EVALUATION OF SLOPE EFFECTS ON SOIL EROSION OF OFF-ROAD VEHCILE TRAILS USING WEPP

Except where reference is made to the work of others, the work described in this thesis is my own or was done in collaboration with my advisory committee. This thesis does not include proprietary or classified information.

Jonathan Donald Melton

Certificate of Approval:

Timothy P. McDonald, Co-Chair
Associate Professor
Biosystems Engineering

Wesley C. Zech, Co-Chair
Assistant Professor
Civil Engineering

Puneet Srivastava
Assistant Professor
Biosystems Engineering

Dan A. Brown
Gottlieb Associate Professor
Civil Engineering

John M. Grace
Research Engineer
US Forest Service

George T. Flowers
Interim Dean
Graduate School

EVALUATION OF SLOPE EFFECTS ON SOIL EROSION OF OFF-ROAD VEHICLE TRAILS USING WEPP

Jonathan Donald Melton

A Thesis

Submitted to

the Graduate Faculty of

Auburn University

in Partial Fulfillment of the

Requirements for the

Degree of

Master of Science

Auburn, Alabama
May 10, 2008

EVALUATION OF SLOPE EFFECTS ON SOIL EROSION OF OFF-ROAD VEHICLE TRAILS USING WEPP

Jonathan Donald Melton

____
Signature of Author

____
Date of Graduation

VITA

Jonathan Donald Melton, son of Donald and Patricia Melton, was born on March 11, 1982 in Mobile, Alabama. He grew up in Stapleton, Alabama, with his older sister Cindy. Upon graduating from Baldwin County High School in May of 2000, he entered Faulkner State Community College in Bay Minnette, Alabama. In August of 2001 he enrolled in the College of Engineering at Auburn University in Auburn, Alabama with a Major in Biosystems Engineering. From August 2002 to August 2003, he participated in Auburn University's Cooperative Education Program working with the USDA's US Forest Service Southern Research Station in Auburn, Alabama. Graduating from Auburn University in May of 2005 with a Bachelor's of Biosystems Engineering Degree, he entered Auburn University's graduate program in Civil Engineering. He worked as a graduate research assistant in Biosystems Engineering Department. He is currently employed by Vision Engineering and Development Services in Sevierville, TN.

THESIS ABSTRACT

EVALUATION OF SLOPE EFFECTS ON SOIL EROSION OF OFF-ROAD VEHICLE TRAILS USING WEPP

Jonathan Donald Melton

Master of Science, May 10, 2008
(B.B.S.E., Auburn University, 2005)

143 Typed Pages

Directed by Timothy P. McDonald and Wesley C. Zech

Erosion and sediment loss from the use of off-road vehicles (ORV) is an escalating problem on national forest lands. The increasing number of ORV riders coupled with decreasing riding areas has caused the United States Forest Service and other agencies to begin development of best management practices (BMPs) that will reduce the amount of erosion and sediment loss occurring on trails.

In order to quantify the sediment loss from ORV trails, two trail sections of the Kentuck ORV trail system in the Talladega National Forest were equipped with sediment sampling devices and rainfall data collectors. These trail sections were located on a mild slope and a steep slope on the existing trail. Storm data were collected and analyzed for five storms during a nine month period. The storm producing the highest amount of soil erosion produced approximately 0.78 tonnes per hectare and 1.46 tonnes per hectare of sediment from mild and steep slopes, respectfully. These data were used to evaluate an erosion model that would allow land managers to predict sediment loss on general trail sections throughout the trail system. The Water Erosion Prediction Project (WEPP) model was used because of its ability to model forest roads. The instrumented trail sections were modeled using WEPP and compared to sediment and runoff data from field experiments to calibrate the model. Upon calibration, a Nash-Sutcliffe efficiency (NSE) of 0.45 was achieved for runoff while a R^2 value of 0.43 and NSE of -0.36 was established for soil erosion. In general, the calibrated model predicted lower runoff, but much higher sediment production, than observed. A second model was calibrated in order to calibrate for sediment production only, which produced a NSE of 0.24. The mild and steep slope data was separated and modeled for each individual slopes. An attempt to validate these models was performed by using the opposite slope for validation. The results from the validation showed that the model was not as good a predictor of expected sediment production for either slope. In addition to the slope comparison, the data was divided into trafficked and non-trafficked data which produced a NSE of -0.11 and 0.76, respectfully. The moderate NSE for the non-trafficked data was expected due to the lack of the additional soil disturbance from the ATV traffic.

The calibrated model for sediment only was used to simulate erosion on varying slopes. From these simulations, recommendations for water diversion structure spacing were developed. Water diversion structures carry runoff from the trail into the surrounding forested areas, reducing the velocity and sediment concentration of water flow over the trail surface. The spacing recommendations developed from this study can be used as BMPs to aid land managers in designing systems to reduce the impacts on ORV trails.

ACKNOWLEDGEMENTS

The author would like to thank Auburn University, Timothy McDonald, and his Graduate Committee for the opportunity to perform the research associated with this thesis. The author would like to thank his parents, Donald and Patricia Melton, for the financial and emotional support throughout his educational experience. The author would also like to thank his fiancée, Jennifer Lofty, for her support during the research process. The author would like to thank Corey Kichler and Gavin Jackson for assistance with the installation of research equipment and processing of data in the laboratory.

Style manual used Auburn University Graduate School Guide to Preparation and Submission of Theses and Dissertations

Computer software used Microsoft Office 2003 --- Microsoft Word 2003, Microsoft Excel 2003 --- Water Erosion Prediction Project (WEPP) model --- Hoboware

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Problem Statement

Over recent decades, the use of off-road vehicles (ORV) for recreation has increased rapidly. Outdoor enthusiasts often use all-terrain vehicles (ATV) to traverse trails on which ordinary vehicles are unable to operate. The thrill and excitement of going to places that were inaccessible in the past has been a major contributor to the growth of ATV use. According to the United States Department of Agriculture (USDA) Forest Service, over 36 million people rode ATVs in 2000 in the United States (USDA, Office of Communication). In 2003, five percent of the visitors to national forests and grasslands consisted of ORV users (Brodbeck, 2005). Because of potential environmental problems associated with their use, this increase in demand for ATV recreation creates a need to protect our public land and its natural resources for future generations.

In 2003, the Chief of the US Forest Service, Dale Bosworth, identified four major threats to our national forest lands. The four major threats were fire and fuels, invasive species, fragmentation, and unmanaged recreation (USDA, Office of Communications, 2004). The use of ORV on national forest lands falls under the category of unmanaged recreation. Unmanaged ORV use, which includes ATVs, is creating a number of undesirable impacts on national forest lands including (1) user-created, unplanned roads and trails, (2) severely eroded soils, (3) damaged wetlands and harm to wetland species, and (4) habitat destruction and degraded water quality due to trail-generated sediment (Foltz, 2006). This major threat to our national forest systems has caused significant changes in management strategies for the Forest Service to combat this and other major threats, but their mission remains the same, "to sustain the health, diversity, productivity of the Nation's forests and grasslands to meet the needs of present and future generations" (USDA, Office of Communications, 2004).

ORV trails, when heavily used and left unmanaged, can cause significant environmental impacts. The erodibility of soil, terrain, and type of vegetation are some primary factors affecting degradation of trail surfaces. Soil erosion is one of the main adverse impacts associated with ORV trails. Erosion is a concern because it tends to degrade water quality and potentially can adversely impact plant and wildlife habitat (Novotny, 2003). Erosion, for example, can lead to sedimentation within water bodies, causing loss of spawning habitat for species that require gravel-bottom streams for reproduction (Novotny, 2003). Sedimentation can also kill some specialized types of vegetation that require undisturbed stream habitat for survival (Novotny, 2003).

The use of site-specific management is a key tool in decreasing the impacts caused by ORV on the trails. Site-specific management involves selecting the best management practice (BMP) for a given area within an entire trail system, then adapting the practice to make it correspond to each specific circumstance. A broad based dip, for example, is used to divert runoff from bare soil surfaces and may be an appropriate erosion control tool for a general location, but the design for a given spot in a trail system may require alteration from standard practice in order to effectively collect water, divert it off the trail, and reduce its velocity by spreading the flow over a large area. These site-specific changes to common practices are necessary to manage trails when they are located on sensitive soils, steep slopes, or in lowland areas.

The use of site-specific BMPs is always the optimal approach when trying to minimize impacts from man-made sources, but information is not always available to base decisions about particular situations. Managers of the Kentuck ORV area of the Talladega National Forest, for example, currently use several site-specific management practices to maintain the trail system. Broad based dips, water-bars, and wing ditch turnouts are applied as is felt appropriate to control erosion, yet problems with the trail system persist. The implemented structures are intended to shed water from the trail to eliminate puddling of water, rutting, and channeling of flow into waterways. Due to heavy trail traffic in both wet and dry periods, high levels of wheel slip associated with ATVs, and steep terrain in which the trail is located, these maintenance techniques tend to be effective short periods of time. Once the trail structure has been compromised, the trail tends to become a source of increased erosion. The economic cost of replacing these erosion control structures is high, as is the environmental impact associated with not keeping them functioning at peak effectiveness. Information is needed by trail managers on which to base decisions concerning frequency of maintenance practices, as well as improved guidelines for application of erosion control structures in general.

The purpose of this study was to investigate erosion processes on ORV trails; specifically, the effect of slope on sediment generation. In addition, the intent was to further develop analytical tools for making decisions regarding the use of sediment control structures on ORV trails. Previous research has shown that the Water Erosion Prediction Program (WEPP) can be used to estimate the sediment load generated at a stream crossing on the Kentuck ORV Trail. The present study was designed to investigate primary production of sediment as a function of trail slope and, to the extent possible, calibrate the WEPP model with the erosion data for use as an analytical tool in making decisions regarding trail design, layout and maintenance. The outcomes of the study should be an understanding of the expected sediment generation of an ORV trail as a function of slope, and a database of parameters that serve as inputs to the WEPP program and are appropriate for analyzing alternative management strategies for the Kentuck trail system. The erosion data will supplement the fundamental understanding of soil detachment and transport from heavily disturbed and compacted trail surfaces. The modeling component of the research will provide an additional opportunity to verify the WEPP program as an analytical tool. Finally, the work will add to the general literature on erosion from ORV trails, a subject about which there is a relative lack of information.

1.2 Objectives

The objects of this research are:

1.) Outfit two sections of the Kentuck ORV trail, one each on a steep and mild slope with instrumentation to measure total sediment transport.
2.) Calibrate WEPP for the Kentuck ORV trail for total sediment loading.
3.) Demonstrate the use of WEPP as a tool for management planning on ORV trails.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Sediment has been identified as one of the most recognized non-point source (NPS) pollutants of streams, lakes, and estuaries (Novotny, 2003). In forested areas, the predominant source of sediment is from the construction and maintenance of access roads. Since ORV trails and forest roads share the same characteristics and theoretical principles in terms of location, use, and in some cases size, most ORV trails are considered as forest roads. Extensive research has been performed on erosion of forest roads but very little research has been performed on ORV trails.   Research has shown that up to 90% of sediment producing erosion in forested areas can be attributed to access roads, while the erosion from the undisturbed areas are negligible (Appelboom, 2001; Van Lear, 1995). The erosion from forest roads is a major component in quality degradation of forest streams and wildlife (Novotny, 2003). The sediment can clog spawning beds, shorten the life of reservoirs, and degrade drinking water. Due to these factors, road management is an important component in preserving and maintaining healthy forest throughout the nation (Grace, 2006). As demand increases for timber products and recreational use increases, roads must be constructed and maintained for access to these areas (Appelboom, 2001). This demand will dramatically increase the potential for sediment production (Appelboom, 2001).

Soil erosion from forest roads is primarily due to the disturbance of the roadbed. Most forest roads have no protection for the soil surface. According to Brooks (2003), the dislodgement of soil particles on the soil surface by energy imparted to the surface by falling raindrops is a primary agent of erosion, particularly on soils with sparse vegetation cover. For example, the energy released at the surface during a large storm is sufficient to splash greater than 200 tons of soil into the air on a single hectare of bare and loose soil (Brooks, 2003). Once a soil particle has been loosened from its position, the runoff tends to flow towards the point of lowest resistance carrying soil particles as it flows. As the runoff begins to collect in small channels, the turbulence of the water causes the particles suspended in the water to dislodge additional particles, which increases erosion. The erosion from these small channels is characterized as rill erosion. The channels formed by rill erosion concentrate the water into a confined area causing the velocity to increase, thereby causing an increase in the turbulence of the flow (Brooks, 2003). This increase in turbulent flow increases the rate at which erosion occurs on bare surfaces such as ORV trails. The volume of water moving down the slope also is an important factor on the soil erosion. Moving water, such as water flowing downhill on a road surface, can be thought of as a source of kinetic energy. This energy is one of the primary physical causes of erosion often seen on forest roads (Brinker, 1995). The velocity of the moving water is a function of the slope on which the road is built. The velocity contributes to the amount of kinetic energy exponentially; thus a small increase in slope steepness rapidly increases the kinetic energy and erosive capacity of moving water (Brinker, 1995).

The use of ORVs causes physical damage to trail soils that increases with each vehicle pass over the trail system. Research on the environmental impact from ORVs has been performed in desert climates, notably because these areas tend to receive a great deal of ORV traffic. Adams et al. (1982) conducted a study in which a comparison of erosive potential was made between motorcycles and off-road trucks on soil compaction and subsequent vegetative growth in desert environments. The study found that though the truck and the motorcycle both impacted soils, the truck produced the greatest impact. Eckert et al (1979) studied the traffic from both motorcycles and trucks on undisturbed areas in desert soils and their response to simulated rainfall. Eckert concluded that the truck increased sediment by 3.5 to 20 times compared to undisturbed areas in just 20 passes, while the motorcycle increased sediment by 2 to 4 times the undisturbed areas, depending on soil type. Kutiel et al. (2000) studied the effects of motorcycles and foot traffic on vegetation on sand dunes. Kutiel's study showed that just one pass from a motorcycle reduced ground cover and plant diversity while it took more than 500 foot passes to decrease vegetation diversity. High sediment flux was found on ORV trails in Ohio by Sacks and da Luz (2003). Their results showed that soil loss was associated with periods of heavy traffic and reached estimated erosion rates of approximately 2000 kg $ha^{-1}yr^{-1}$.

2.2 Management Practices

In 1972 the Clean Water Act (CWA) was passed with the sole purpose to protect the chemical, biological, and physical integrity of our nation's most valuable resource, water. In 1977, the act was amended and the Environmental Protection Agency (EPA) was given the authority of permitting, enforcement, and administration of the laws set forth by the CWA. Section 208 of the CWA called for area-wide water pollution control planning in areas designated by the governor of each state that would include both point and nonpoint sources and pollution abatement programs (Novotny, 2003). Section 208 of the amendments identified silviculture as a NPS of pollution and required that states set guidelines (i.e. BMPs) to reduce NPS pollution. States were delegated the responsibility to define and develop either regulatory or voluntary BMPs for forestry practices (Novotny, 2003). BMPs for forestry practices are recommended for all aspects of forest operations such as streamside management zones (SMZ), stream crossings, forest roads, timber harvesting, forested wetland management, and reforestation. BMPs relating to forest roads are perhaps the most critical practices to influence the environmental impacts of forest operations (Grace, 2005b). The applications of forest road BMPs to protect water quality have become a common practice in forest activities in the United States in response to the CWA (Grace, 2005b). BMP use on forest operations, while voluntary, is strongly recommended in order to protect our resources and also prevent strict regulation on the silvicultural operations. The BMPs developed in Alabama's Best Management Practices for Forestry Manual include BMPs for Streamside Management Zones (SMZ), Stream Crossings, Forest Roads, Timber Harvesting, Reforestation/Stand Management, Forested Wetland Management, and Revegetation/Stabilization. The forest road BMPs include the proper planning, adequate drainage, crowned roads, turnout ditches, outsloped roads, insloped roads, excessive road steepness, water bars, broad-base dips, outfall protection, control of non-essential traffic, and construction and maintenance of permanent roads. The Alabama's Best Management Practices for Forestry Manual uses charts in order to show the recommended distances between structures such as water bars and broad-base dips for specific slope percentages (AFC, 1993). The appropriate spacing between water diversion devices depends on the steepness of the road grade and the erosivity of the soil. The steeper the grade, the greater the velocity of the water body and the closer water diversion devices must be placed together (Brinker, 1995). Brinker developed an equation for the calculation of water diversion spacing for forest roads applications.

2.3 Prediction of Soil Loss

Since the early 1950's, there has been a need to develop a tool to aid forest managers in planning or evaluating forest road operations. In recent years, several models have emerged that can be applied in land management. These models include the Universal Soil Loss Equation (USLE), the Modified Universal Soil Loss Equation (MUSLE), the Revised Universal Soil Loss Equation version 2 (RUSLE2), the WATSHED model and the Water Erosion Prediction Project (WEPP).

The Universal Soil Loss Equation (USLE), developed in the 1960s, was primarily for agricultural use but was updated for use in non-agricultural conditions such as construction sites. USLE predicts long term average annual erosion on field slopes from rainfall patterns, soil types, topography, crop system and management practices. Soil loss that might occur from gully, wind, or tillage erosion cannot be predicted due to the fact that USLE only predicts the amount of soil loss from sheet or rill erosion (USDA ARS, 2007). In order to predict soil loss for a given area, five major factors are used. The factors are (1) rainfall, (2) soil erodibility, (3) slope length and gradient, (4) crop vegetation and management practices, and (5) support practices. These factors were developed from over 11,000 plot-years of data collected in 1930s to 1950s (USDA ARS, 2007).

The Modified Universal Soil Loss Equation (MUSLE) is an updated version of USLE, which has been updated in order to estimate soil loss from individual storm events. This model is an improvement on USLE but should be used with caution due to the fact that it was developed on limited data from Texas and the Southwestern United States.

The Revised Universal Soil Loss Equation Version 2, (RUSLE2), is the latest addition of erosion prediction models based on the original USLE. RUSLE2 estimates soil loss, sediment yield, and sediment characteristics from rill and interrill (sheet and rill) erosion caused by rainfall and its associated overland flow. RUSLE2 uses factors that represent the effects of climatic erosivity, soil erodibility, topography, cover management and support practices to compute erosion (RUSLE2, 2003). RUSLE2 is not a simulation model that attempts to mathematically replicate field processes. RUSLE2 is used to guide conservation planning, inventory erosion rates over large areas, and estimate sediment production on upland areas that might become sediment yield in watersheds (RUSLE2, 2003). An advantage to RUSLE2 is that the model has the capability to estimate the sediment deposition that occurs on a landscape, compared to RUSLE1 and USLE that only estimated the total sediment at the output of the landscape. One drawback to the model is that it does not have the capacity to estimate erosion from concentrated flows such as gullies or stream channels. According to the USDA's RUSLE2 User Guide, the four major factors affecting interrill and rill erosion are climate, soil, topography, and land use. The North Carolina Department of Transportation

(NCDOT) has introduced the use of RUSLE2 into their erosion and sediment control planning. According to a case study by Ted Sherrod, the NCDOT has used RUSLE2 in order to estimate erosion rates on paving projects for secondary roads. RUSLE2 was used to simulate the erosion control structures on the narrow right of ways in order to determine the most applicable solution for low budget projects. Through the use of RUSLE2 the NCDOT has been able to demonstrate that throughout most of the state, sediment delivery rates are far less than the required 3600 ft^3/acre/year (Sherrod, 2004). Most are in the 35 – 1550 ft^3/acre/year range when ditchline grades are less than 2.0% (Sherrod, 2004).

The Water Erosion Prediction Project (WEPP) is possibly the most robust model available for road erosion prediction currently available (Grace, 2005). WEPP, which was developed by the USDA, represents a new erosion prediction technology based on the fundamentals of stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics. The most notable advantages include capabilities for estimating spatial and temporal distributions of soil loss, and since the model is process-based it can be extrapolated to a broad range of conditions that could be more practical or more economical than field tests. In a small watershed, sediment yield from entire fields can be estimated. Processes considered in hillslope profile model applications include rill and interrill erosion, sediment transport and deposition, infiltration, soil consolidation, residue and canopy effects on soil detachment and infiltration, surface sealing, rill hydraulics, surface runoff, plant growth, residue decomposition, percolation, evaporation, transpiration, snow melt, frozen soil effects on infiltration and erodibility, climate, tillage effects on soil properties, effects of soil random roughness, and contour effects including potential overtopping of contour ridges (NSERL, 1995). The model also has the ability to model spatial and temporal variability in topography, surface roughness, soil properties, crops, and land use conditions on hillslopes (NSERL, 1995). WEPP allows a linkage between hillslope profiles to channels and impoundments for watershed applications. Water and sediment from one or more hillslopes can be routed through a small field scale watershed. Almost all of the parameters updating for hillslopes is duplicated for channels. Channel detachment, sediment transport and deposition are all simulated in the model. Simulations can be made for the removal of sediment from the flow from impoundments such as farm ponds, terraces, culverts, filter fences and check dams (NSERL, 1995).

The use of models such as WEPP is becoming a key tool for the planning and development of BMPs. Researchers are now experimenting and calibrating WEPP to verify its accuracy for use in prediction of erosion from roads. From September 1995 to December 2003 a study was performed on a forest road located in the Talladega National Forest to compare actual erosion and predicted erosion using WEPP. WEPP predictions of sediment yield from cut- and fill slopes with two vegetation treatments and an untreated condition were compared to yields observed from the replicated erosion control plots over an 8-year period (Grace, 2005). The model resulted in model efficiencies ranging from 0.51 to 0.92 for the cutslope and 0.53 to 0.99 for the fillslope. These relatively high model efficiencies indicate that the model adequately describes sediment yields observed in the field experiment (Grace, 2005). Brodbeck also performed a study on ORV trails comparing field data with predicted data through WEPP. The data consisted of total suspended solids (TSS) data from the up- and down-stream sides of a stream crossing which was used to calculate the sediment loading. The values were determined using the Hillslope version of the WEPP model. The watershed version of the WEPP model was determined not to be suitable for modeling erosion from ORV trails in an effort to develop BMPs (Brodbeck, unpublished thesis 2005). According to Ayala (2005), the study suggests that ORV trail stream crossings have potential to contribute large sediment loads from storm events that have a return interval of 0.5 year or higher. In 2001, Klik and Zartl (2001) showed that WEPP simulated storm runoff with acceptable accuracy when effective hydraulic conductivity was calibrated with measured runoff. They showed that the WEPP model was able to simulate runoff amounts as well as variability between events. The soil erodibilities for this research had to be multiplied by factors of 9-10 for Interrill Erodibility (K_i) and for 1-3 Rill Erodibility (K_r) to match observed soil losses.

2.4 Summary

Literature on the use of erosion prediction models for application on ORV trails in the Southeast is very limited. Currently there are few studies that have been performed using WEPP as a simulation method to predict erosion rates for ORV trails. These mainly are associated with stream crossings that occur on the trail systems. Due to this lack of information, research is needed in these areas in order to quantify erosion rates, test current management practices, and develop additional management practices for ORV applications.

CHAPTER 3: RESEARCH PROCEDURES

3.1 Introduction

This project was funded by the USDA Forest Service, Southern Research Station, Forest Operations Research Unit. It was a joint effort between the USDA Forest Service's Talladega Ranger District located in Talladega, Alabama, and Auburn University's Department of Biosystems Engineering. The overall goal of this project was to investigate erosion processes on ORV trails of varying gradients and to further develop the WEPP erosion model for use as a tool in evaluating trail design and maintenance alternatives, in particular for the Kentuck ORV trail system.

3.2 Site Location

The research site was located on the Kentuck ORV trail system, 33° 31' 49" N, 85° 51'50" W , part of the Talladega National Forest in the Talladega Ranger District located in east central Alabama (see Figure 3.1). The area is generally quite hilly with terrain dominated by high ridges separated by steep-sided draws. The Kentuck ORV trail system is a managed recreational use area providing about 48 km of trails motorized ATVs, primarily four-wheelers and off-road motorcycles. The trails are unpaved and have an average width of 3 meters. Current trail maintenance procedures consist principally of broad-based dips, water-bars, and wing ditch turnouts. Water crossings are typically small timber bridges and culverts to reduce in-stream incursions by ATVs. The trail system is divided into four loops, with three longer trails connected by one interior loop. This interior loop, known as the blue trail, is about 3.3 km long (see Figure 3.2). Primarily because of accessibility, the experimental plots established for this study were located on the blue trail. This particular trail was also chosen because previous erosion work had been carried out on it (Brodbeck, 2007), providing a reference point from which to interpret results.

Figure 3.1 -- Location of research site.

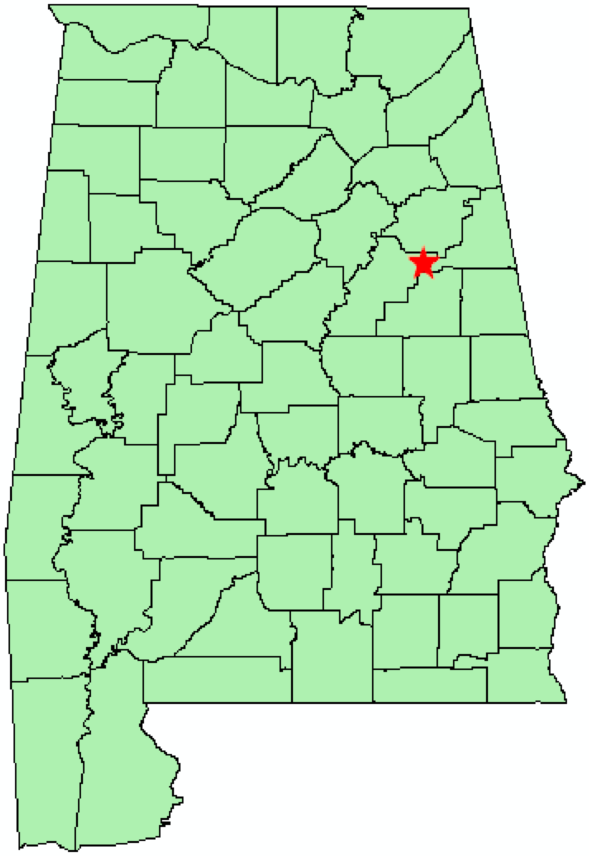


Figure 3.2 -- Trail map.

