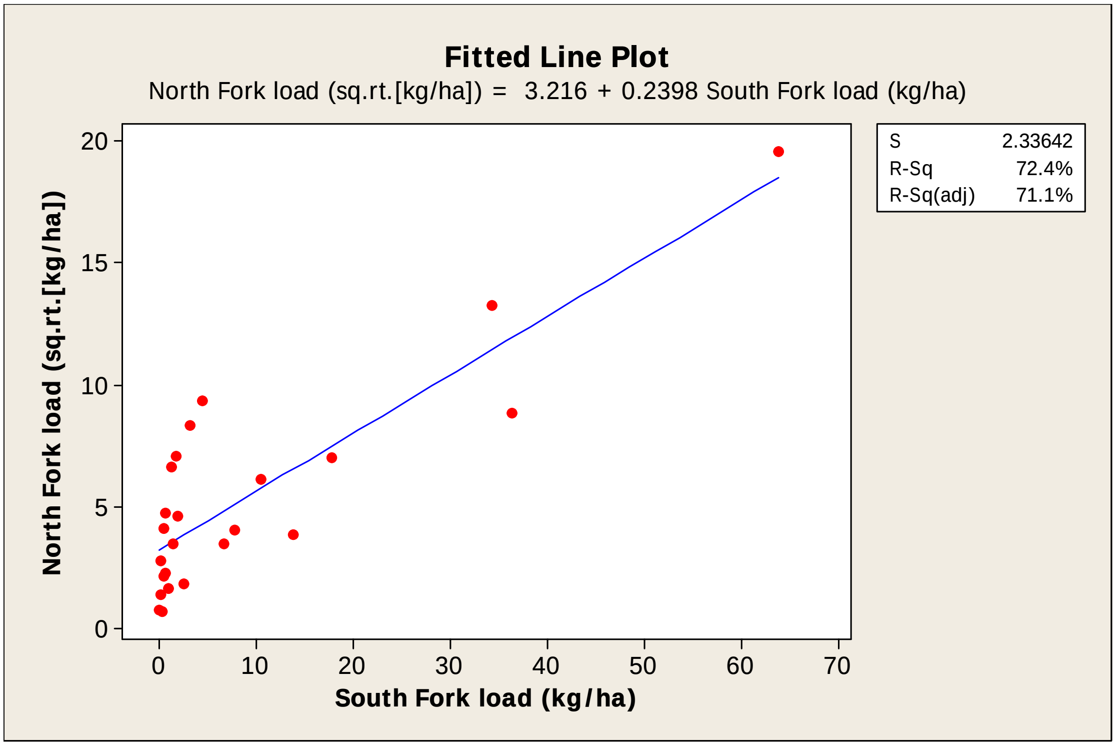

Figure 5-9. Regression plot of North Fork sq.rt.(load) versus South Fork load.

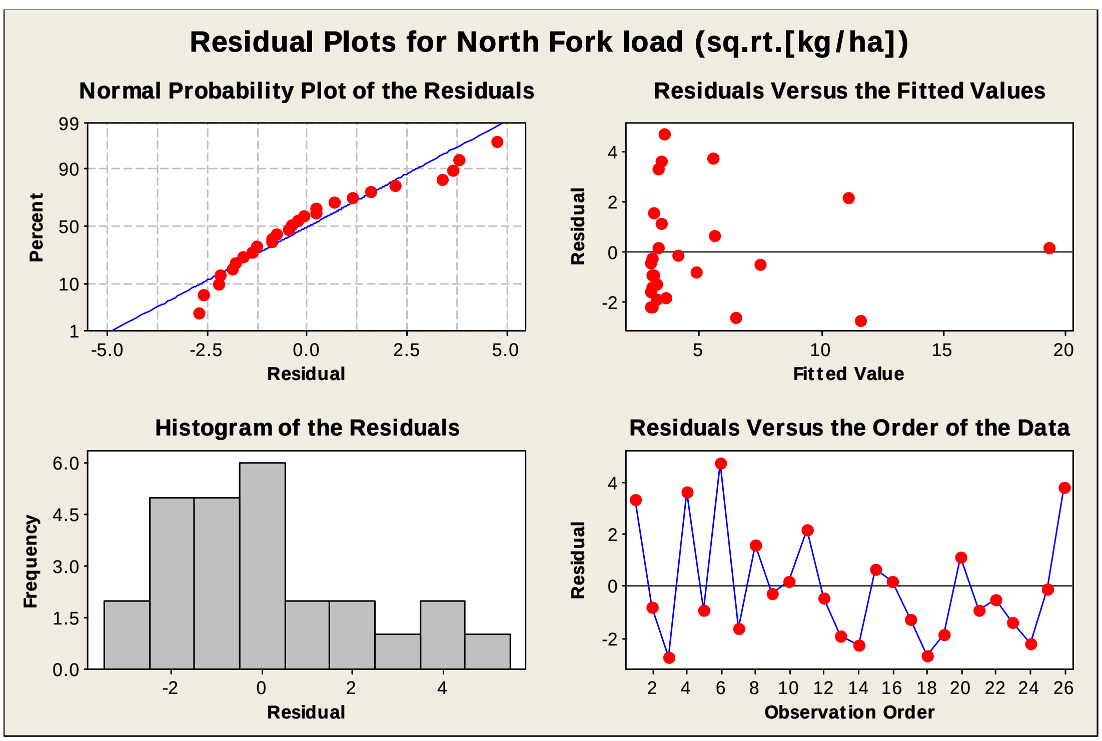

Figure 5-10. Residual plots of North Fork sq.rt.(load) versus South Fork load, indicating violations of regression assumptions.

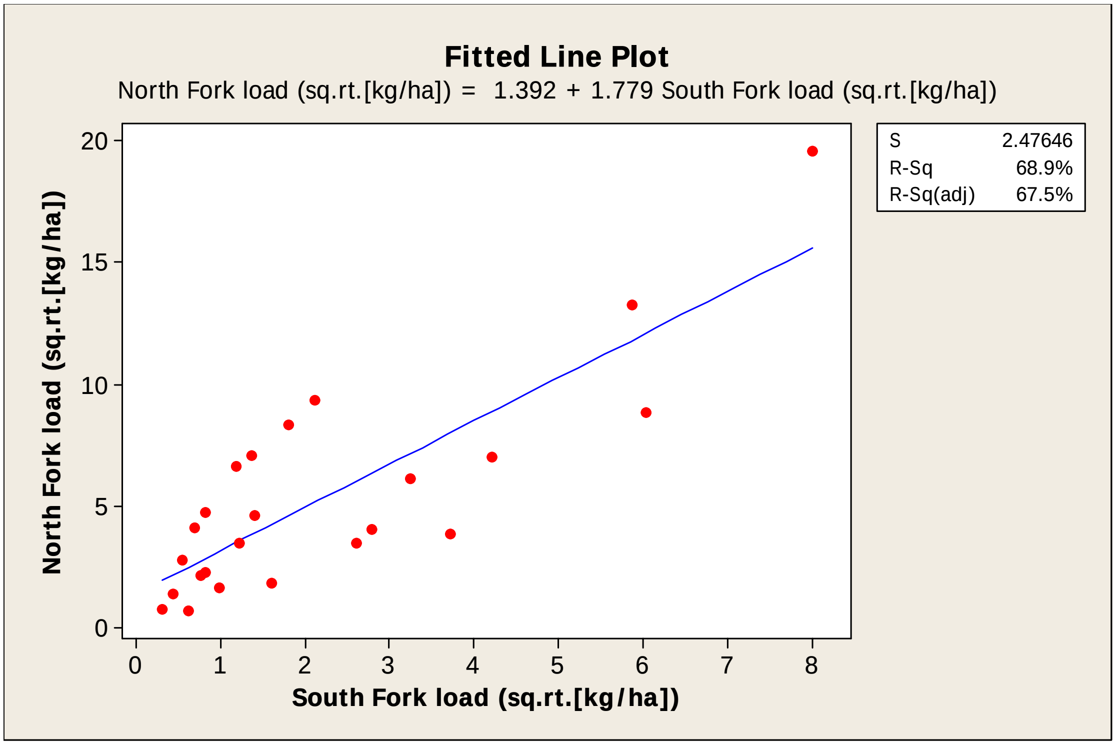

Figure 5-11. Regression plot of North Fork sq.rt.(load) versus South Fork sq.rt.(load).

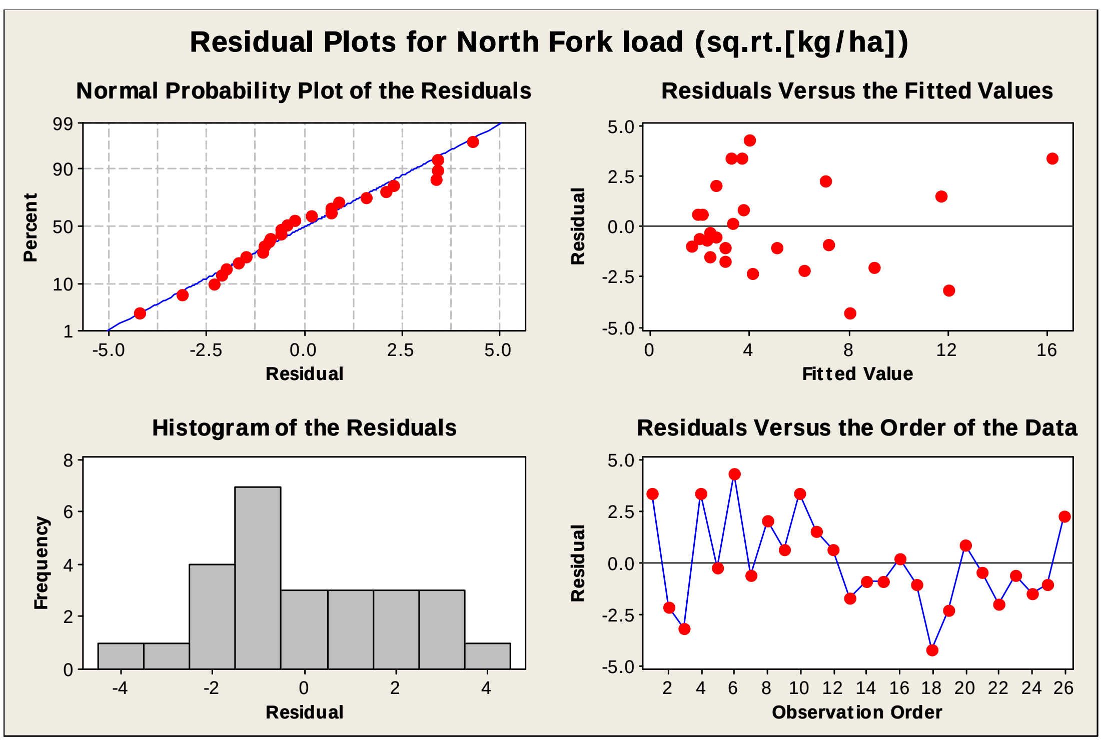

Figure 5-12. Residual plots of North Fork sq.rt.(load) versus South Fork sq.rt.(load), indicating violations of regression assumptions.