A survey of the blue trail in the vicinity of the previous study revealed some limitations on the potential range of trail gradients that could be studied. Any plot chosen for this study had to meet several criteria for acceptability, including being of sufficient length and relatively straight, have a defined turnout at the bottom for installation of the experimental equipment, and not be located such that rider safety would be compromised any modifications done to the trail. Only two sites having the proper characteristics were identified, one each with a mild and steep gradient. The first was on a mild slope of approximately 3.5% and 16.2 meters. The turnout for this site was situated at the bottom of the slope and was approximately 30 feet long and on a 7% gradient. The second site was located on a steeper section of trail with slope of about 20% and length of 36 meters. The turnout for the steeper plot was approximately 35 feet long on a 4.5% slope. For both plots, a waterbar was used to divert flow off the trail into the turnout.

Prior to installation of the experimental plots, the trail sections were shaped using a small bulldozer (see Figure 3.3) to a condition that was considered to be optimal according to Forest Service guidelines. The reshaping eliminated ruts that would have channeled flow down the trail, and ensure that waterbars and turnouts would function correctly.

Figure 3.3 -- US Forest Service bull dozer performing maintenance.

3.3 Sampling Description

Both plots were instrumented to measure runoff and sediment production. The equipment used to measure both variables was installed at the end of the turnouts described above. The basic procedure used was to measure complete runoff volume and divert a fixed, small percentages of the runoff for later analysis of sediment concentration.

3.3.1 Sediment Sampling

Runoff volume on each plot was measured using a tipping bucket sampler (Khan and Ong, 1997), a device that alternately accumulates a fixed quantity of water on each side of a collection tub. As one side becomes filled, the tub tips on a rocker such that the collected sample is dumped into a channel and the other side of the tub begins collection. The particular tipping bucket used was designed especially for erosion sampling, principally by sizing the tub to give accurate measurements over the range of expected runoff volume. The tipping bucket was designed for storms ranging from 0.058 to 110 millimeters per hour and soil losses of 8.08 to 89.32 metric tons per hectare. The tipping rate of the bucket was not too slow to cause sedimentation between tipping cycles, but was also not so fast to change volume between tips. The samplers were constructed in the Biosystems Engineering Department mechanical shop.

The tipping volume of the samplers was calibrated before field-testing. The calibration procedure involved using a hose to direct water onto the sampling bucket and counting the number of tips required to accumulate a know quantity of water typically 10 liters. This experiment was repeated until the standard error of the mean of the estimated collector volume was less than 0.005 liters.

As runoff occurred during a storm, the flow entered the sampler, causing it to tip once the required volume was reached. As the sampler tipped, the water was poured over a collection pipe with multiple holes to allow a portion of the water to flow through. The sample collected in these holes was then routed into a collection bucket through a series of pipes. The number and diameter of holes in the pipe was fixed to divert about 1% of total runoff into the collection bucket. Figure 3.4 is a picture of the sampler configuration as installed on the milder trail section. Of note in the photo is the sheet-metal apron used to collect water from the turnout ditch into the tipping bucket.

For this type of sampler, measurement of runoff volume was equivalent to counting the number of tips. A HOBO® Pendant Event Logger was used in this study to record the time, date and number of tips during field data collection. The event logger counts were triggered using a mechanical switch that was attached to the tipping bucket. The Pendant® Event Logger was also used to record ambient temperature at a predetermined time interval.

The water collected in the sampling buckets after each storm was emptied into sealable buckets for transport back to campus. Data from the event logger were downloaded using a device from HOBO® designed for that purpose, and the loggers and samplers were reset for the next storm. Once back on campus, the tip data was loaded into a custom spreadsheet and a hydrograph was generated. Sediment samples were placed in the Biosystems Engineering Wet Lab cooler for later analysis.

Figure 3.4 -- Tipping bucket sampler during installation on the mild slope.

3.3.2 Rainfall Data

Rainfall data was collected using an ISCO® 674 Tipping Bucket rain gauge located approximately 300 meters from the experimental plots. The ISCO® 674 rain gauge measured both the intensity and the duration of each rainfall event. The rainfall data was stored directly on an ISCO® 6700 water sampler and was downloaded after each storm event using hardware from the manufacturer.

3.3.3 Sediment Analysis

Total sediment from each plot was estimated from the runoff samples collected using the above equipment. The entire sample was poured into an oven-safe container, weighed, and placed into an oven held at a constant 103°C. The containers were weighed every 24 hours and removed when two consecutive weights were found to be the same. Tare weight of the container was subtracted and the difference was the total weight of sediment in the sample. The total sediment loading was then calculated using the equation.

$$S = \frac{A - B}{C}$$

where:

S = total sediment from the experimental plot, kg

A = dry weight of sample and pan, kg

B = tare weight of the pan, kg

C = sample percentage of total runoff, = 1%.

The results from the lab analysis were compiled in combination with the information from the HOBO pendant data logger in order to calculate the sediment loading for each storm event for both research sites.

3.4 Erosion Prediction Modeling with WEPP

The erosion modeling for this project was performed with the USDA's Water Erosion Prediction Project (WEPP). Two of WEPP's main interfaces options are the hillslope and watershed interface. They differ mainly in the extent of the area modeled. For the purpose of this project, the hillslope interface provided the ability to model the details of a single slope section, much like the trail itself. The watershed interface is normally used to model large areas with less specific soil and management information.

The hillslope interface uses file builder programs to generate and format the significant amount of input data that are required to run the WEPP model. The builder programs allow the user to specify management practices and input data for climate, slope, soil, cover management, and, if needed, irrigation. The hillslope interface also provides a user the option of simulating a single storm or an extended period of time using computer-generated weather inputs.

3.4.1 Weather Generator

WEPP uses a weather generator to drive long-term simulations that calculate average annual sediment yield. This weather generator program is known as CLIGEN v. 4.3 and requires the user to specify a weather station location from which realistic rainfall information can be acquired. The Anniston, Alabama rain gauge station was chosen for the long-term simulation due to its proximity to the research site (located approximately 5.5 km from the trail).

3.4.2 Hillslope Designation and Model Calibration

Hillslopes in WEPP are defined by many parameters collected into three functional groups, known as layers. The first layer, defined as a management layer, allows the user to establish specific management practices for a given hillslope. Management information was available in the database for agricultural and forest road applications. The specialized forest road applications management database was used for the modeling performed in this study. The specific management practice chosen was an insloped, unrutted forest road with a bare ditch, which was felt to most closely approximate how the ORV trails were managed.

The second input layer defined the trail extent and profile. This information was measured using a clinometer and meter tape for each trail and turnout section. A hillslope definition for input to WEPP consisted of data describing the specific trail and turnout as contiguous sections of a single slope. A graphical representation of the two hillslopes defined for this study is shown in figures 3.5 and 3.6.

Figure 3.5 -- Mild slope with insloped unrutted forest road-bare ditch management layer.

Single Storm Simulation	Value	Units
Single Storm Precipitation		in
Single Storm Runoff		in
Single Storm Soil Loss		ton/A
Single Storm Sediment Yield		ton/A

Figure 3.6 -- Steep slope with insloped unrutted forest road-bare ditch management layer.

Single Storm Simulation	Value	Units
Single Storm Precipitation		in
Single Storm Runoff		in
Single Storm Soil Loss		ton/A
Single Storm Sediment Yield		ton/A

The third input layer was used to describe soil information for the specific location and site conditions. Through literature review on WEPP it was determined that the most sensitive soil parameters for WEPP are: the interrill erodibility, rill erodibility, critical shear, and effective hydraulic conductivity (Brodbeck, 2005). These parameters have a physical interpretation and can be measured, but are difficult to determine experimentally. Moreover, the relationship between these parameters as defined physically and as used in the WEPP simulation is not always one and the same. For example, the hydraulic conductivity parameter is defined physically as a measure of how quickly water moves through a given soil under the force of gravity and is indicative of the its relative porosity. As defined in WEPP, however, the effective hydraulic conductivity is related to the actual hydraulic conductivity, though not equal.

WEPP provides an alternative to physically measuring the parameters important to the simulations in which reasonable estimates can be calculated using a set of equations. The resulting estimates are appropriate for how WEPP itself interprets them. The equations use as input soil physical properties that are relatively easy to measure, including textural characteristics, organic matter content, and cation exchange capacity. The equations for critical soil parameters used by WEPP are:

$$\begin{aligned} K_i &= 2{,}728{,}000 + 192{,}100\,S_{vf} \\ K_r &= 0.00197 + 0.0003\,S_{vf} + 0.03863e^{-1.84\,O} \\ K_b &= -0.265 + 0.0086\,S^{1.8} + 11.46E_C^{-0.75} \\ T_c &= 2.67 + 0.65\,C - 0.058\,S_{vf} \end{aligned} \qquad [3.2]$$

where K_i is interrill erodibility (kg s m^{-4}) which is a measure of sediment delivery rate to rills, S_{vf} is percent very fine sand in the soil, K_r is rill erodibility (s m^{-1}) and a measure of soil susceptibility to detachment by concentrated flow, O percent organic matter in the soil, K_b is effective hydraulic conductivity (mm hr^{-1}), S is percent sand in soil, E_C is soil cation exchange capacity (meq $100g^{-1}$), T_c is soil critical shear (N m^{-2}), and C is percent clay in the soil.

The interrill erodibility, rill erodibility, critical shear, and effective hydraulic conductivity calculated were used as initial input parameters in the WEPP soil component layer. Soils were considered uniform throughout the hillslope, the same whether on the trail or on turnout. This was, by observation, not the case in fact. The turnouts tended to have a layer of loose deposited sandy material on the surface, whereas the trails tended to be uniformly densely compacted with little to no loose material on the surface. Soils beneath the surface of the turnouts, however, were compacted to a similar level as the trails. It was decided, however, that using two soil types in the WEPP soil layer definition (one each for trails and turnouts) would make the calibration process more difficult. Calibrating WEPP to some ‘average’ level of soil parameters was felt to be more appropriate than introducing an additional level of complexity when tuning the model.

With the WEPP input layers initialized, multiple event-by-event simulations were conducted and the results compared to measured values of runoff and sediment production. Soil parameter definitions were then altered in what was felt an appropriate manner and the simulations run again. This process was repeated until no further improvements were seen in the correlation between simulated and measured runoff and sediment. The measure of correlation used between simulated and measured variables was the Nash-Sutcliffe efficiency. When this value reached a maximum, the model was considered calibrated.

There were two alternatives when calibrating the WEPP model: a) step-wise calibration of runoff followed by sediment and b) ignoring runoff and calibrate directly to sediment. Both alternatives were attempted, but the later of the two methods tended to produce higher Nash-Sutcliffe correlations.

Because of the limited storm data available, it was not possible to divide the available data into unique calibration and validation sets. As an alternative, data were divided by slope and calibration was performed on one class (mild or steep) and validation was performed using the other. This process was repeated in both directions, i.e. the calibration and validation roles were reversed.

The storm data collected occurred over a period of time in which the trail was both open to traffic, and closed. This fact allowed an additional comparison of model and measured results between trafficked and non-trafficked conditions.

3.4.3 Statistical Analysis

In order to analyze for correlation between the actual field data and the predicted data from the model, the Nash-Sutcliffe efficiency (NSE) was used for the hydrology modeling and R^2 was used for the sediment loading.

According to Moriasi et al. (2007) the Nash-Sutcliffe efficiency is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information"). The NSE evaluates how field data compared to the predicted data fits a 1:1 line. The equation for the NSE is as follows:

$$NSE = 1 - \frac{\sum (Q_m - Q_p)^2}{\sum (Q_m - Q_a)^2} \qquad [3.3]$$

Where:

Q_m = the measured sediment or runoff,

Q_p = the model-predicted sediment or runoff,

Q_a = the average measured sediment or runoff.

The range for the NSE values are between -∞ and 1, with 1 being the best fit. The model is considered to have acceptable performance if the NSE is between 0.0 and 1.0. While values greater than 0 are acceptable, values 0.0 to 0.5 are consider poor with 0.5 to .75 are moderate and .75 to 1.0 being good. Negative values are usually considered unacceptable performance. According to Moriasi et. al. (2007), the Nash-Sutcliffe is recommended by the American Society of Civil Engineers (ASCE) for hydrologic modeling.

The R^2 value is an index of the degree of linear relationship between observed and simulated data (Moriasi et al., 2007). The R^2 value ranges from 0 to 1, with zero having no linear relationship. The R^2 value represents the proportion of variance with the higher the number the less variance, therefore values greater than 0.5 are usually considered acceptable for model calibration (Moriasi et al., 2007).

3.4.4 Model Validation

Model validation consists of running simulations with the calibrated model for storm events where field data has been collected. The predicted values from the calibrated model could then be compared to those from the actual field data collected. The validity of the calibrated model was judged by comparing the NSE of the validation set of data to that of the calibration set. If the NSE for the validated model was similar to that of the calibrated model, the validation was considered acceptable.

CHAPTER 4: RESULTS

4.1 Runoff Sampling

Runoff sampling was performed for approximately nine months, from October 2006 through June 2007. During that time period, eight storm events occurred on the trail sites. Due to a malfunction in the sampling equipment, complete data was recorded for five storms. For the storms with complete data sets, the cumulative rainfall, rainfall intensity, rainfall duration, total runoff, and total sediment yield were recorded. Data are summarized in Table 4.1 for rainfall and Table 4.2 for runoff and sediment loading.

The storm producing the largest sediment loading occurred on December 22, 2006. Rainfall for the event totaled 30.7 centimeters over 6.75 hours with a maximum intensity of approximately 0.71 centimeters per hour. The sampling system recorded a volume of 2190 liters from the mild slope and 2670 liters of runoff from the steep slope (Figure 4.1). Total sediment loss resulting from this storm for the mild and steep slopes was 0.71 tonnes per hectare and 2.5 tonnes per hectare, respectively.

Table 4.1 -- Rainfall data.

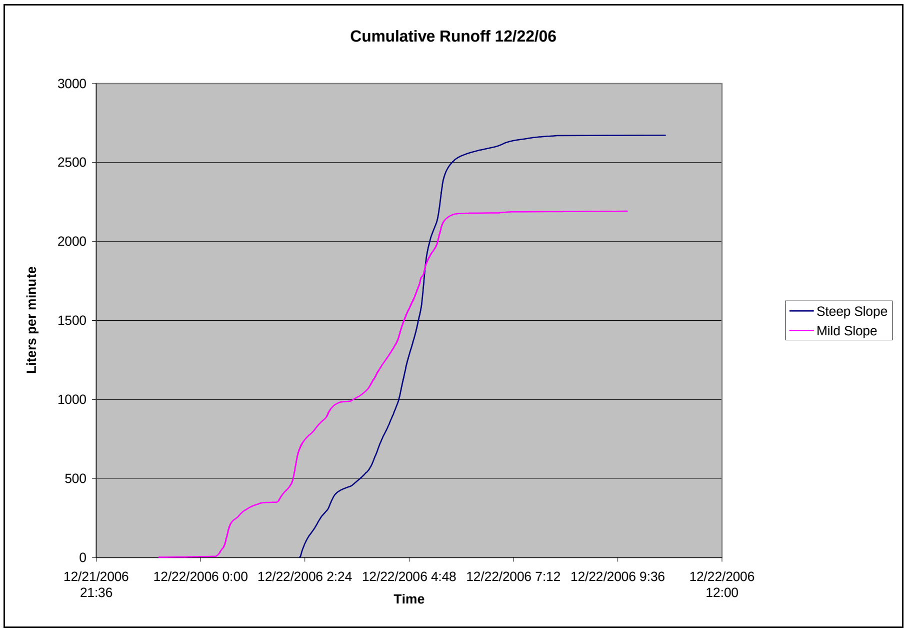
Storm Date	Max Rainfall Intensity (cm/hr)	Rainfall Duration (hr)	Total Cumulative Rainfall (cm)
11/15/2006	1.22	9.5	5.79
12/22/2006	0.71	6.75	3.07
2/1/2007	0.91	3.75	2.67
3/1/2007	1.42	0.5	0.36
3/15/2007	2.82	4.25	5.08

The storm on December 12, 2006 produced the largest sediment loading, although it did not have the highest runoff volume or largest rainfall amount during the sample period. The storm that had the highest runoff volume occurred on November 15, 2006 with the mild slope producing 6110 liters, and the steep slope 7750 liters of runoff. This storm also produced the highest cumulative rainfall during the study period. The highest rainfall intensity occurred in March with a maximum intensity reaching 2.82 centimeters per hour and 5.08 centimeters of cumulative rainfall. For data on all storm events, refer to Appendix A.

Table 4.2 -- Sediment yield.

Storm Date	Plot	Total Runoff (L)	Total Sediment Loading (Kg)	Total Sediment Loading (T/Ha)
11/15/2006	Mild	6112	11.01	1.76
	Steep	7746	53.17	4.62
12/22/2006	Mild	2186	28.81	4.61
	Steep	2672	101.17	8.78
2/1/2007	Mild	2551	5.31	0.85
	Steep	2180	11.52	1.00
3/1/2007	Mild	567	1.7	0.27
	Steep	1908	7.91	0.69
3/15/2007	Mild	2095	16.57	2.65
	Steep	5489	45.32	3.93

Figure 4.1 -- Cumulative runoff for 12/22/2006.



4.2 WEPP Model Calibration and Validation

4.2.1 Runoff Calibration

The WEPP model requires several parameters be provided, the most important of which are interrill erodibility, rill erobility, critical shear, and effective hydraulic conductivity. These parameters were estimated from soil samples taken from the trail running surface and analyzed at the Auburn Soil Testing Laboratory. The soil analysis indicated trail soils were a silty clay loam composed of 23% clay, 19% sand, 59% silt, and 0% organic matter, refer to Table 4.3. Using the equations discussed in the research procedures, the required WEPP input parameters were calculated and are listed in Table 4.4.

Table 4.3 -- Soil test results

Soil Parameter	Value
% Clay	23
%Silt	59
% Sand	19
% Very Fine Sands	27
% Rock	0
% Organic Matter	0
Cation Exchange Capacity	12

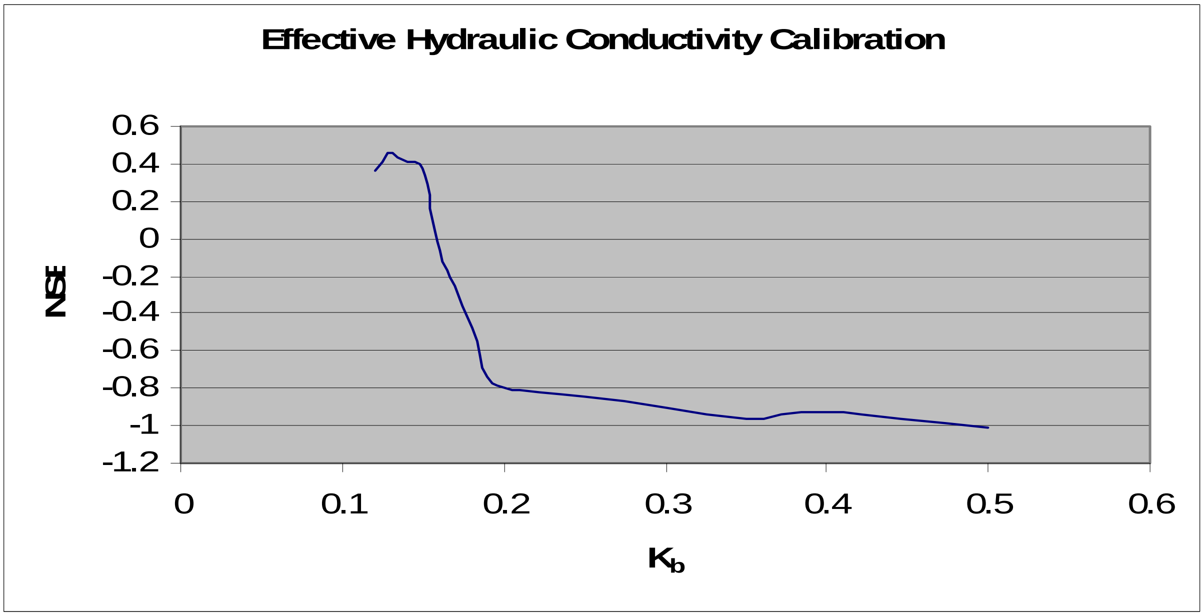
Table 4.4 -- Calculated soil parameter values.

Parameter	Value
Interrill Erodibility (kg*s/m4)	7.91E+06
Rill Erodibility (s/m)	0.010
Critical Shear (N/m2)	2.57
Effective Hydraulic Conductivity (mm/h)	3.19

The calculated values were input into WEPP along with the slope lengths, steepness, and observed weather information. Simulations were performed and compared to the actual data collected from the plots. The simulation with the calculated soil parameters values (Table 4.4) resulted in no predicted runoff or sediment yield. This was a significant departure from the observed sediment production behavior of the trails and was felt to be most likely a result of the high estimated effective hydraulic conductivity (EHC), which represented an undisturbed soil condition. The trail receives a high volume of ORV traffic and its surface has become densely compacted over time. The calculated hydraulic conductivity value for an undisturbed soil might, therefore, not apply. In addition to the traffic effect, the trail has been repeatedly reshaped using a bulldozer during maintenance intervals. As a consequence, the trail surface has been cut into the landscape to a depth of about 2 feet on average, or deeply into the subsurface soil horizon. This layer was a dense clayey material having low natural permeability.

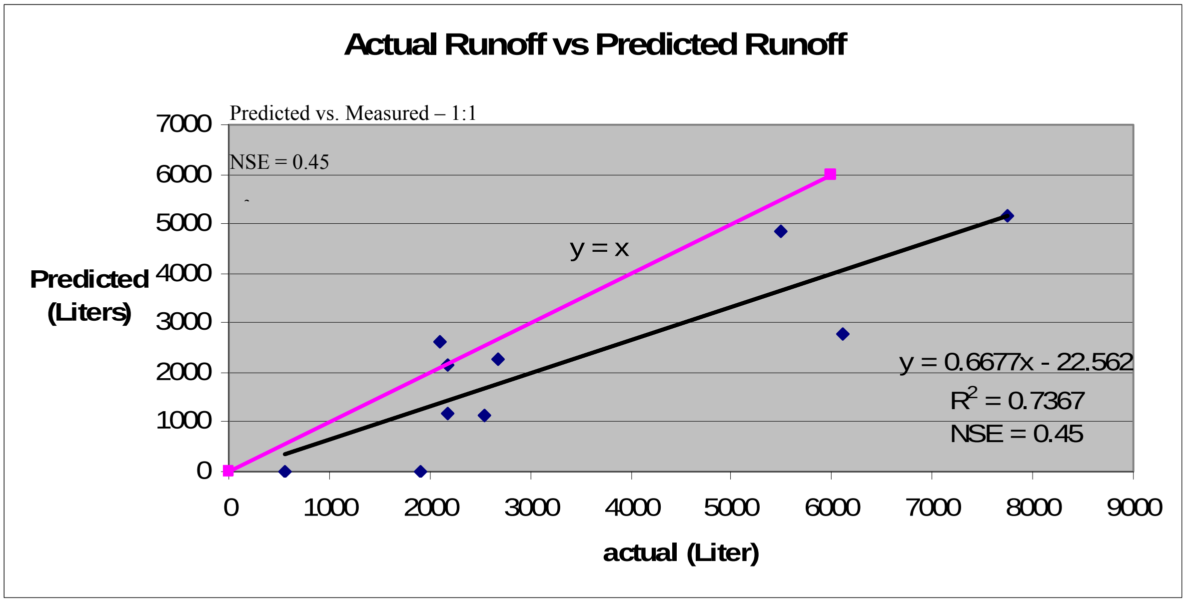
The EHC value was therefore systematically changed first in order to achieve the maximum Nash Sutcliffe Efficiency (NSE), refer to Appendix C for values tested and sensitivity plots. A maximum in NSE occurred at EHC of 0.13 mm hr^{-1} with the other parameters held fixed at their calculated values (from Eq 3.2) - see Figure 4.2. The maximum NSE was 0.45, a value considered acceptable for simulations, but not above 0.5, the threshold generally accepted as representing a ‘good fitting’ model.

Figure 4.2 -- Effective hydraulic conductivity calibration for runoff.



Having fixed an EHC value, the WEPP model was run for the measured storms using calculated values (Eq 3.2) for the erodibility and critical shear factors. Figure 4.3 is a graph showing measured and predicted runoff for the model as specified using these parameters along with a 1:1 line as a reference. The model consistently under predicted runoff for the conditions tested.

Figure 4.3 -- Actual runoff compared to predicted runoff after calibration using WEPP.