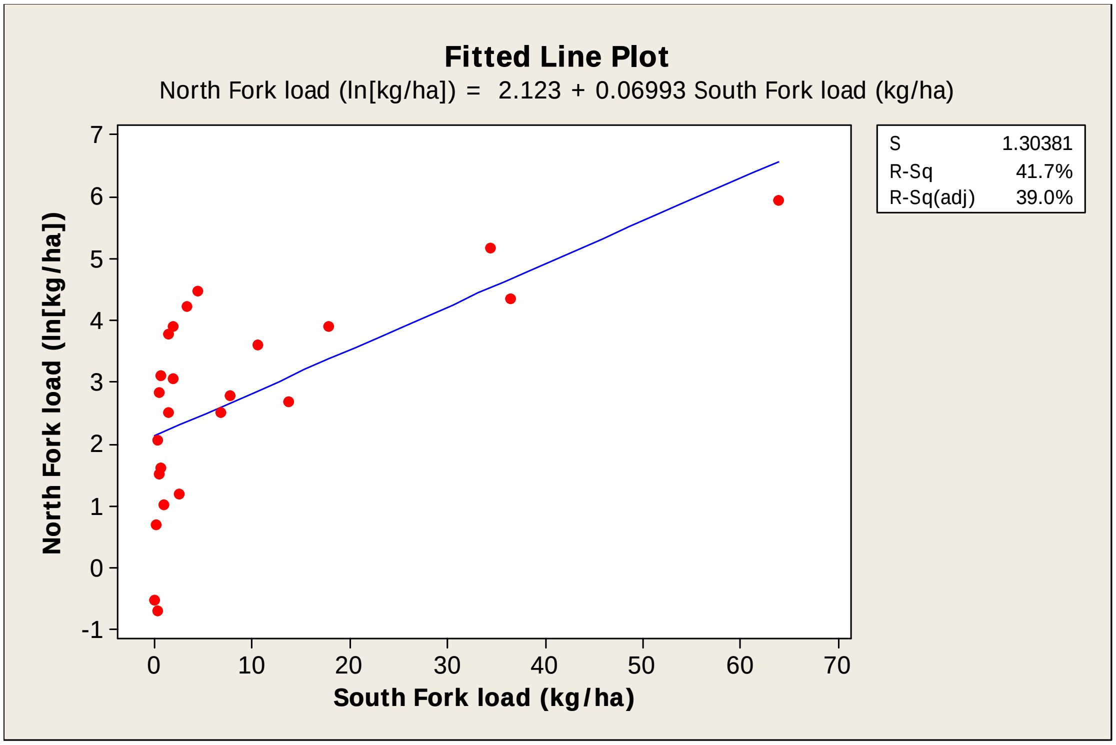

Figure 5-13. Regression plot of North Fork ln(load) versus South Fork load.

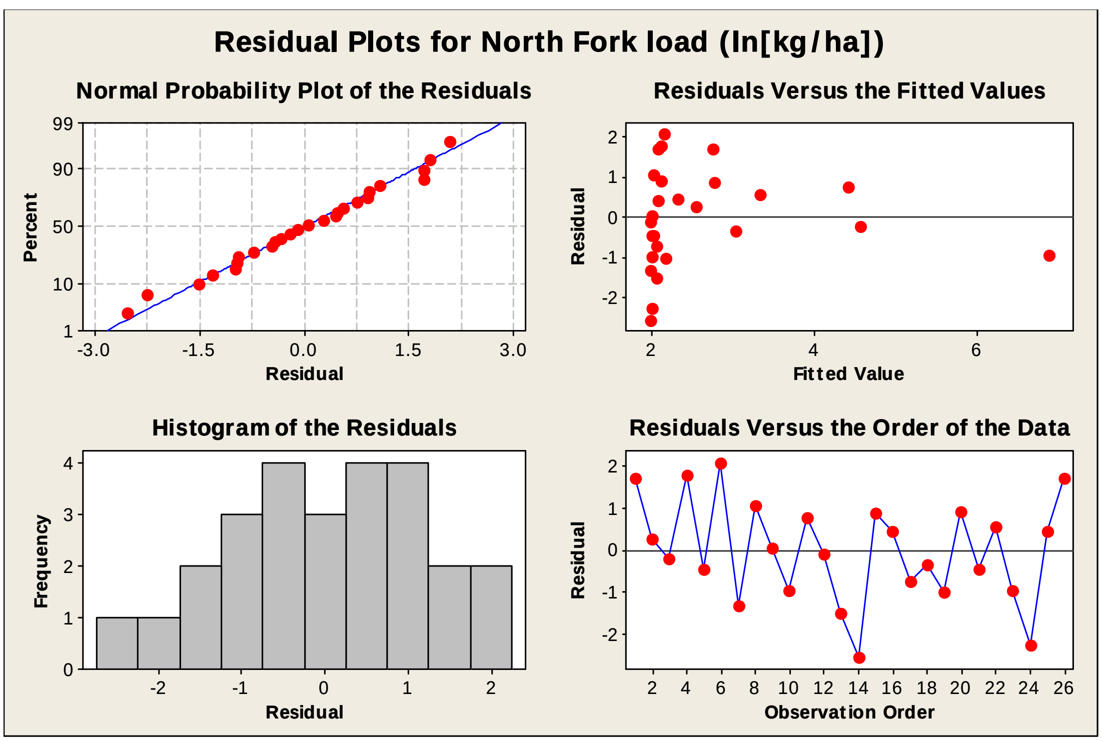

Figure 5-14. Residual plots of North Fork ln(load) versus South Fork load, indicating violations of regression assumptions.

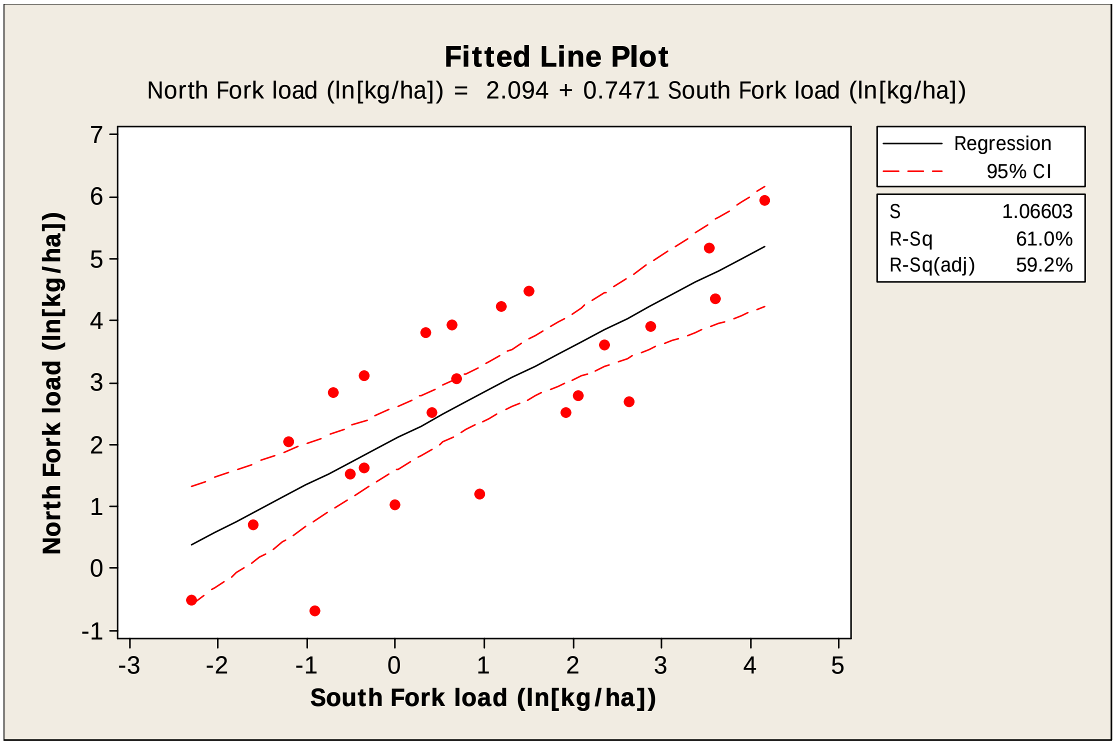

Figure 5-15. Regression plot of North Fork ln(load) versus South Fork ln(load).

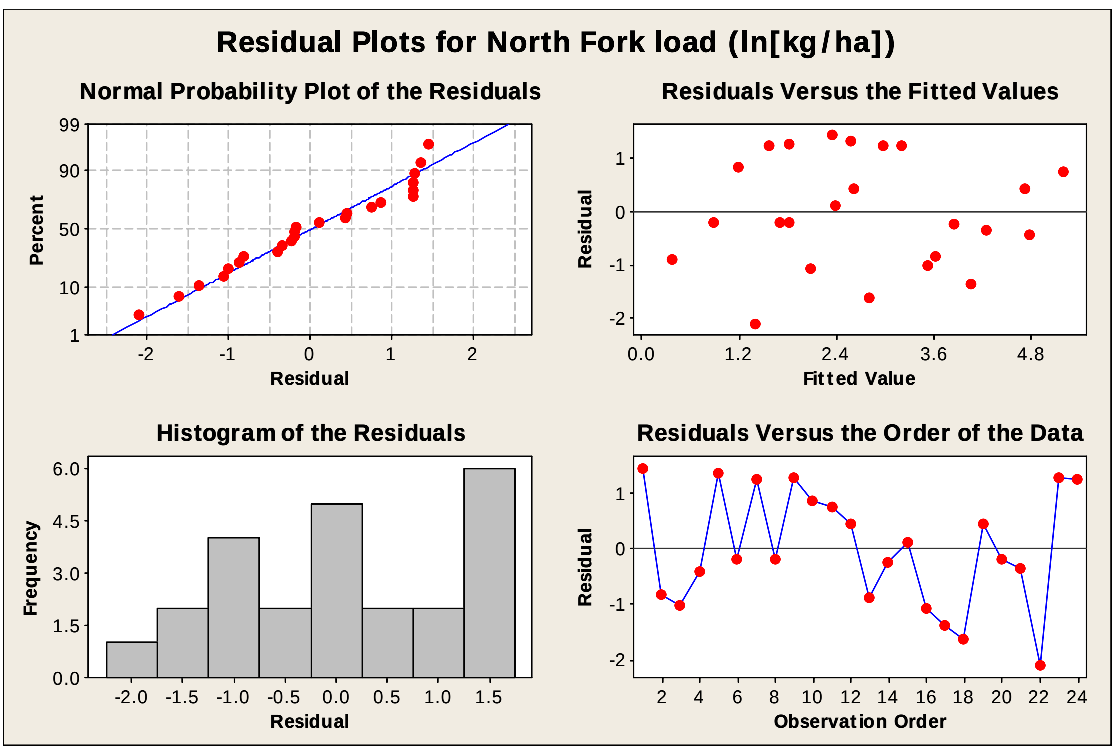

Figure 5-16. Residual plots of North Fork ln(load) versus South Fork ln(load), indicating regression assumptions have been met.