4.2.2 Sediment Calibration

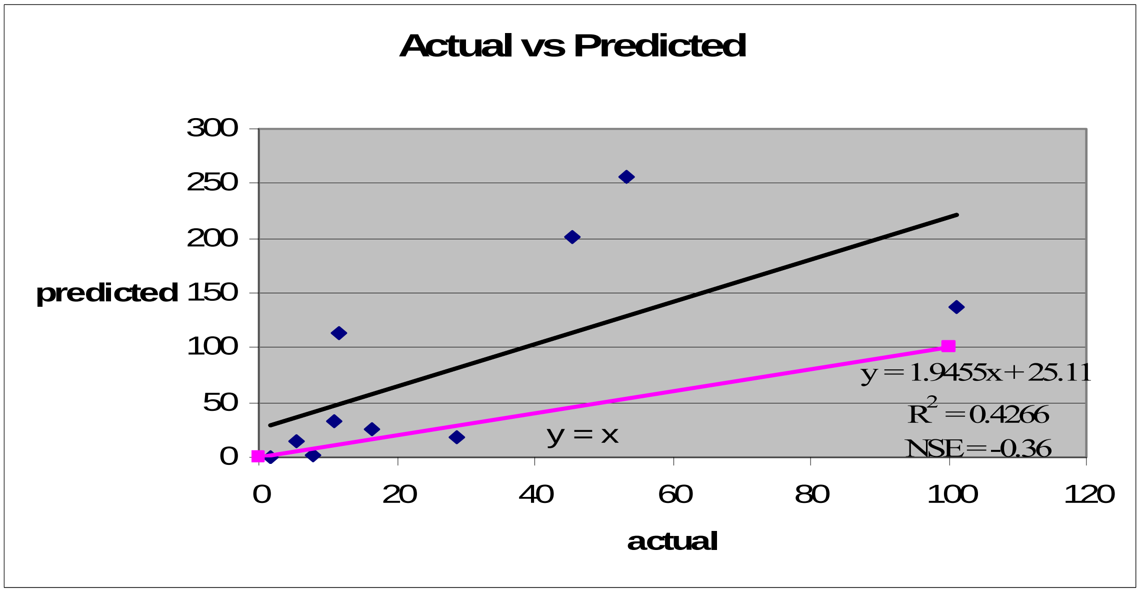
The gross calibration of the model with measured runoff was achieved through changes in hydraulic conductivity. Further adjustments were subsequently made to the other parameters (interrill erodibility, rill erodibility, and critical shear) to fine-tune the predictions of sediment yield. Once again, the objective in changing the parameters was to produce a better linear relationship between the predicted and measured data. The values of these parameters were adjusted and simulated in WEPP to produce the highest coefficient of determination (R^2), see Appendix C for all values and related R^2 values. The R^2 measure was used to assess quality of the predictions for sediment since NSE values were typically below 0, and therefore unacceptable. Parameter values were fixed by first changing critical shear until the maximal R^2 was observed. The process was repeated for the two erodibility factors. This sequential approach to WEPP model calibration seemed to work very well, but was not guaranteed to produce the globally maximal NSE or R^2. Final parameter values are summarized in Table 4.5.

Table 4.5 – Parameter values used to calibrate WEPP.

Parameter	Calibrated Value
Interrill Erodibility (kg*s/m4)	3.00E+06
Rill Erodibility (s/m)	0.0005
Critical Shear (N/m2)	12.5
Effective Hydraulic Conductivity (mm/h)	0.130

The final regression of the predicted versus actual sediment production is shown in Figure 4.4. The model had a slope of approximately 2 to 1, consistently over predicting sediment, with R^2 of 0.43, and NSE of -0.36. In general, the calibrated WEPP model therefore predicted lower runoff, but much higher sediment production, than observed. This implied that the model estimated much higher concentrations of sediment in a smaller volume of runoff.

Figure 4.4 -- Actual sediment yield compared to predicted sediment yield after calibration using WEPP.



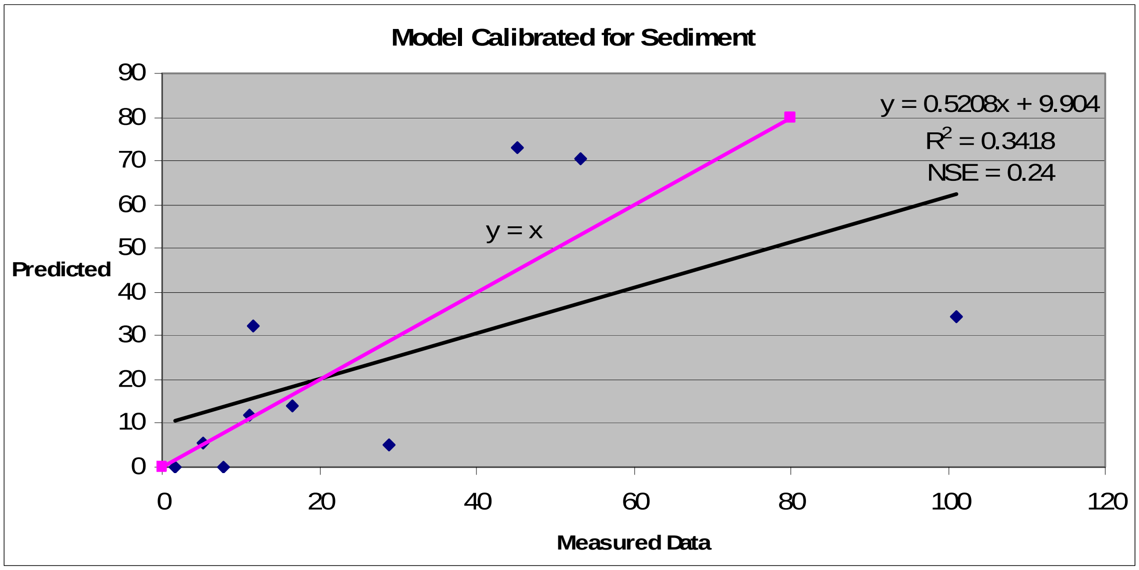
4.2.3 Sediment – Only Calibration

The original model was calibrated to runoff and sediment production, but the calibrated model performance was not close to the observed erosion behavior. As an alternate approach, a calibration directly to sediment, bypassing runoff, was attempted. The same calibration process was performed as in the previous approach. For the recalibration of the model, the NSE was used to determine the goodness of fit since this statistic represents a 1:1 slope instead of a standard linear relationship. The soil parameters were again adjusted and simulated in order to determine values producing the best model fit, see Appendix D for detailed parameter and NSE values. Table 4.6, shows the final values obtained from this calibration. The final model had NSE of 0.24, still less than 0.5 but much higher than the –0.36 for the model calibrated first to runoff.

Table 4.6 -- Model calibrated for sediment only

Recalibration of Sediment using the NSE for goodness of fit	
Parameters	Value
Interrill Erodibility (kg*s/m^4)	3.30E+06
Rill Erodibility (s/m)	0.0001
Critical Shear (N/m^2)	0.006
Effective Hydraulic Conductivity (mm/h)	0.08

Figure 4.5 – Model calibrated for sediment, without previous calibration for runoff.



4.2.4 WEPP Model Validation

The measured data were divided into mild and steep slope categories to perform a limited validation of the calibrated model. The process was to alternately calibrate the model on one slope class and validate on the other. Given the calibrated model could be confirmed as valid, the model itself could be used to evaluate the effect of slope on erosion rates.

A similar procedure as in the above analysis was used to calibrate the model independently for the mild and steep slope data sets. Refer to Appendices E and F for a summary of the parameter values used and resulting NSE for the mild and steep slope calibrations, respectively. The mild slope calibration produced a model with maximum NSE of -0.18 with the parameter values in Table 4.7. Using the mild slope parameters to estimate sediment production on the steep slope resulted in NSE of -1.12, see Figure 4.6. The calibration on the steep slope had NSE of 0.11, somewhat higher than for the mild slope. Table 4.8 contains final parameter estimates for the steep slope calibration. The comparison of measured and calibrated values for the mild slope resulted in a NSE of -1.77, refer to Figure 4.7. In both cases, the calibrated model was not as good a predictor of expected sediment production for the other slope.

Table 4.7 -- Mild slope calibration

Calibration of Mild Slope	
Parameters	Value
Interrill Erodibility (kg*s/m^4)	5.20E+06
Rill Erodibility (s/m)	0.00016
Critical Shear (N/m^2)	0.01
Effective Hydraulic Conductivity (mm/h)	0.09

Figure 4.6 – Validation using model parameters estimated from mild slope data for the steep slope.

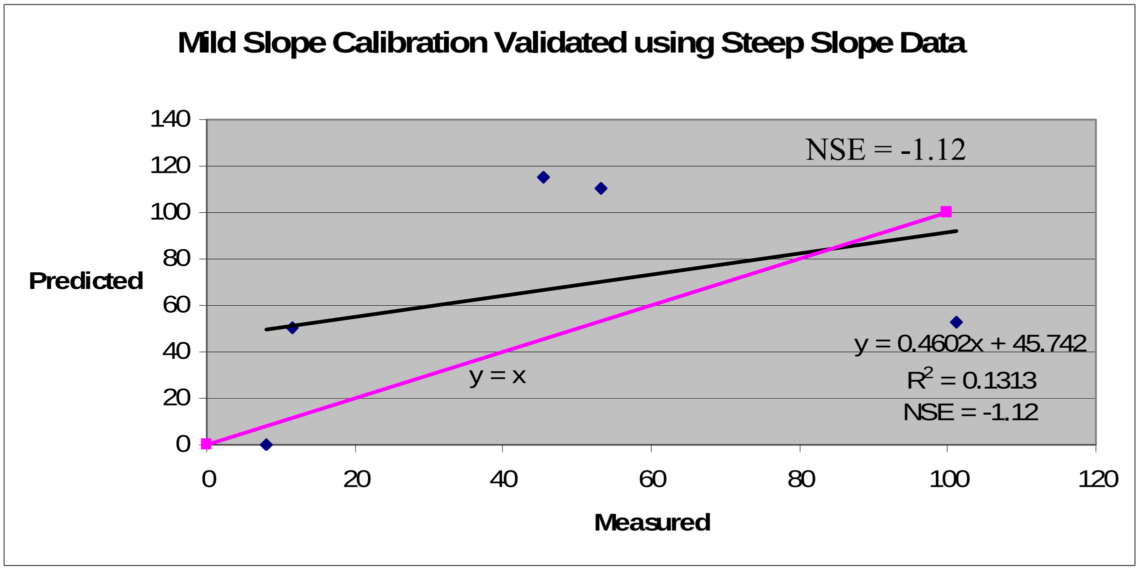


Table 4.8 -- Steep slope calibration

Calibration of Steep Slope	
Parameters	Value
Interrill Erodibility ($kg*s/m^4$)	1.10E+06
Rill Erodibility (s/m)	0.00012
Critical Shear (N/m^2)	0.009
Effective Hydraulic Conductivity (mm/h)	0.085

Figure 4.7 – Validation using model parameters estimated from the steep slope data for the mild slope.

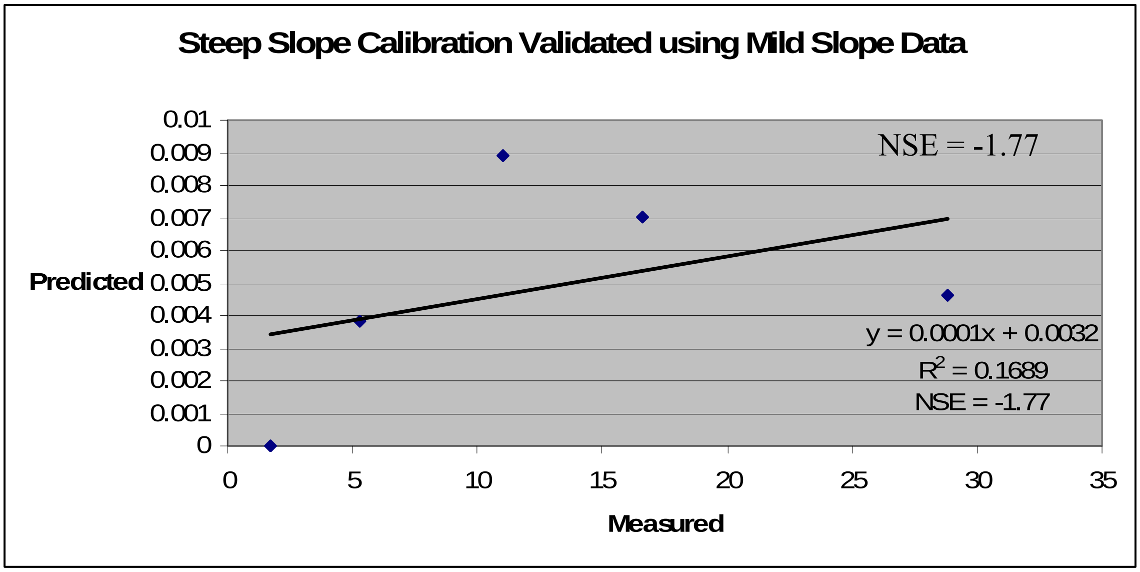
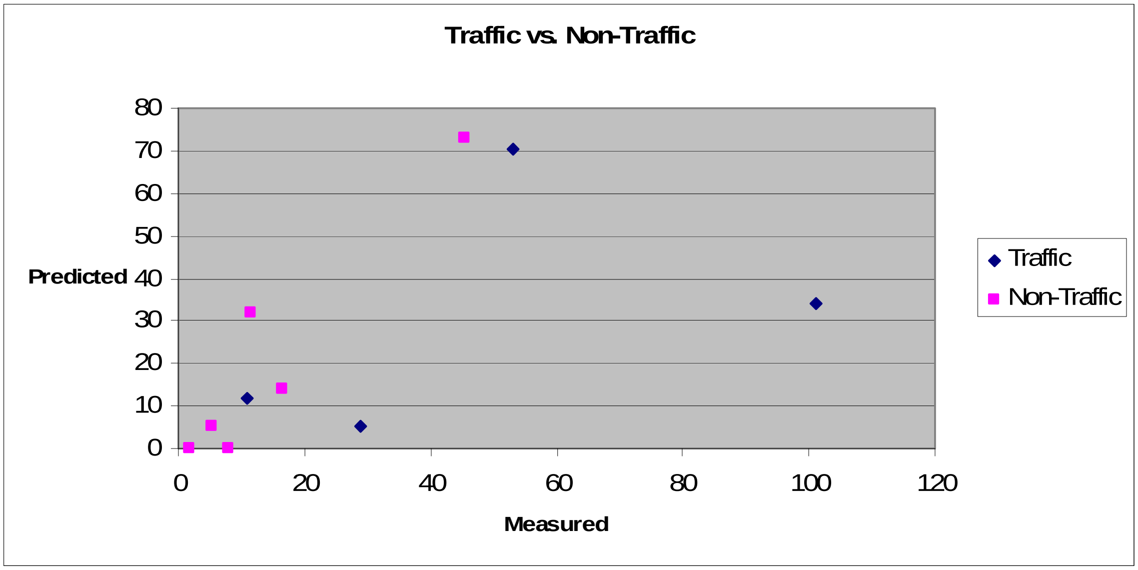


Figure 4.8 – Traffic vs. Non-Traffic period.



4.2.5 Effect of Traffic

Figure 4.8 is a plot of predicted and measured sediment from the combined calibration for sediment only with the points classified by time period. During the periods October through December, 2006 and April through June, 2007 the trail system was open for use. From January to April, 2007 the trail was closed and no traffic was permitted. It was clear from the data that the model sediment predictions were closer to measured values for the non-trafficked period. For the storms during the trafficked period, the WEPP model significantly under predicted the amount of sediment relative to the observed. Two calibrations of the WEPP model were therefore made to determine the effect of the traffic.

The calibration for the traffic period resulted in NSE of -0.11 while the non-trafficked period produced a NSE value of 0.76; see Appendix G and H for parameter and NSE values. The calibrated values for each of the processes are shown in Tables 4.8 and

4.9. Refer to Figures 4.9 and 4.10 for plots of measured and predicted sediment data for trafficked and non-trafficked conditions, respectively. The results from the calibration process for the two models indicated WEPP was more accurate for the non-trafficked time period. The erosion from the non-trafficked period resulted from weather occurrences only. The WEPP model was designed to simulate soil erosion from precipitation only and does not account for traffic on the ORV trails. Anthropogenic factors are much less predictable and have been researched to a much lesser extent than precipitation. From this research (Tables 4.8 and 4.9), it was clear that traffic increased WEPP erosion parameters by a factor of about 2. It was also clear that simply changing the model input parameters did not account fully for the observed changes in erosion, as was seen in the much lower NSE for the trafficked condition. Some other type of erosion mechanism must not be accounted for in WEPP, probably related to soil loosening from the action of the tires on the trail surface. Further research will be needed to both confirm this result and to propose a means of accounting for this traffic factor in the model itself.

Table 4.9 -- Calibrated values for trafficked period

Parameters	Value
Interrill Erodibility ($kg*s/m^4$)	4.26E+06
Rill Erodibility (s/m)	0.00012
Critical Shear (N/m^2)	0.008
Effective Hydraulic Conductivity (mm/h)	0.071

Table 4.10 -- Calibrated values for non-trafficked period

Parameters	Value
Interrill Erodibility ($kg*s/m^4$)	4.10E+05
Rill Erodibility (s/m)	9.00E-05
Critical Shear (N/m^2)	0.0058
Effective Hydraulic Conductivity (mm/h)	0.152

Figure 4.9 – Calibrated data for trafficked period

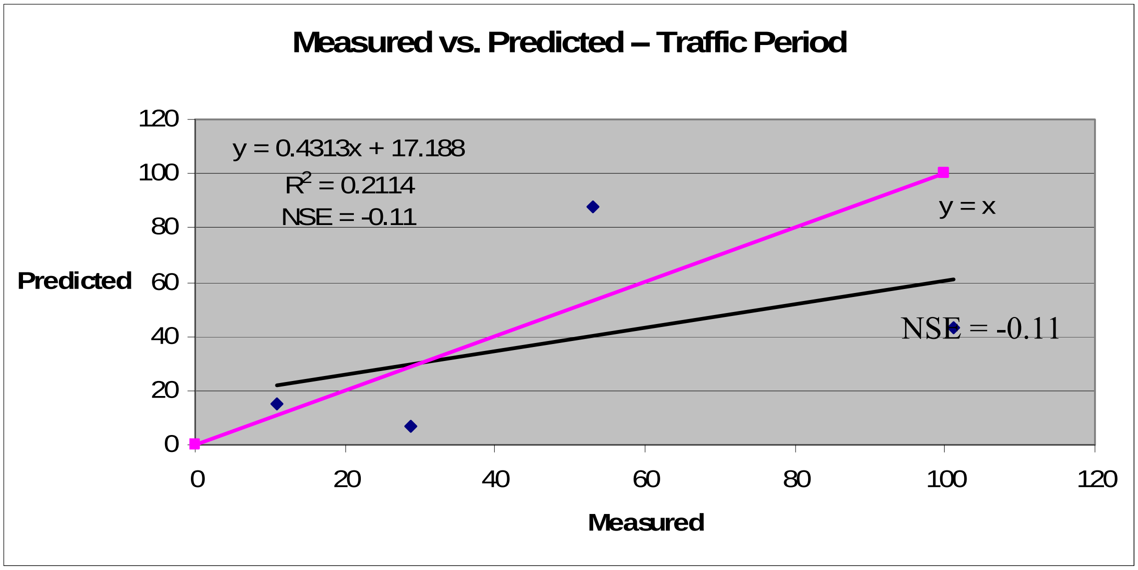
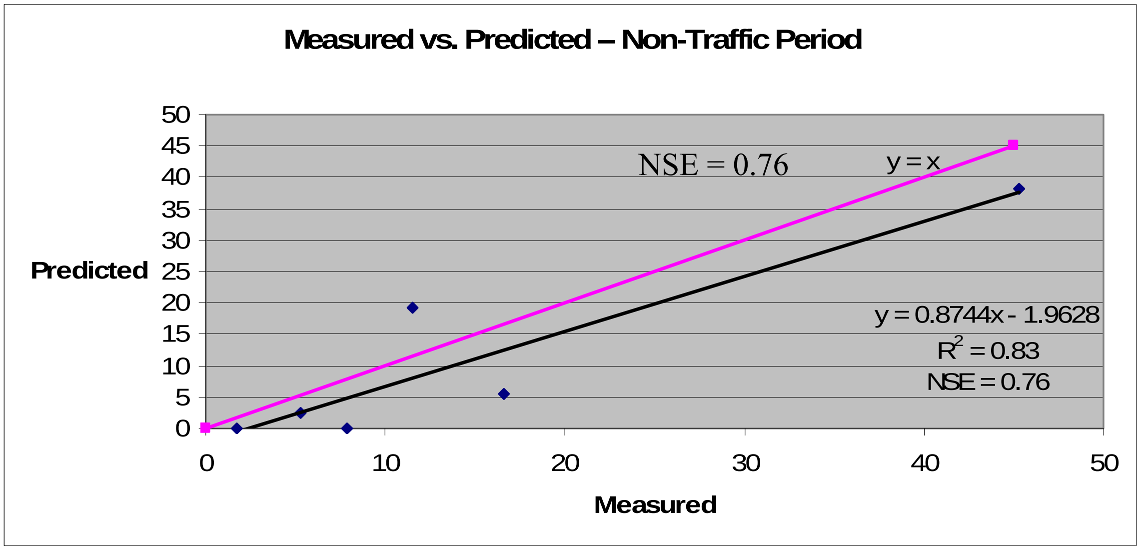


Figure 4.10 – Calibration of non-trafficked period.



The results of the six calibration processes (refer to table 4.11) showed that the non-trafficked data was the most accurately predicted from the model simulations while the trafficked period produced an unacceptable goodness of fit (NSE) value. Apparently, the runoff model of WEPP was also less accurate than the sedimentation prediction portion since bypassing the runoff calibration step increased the accuracy of predictions, although neither one was accurate enough to call it a ‘good’ fit. The effect of slope was also not large. Calibrated model parameters were similar between the mild and steep slopes, differing by greater than 25% only in the case of the inter-rill erodibility, which went down quite a bit between the mild and steep slope conditions. The drop in inter-rill erodibility could be associated with the type of soil. The steep slope was more deeply dug into the landscape, into a different soil horizon than the mild slope. In general, the WEPP model performed fairly well in predicting erosion, but further research is needed if high correlation with measured erosion is desired. Most important will be developing a means of accounting for surface soil disturbance, principally wheel traffic, into the model.

Table 4.11 – Summary of calibration data.

Calibration	Slope used for Calibration	Calibrated NSE	Interrill Erodibility	Rill Erodibility	Critical Shear	Effective Hydraulic Conductivity	Slope used for Validation	Validated NSE
			Ki	Kr	Tc	Kb		
Original Calibration	Both	-0.36	3.00E+06	0.00050	12.5	0.130	NA	NA
Calibration for Sediment only	Both	0.24	3.30E+06	0.00010	0.0060	0.080	NA	NA
Mild Slope	Mild	-0.19	5.20E+06	0.00016	0.0100	0.090	Steep	-1.12
Steep Slope	Steep	0.10	1.10E+06	0.00012	0.0090	0.085	Mild	-1.77
Trafficked	Both	-0.11	4.26E+06	0.00012	0.0080	0.071	NA	NA
Non-Trafficked	Both	0.76	4.10E+05	0.00009	0.0058	0.152	NA	NA

4.3 BMP Simulation

Current practice is to use BMPs developed for forest roads for ORV trails as well, primarily because there has been little research directed toward developing BMPs for ORV trails. The WEPP model calibrated for this project offered an opportunity to evaluate WEPP for the use of developing management alternatives for trails. The WEPP model was used to simulate trail erosion for a 30-year time period in order to estimate average annual sediment loss. The simulations were performed on multiple slopes to determine the maximum distance between water diversion structures. In all simulations, it was assumed that all water was diverted off the trail at each water diversion structure.

In order to run the simulations, WEPP requires a maximum sediment loading value. According to Ayala (2005), the National Forest in Alabama considers more than 44.5 tons/ha/year (18 tons/acre/year) of sediment yield from temporary roads and disturbed areas as unacceptable and this value was used in all simulations.

Given the maximum allowable sediment export level, simulations were run at a given slope to calculate the length of trail at which the threshold erosion level would be exceeded. The model calibrated for sediment production only was used in order to estimate the recommended water bar spacing. Table 4.12 lists the maximum slope lengths between water diversion structures, produced by WEPP, to ensure compliance with the erosion limit. This table shows the results from the WEPP model, these values were simulated and are estimates of structure spacing. Due to the limited data used to calibrate and validate the model these results should not be used in practice until the model has been validated and the results have been verified. The spacing was calculated such that the hillslope would not exceed the maximum loading at the point at which water leaves the trail and enters the diversion.

Table 4.12 -- Water diversion structures spacing from WEPP results.

Recommended Water Diversion Structure Spacing	
Slope (%)	Spacing (ft)
2	265
4	100
6	55
8	30
10	18
12	14
14	8

Once the structure results were calculated, we compared these spacing values to diversion spacing information established by Brodbeck (2005) at Auburn University, see Table 4.12. Brodbeck suggested spacing for the milder slopes were much less than that calculated from our simulations. Brodbeck recommended 46 feet for a 4% slope while our simulations showed that a spacing of 100 feet was appropriate. Brodbeck suggests a 22 feet spacing on a 14 % hillslope, whereas our model suggests that a 8 ft maximum spacing should be installed. The recommendations from both models are designed for trails that are not in proximity with a stream channel or other water body. The difference in spacing could be associated with the difference in field collection. The data collected by Brodbeck occurred at a stream crossing in which TSS and stream flow data were collected and analyzed. The data collected for this project consisted of runoff samples from two hillslopes with different steepness which was then used to calculate total sediment loading. The different data collection locations could be the reason for the differences in the spacing results.

Table 4.13 -- Water diversion spacing developed by Brodbeck

Recommended Diversion Structure Spacing developed by Brodbeck	
Slope (%)	Spacing (ft)
4	46
6	36
8	33
10	29
12	27
14	22
18	19

In the past, the BMPs used on ORV trails were adopted from forest roads. We compared the calculated water bar spacing from WEPP to the recommended water bar spacing for forest roads. In 1995 Brinker developed tables to assist managers in water bar spacing. The spacing recommended for water bar spacing for skid trails and logging roads is in Table 4.14 taken from (Brinker, 1995). This table shows that the recommended spacing for a road with a 2 % grade is 250 ft. This spacing is similar on milder slopes, but the slope length resulting from this research for steeper slopes is much shorter.

Table 4.14 -- Recommended distances between water bars on skid trails and logging roads after logging is complete (Brinker, 1995).