Transformations for the North Fork versus Upper North Fork Analysis

The same stepwise procedure used for selecting a transformation for the North Fork versus South Fork analysis is used to select a transformation for the North Fork (Y variable) versus Upper North Fork (X variable) analysis. A square root transformation of the Y variable is first selected, with the regression plot shown in Figure 5-17 and associated residual plots shown in Figure 5-18. Non-Normality appears to still be problematic and heterogeneity of variance is strongly problematic. Next, square root transformations of both variables are attempted with the regression plot shown in Figure 5-19 and the associated residuals plot shown in Figure 5-20. Both non-Normality and heterogeneity of variance are problematic. A natural log transformation of the Y variable is selected next, with regression and associated residual plots shown in Figures 5-21 and 5-22, respectively. Both non-Normality and heterogeneity of variance continue to be a problematic. Next, both variables are natural log transformed and the regression and associated residual plots are shown in Figures 5-23 and 5-24, respectively. This transformation of both variables successfully achieved both Normality and homogeneity of variance. Therefore, the natural log transformation of both the North Fork event loads and the Upper North Fork event loads is selected for final analysis.

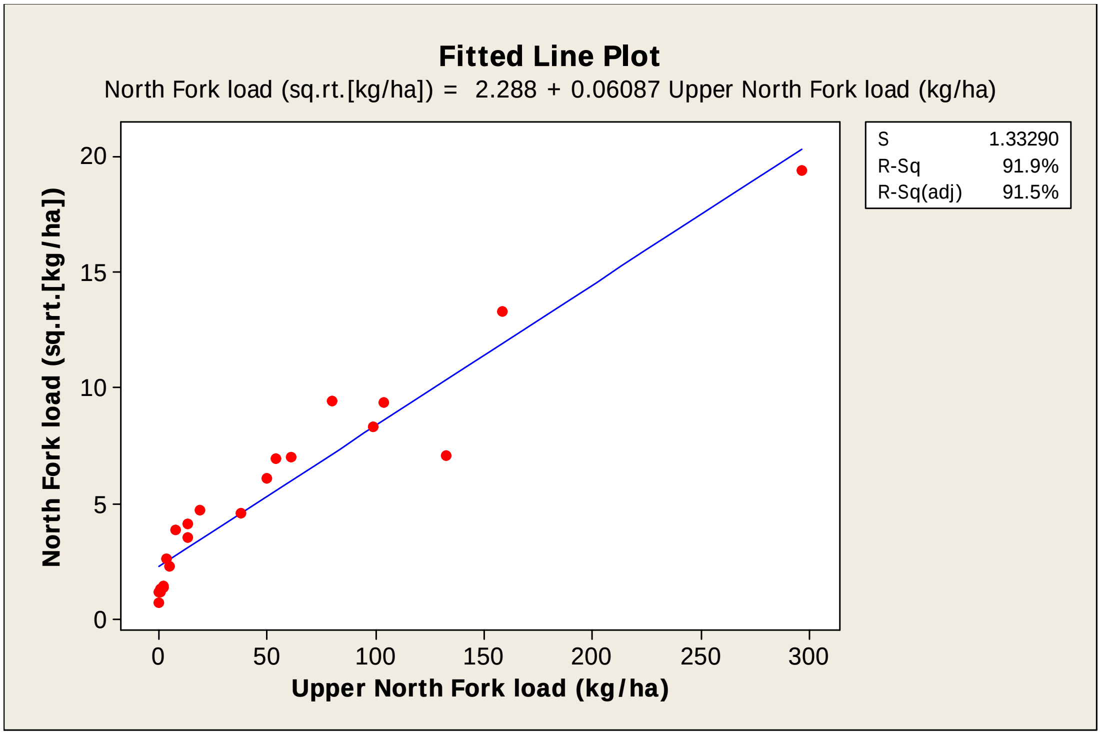

Figure 5-17. Regression plot of North Fork sq.rt.(load) versus Upper North Fork load.

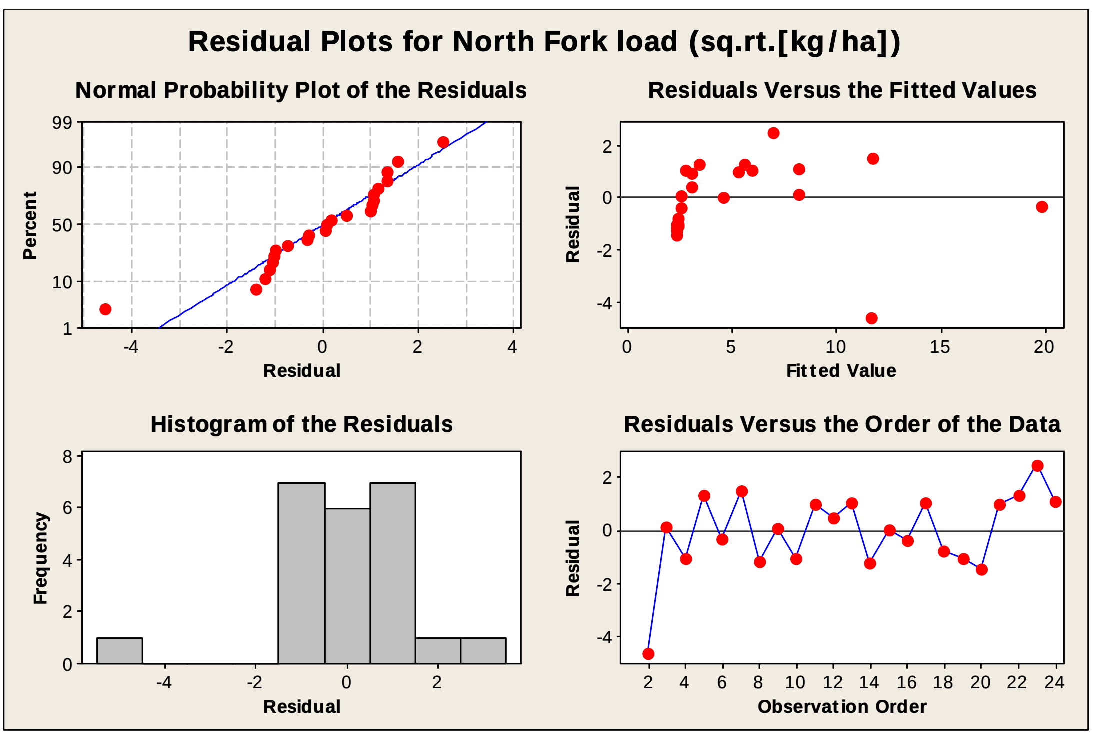

Figure 5-18. Residual plots of North Fork sq.rt.(load) versus Upper North Fork load, indicating violations of regression assumptions.

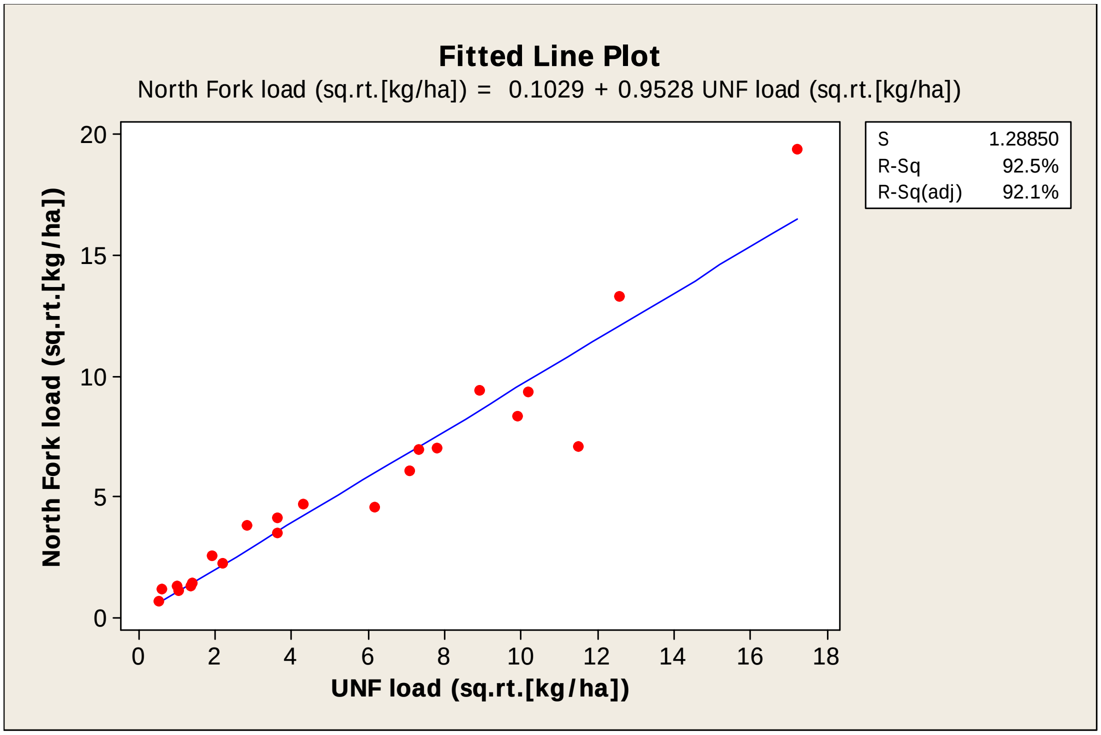

Figure 5-19. Regression plot of North Fork sq.rt.(load) versus Upper North Fork sq.rt.(load).

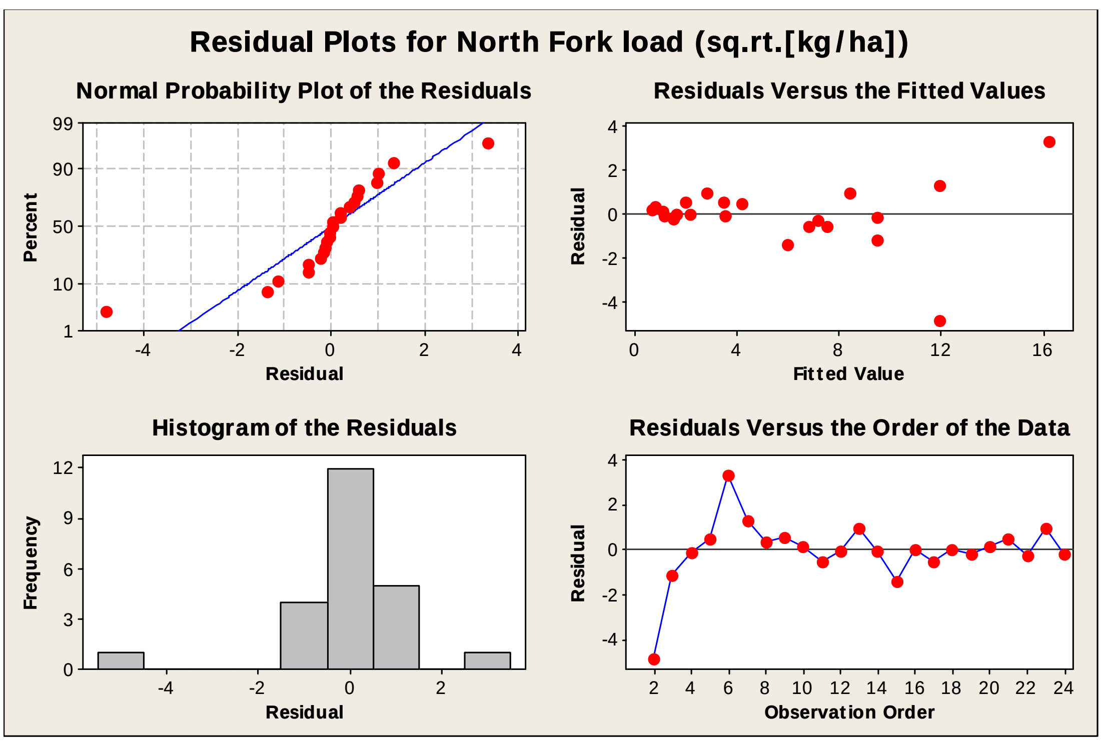

Figure 5-20. Residual plots of North Fork sq.rt.(load) versus Upper North Fork sq.rt.(load), indicating violations of regression assumptions.

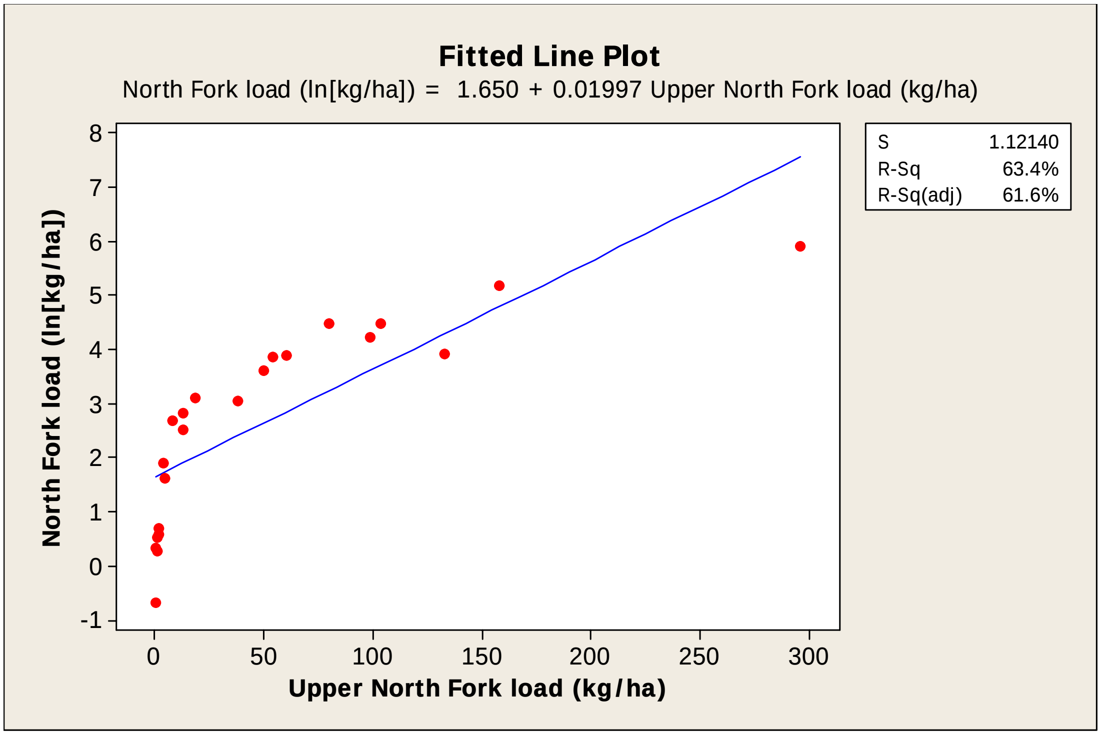

Figure 5-21. Regression plot of North Fork ln(load) versus Upper North Fork load.

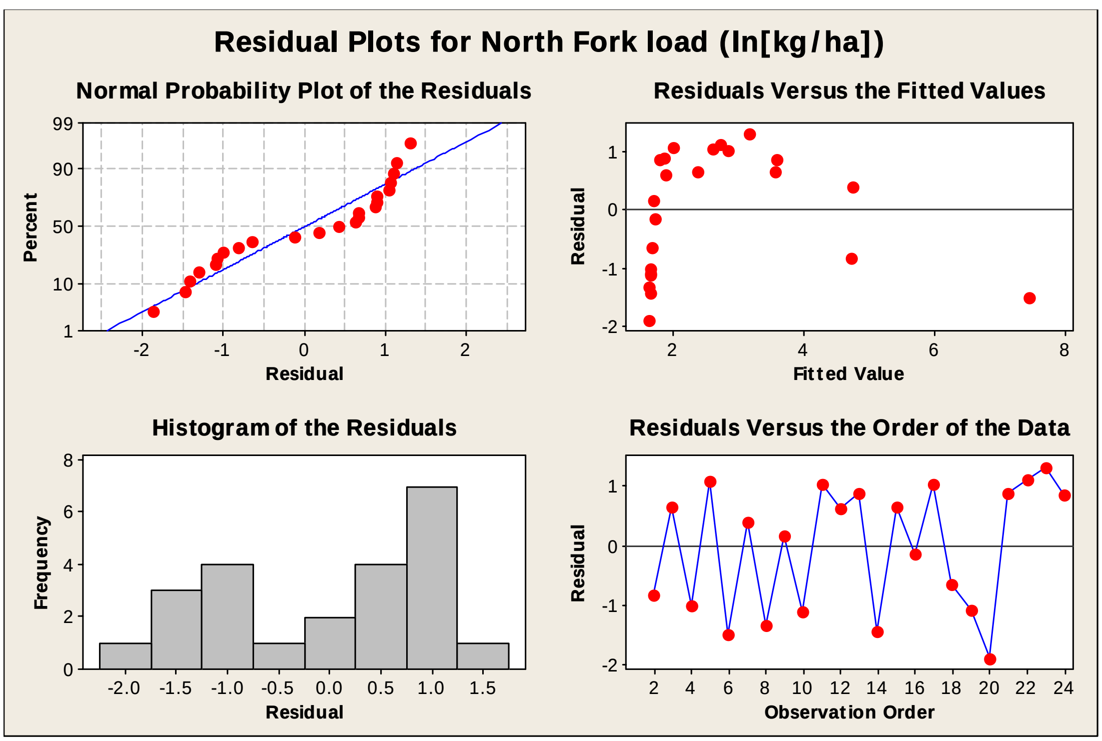

Figure 5-22. Residual plots of North Fork ln(load) versus Upper North Fork load, indicating violations of regression assumptions.

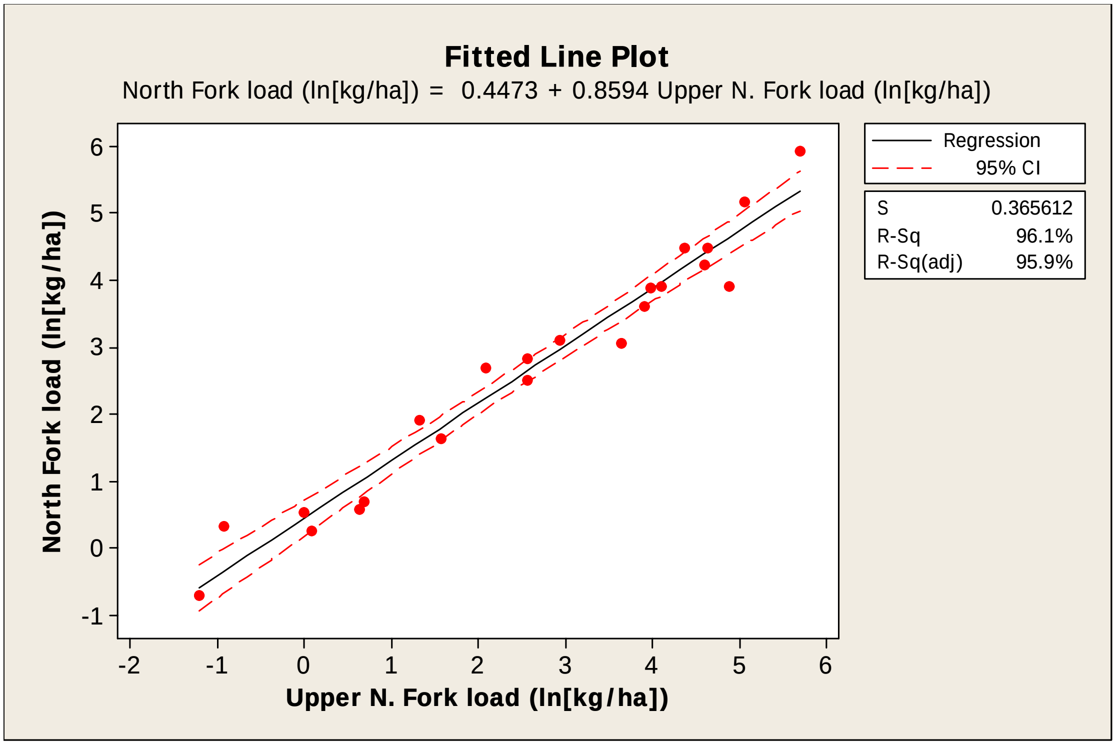

Figure 5-23. Regression plot of North Fork ln(load) versus Upper North Fork ln(load).