Recommended Distances Between Water Bars On Skid Trails and Logging Roads After Logging Is Complete.	
Road Grade	Spacing (feet)
2	250
5	135
10	80
15	60
20	45
25	40
30	35
40	30

CHAPTER 5: CONCLUSION

The goal of his project was to study the sediment loading from ORV trails and to use WEPP to calculated maximum slope lengths for varying slopes using field data.. Two sites were studied on the Kentuck ORV trail system for approximately 9 months. During this time period the trail received 8 storms, three of which were not sampled due to equipment malfunction. A runoff sample was taken from the remaining five storms in order to determine the amount of sediment being eroded from the trail. In addition to the runoff sample, the total runoff, runoff intensity, rainfall, and rainfall intensity were also recorded for use in the analysis. Data analysis was performed to calculate the total amount of sediment being eroded from the trail. This data was used to simulate the erosion from the trail system through the Water Erosion Prediction Project model, WEPP. The trail sections were simulated and compared to the actual field data collected from the site. Using this process, WEPP was calibrated in order to increase the accuracy of the simulations. With the model calibrated, it was used to develop BMPs for the trail system.

5.1 Objective 1

The 5 storms sampled produced approximately 169 millimeters of rainfall, in a region that typically receives approximately 1300 millimeters per year. This produced a total of 63.4 kg and 219.09 kg of sediment from the mild and steep slopes, respectfully. Due to unusual weather conditions the location only received one storm event with one inch cumulative rainfall. During this time, a storm occurred producing 3.07 centimeters of rainfall on December 22, 2006. The storm peaked at 0.71 centimeters per hour with duration of 6.75 hours. This storm caused approximately 28.81 kg and 101.17 kg from the mild and steep slope, respectively.

5.2 Objective 2

Using the data collected from the storms, the WEPP Hillslope Interface was calibrated to predict sediment loading. Using information taken from soil samples on the trails, required soil parameters were determine and input into the WEPP software. Using the Nash-Sutcliffe efficiency, the field data were compared to predicted data from the model. WEPP was calibrated for multiple scenarios in order to see the effects of slope and traffic on the trail. The model that was calibrated for the non-trafficked period produced the highest NSE of 0.76. This model was expected to produce the highest values since it only accounted for the weather related erosion on the trail and not the added variable of ATV traffic. The calibration for sediment production which included both slopes produced the second highest NSE of 0.24. Due to the lack of field data, this was the best calibration that could be obtained for ORV use on the trail

5.3 Objective 3

The calibrated WEPP model was used calculate slope lengths for ORV trails. This was needed because of the lack of data available on ORV trails. The results indicated that the maximum spacing for water diversion structures is approximately the same as was published by Brinker (1995) for mild slopes. Simulations showed that while on mild slopes, the results are approximately the same as forest roads while spacing on steep slopes are much less than on forest roads. The spacing resulting from the data collected were used for the purpose for modeling varying slopes. The calibration model did not produce an acceptable model to accurately predict the max loading. Therefore, these slope lengths should not be used in practice until more research can conform there accuracy.

5.4 General Conclusion

It is concluded that ORV trail systems such as the Kentuck ORV area can be a serious threat to the water resources on our forest landscapes. Through the use of specialized BMPs, along with additional research and BMP development the threat from sediment pollution from ORV trails can be lowered. This is essential for the protection of our forested lands and the recreational use of those lands.

5.5 Future Research

In the future, additional research should be performed on the ORV trail to further reduce the environment impacts of the trail systems.

- Research of erosion from the use of ORVs would add significant information to the research performed in this study. The type of ORV, type of tires, and the aggressiveness of the driver all have an effect on the sediment production. Due to these factors, an in-depth study should be performed in order to determine the type and speed of the ORVs operating on the trails. This could be done through motion sensing cameras at each location. These cameras would show the exact number of riders and speed at which the riders crossed through the study area. A controlled study of soil damage from ORVs would also generate information that could be used in this study.

- Research on the erosion from the turnouts located on the trail could be used in the model from this project to increase the model's efficiency. For this project, the soil was considered uniform throughout the slope. The soil in the trail and turnout are of similar type, but the compaction is much lower in the turnout. Sediment loading from the turnout could be measured and calibrated in WEPP, then used in the model along with data from the trail itself. This additional data for the turnout could increase the ability of the model to accurately predict the trail erosion.
- Additional field data would greatly improve the results from this study. The additional data could be generated through an extended study at the two locations from this research, or by the addition of sampler locations. More field data would allow for an improved model calibration and more complete validation procedures. The data collected for this project occurred during an extremely dry period. Further data collection could sample data through normal weather conditions, and also wet conditions, which would add to more accurate average annual erosion data. The average annual erosion data could be used to simulate the trail system in RUSLE2. RUSLE2 was designed more for planning and uses only average annual sediment production.

- Other factors could affect the prediction ability of the model also. These factors should be addressed to determine there affect on erosion from the trail in future research. These factors include: time of year, temperature affects on soil parameters, effect of maintenance practices on soil erosion, and traffic direction, especially related to uphill or downhill driving.

REFERENCES

Adams, J.A., A.S. Endo, L.H. Stolzy, P.G. Rowlands, and H.B Johnson. 1982. Controlled experiments on soil compaction produced by off-road vehicles in the Mojave Desert, California. Journal of Applied Ecology 19:167-175.

Alabama Forestry Commission. 1993. *Alabama's Best Management Practices for Forestry*. Montgomery, Al.

Appelboom, T.W., G.M. Chescheir, R.W. Skaggs, D.L. Hesterberg. 2001. Evaluating Forest Road Management Practices for Reducing Sediment Production and transport From Forested Watersheds. *ASAE 701P10007*

Ayala, R. D., P. Srivastava, C. J. Brodbeck, E. A. Carter, and T.P. McDonald. Water Quality Impacts from an ORV Trail Stream Crossing in the Talladega National Forest, Alabama, USA. Presented at the Annual COFE Meeting. 2005.

Brinker, R.W. 1995. *Forest roads and construction of associated water diversion devices*. Alabama Cooperative Extension Service. ANR-916.

Brodbeck, C.J., 2005. *Modeling Water Quality Impacts Off Road Vehicles in Forested Watersheds.*. Auburn, AL. MS Thesis, Auburn University.

Brooks, K.N., P.F. Ffolliott, H.M. Gregersen, and L.F. Debano. 2003. *Hydrology and the Management of Watersheds*. Ames, Iowa.: Blackwell Publishing.

Eav, L. Unmanaged recreation. Key Messages and Talking Points from the Fourt Threats of Leadership Information Packer, USDA Forest Service, Office of Communication – Washington D.C.

Eckert, Jr., R.E., M.K. Wood, W.H. Blackburn, and F.F. Peterson. 1979. Impacts of off-road vehicles on infiltration and sediment production of two desert soils. Journal of Range Management 32(5):394-397.

Foltz, R.B., 2006. Erosion from all terrain vehicle (ATV) trails on National Forest lands. ASABE Paper Number 068012. St. Joseph, MI: ASABE. Pranson, M.A., managing ed. 1985. Standard methods for the examination of water and wastewater, 16th ed. Baltimore, MD: Port City Press.

Grace, J.M. 2002. Overview of Best Management Practices related to Forest Roads: The Southern States. *ASAE Meeting Presentation. Paper No: 025013*

Grace, J.M. 2005. Application of WEPP to a Southern Appalachian Forest Road. *ASAE International Meeting Presentation Paper No: 052016*

Grace, J.M. 2005b. Forest Operations and Water Quality in the South. *Trans. ASAE* 48(2):871-880

Grace, J.M. and B.D. Clinton. 2006. Forest Road Management to Protect Soil and Water. *ASABE International Meeting Presentation Paper No: 068010.*

Khan A.A., and C. K. Ong. 1997. Design and calibration of tipping bucket system for field runoff and sediment quantification. Journal of Soil and Water Conservation. 52(6) 437-443.

Klik, A, and A.S. Zartl. 2001. Comparison of Soil Erosion Simulations Using WEPP and RUSLE with Field Measurements. Soil Erosion Research for the 21st Century, Proc, Int. Conf. ASABE Pub # 701P0007.

Kutiel, P., E. Eden, and Y.Zhevelev. 2000. Effect of experimental tramping and off-road motorcycle traffic on soil and vegetation of stabilized coastal dunes, Isreal. Environmental Conservation 27(1) : 14-23.

Moriasi, N., J.G. Arnold, M.W. Van Liew, R.L. Bingner, R.D. Harmel, and T. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of ASABE.* In press.

Novotny, V. 2003. Water Quality: Diffuse Pollution and Watershed Management. New York: John Wiley & Sons.

NSERL. 1995. USDA-Water Erosion Prediction Project Hillslope Profile and Watershed Model Documentation. NERSL National Soil Erosion Research Laboratory

Ohio State University. Streams: Stream Restoration, Ecology, and Aquatic Management Solutions. http://streams.osu.edu/book/equation_pdf/Ch9-Equations.pdf. Last visited October 7, 2007.

Sack, D., and S. da Luz. 2003. Sediment flux and compaction trends on off-road vehicle (ORV) and other trails in an Appalachian forest setting. Physical Geography 24(6): 536-554.

Sherrod, T., A. Blankenship. RUSLE2 Analysis as an Erosion and Sedimentation Control Design Alternative for Linear Transportation Projects. North Carolina department of Transportation Transaction. 2004.

USDA-ARS. 2003. USDA- Revised Universal Soil Loss Equation, Version 2: User's Guide. USDA-NRCS, Columbus Ohio.

USDA-ARS MWA. Universal Soil Loss Database. http://topsoil.nserl.purdue.edu/usle/page7.html. Last visited October 7, 2007.

APPENDIX A

Rainfall and Sediment Sampling

Figure A.1 – Cumulative rainfall for 11/15/2006.

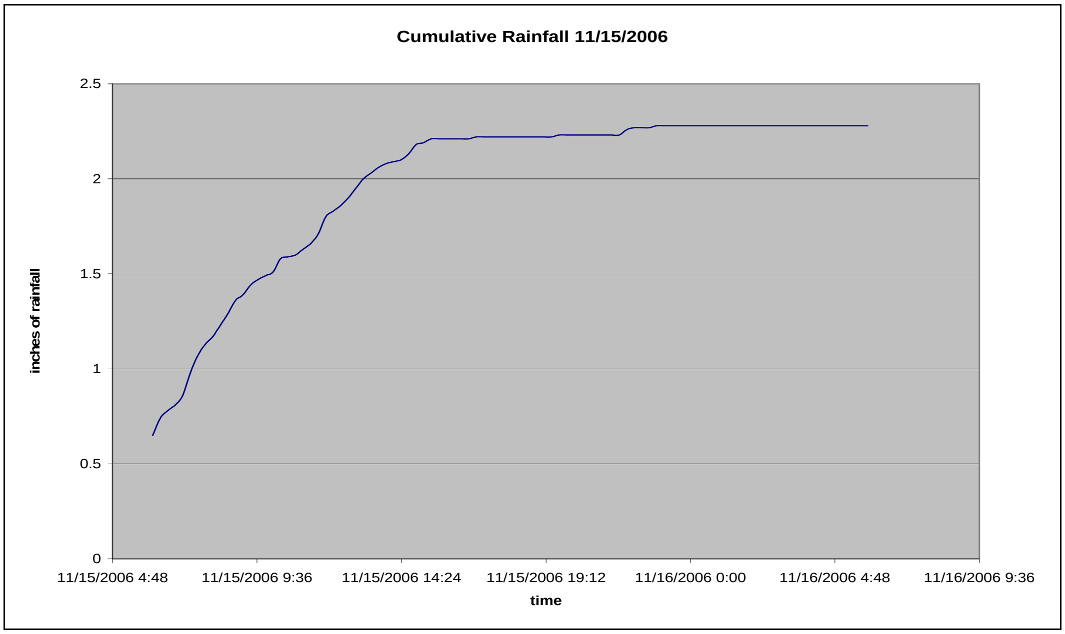


Figure A.2 – Rainfall hydrograph for 11/15/2006.

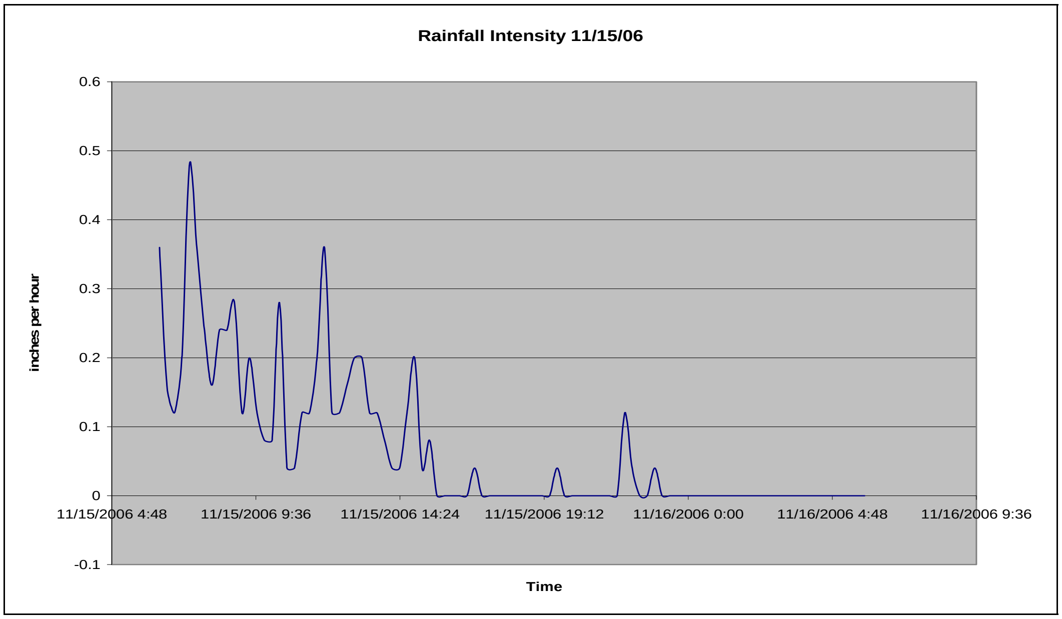


Figure A.3 – Cumulative runoff for mild and steep slope plots for 11/15/2006.

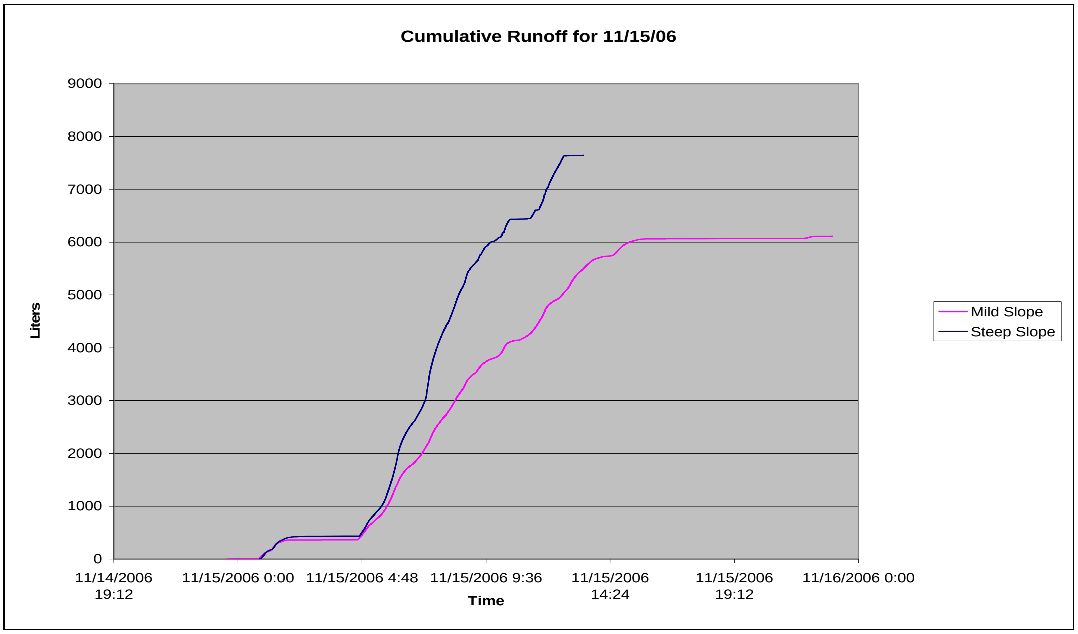


Figure A.4 -- Runoff intensity for 11/15/06.

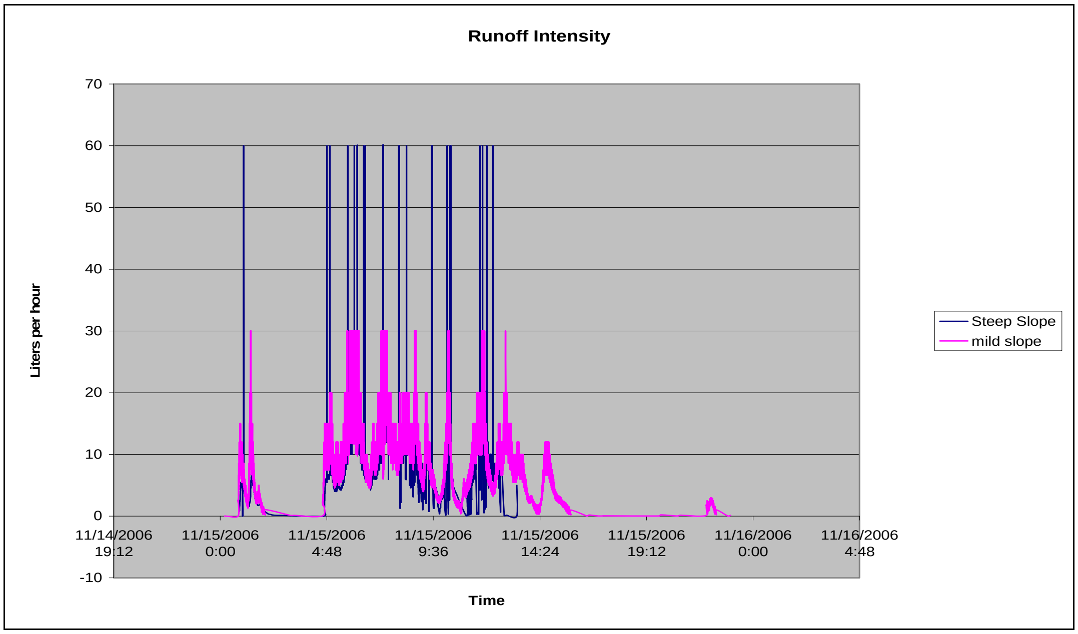


Figure A.5 – Cumulative rainfall for 12/22/2006.

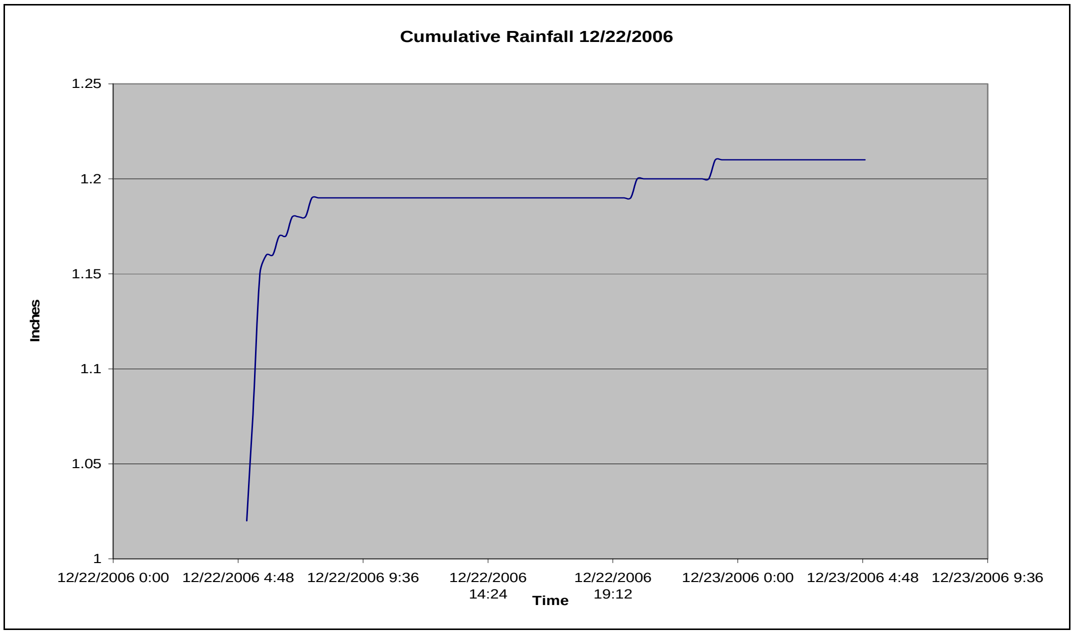


Figure A.6 --Rainfall hydrograph for 12/22/2006.

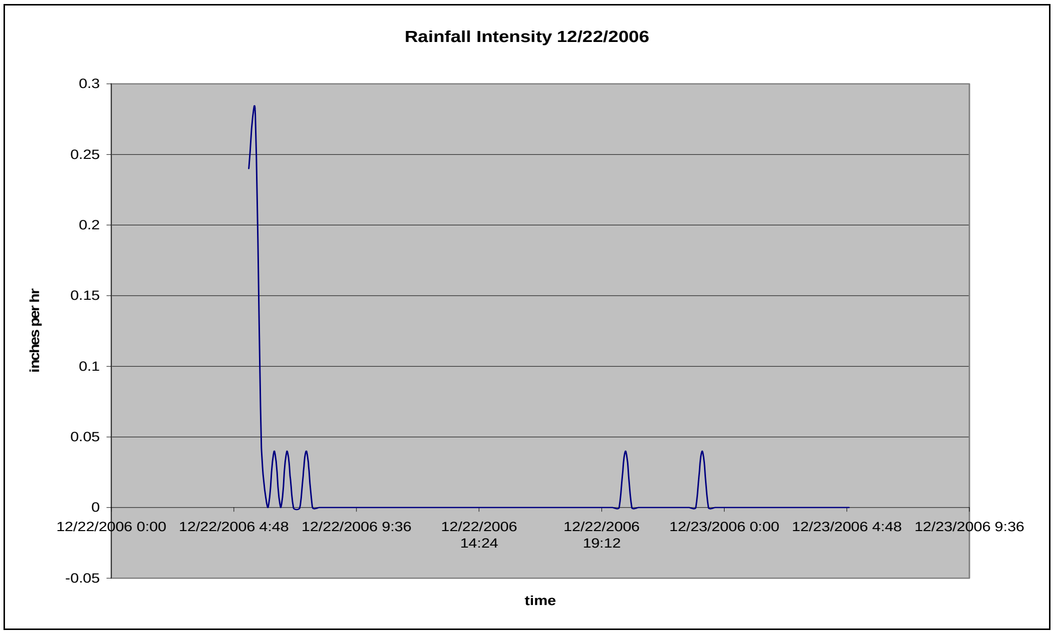


Figure A.7 – Cumulative runoff for mild and steep slope plots for 12/22/2006.

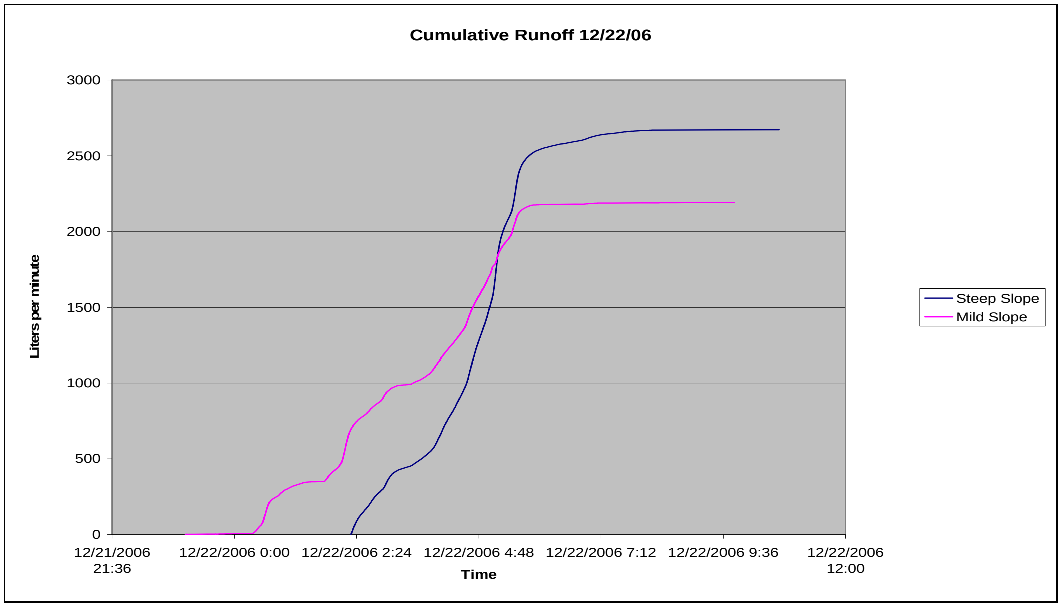


Figure A.8 -- Runoff intensity for 12/22/06.