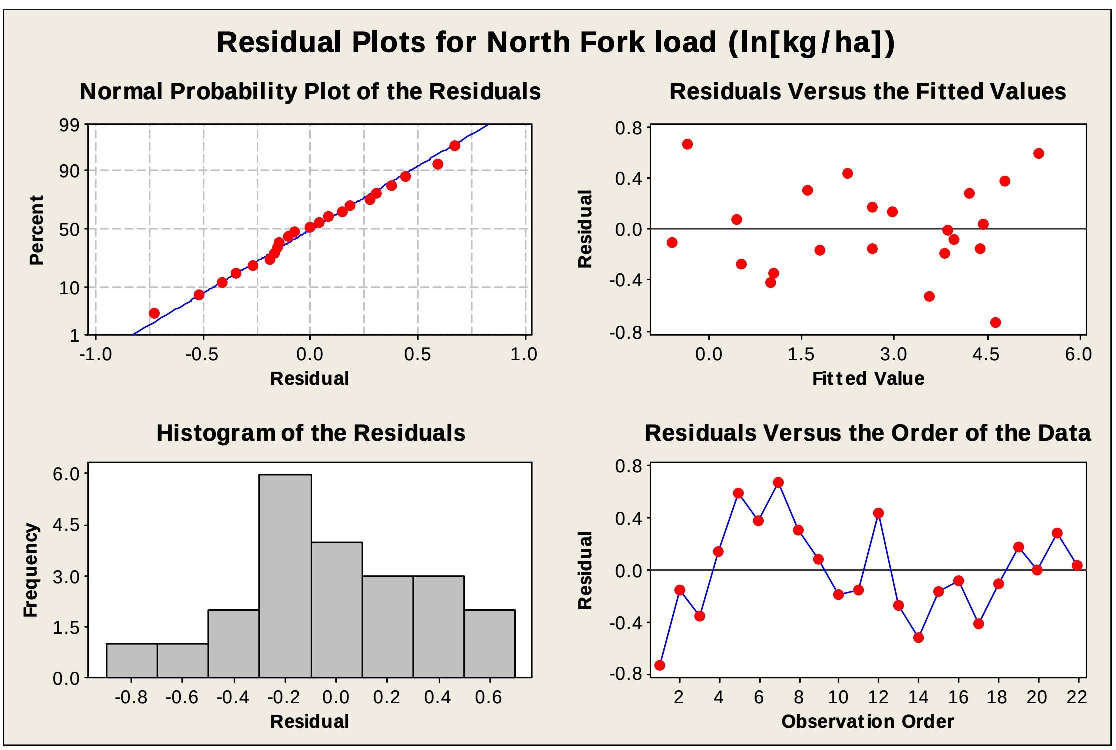

Figure 5-24. Residual plots of North Fork ln(load) versus Upper North Fork ln(load), indicating regression assumptions have been met.

Summary of Transformations and Regressions

Values of R^2 cannot be compared between the different transformation regression plots, as each model is attempting to predict a different variable (Helsel and Hirsch, 2002). The strength of the R^2 for the non-transformed regressions was not valid due to the violations of the regression assumptions. The R^2 values associated with the final regressions utilizing a natural log transformation of both X and Y variables are valid. The adjusted R^2 value of 0.96 for the North Fork versus Upper North Fork regression is considerably higher than the adjusted R^2 value of 0.59 for the North Fork versus South Fork regression. A high level of significance is associated with both final regressions (NF versus SF $p\text{-value}<0.001$ for the F-test at $\alpha=0.05$, NF versus UNF $p\text{-value}<0.001$ for the F-test at $\alpha=0.05$). The residual plots reveal the transformations were effective at resolving non-Normality of error and heterogeneity of variance problems. The residuals of each regression were also tested for autocorrelation using the Durbin-Watson statistic. No evidence was detected of the presence of autocorrelation in the either data series.

The confidence intervals for each regression differed considerably with the North Fork versus Upper North Fork regression resulting in a much narrower confidence interval compared to the North Fork versus South Fork regression. The difference in confidence interval size is largely due to the higher standard deviation of the North Fork versus South Fork regression.

Paired and Nested Change Detection

A visual assessment of Figures 5-15 and 5-23 provides the appearance that small changes between the North Fork and Upper North Fork will be easier to detect than changes between the North Fork and South Fork. The confidence interval can help establish the magnitude of change capable of being detected in the post-harvest period. A narrower confidence interval enables smaller magnitudes of change to be detected. A quantifiable assessment of the magnitude of change detectable is more complex than finding the difference between the confidence interval and regression line. The confidence interval for the transformed data is only valid for the regression line of the transformed data. Simple back-transformation of the confidence interval into non-logarithmic numbers is not valid (Helsel and Hirsch, 2002). However, an alternative to transforming the confidence interval is to generate a synthetic dataset that represents a percentage increase in the original data. The new dataset is then transformed and new regression lines are produced and compared to the original regressions. An assessment of where the new regression line falls in relation to the confidence interval of the original data can then be made.

Detectable change for North Fork versus South Fork Paired Watershed Study

Example percentage increases in suspended sediment load at the North Fork for the North Fork versus South Fork paired watershed study is shown in Table 5-9. Table 5-9 lists the original data and various theoretical percentage increases (30%, 50%, 70%, 90%, and 110%) generated for all events measured to date at the North Fork station, while the South Fork loads are held constant. New regressions performed for the theoretical increases are plotted in relation to the original regression and associated 95% confidence interval in Figures 5-25, 5-26, 5-27, 5-28, and 5-29. The theoretical increases start at 30 percent because the new regression line falls well within the domain of the original confidence interval at that percentage increase. Change is difficult to confidently detect throughout a majority of the dataset range until increases at the North Fork exceed 90 percent. Once increases exceed 90 percent, the new regression line is visually exceeding the original confidence interval. The assessment is complicated, however, by the curvature of the confidence interval, forcing changes at the ends of the data range to be relatively greater for detection.

Table 5-9. Theoretical North Fork load increases for the NF versus SF analysis.

Theoretical North Fork Load Increases						
Analysis Event #	Existing Load (kg/ha)	+ 30% Existing Load (kg/ha)	+ 50% Existing Load (kg/ha)	+ 70% Existing Load (kg/ha)	+ 90% Existing Load (kg/ha)	+ 110% Existing Load (kg/ha)
1	44.5	57.9	66.8	75.7	84.6	93.6
2	16.4	21.4	24.6	27.9	31.2	34.5
3	12.3	16.0	18.4	20.9	23.3	25.8
4	78.6	102.1	117.8	133.6	149.3	165.0
5	50.4	65.5	75.6	85.7	95.7	105.8
6	4.6	6.0	6.9	7.8	8.8	9.7
7	69.4	90.2	104.1	118.0	131.8	145.7
8	2.0	2.5	2.9	3.3	3.7	4.1
9	22.4	29.1	33.6	38.1	42.5	47.0
10	7.8	10.1	11.6	13.2	14.8	16.3
11	383.3	498.3	574.9	651.6	728.3	804.9
12	176.3	229.1	264.4	299.7	334.9	370.2
13	0.6	0.7	0.9	1.0	1.1	1.2
14	37.3	48.5	55.9	63.4	70.8	78.3
15	12.3	16.0	18.5	20.9	23.4	25.8
16	2.8	3.7	4.2	4.8	5.4	5.9
17	14.7	19.1	22.0	25.0	27.9	30.9
18	3.3	4.2	4.9	5.5	6.2	6.9
19	21.2	27.5	31.8	36.0	40.2	44.5
20	5.1	6.6	7.6	8.6	9.6	10.6
21	49.4	64.3	74.1	84.0	93.9	103.8
22	0.5	0.7	0.8	0.9	1.0	1.1
23	17.1	22.3	25.7	29.1	32.5	36.0
24	87.8	114.2	131.8	149.3	166.9	184.5

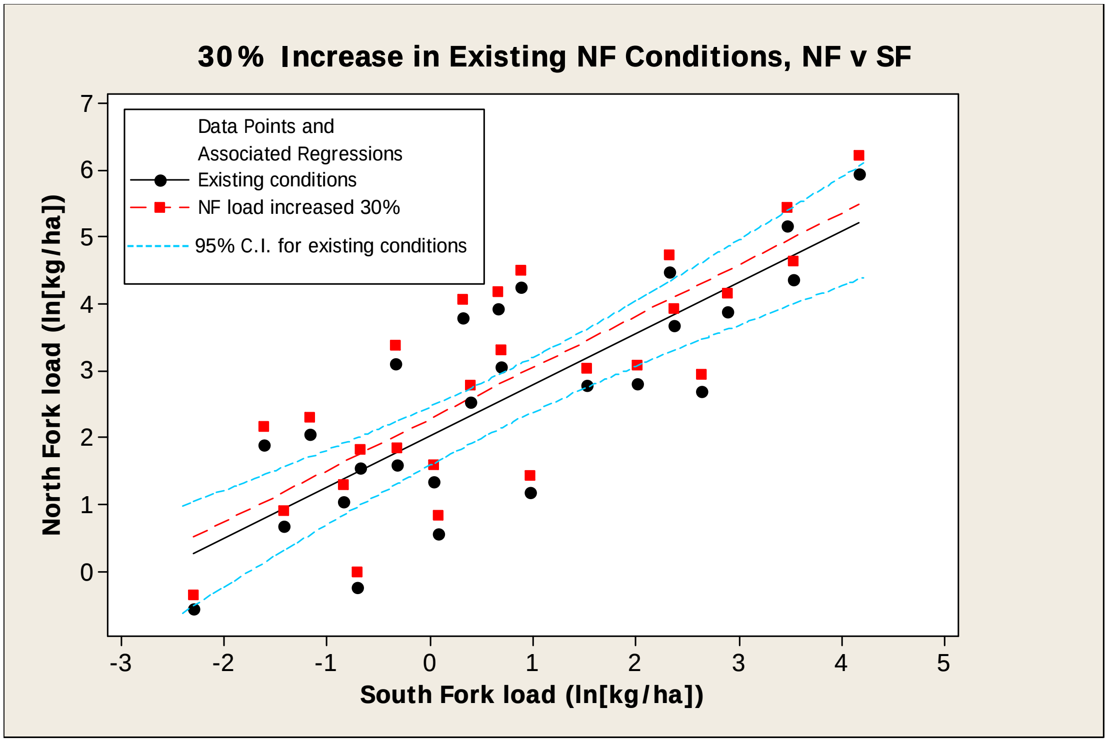

Figure 5-25. 30% NF increase and original NF versus SF regression and confidence interval.