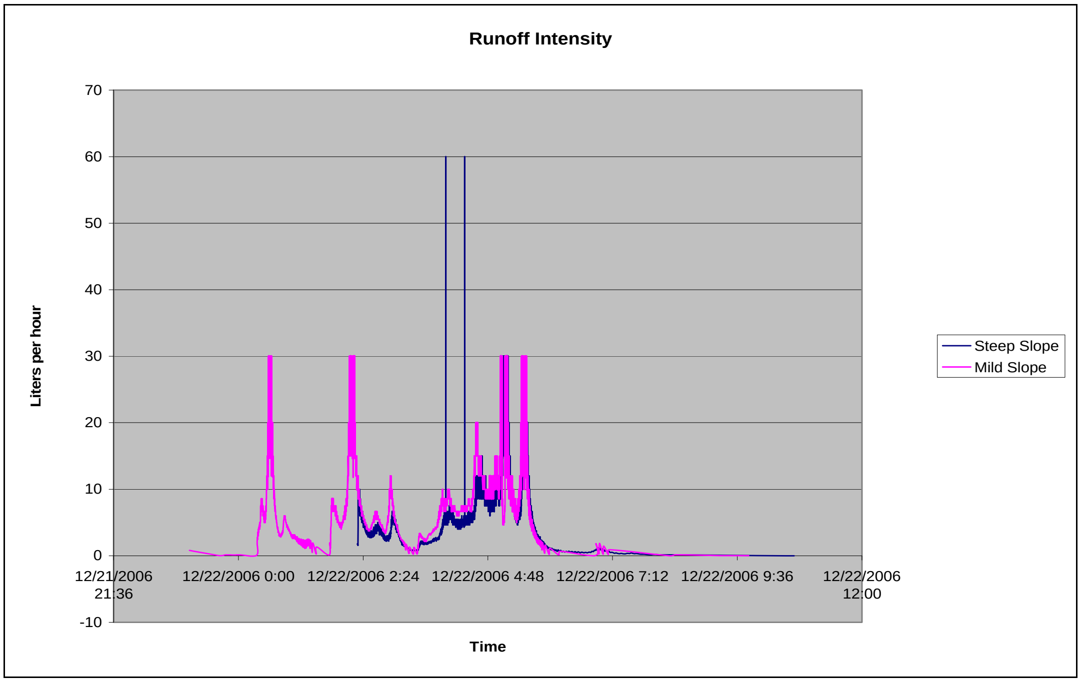


Figure A.9 – Cumulative rainfall for 2/1/2007.

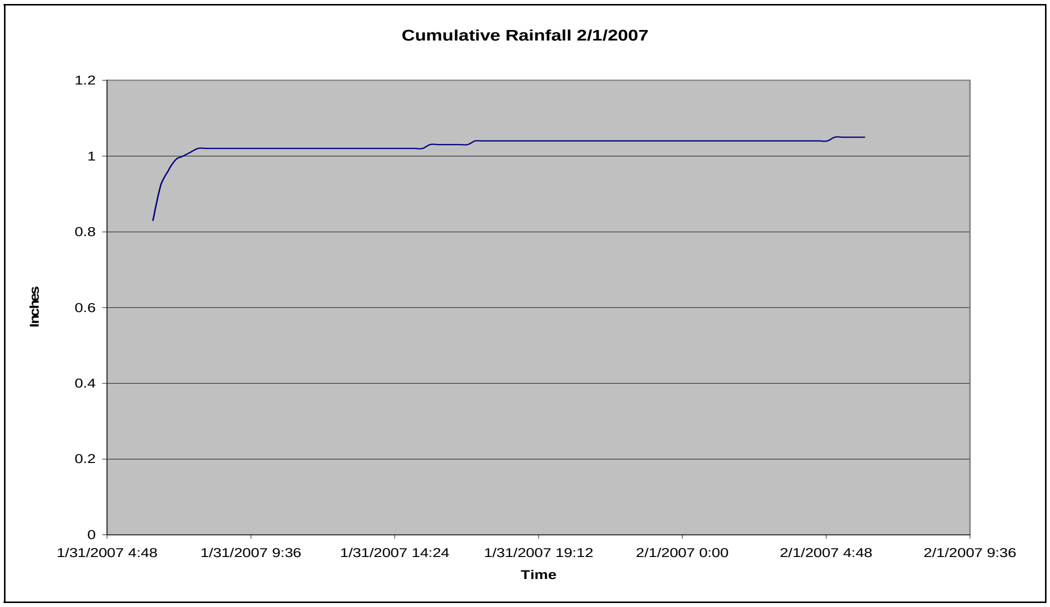


Figure A.10 – Rainfall hydrograph for 2/1/2007.

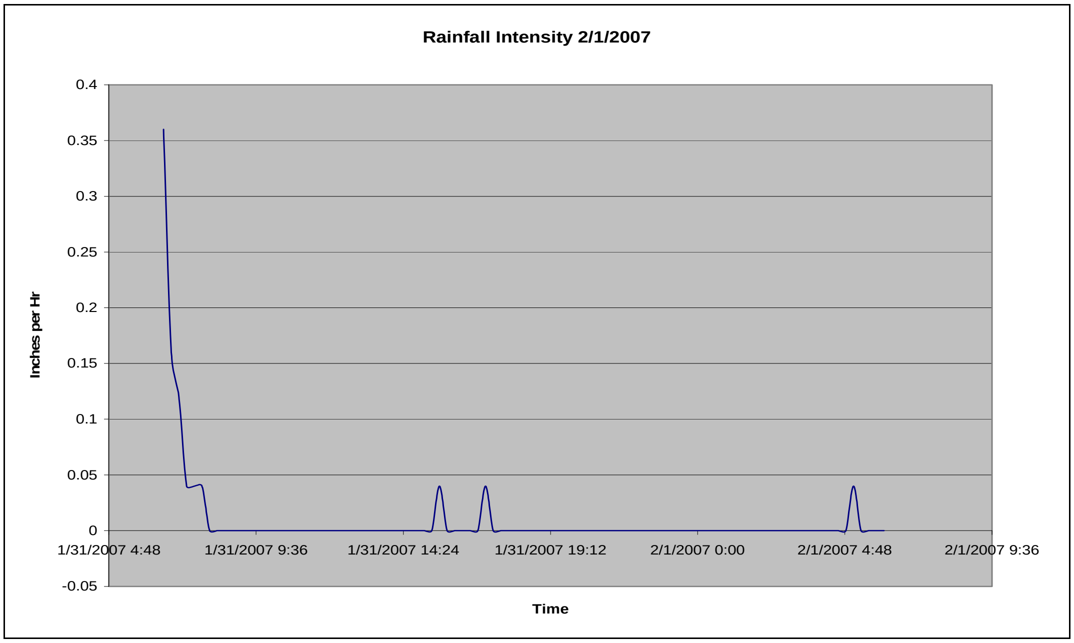


Figure A.11– Cumulative runoff for mild and steep plots for 2/1/2007.

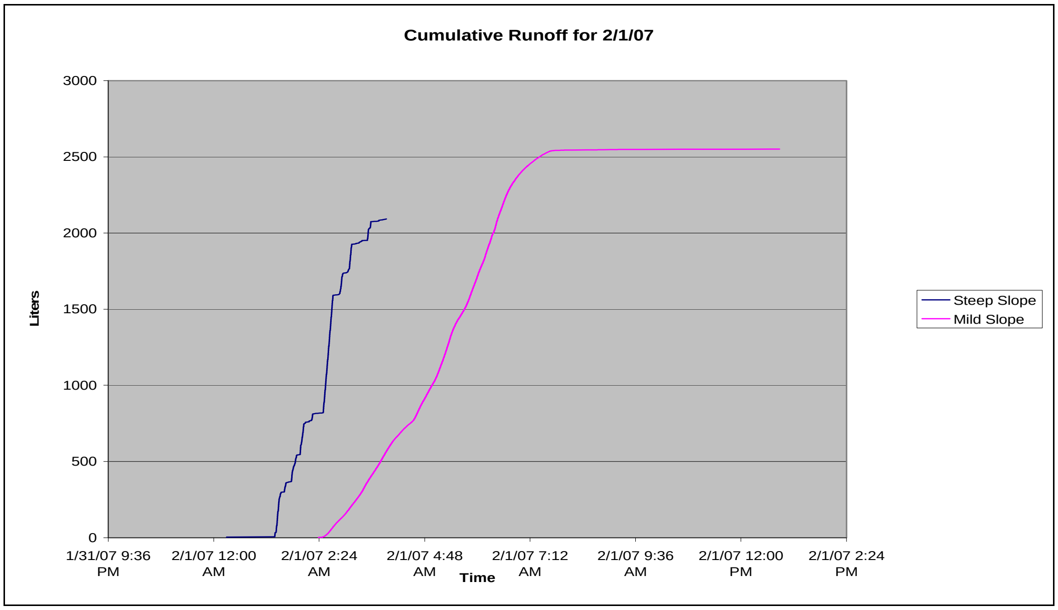


Figure 12 -- Runoff intensity for 2/1/07.

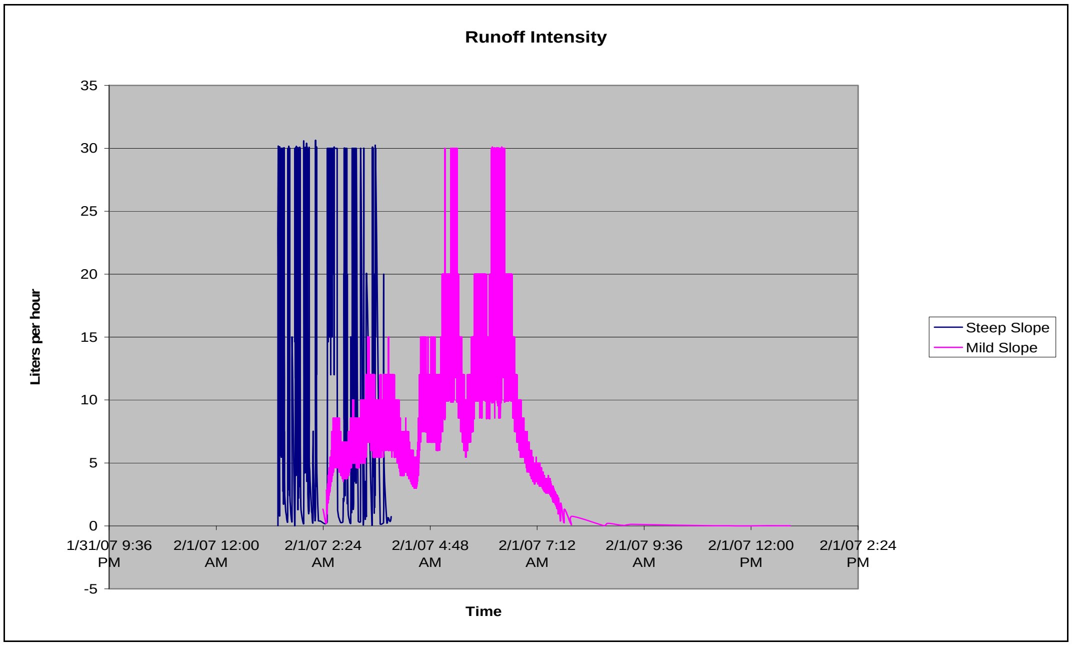


Figure A.13 – Cumulative rainfall for 3/1/2007.

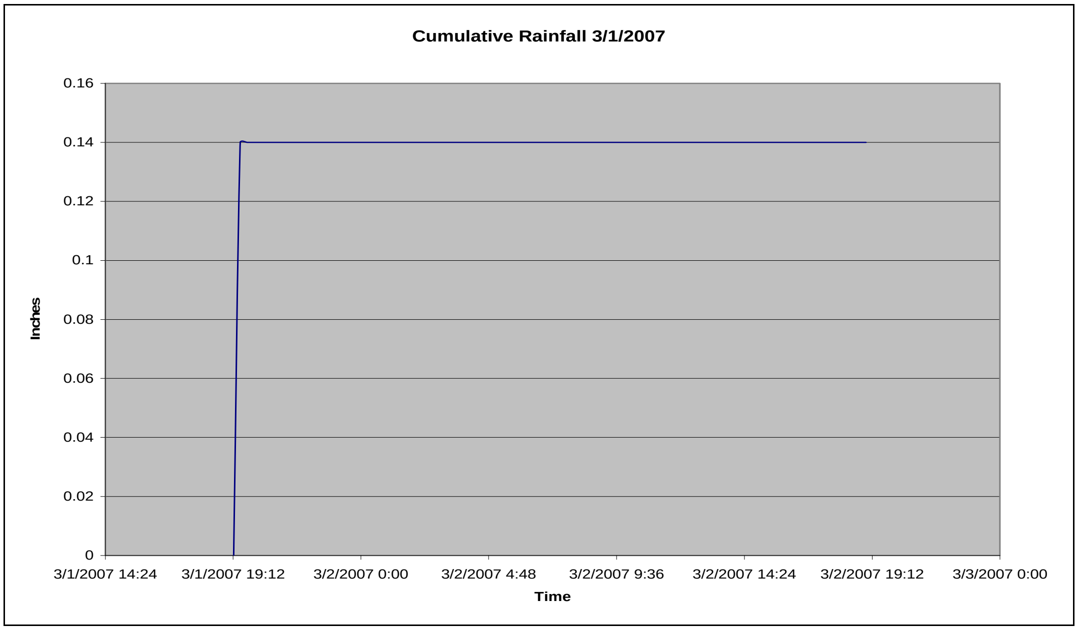


Figure A.14 – Rainfall hydrograph for 3/1/2007.

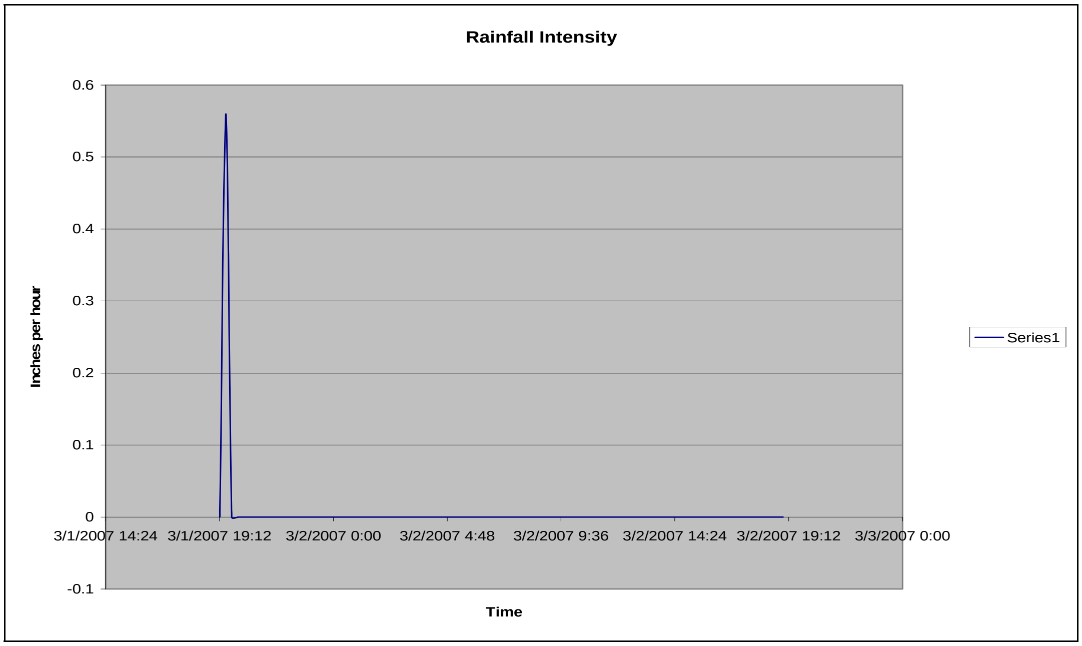


Figure A.15 – Cumulative runoff for mild and steep slope plots for 3/1/2007.

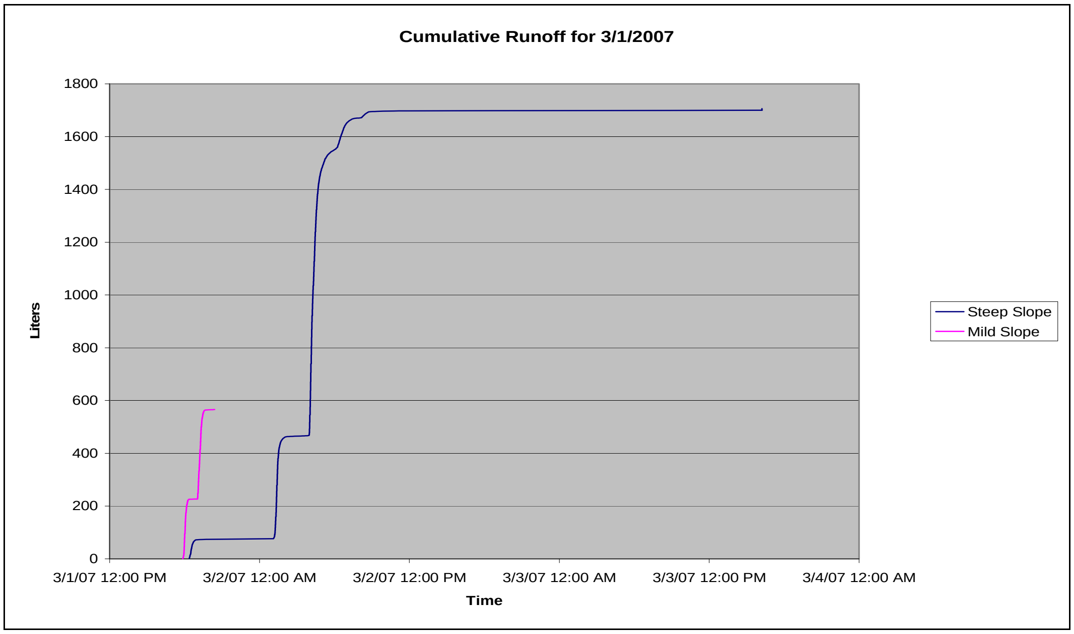


Figure A.16 -- Runoff intensity for 3/1/07.

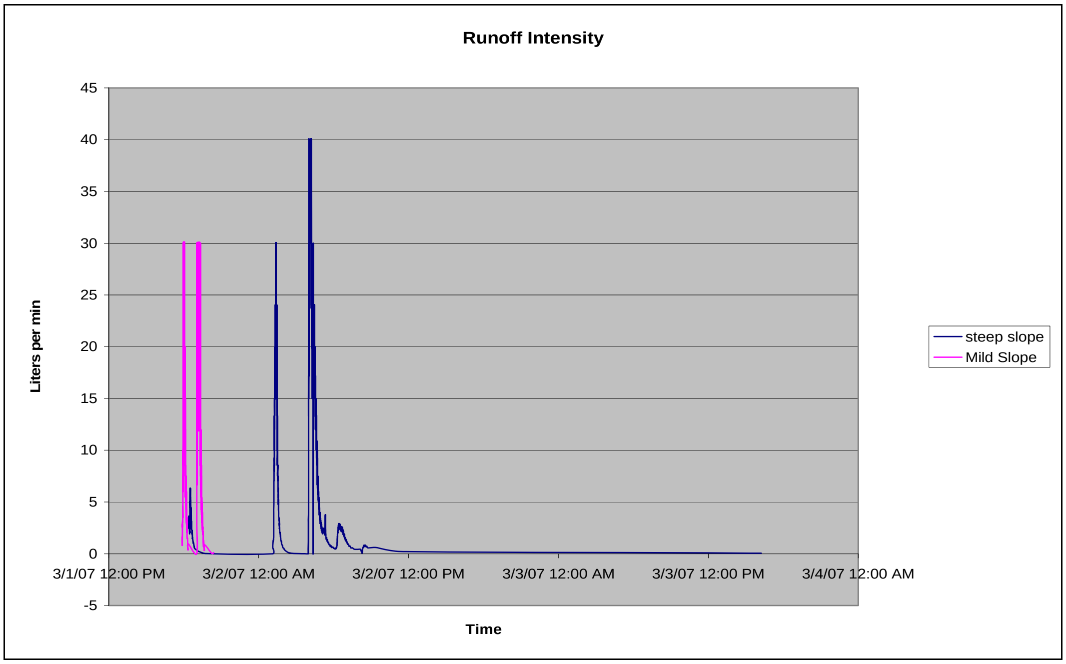


Figure A.17 – Cumulative rainfall for 3/15/2007.

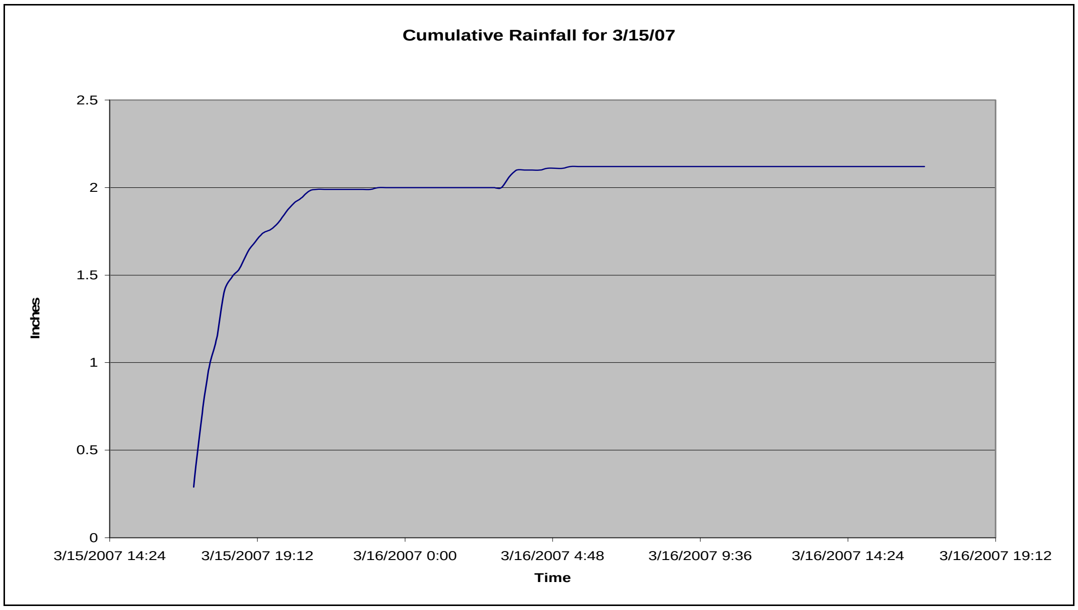


Figure A.18 – Rainfall hydrograph for 3/15/2007.

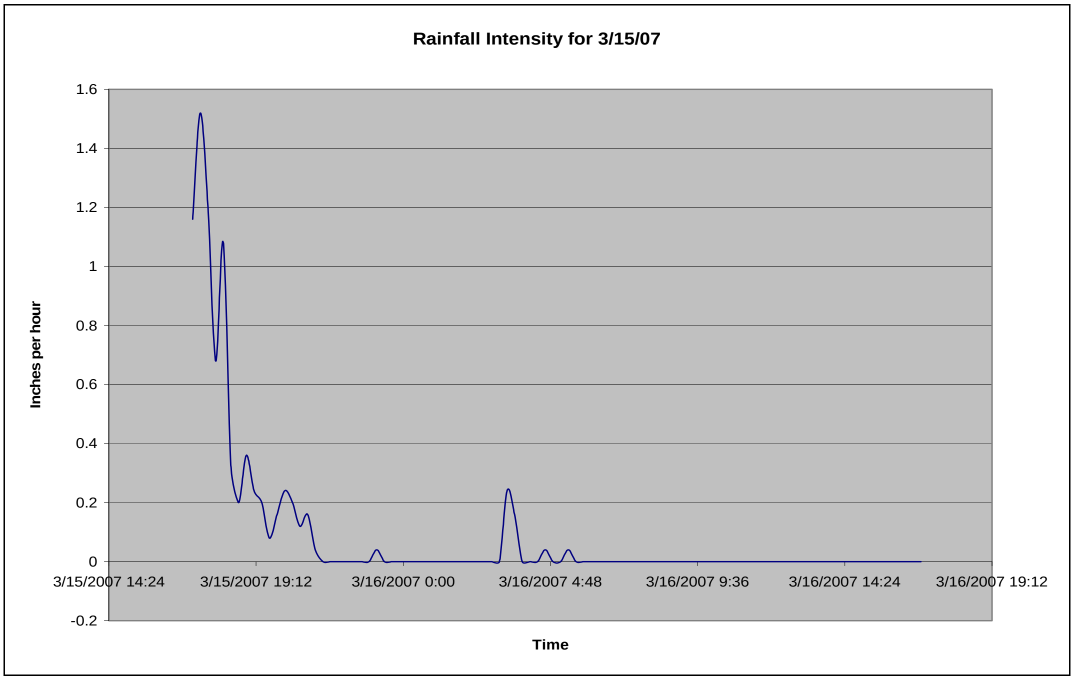


Figure A.19 – Cumulative runoff for mild slope and steep slope for 3/15/2007.

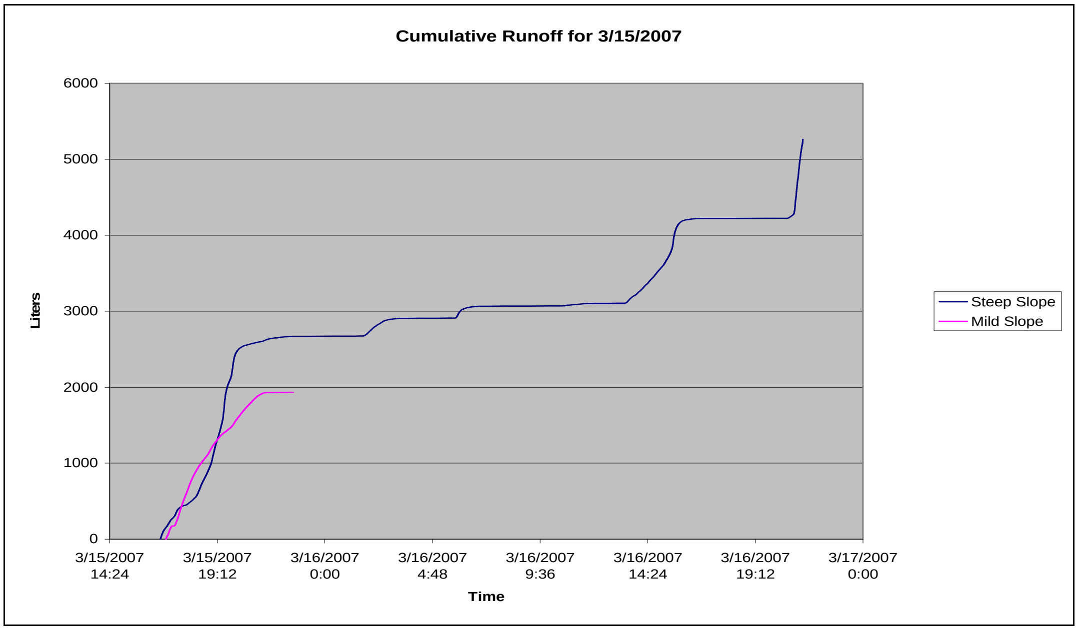
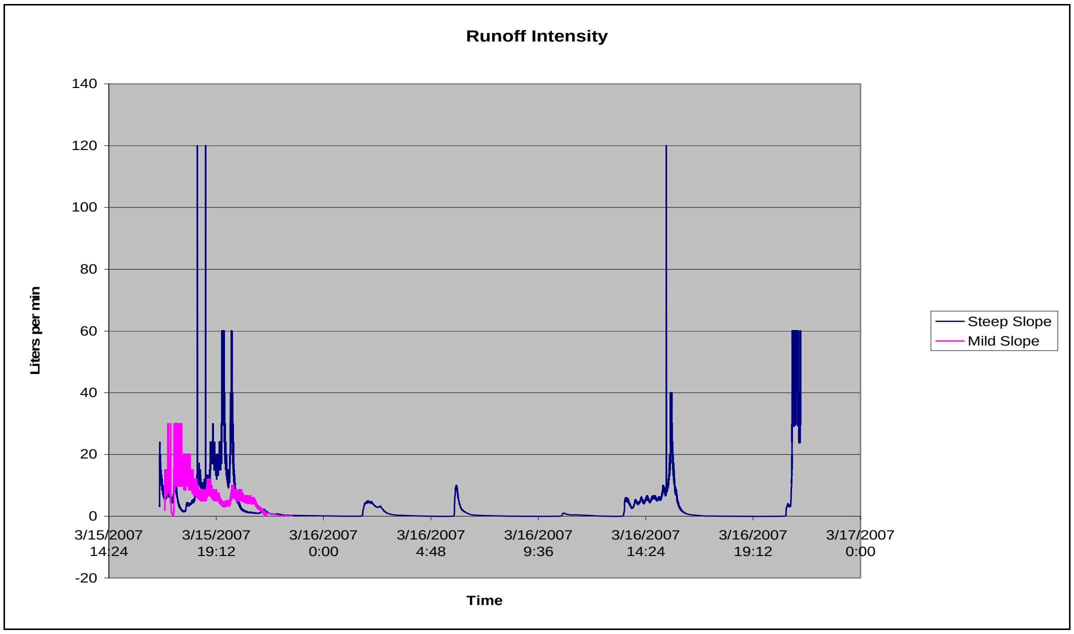


Figure A.20 -- Runoff intensity for 3/15/2007.



APPENDIX B

Rainfall and Runoff Data

Table B.1 -- Rainfall and runoff data collected from sites.

Mild Slope

Plot Size trail length = 54 ft Plot area 672 ft^2
turnout length= 30 ft 0.015 Acre
trail width = 8 ft

Storm Date	Storm Duration (hr)	Max Storm Intensity (in/hr)	Storm Rainfall (in)	Duration to Peak intensity	Actual Runoff (L)	Actual Sediment Yield (Kg)
11/15/2006	9.5	0.48	2.28	0.13	6112	11.012
12/22/2006	6.75	0.28	1.21	0.67	2186	28.809
2/1/2007	3.75	0.36	1.05	0.60	2551	5.310
3/1/2007	0.5	0.56	0.14	0.50	567	1.697
3/15/2007	4.25	1.11	2	0.24	2095	16.570

Steep Slope

Plot Size trail length = 120 ft Plot area 1240 ft^2
turnout length= 35 ft 0.028 Acre
trail width = 8 ft

Storm Date	Storm Duration (hr)	Max Storm Intensity (in/hr)	Storm Rainfall (in)	Duration to Peak intensity	Actual Runoff (L)	Actual Sediment Yield (Kg)
11/15/2006	9.5	0.48	2.28	0.13	3873.00	53.168
12/22/2006	6.75	0.28	1.21	0.67	1336.00	101.172
2/1/2007	3.75	0.36	1.05	0.60	1090.00	11.518
3/1/2007	0.5	0.56	0.14	0.50	1907.86	7.914
3/15/2007	4.25	1.11	2	0.24	5488.76	45.319

Table B.2 -- Sediment data from research sites.

Date of Storm	Slope	Runoff Vol (L)	Runoff Sample Size	Pan Wt. (g)	Dry Wt. (g)	Sediment Wt. (g)	Total Sediment in sample (g)	Total Sediment Loading (g)	Total Sediment Loading (kg)
11/15/2006	Mild	6112	0.01	764.54 590.2 584.7	764.9 601 637.5	0.36 10.8 52.8	63.96	11011.93	11.01
11/15/2006	Steep	7746	0.01	572.8 728.85	593.6 831.6	20.8 102.75	123.55	53167.68	53.17
12/22/2006	Mild	2186	0.01	572.9	823.3	250.4	250.4	28809.18	28.81
12/22/2006	Steep	2672	0.01	584.9	1417.9	833	833	101171.64	101.17
2/1/2007	Mild	2551	0.01	729.8	781.84	52.04	52.04	5310.16	5.31
2/1/2007	Steep	2180	0.01	765	860.1	95.1	95.1	11517.67	11.52
3/1/2007	Mild	567	0.01	584.93	589.57	4.64	4.64	1697.34	1.70
3/1/2007	Steep	1907.86	0.01	590.15	906.7	316.55	316.55	7913.75	7.91
3/15/2007	Mild	2095	0.01	730.95	874.5	143.55	143.55	16569.55	16.57
3/15/2007	Steep	5488.76	0.01	766.8	921.2	154.4	154.4	45318.99	45.32

APPENDIX C

Parameter Calibration for Runoff and Sediment Production

Table C.1 -- Calibration of effective hydraulic conductivity for runoff and sediment

Effective Hydraulic Conductivity		
	(Kb)	NSE value
Ki=3e005	0.5	-1.01281
Kr=0.0005	0.4	-0.92853
Tc=0.05	0.35	-0.9605
	0.3	-0.89901
	0.25	-0.8474
	0.2	-0.79231
	0.19	-0.73417
	0.18	-0.47872
	0.17	-0.25759
	0.16	-0.06488
	0.15	0.372289
	0.14	0.410045
	0.13	0.45408
	0.125	0.407816
	0.12	0.3588
	Max NSE=	0.45408

Figure C.1 – Calibration of effective hydraulic conductivity for runoff and sediment

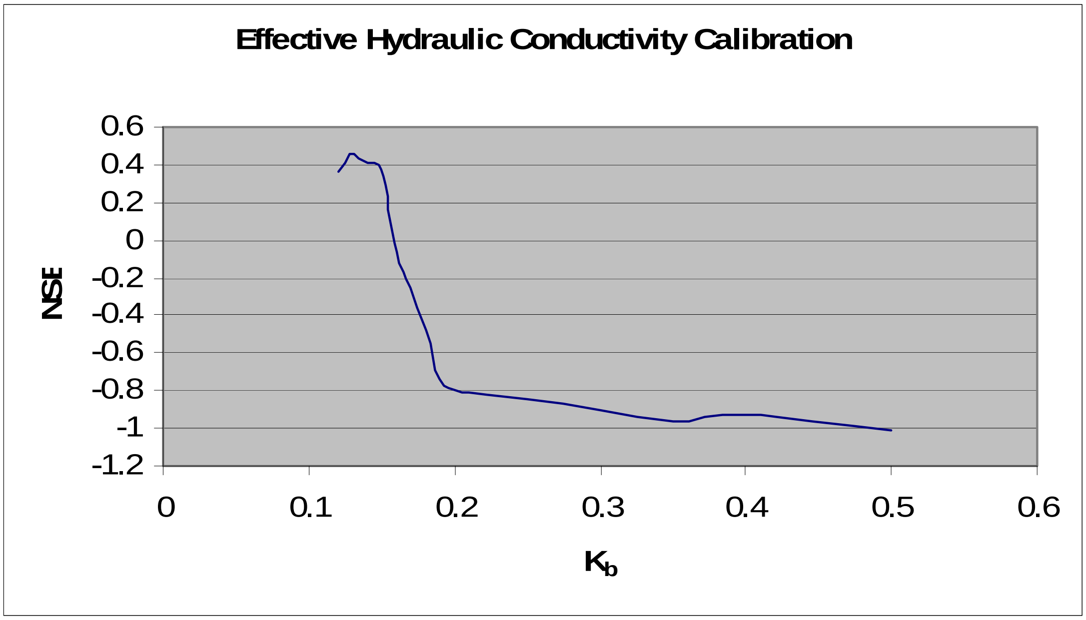


Table C.2 -- Calibration of critical shear

for runoff and sediment

Critical Shear		
	(Tc)	R^2 value
Ki=3.0e006 Kr=0.0005 Kb=0.13	0.1	0.4182
	0.2	0.4163
	0.05	0.4191
	0.04	0.4192
	0.03	0.4194
	0.02	0.4196
	0.01	0.4198
	0.005	0.4199
	0.004	0.4199
	Max R^2 =	0.4199

Figure C.2 – Calibration of critical shear for runoff and sediment

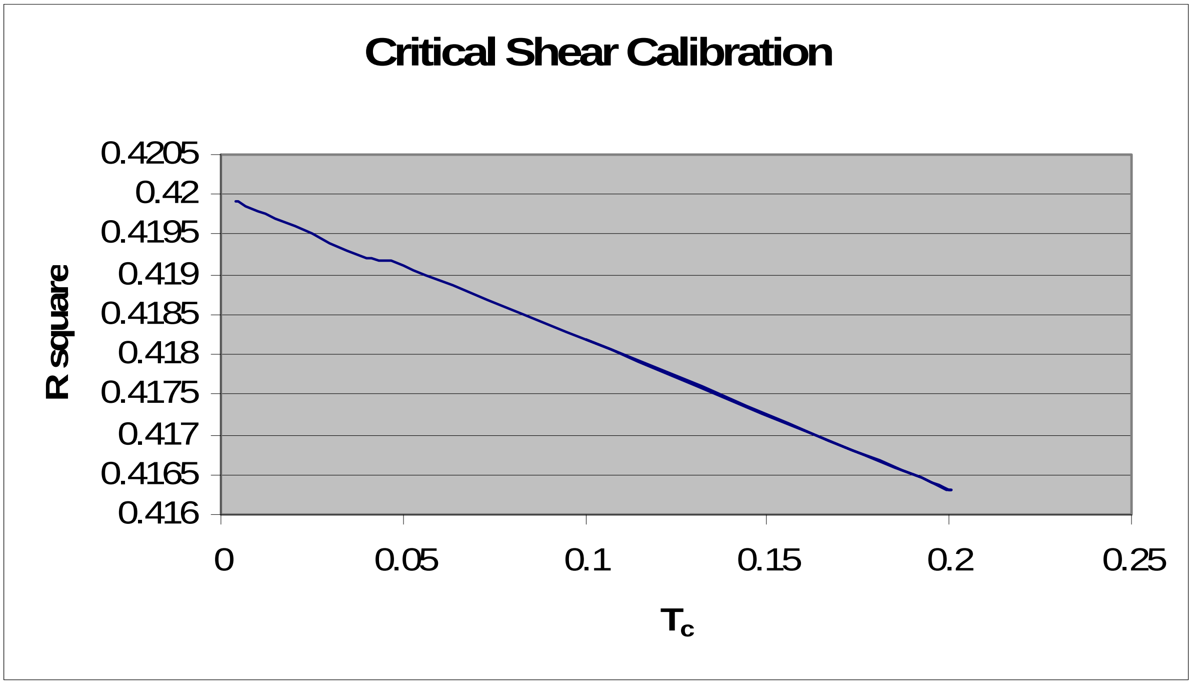


Table C.3 -- Calibration of rill erodibility

for runoff and sediment

Rill Erodibility		
	(Kr)	R^2 value
Ki=3.0e006	0.0008	0.4192
Tc=0.005	0.0007	0.4199
Kb=0.13	0.0006	0.4204
	0.0005	0.4206
	0.0004	0.4202
	Max R^2 =	0.4206

Figure C.3 – Calibration of rill erodibility for runoff and sediment.

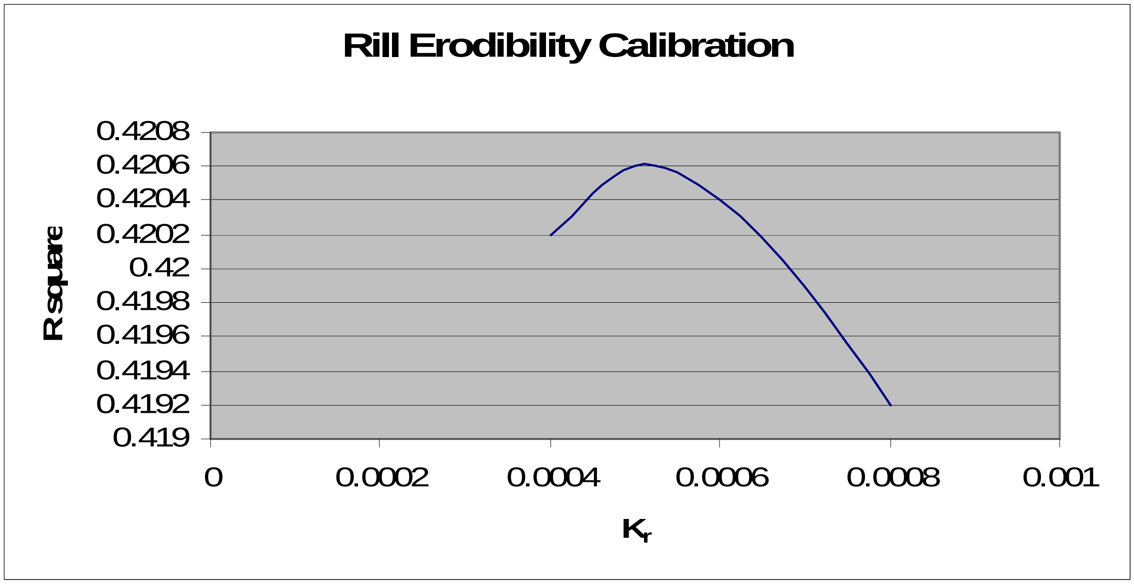
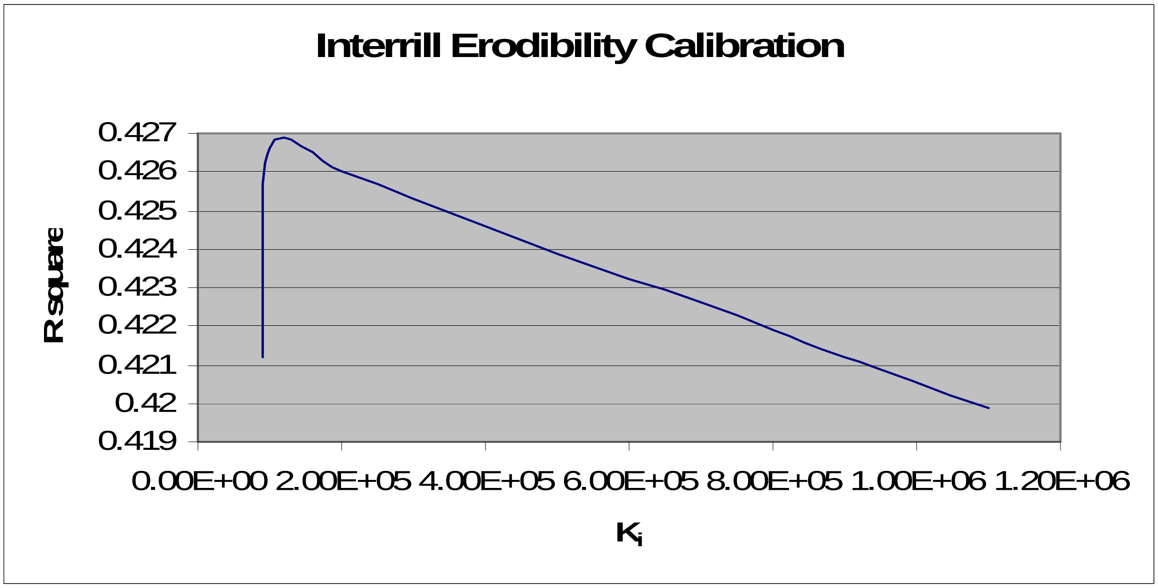


Table C.4 -- Calibration of interrill

erodibility for runoff and sediment

Interrill Erodibility		
	(Ki)	R^2 value
Kr=0.0005 Tc=0.005 Kb=0.13	1.10E+06	0.4199
	9.00E+05	0.4212
	8.00E+05	0.4219
	7.00E+05	0.4226
	6.00E+05	0.4232
	5.00E+05	0.4239
	4.00E+05	0.4246
	3.00E+05	0.4253
	2.00E+05	0.426
	1.00E+05	0.4266
	9.00E+04	0.4212
	Max R^2 =	0.4266

Figure C.4 – Calibration of interrill erodibility for runoff and sediment



APPENDIX D

Parameter Calibration for Sediment Production

Table D.1 -- Calibration for rill erodibility for sediment production

Rill Erodibility		
	(Kr)	NSE value
K_i=6.0e006	0.05	-918.2707

T_c=2.57	0.01	-750.0188
K_b=.013	0.0075	-665.8518
	0.005	-443.1096
	0.0025	-143.3983
	0.001	-25.15484
	0.0009	-20.29555
	0.0008	-15.90674
	0.0007	-12.00845
	0.0006	-8.620284
	0.0005	-5.762646
	0.0004	-3.453229
	0.0003	-1.717375
	0.0002	-0.573163
	0.0001	-0.044787
	0.00009	-0.026533
	0.00008	-0.015051
	0.00007	-0.009664
	0.00006	-0.010932
	Max NSE=	-0.009664

Figure D.1 – Calibration of rill erodibility.

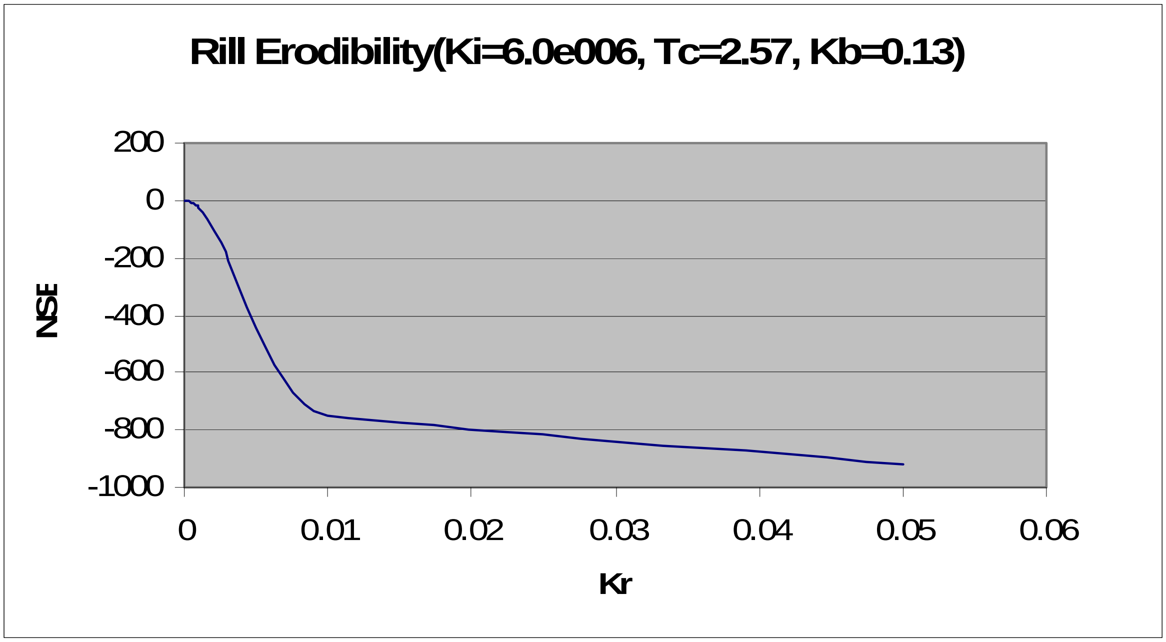


Table D.2 -- Calibration for critical

shear for sediment production

Critical Shear		
	(Tc)	NSE value

K_i=6.0e006	2.5	-0.007631
K_r=0.00007	2.25	-0.001204
K_b=.013	2	0.005517
	1.75	0.011844
	1.5	0.018285
	1.25	0.024687
	1	0.034254
	0.75	0.039267
	0.5	0.042696
	0.25	0.047449
	0.1	0.050166
	0.01	0.052061
	0.001	0.052171
	0.009	0.052061
	0.008	0.051954
	0.006	0.052401
	0.005	0.052401
	0.004	0.052171
	0.0001	0.052171
	Max NSE=	0.052401

Figure D.2 – Calibration of critical shear for sediment production.

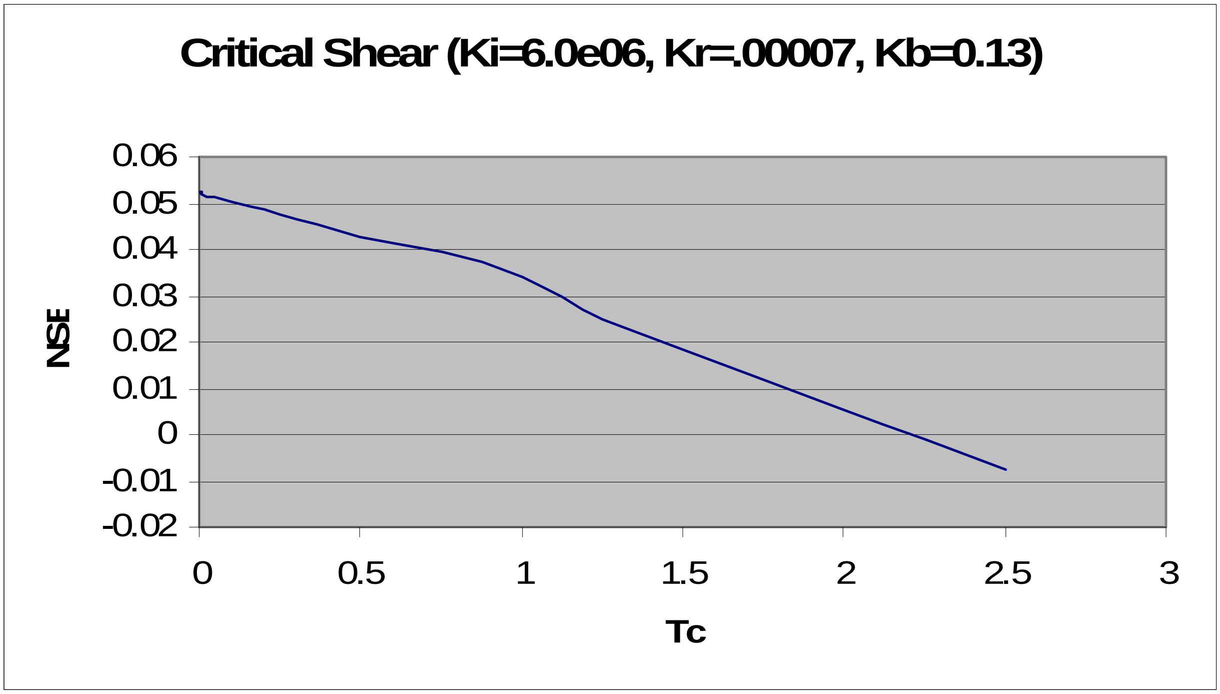

Critical Shear (Ki=6.0e06, Kr=.00007, Kb=0.13)
NSE
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
0
0.5
1
1.5
2
2.5
3
Tc

Table D.3 -- Calibration for interrill

erodibility for sediment production

Interrill Erodibility		
	(Ki)	NSE value
K_r=0.00007 T_c=0.006 K_b=0.13	6.00E+06	0.052401
	6.10E+06	0.04359
	5.90E+06	0.067866
	5.80E+06	0.067866
	5.70E+06	0.075683
	5.60E+06	0.082601
	5.50E+06	0.089259
	5.00E+06	0.119105
	4.50E+06	0.141449
	4.00E+06	0.155622
	3.50E+06	0.162777
	3.40E+06	0.163035
	3.30E+06	0.16353
	3.20E+06	0.163197
	3.00E+06	0.161804
	Max NSE=	0.16353

Figure D.3 – Calibration of interrill erodibility for sediment production.