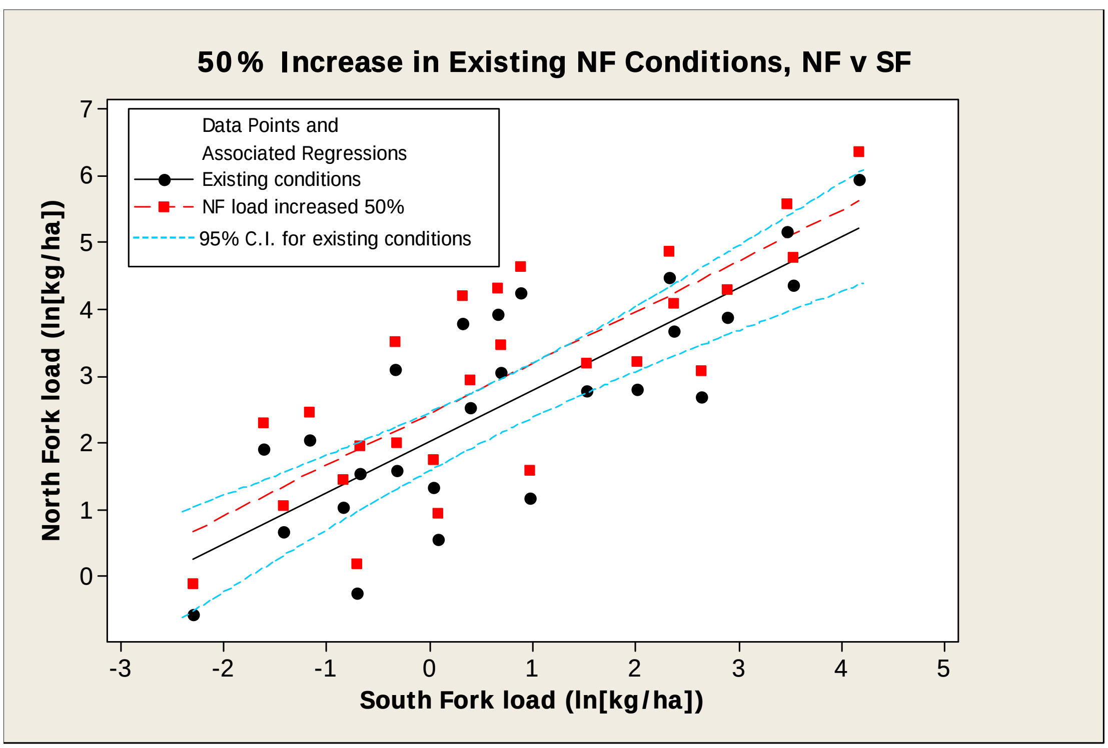

Figure 5-26. 50% NF increase and original NF versus SF regression and confidence interval.

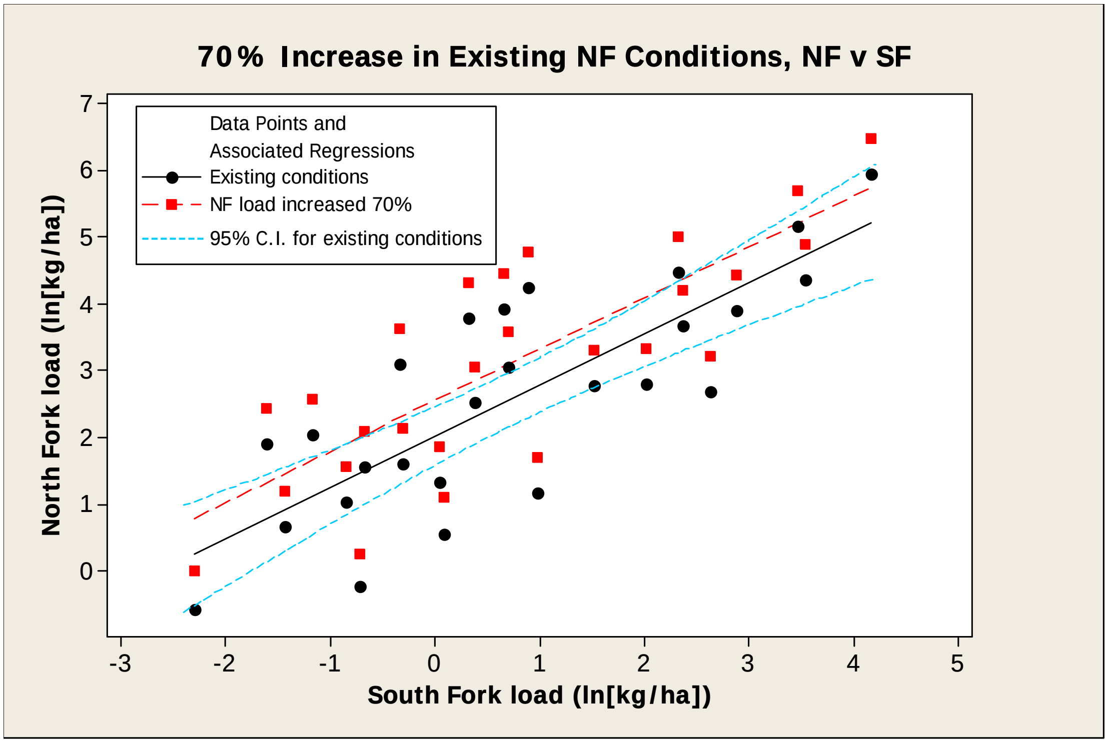

Figure 5-27. 70% NF increase and original NF versus SF regression and confidence interval.

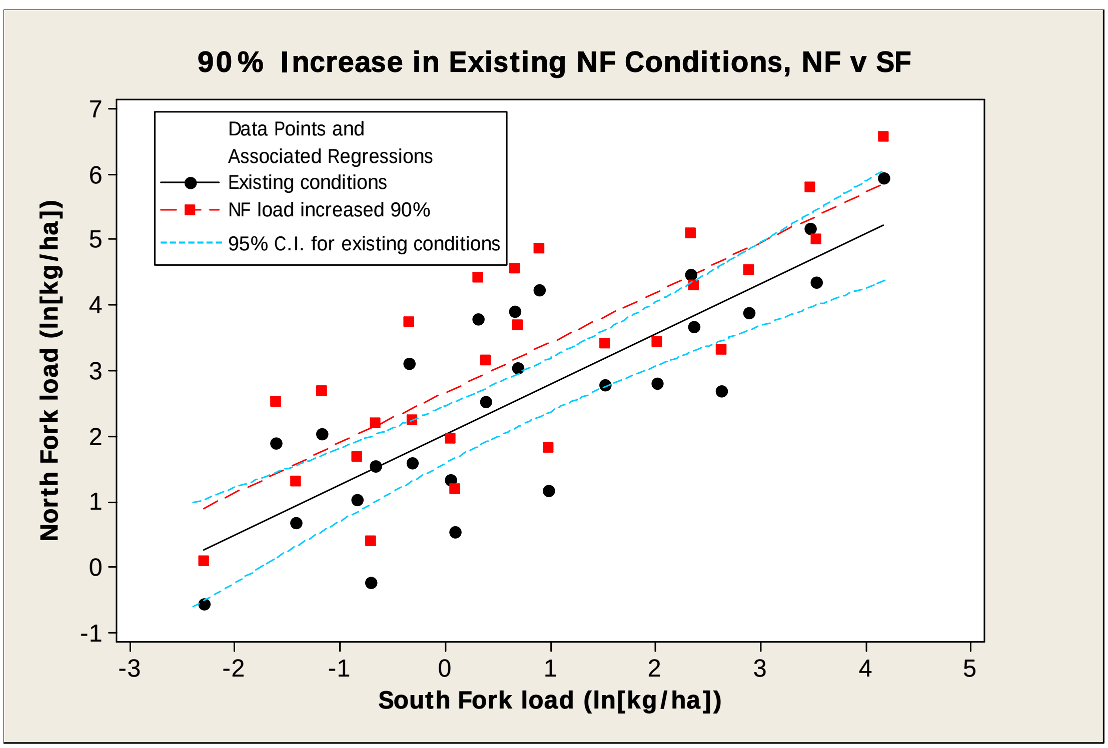

Figure 5-28. 90% NF increase and original NF versus SF regression and confidence interval.

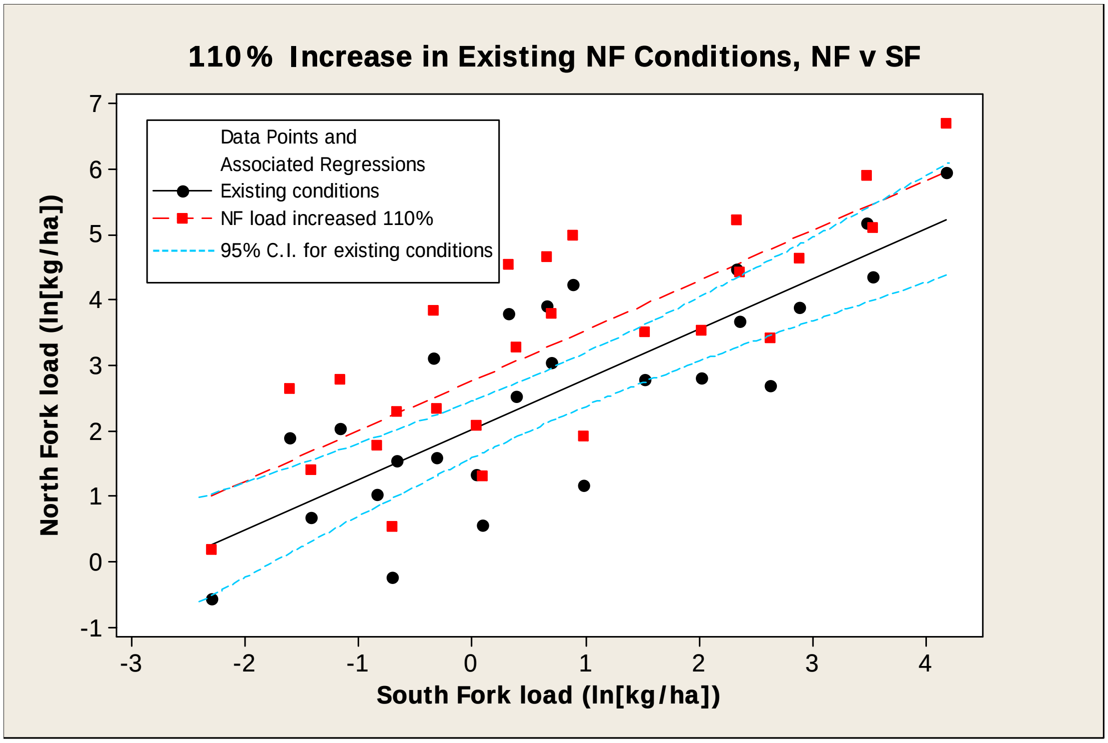

Figure 5-29. 110% NF increase and original NF versus SF regression and confidence interval.

Detectable Change for North Fork versus Upper North Fork Paired Watershed Study

Similar to the previous comparison, example percentage increases in suspended sediment load at the North Fork for the North Fork versus Upper North Fork nested watershed study is shown in Table 5-10. Table 5-10 lists the original data and various percentage increases generated for all events measured to date at the North Fork station, while the Upper North Fork loads are held constant. Example percentage increases are smaller than those used for the North Fork versus South Fork analysis due to the narrower confidence intervals for the North Fork versus Upper North Fork analysis. The new regressions and confidence interval comparisons are shown in Figures 5-30, 5-31, and 5-32. Change becomes detectable when the North Fork sediment load is increased by approximately 30%, as evidenced by the new regression line exceeding the upper limit of the original confidence interval. Curvature of the confidence interval is reduced compared to the North Fork versus South Fork analysis, resulting in a more valid assessment.