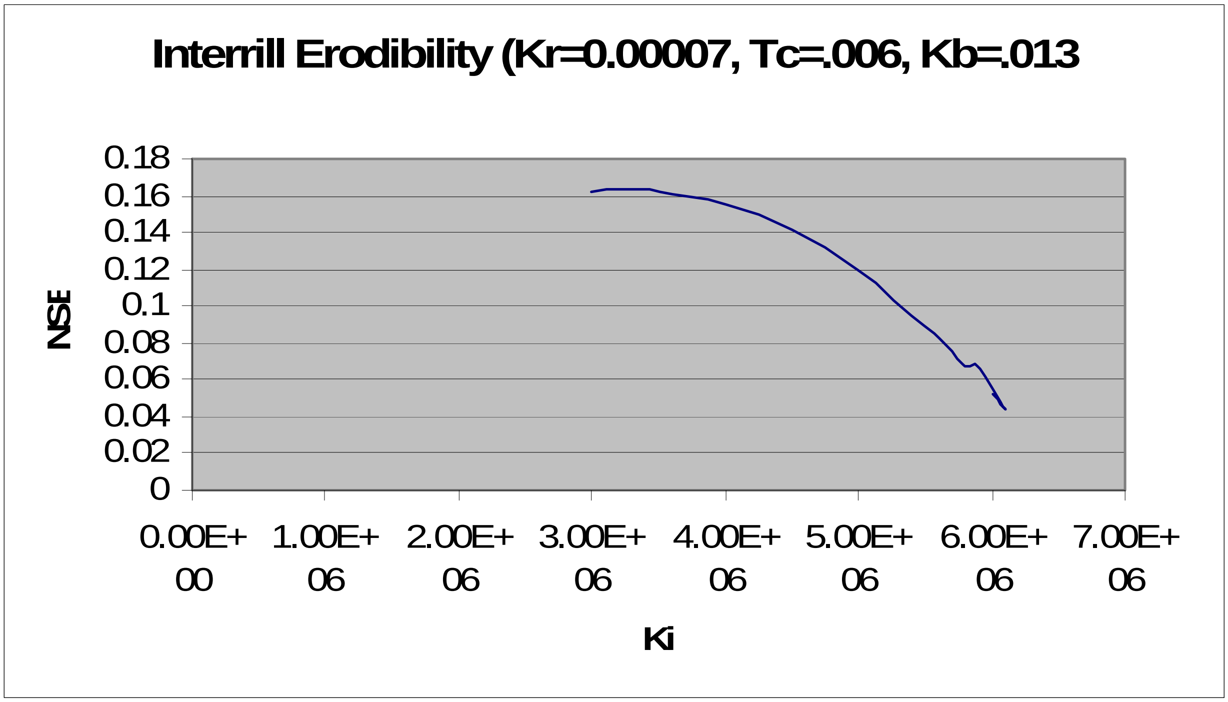
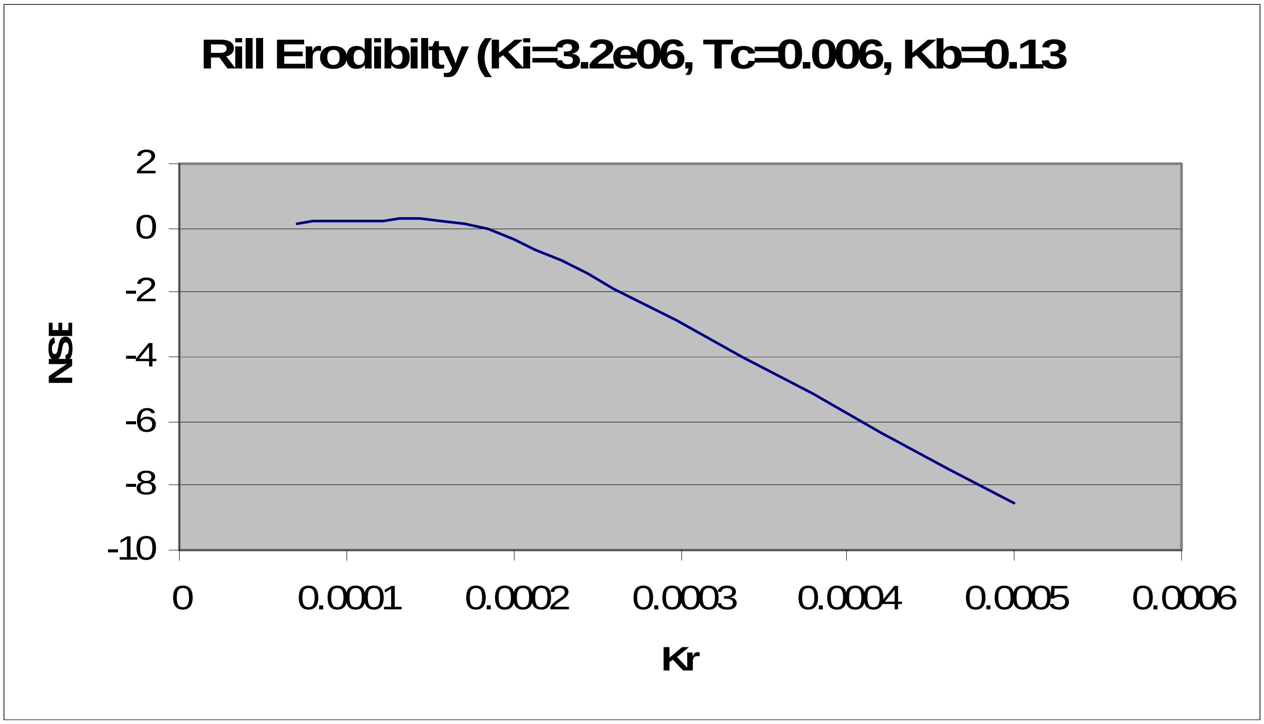


Table D.4 -- Calibration for effective hydraulic conductivity for sediment production

Effective Hydraulic Conductivity		
	(Kb)	NSE value
K_i=3.2e006 K_r=0.0001 Tc=0.006	1	-0.45666
	0.6	-0.27898
	0.52	-0.18386
	0.48	-0.16071
	0.15	0.201756
	0.13	0.214655
	0.12	0.219767
	0.1	0.228355
	0.09	0.232128
	0.08	0.235114
	0.07	-0.4151
	0.06	-0.4151
	Max NSE=	0.235114

Figure D.4 – Calibration of effective hydraulic conductivity for sediment production.



APPENDIX E

Calibration of Mild Slope

Table E.1 -- Calibration of interrill

erodibility on mild slope

Interrill Erodibility		
	(Ki)	NSE value
K_r=0.0001 T_c=0.006 K_b=0.13	3.20E+06	-0.34185
	3.30E+06	-0.33529
	3.40E+06	-0.32748
	3.50E+06	-0.32008
	3.60E+06	-0.3131
	3.70E+06	-0.30816
	3.80E+06	-0.30202
	3.90E+06	-0.2963
	4.00E+06	-0.29101
	4.20E+06	-0.2833
	4.40E+06	-0.27569
	4.60E+06	-0.2712
	4.80E+06	-0.26697
	5.00E+06	-0.26577
	5.10E+06	-0.26512
	5.20E+06	-0.26491
	5.30E+06	-0.26638
	5.40E+06	-0.26718
	Max NSE=	-0.26491

Figure E.1 – Calibration of interrill erodibility on mild slope.

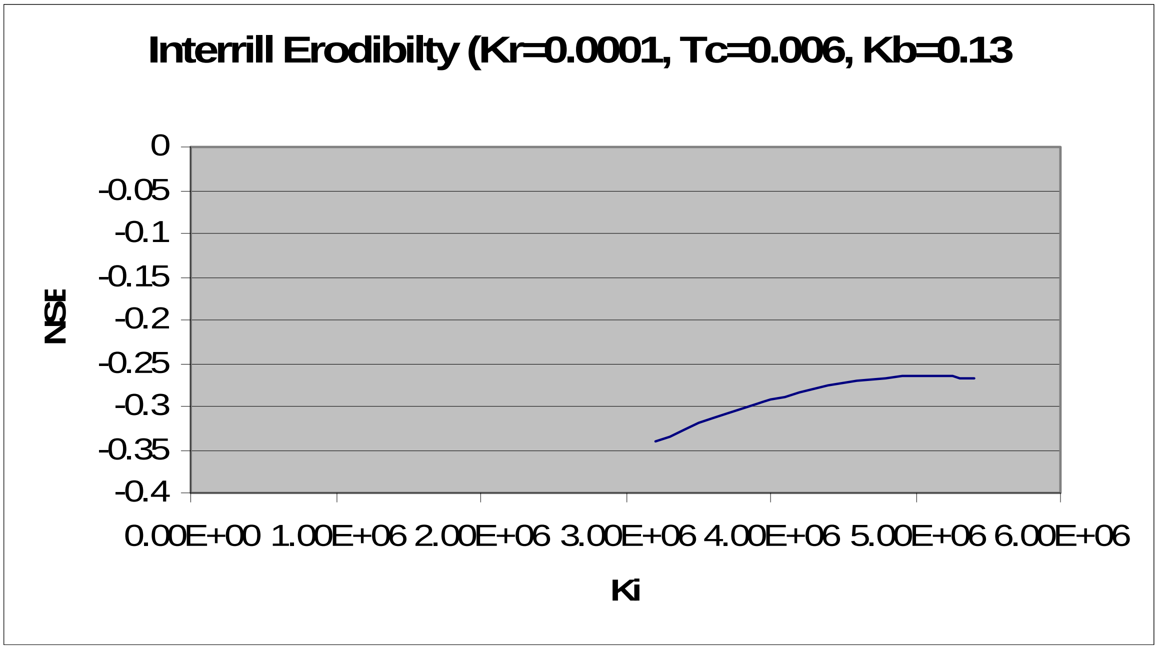


Table E.2 -- Calibration of rill erodibility on mild slope

Rill Erodibility		
	(Kr)	NSE value
K_i=5.2e006	0.0005	-2.13696
0.006	0.0002	-0.24432
K_b=.013	0.00017	-0.21404
	0.00016	-0.21119
	0.00015	-0.2115
	0.00011	-0.24736
	0.0001	-0.26491
	Max NSE=	-0.21119

Figure E.2 – Calibration of rill erodibility on mild slope.

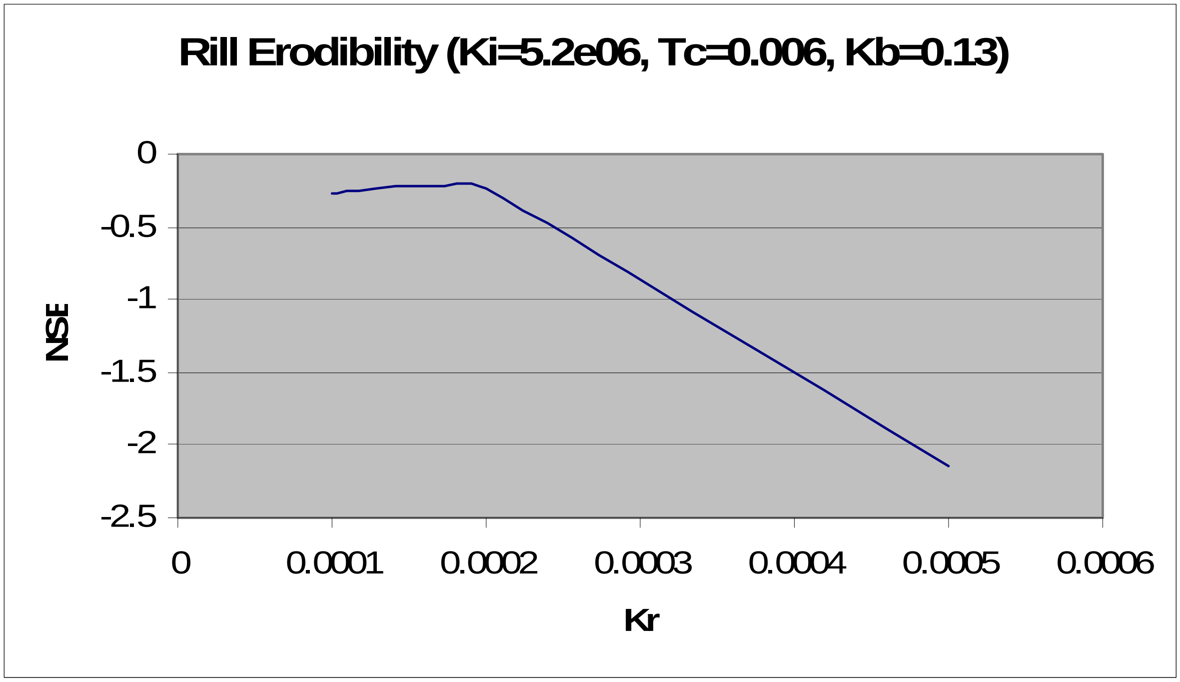


Table E.3 -- Calibration of

critical shear on mild slope

Critical Shear		
	(Tc)	NSE value
K_i=5.2e006	0.01	-0.21174
K_r=0.00016	0.009	-0.21079
K_b=.013	0.008	-0.21079
	0.007	-0.21079
	0.006	-0.21119
	Max NSE=	-0.21079

Figure E.3 – Calibration of critical shear on mild slope

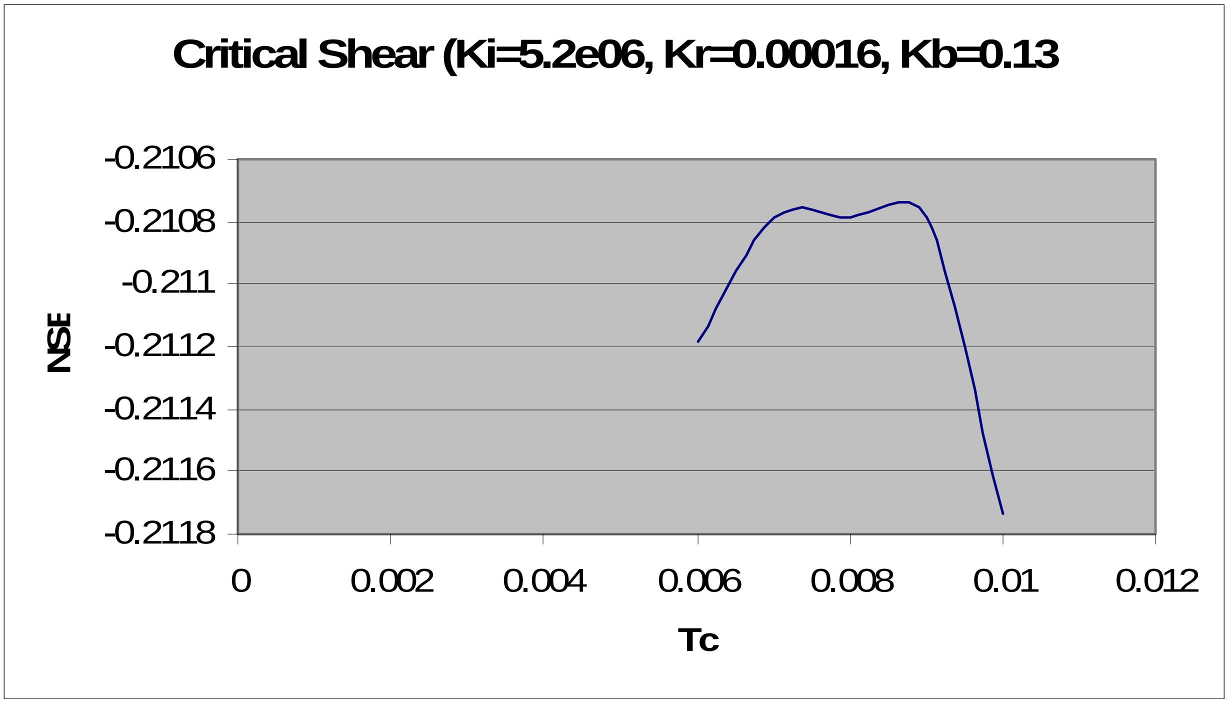
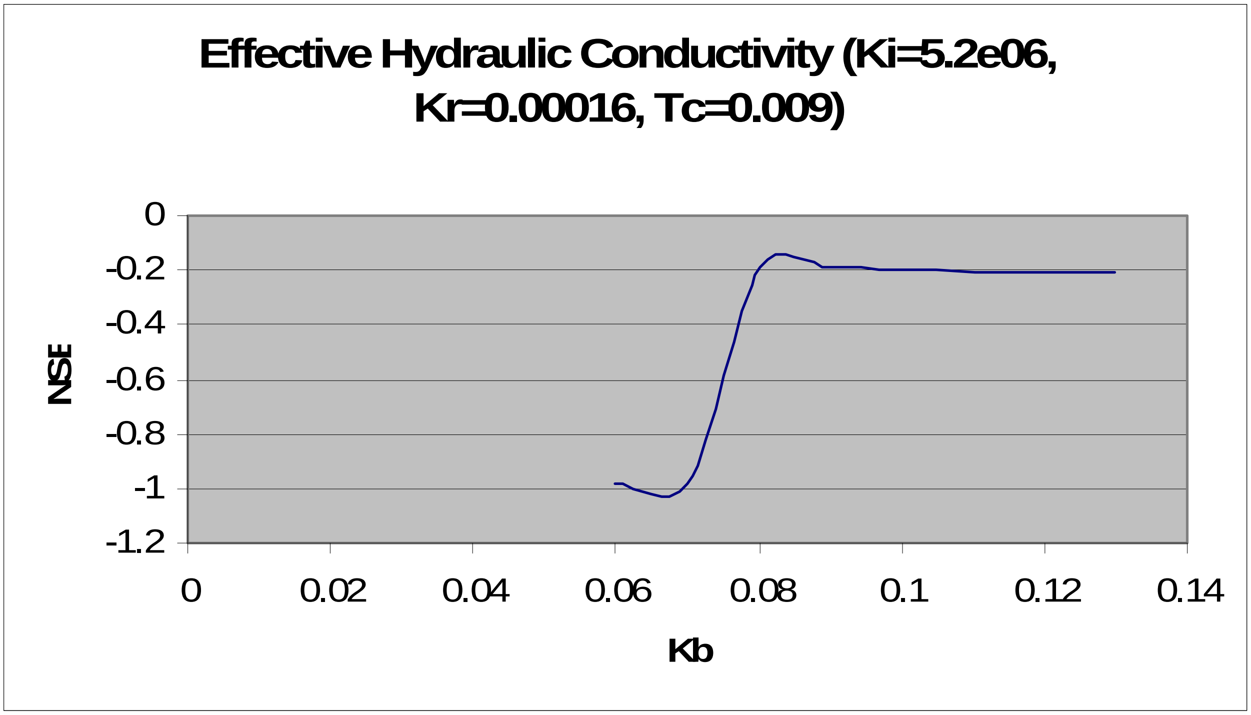


Table E.4 -- Calibration of effective

hydraulic conductivity on mild slope

Effective Hydraulic Conductivity		
	(Kb)	NSE value
K_i=5.2e006 K_r=0.00016 Tc=0.009	0.13	-0.21174
	0.12	-0.20403
	0.1	-0.19414
	0.09	-0.19018
	0.08	-0.18489
	0.07	-0.98212
	0.06	-0.98212
	Max NSE=	-0.18489

Figure E.4 – Calibration of effective hydraulic conductivity on mild slope.



APPENDIX F

Calibration of Steep Slope

Table F.1 -- Interrill erodibility

calibration on steep slope

Interrill Erodibility		
	(Ki)	NSE value
K_r=0.0001 T_c=0.006 K_b=0.13	3.20E+06	-0.05415
	3.00E+06	-0.03791
	2.80E+06	-0.02061
	2.60E+06	-0.00514
	2.40E+06	0.008256
	2.20E+06	0.019875
	2.00E+06	0.029664
	1.80E+06	0.037421
	1.60E+06	0.043375
	1.40E+06	0.047303
	1.20E+06	0.049561
	1.10E+06	0.050264
	1.00E+06	0.049848
	9.00E+05	0.049606
	8.00E+05	0.048239
	Max NSE=	0.050264

Figure F.1 – Calibration of interrill erodibility on steep slope.

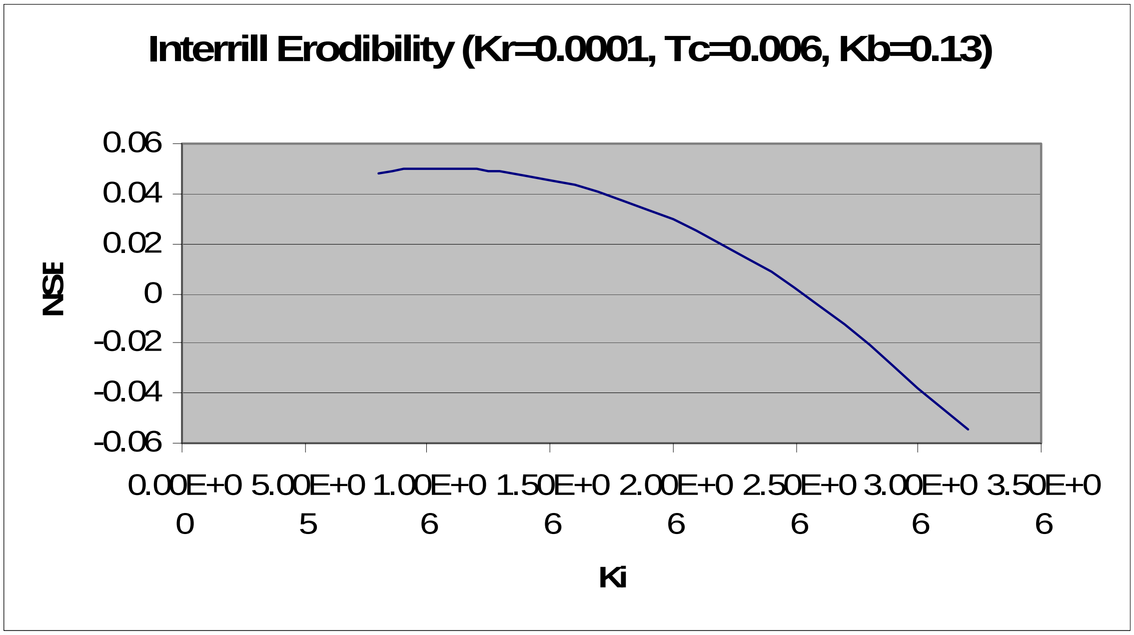


Table F.2 -- Rill erodibility

calibration on steep slope

Rill Erodibility		
	(Kr)	NSE value
K_i=1.1e006	0.0002	-0.51614
T_c=0.006	0.00015	0.006348
K_b=.013	0.00013	0.081673
	0.00012	0.090807
	0.00011	0.08065
	0.0001	0.050264
	Max NSE=	0.090807

Figure F.2 – Calibration of rill erodibility on steep slope.

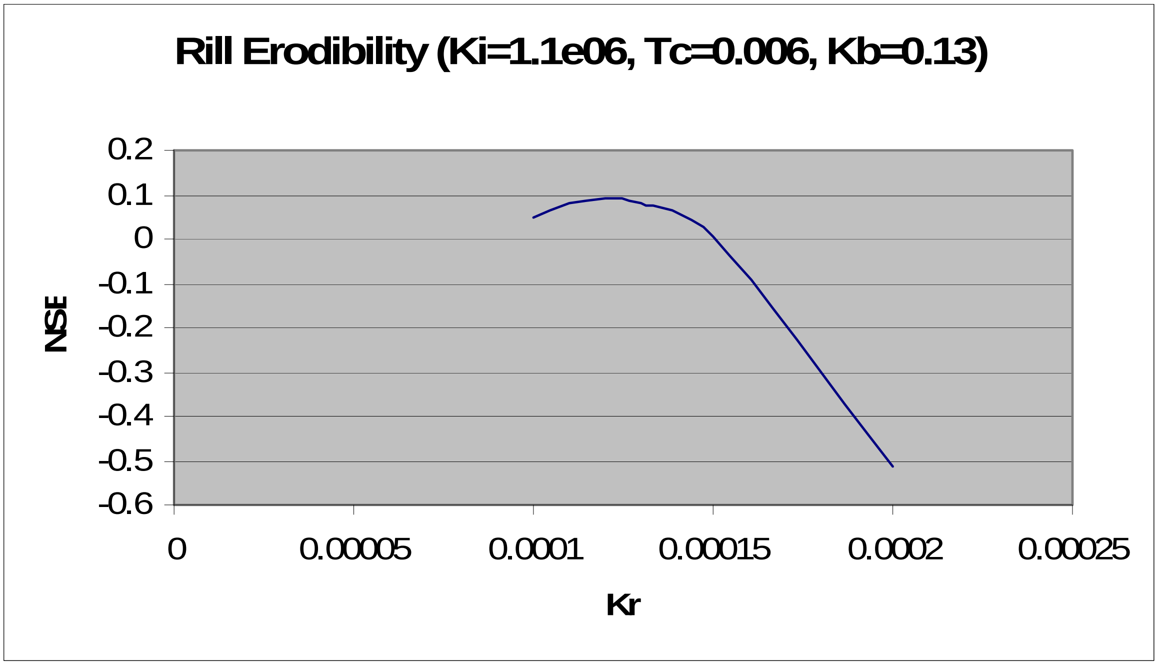


Table F.3 -- Critical shear

calibration on steep slope

Critical Shear		
	(Tc)	NSE value
K_i=1.1e006	0.006	0.090807
K_r=0.00012	0.007	0.090935
K_b=.013	0.008	0.090935
	0.009	0.091074
	0.01	0.090478
	Max NSE=	0.091074

Figure F.3 – Calibration of critical shear on steep slope.