Table 5-10. Theoretical North Fork load increases for the NF versus UNF analysis.

Theoretical North Fork Load Increases				
Analysis Event #	Existing Load (kg/ha)	+ 10% Existing Load (kg/ha)	+ 30% Existing Load (kg/ha)	+ 50% Existing Load (kg/ha)
1	50.4	55.4	65.5	75.6
2	69.4	76.3	90.2	104.1
3	2.0	2.2	2.5	2.9
4	22.4	24.6	29.1	33.6
5	376.3	413.9	489.1	564.4
6	177.0	194.7	230.1	265.5
7	1.4	1.5	1.8	2.1
8	6.7	7.4	8.7	10.1
9	1.7	1.9	2.3	2.6
10	37.3	41.0	48.5	55.9
11	12.3	13.5	16.0	18.5
12	14.7	16.2	19.1	22.0
13	1.3	1.4	1.6	1.9
14	21.2	23.3	27.5	31.8
15	5.1	5.6	6.6	7.6
16	49.4	54.4	64.3	74.1
17	1.8	2.0	2.4	2.8
18	0.5	0.6	0.7	0.8
19	17.1	18.8	22.3	25.7
20	48.2	53.0	62.7	72.3
21	89.0	97.9	115.7	133.5
22	87.8	96.6	114.2	131.8

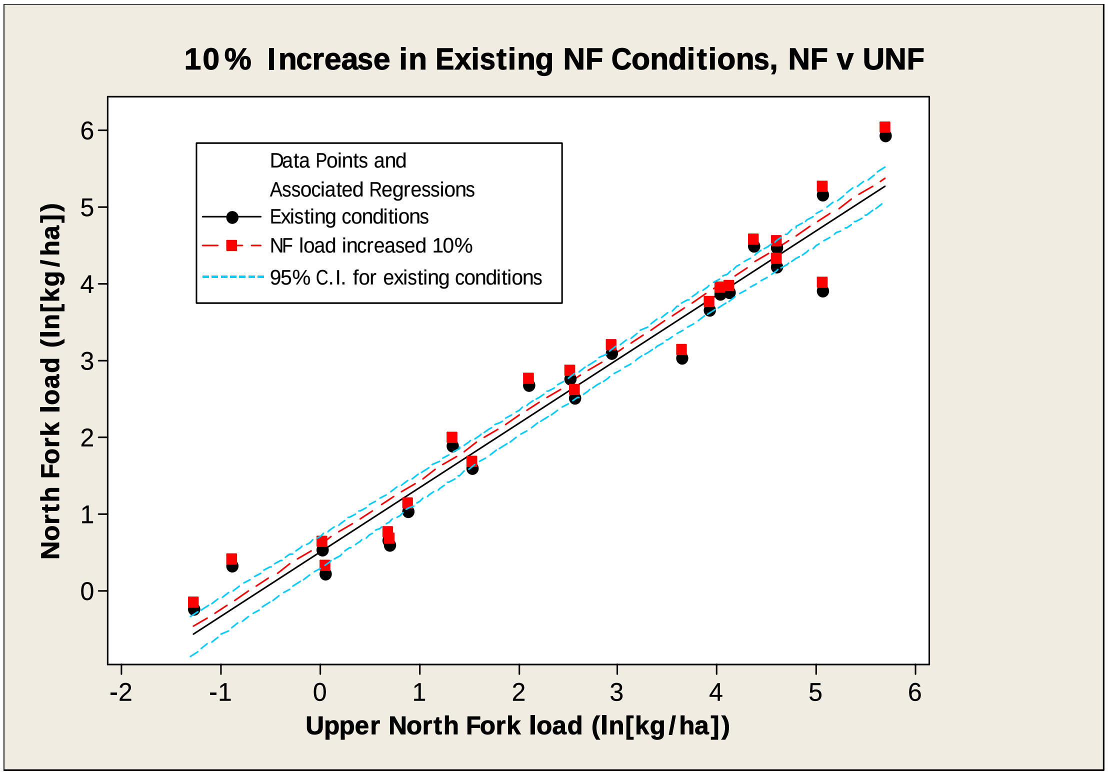

Figure 5-30. 10% NF increase and original NF versus UNF regression and confidence interval.

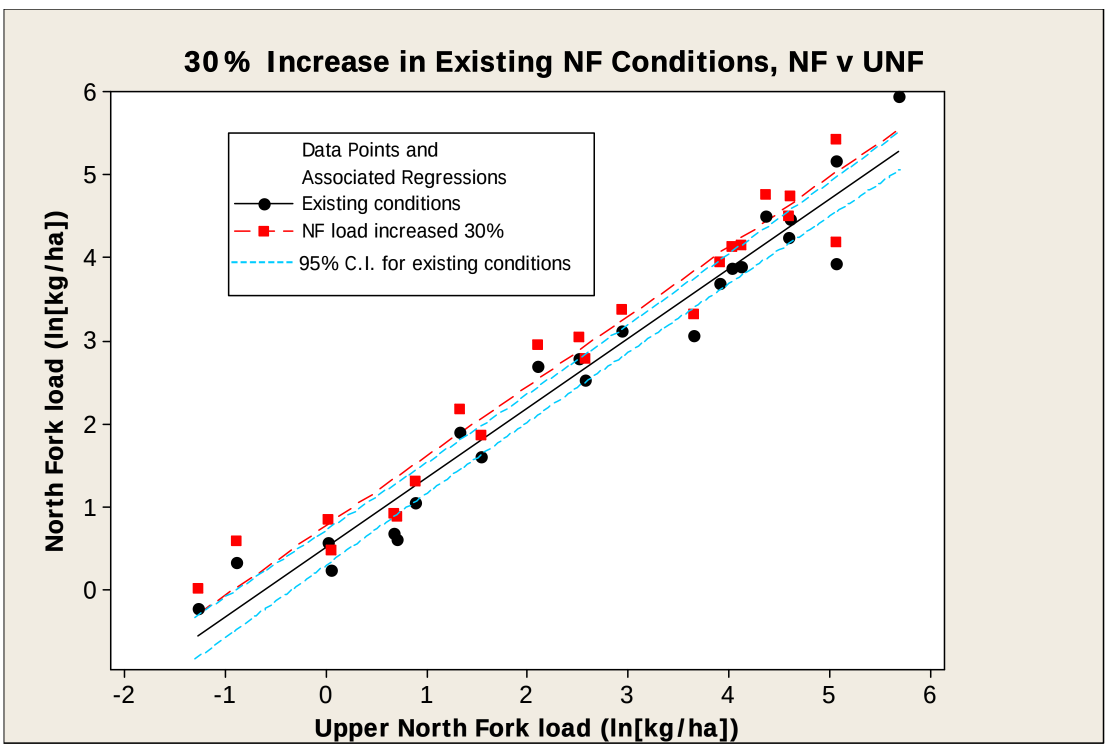

Figure 5-31. 30% NF increase and original NF versus UNF regression and confidence interval.

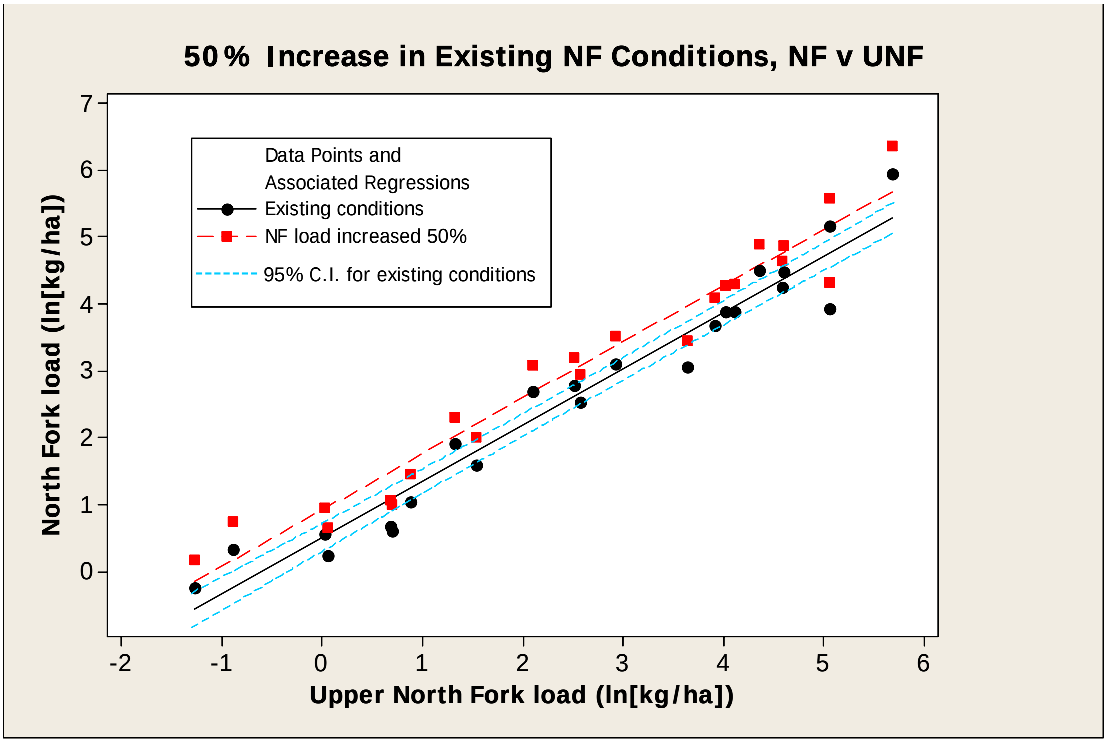

Figure 5-32. 50% NF increase and original NF versus UNF regression and confidence interval.

CHAPTER 6

Conclusions

Data collected thus far in the Little Creek study have yielded a sufficient number of event-specific suspended sediment loads to enable simple linear regression analysis. The establishment of the suspended sediment loads required a continuous record of flow data paired with suspended sediment concentration data at each monitoring station. The regression analysis helps establish the pre-harvest calibration for the Little Creek study, though an additional year of calibration data is planned for measurement during the 2006-2007 rain season. The calibration results, thus far, are encouraging given the degree of uncertainty associated with calibration potential under highly variable climatic conditions in steep terrain watersheds in the California Coastal Mountains.

Suspended sediment loads for the nested part of the watershed study (North Fork versus Upper North Fork) yielded a strong regression correlation coefficient (R^2 = 0.959) and a relatively narrow confidence interval around the regression line. These results are indicative of a statistically strong correlation between the two monitoring stations. The paired component of the watershed study (North Fork versus South Fork) returned a lower regression correlation coefficient (R^2 = 0.592) and a wider confidence interval around the regression line. Therefore, the correlation is considerably stronger for the nested watershed component of the study. For the nested component, theoretical increases of approximately 30% in all events measured to date at the North Fork result in a new regression line that falls outside the confidence interval of the original regression. For the paired component, theoretical increases of approximately 90% in all events measured to date at the North Fork are needed for a new regression line to fall outside the confidence interval of the original regression. Such increases may be considered the detectable level of change for the paired and nested watershed analysis. This is important in that sediment increases on the North Fork will only be detectable with the nested comparison if there is an increase of at least 30%, and with the paired comparison if there is an increase of at least 90%. Another way of stating this is that the background variability found in the last five years of the study is much greater within the paired component than the nested component

Potential Increases in Suspended Sediment Based on Event Size

The theoretical increases at the North Fork station and regression comparisons provide a potential tool for assessing the detectable magnitude of change. However, the increases used in both the paired and nested comparisons are not likely to be uniform throughout the data range. Based on previously mentioned studies, greater increases are more likely for the smaller events relative to large events. Sloping regression lines in such a situation may exist within the domain of the 95% confidence interval at one end of the dataset and outside the domain at the other end.

Possible reasons for greater increases in the smaller storms at the beginning of the year include runoff from roads and stream crossings. The road surfaces are much less permeable than the surrounding forest ground surface, where most of the initial rainfall is stored in the relatively dry soil resulting in slower percolation to the stream channel. The road surfaces, however, quickly transport rainfall to ditches that may flow directly to stream channels, particularly near stream crossings. This direct transport of sediment from roads is most noticeable early in the year when there is relatively little flow and sediment transport in the channel. Later in the year, after the forest soils are at or near saturation, the channel is likely transporting a relatively large amount of sediment and at higher flows. The majority of this sediment may come from a variety of sources, such as streambank erosion, that may be more related to increasing the extent of the hydrologically active area in the watershed or increasing hydraulic forces. Such contributions may then mask any inputs from roads.

Common Difficulties Among Stations

In general, capturing the largest events in the Little Creek watershed has been difficult. In addition to equipment errors, the dynamics of the Little Creek watershed result in very difficult sampling conditions during extreme events. Changes in bed elevation that cause streambed enrichment of the samples can be a recurring problem. This enrichment typically occurs during the receding limb of the hydrograph when the intake keel drops back down in the water column. The steep channel gradient of the watershed ensures a shallow water column, and the intake must often be placed only a few inches from the streambed at the start of an event to ensure submergence for sampling. This is particularly true for the first few storms of the season when the antecedent flow conditions are very low. A high amount of sediment transport in the first few storms of the year often results in small-scale rearrangement of the streambed. Small changes in the bed elevation are sufficient to cause the keel intake to pump bed material. Frequent site visits are important to ensure the intake is placed at the proper elevation in the water column. However, personnel safety would often be compromised during site visits during extreme events. Hazards ranging from falling trees to potential debris flows become increasingly likely during larger events. The area of the Little Creek watershed is frequently under a National Weather Service flash flood warning during major storm events.

The problem of streambed enrichment is variable between stations and is largely due to the hydraulic characteristics and sediment flux variations between the stations. The sediment flux is similar between the NF and UNF stations, but the hydraulic characteristics are different. The intake for the Upper North Fork station is placed in a section of channel that maintains the typical channel slope of that stream reach. In addition, the channel slope in this section of the watershed is steeper than near the NF station and therefore, small gravel particles are typically flushed through the stream reach with little change to the bed elevation. Further, the UNF station did not require a constructed flume because of the greater stability of a cobble-dominated channel bed. The absence of a flume maintains a steeper channel section at the intake location. The streambed near the North Fork flume consists of smaller particles that are more prone to bed elevation changes during storm events. The construction of a flume at the North Fork was necessary to achieve channel elevation and cross-sectional control for the long-term project. The width of the channel coupled with slope changes allows the thalweg to change slightly during storm events. These thalweg and bed elevation changes are relatively small in magnitude, but as previously mentioned only small changes are necessary to cause the sampling intake to become enriched with gravel-sized bed particles. Sediment flux at the South Fork is typically much less than at the North Fork, and streambed enrichment has not been as problematic at the South Fork.

Lower Sediment Export of the South Fork

There are several possible explanations for the lower sediment export in the South Fork as compared to the North Fork. The lower response is important because it highlights the difficulty of making assumptions about side-by-side watersheds with similar features. The difference in observed sediment export may be attributed to soils, topography, geology, and prior management involving road construction. While geology and soil types are very similar between the watersheds, soil thickness and topography may be different enough to affect the sediment export. For example, bedrock is exposed in the middle portion of the South Fork channel, reducing the amount of in-channel sediment available. Also, there may be less active channel lengths in the South Fork, thus reducing in-channel erosion sources. Additionally, multiple large landslides incorporating a large amount of woody debris have deposited directly into the lower portion of the South Fork. Lower flow events remain subsurface through these landslide deposits, possibly trapping a significant amount of sediment. Management history of road building does differ between the two watersheds. The number of roads and road stream crossings in the North Fork watershed are greater, and may be enough that the effect is significant. If so, whether the roads continue to contribute sediment or there is a legacy effect of sediment delivered to the channel from prior years is not known. As previously referenced, roads and stream crossings may be responsible for significant increases in sediment delivered to a stream channel. The difference in sediment export is likely a combination of the above factors, though relative contributions are not known at this time.

Data Anomalies

Some of the apparent anomalies in the data can be explained by field observations during storm events. Though quantitative data was not collected to substantiate these observations, substantial visual evidence was available. One event that strongly deviates from the average NF versus UNF relationship is the first event of the 2002-2003 season. The UNF load (25,337 kg total or 132.7 kg/ha) is substantially higher than the NF load (14,068 kg total or 50.4 kg/ha) most likely due to a Class III stream diversion installed in summer 2002. The Class III was historically diverted upstream from the new diversion into a swale that subsequently became saturated in the winter and prone to slumping. In winter 2001/2002, a large slump occurred in a section of road within the swale. The old Class III diversion was redirected back into the original channel via an old skid trail, though this diversion required new shaping of the skid trail. This exposed bare soil on the skid trail combined with a cut in the slope that contributed a significant amount of sediment to the Class III during the first storms of the winter. The Class III empties into the North Fork approximately 400 feet upstream from the Upper North Fork monitoring station. During the first and second storms of the year, the Class III was visually transporting a large amount of sediment while the North Fork above this confluence was much less turbid, particularly on the rising limb of the hydrograph.

The anomalous relationship between the NF and UNF stations during the storm events described above were retained in the calibration dataset as representative of a managed watershed. Managed watersheds typically have road systems in place that must be maintained regardless of harvesting activities. Maintenance efforts similar to the aforementioned diversion can be necessary to prevent larger problems from occurring, such as landsliding. Therefore, a storm event that is influenced by such management activity remains permissible within the calibration dataset.

An additional peculiarity in the data is found in the event-specific regressions for the South Fork station. The SSC versus turbidity regressions for two events result in low R^2 values less than 0.5, while the typical SSC versus turbidity regressions result in higher R^2 values. The low R^2 values indicate highly variable relationships between SSC and turbidity. Possible reasons for such variability include sediment sources such as small bank slumps occurring within a short distance upstream from the monitoring station. The smaller particles, such as silts and clays, from such a sediment pulse could be transported relatively quickly through the monitoring station. These very fine particles would increase the turbidity but would have a lesser effect on the suspended sediment concentration. The sand sized particles that would have a greater effect on suspended sediment may either take longer to reach the pump intake or may not be mixed high enough in the water column. The low amount of mixing is particularly likely on the South Fork given the reduced stream competence of the lower flows. Multiple brief pulses of increased fine particles could greatly increase the variability of the SSC versus turbidity relationship.

Benefits of the Little Creek Study

While increases in sediment at the North Fork are more easily detected using the nested relationship, the paired watershed relationship continues to hold value. The paired analysis provides a depiction of the variability existing between physiographically similar watersheds in this region. In addition, any events not sampled at the Upper North Fork due to unforeseen errors may be captured at the South Fork and still available for analysis. While the paired relationship is not as strong as the nested relationship, the paired relationship is still significant and change may be detected.

An additional benefit of this study is to show the efficiency of grab samples to describe sediment relationships. The rapidly changing SSC and turbidity values (as (shown in Figures 5-1 and 5-2) during a storm event will cause sediment load conclusions based on grab samples to be very different depending on when the sample is taken. Attempting to time a grab sample with the peak of an event would be very difficult given the rapid rise and fall of the hydrograph. Samples taken a few hours before or after the peak would yield very different sediment load estimates as compared to the peak. A short time interval sampling strategy is needed over the course of a storm event to accurately quantify the storm event load. However, even if sediment loads are accurately quantified for a single event, other issues may occur if trying to extrapolate the results between events. The per unit area loads in the North

Fork versus Upper North Fork relationship reveal the need for consistent sampling to determine upstream versus downstream relationships. Per unit area sediment loads are higher at the NF for 12 of the 22 of the measured events and higher at the UNF for 9 of the 22 measured events. Capturing sediment loads between stations over multiple storm events under a wide range of antecedent hydrologic conditions is important to developing a representative relationship.

CHAPTER 7

Recommendations

A repeat of this project from the beginning would benefit from specific changes in instrumentation. The need for such changes is justified by the major sources of error that have invalidated some events (see Chapter 5). Event data for the Upper North Fork in 2001/2002 was not available because of stage data reliance on one method of continuous stage monitoring that was later found to be in error. Multiple methods of continuous stage recording are therefore strongly recommended. An additional source of error was bed material contamination of the water quality samples. A different keel design for the pump intake that is not as susceptible to streambed enrichment and clogging would be beneficial. An "articulated boom" design similar to that developed at Caspar Creek by the USDA Pacific Southwest Research Station would maintain the intake higher in the water column following an episode of streambed aggradation. Additionally, proper deep cycle batteries for pump samplers that withstand multiple complete discharge/charge cycles would help avoid power failures by promoting longer battery life.

The assessment of regression lines representing theoretical sediment increases in relation to existing conditions represents one method of determining detectable change after treatment. Other statistical methods could prove beneficial to assessing changes in the regression from before and after the treatment. Such methods could include the Chow test (Chow, 1960) to test whether the coefficients of two linear regressions are equal, or a double mass curve analysis to suggest changes in station relationships. A control station relationship analysis of the Upper North Fork versus South Fork could also benefit the before and after treatment analysis. Changes in the behavior of either control station that would affect the paired or nested comparison could be detectable using such an analysis. This is important to help ensure that observed paired or nested changes have occurred in the treatment watershed and not in the control. Incorporating rainfall totals and intensities may also be helpful if some differences in station relationships can be correlated with the rainfall dynamics.

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