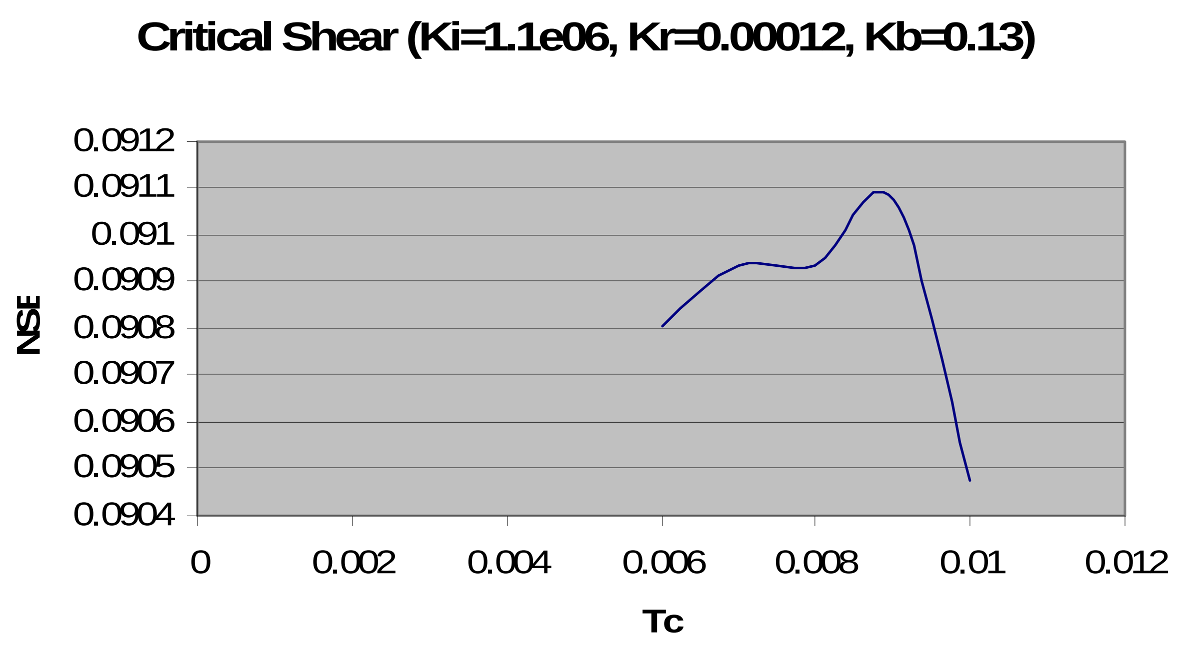
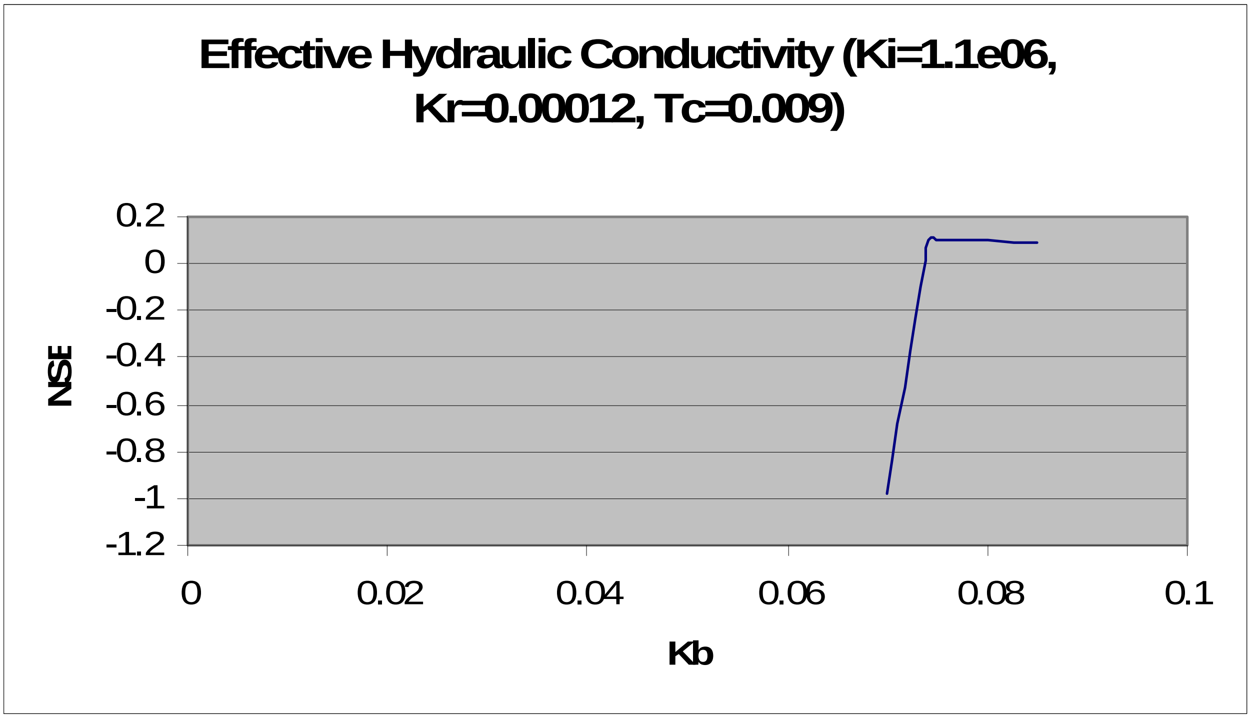


Table F.4 -- Effective hydraulic conductivity

calibration on steep slope

Effective Hydraulic Conductivity		
	(Kb)	NSE value
K_i=1.1e006	0.085	0.095153
K_r=0.00012	0.076	0.105616
Tc=0.009	0.075	0.106232
	0.074	0.105616
	0.07	-0.98167
	Max NSE=	0.106232

Figure F.4 – Calibration of effective hydraulic conductivity on steep slope.



APPENDIX G

Calibration of Trafficked Period

Table G.1 -- Interrill erodibility

calibration for trafficked period

Interrill Erodibility		
	(Ki)	NSE value
K_r=0.0001	3.30E+06	-0.16269
T_c=0.006	3.50E+06	-0.15929
K_b=0.08	3.75E+06	-0.15728
	4.00E+06	-0.15613
	4.25E+06	-0.15605
	4.26E+06	-0.15585
	4.27E+06	-0.15638
	4.50E+06	-0.15706
	Max NSE=	-0.15585

Figure G.1 – Calibration of interrill erodibility for trafficked period.

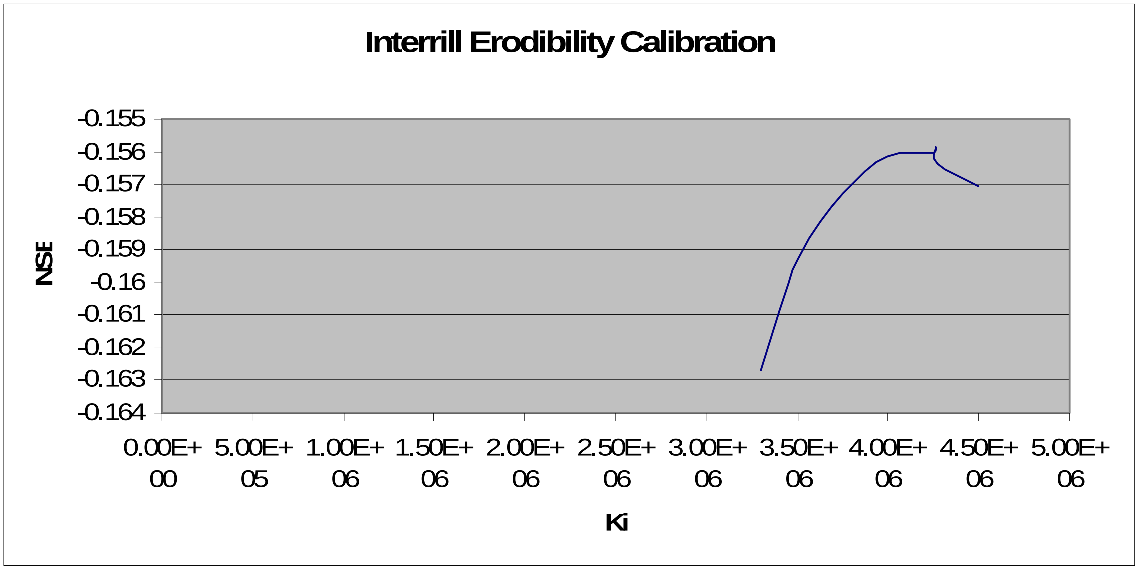


Table G.2 -- Rill erodibility

calibration for trafficked period

Rill Erodibility		
	(Kr)	NSE value
K_i=4.26e006	0.0001	-0.15585
T_c=0.006	0.00011	-0.13375
K_b=0.08	0.00012	-0.1268
	0.00013	-0.13557
	0.00015	-0.19968
	Max NSE=	-0.1268

Figure G.2 – Calibration of rill erodibility for trafficked period.

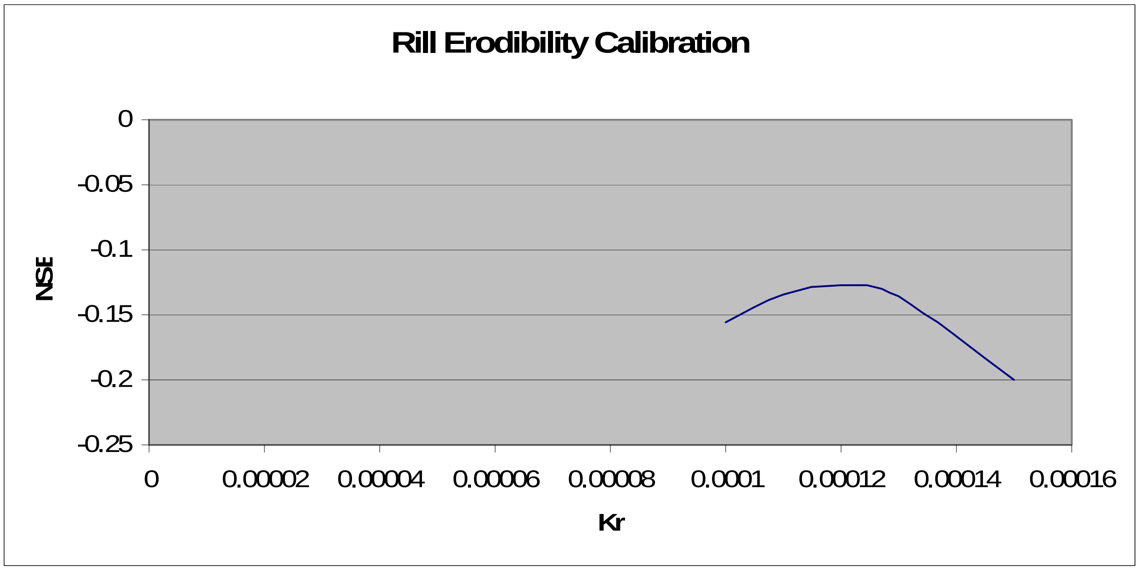


Table G.3 -- Critical shear

calibration for trafficked period

Critical Shear		
	(Tc)	NSE value
K_i=4.26e006	0.006	-0.1268
K_r=0.00012	0.007	-0.1268
K_b=0.08	0.008	-0.12656
	0.009	-0.12723
	Max NSE=	-0.12656

Figure G.3 – Calibration of critical shear for trafficked period.

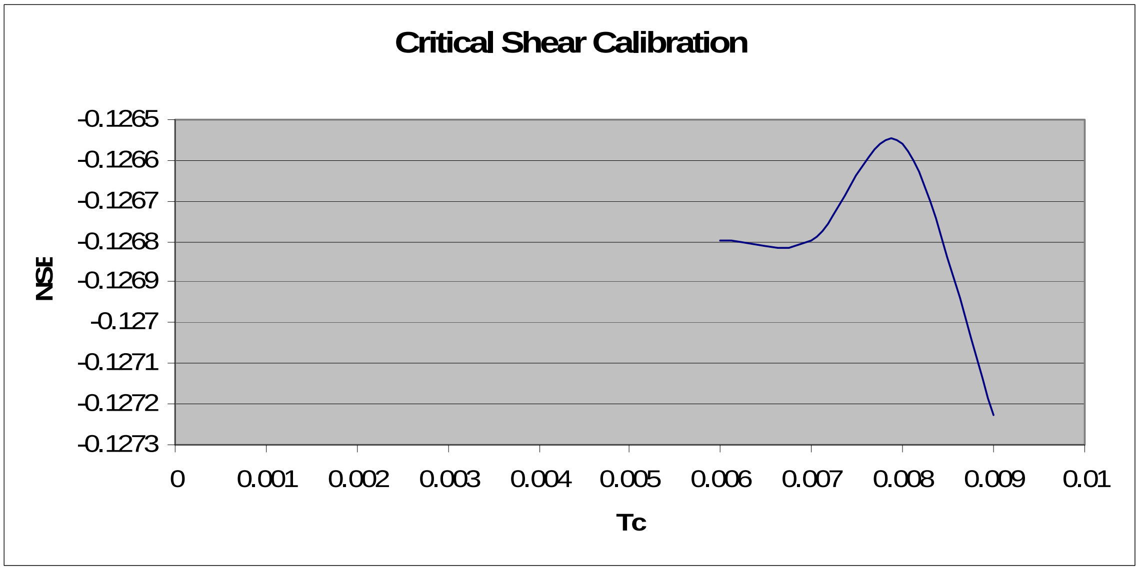
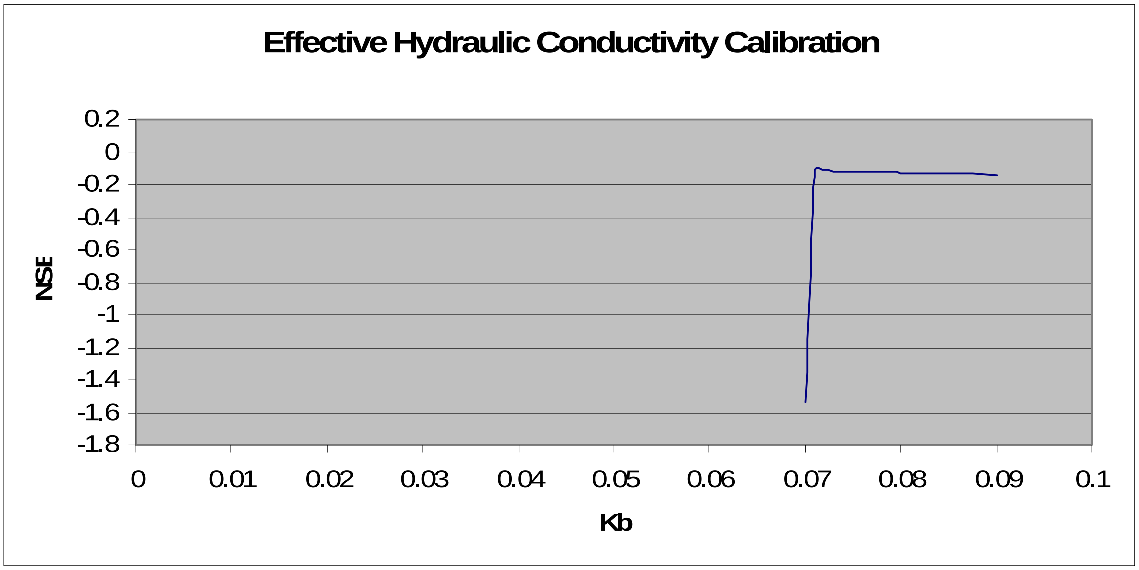


Table G.4 -- Effective hydraulic

conductivity for trafficked period

Effective Hydraulic Conductivity		
	(Kb)	NSE value
K_i=4.26e006	0.09	-0.14049
K_r=0.00012	0.085	-0.13309
Tc=0.008	0.081	-0.12812
	0.08	-0.12656
	0.079	-0.12204
	0.075	-0.11719
	0.074	-0.11573
	0.073	-0.11454
	0.072	-0.11311
	0.071	-0.11195
	0.07	-1.5348
	Max NSE=	-0.11195

Figure G.4 – Calibration of effective hydraulic conductivity for trafficked period.



APPENDIX H

Calibration of Non-Trafficked Period

Table H.1 -- Interrill erodibility calibration for non-trafficked period

Interrill Erodibility		
	(Ki)	NSE value
K_r=0.0001	3.40E+06	-0.10296
T_c=0.006	3.30E+06	-0.04888
K_b=0.08	3.20E+06	0.027744
	3.10E+06	0.053299
	3.00E+06	0.103018
	2.90E+06	0.150044
	2.80E+06	0.194245
	2.70E+06	0.238386
	2.60E+06	0.278986
	2.50E+06	0.318342
	2.40E+06	0.3561
	2.30E+06	0.392089
	2.20E+06	0.426221
	2.10E+06	0.458543
	2.00E+06	0.488975
	1.90E+06	0.516967
	1.80E+06	0.54444
	1.70E+06	0.568809
	1.60E+06	0.591904
	1.50E+06	0.636167
	1.40E+06	0.632752
	1.20E+06	0.665871
	1.00E+06	0.692136
	8.00E+05	0.711241
	6.00E+05	0.722283
	4.20E+05	0.726197
	4.10E+05	0.726253
	4.00E+05	0.726244
	3.90E+05	0.726261
	3.00E+05	0.725428
	2.00E+05	0.72326
	Max NSE=	0.726261

Figure H.1 – Calibration of interrill erodibility for non-trafficked period.

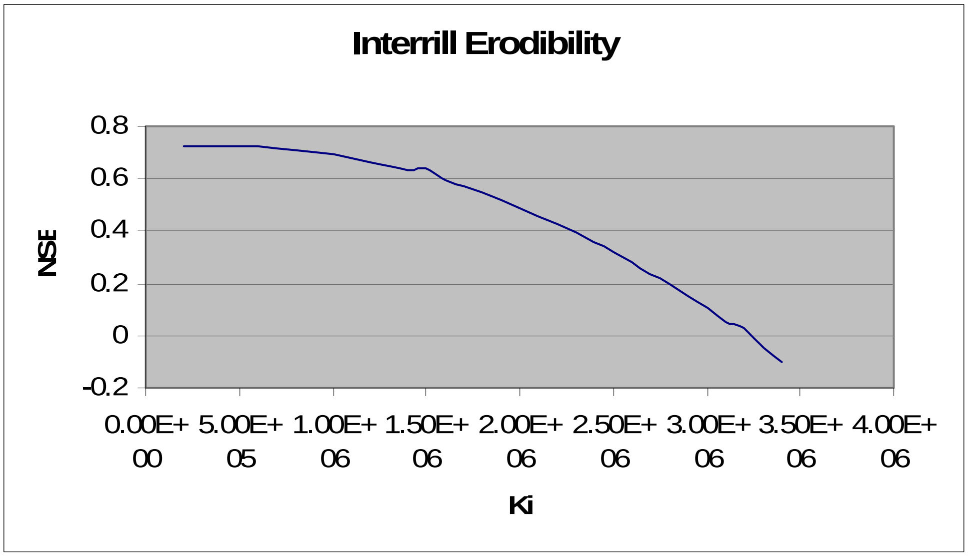


Table H.2 -- Rill erodibility calibration

for non-trafficked period

Rill Erodibility		
	(Kr)	NSE value
K_i=3.90e005	0.00011	0.671071
T_c=0.006	0.0001	0.726253
K_b=0.08	0.00009	0.746634
	0.00008	0.730471
	Max NSE=	0.746634

Figure H.2 – Calibration of rill erodibility for non-trafficked period.

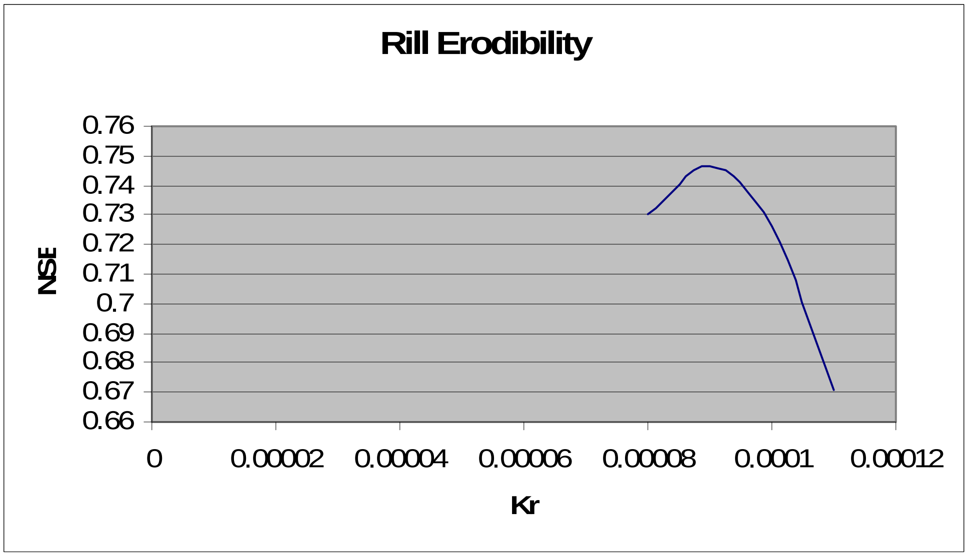


Table H.3 -- Critical shear calibration

for non-trafficked period.

Critical Shear		
	(Tc)	NSE value
K_i=3.90e005	0.005	0.746366
K_r=0.00009	0.0055	0.746366
K_b=0.08	0.0056	0.746812
	0.0057	0.746812
	0.0058	0.746812
	0.0059	0.746634
	0.006	0.746634
	Max NSE=	0.746812

Figure H.3 – Calibration of critical shear for non-trafficked period.

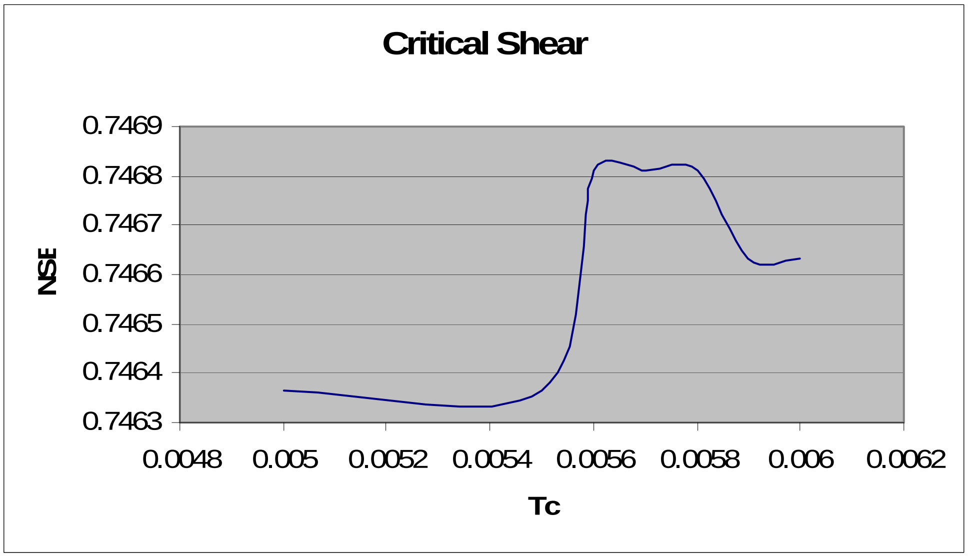
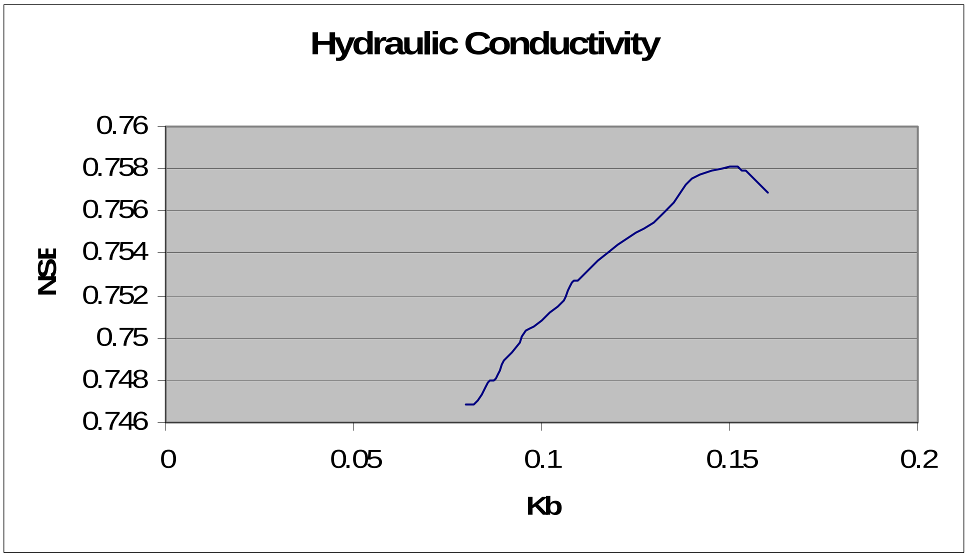


Table H.4 -- Effective hydraulic conductivity

for non-trafficked period

Effective Hydraulic Conductivity		
	(Kb)	NSE value
K_i=3.90e005	0.08	0.746812
K_r=0.00009	0.082	0.746817
Tc=0.0058	0.084	0.747365
	0.086	0.74799
	0.088	0.748073
	0.09	0.748904
	0.092	0.74934
	0.094	0.749796
	0.096	0.750377
	0.098	0.750543
	0.1	0.750842
	0.102	0.751198
	0.104	0.751454
	0.106	0.751744
	0.108	0.752596
	0.11	0.752789
	0.115	0.753645
	0.12	0.754378
	0.125	0.754989
	0.13	0.755477
	0.135	0.756415
	0.14	0.757521
	0.15	0.758116
	0.151	0.758084
	0.152	0.758137
	0.153	0.757913
	0.154	0.757872
	0.16	0.756849
	Max NSE=	0.758137

Figure H.4 – Calibration of effective hydraulic conductivity for non-trafficked period.



APPENDIX I

Tipping Bucket Design

Figure I.1 -- Tipping bucket design.

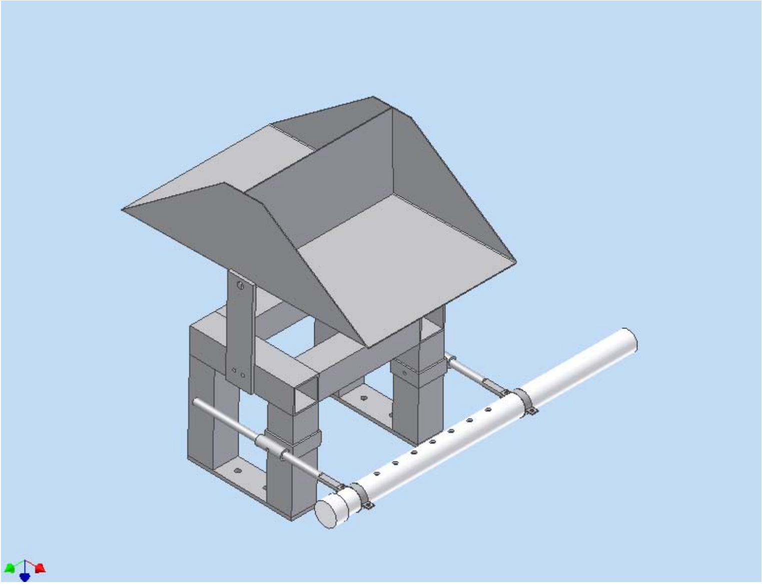


Figure I.2 – Tipping bucket base.

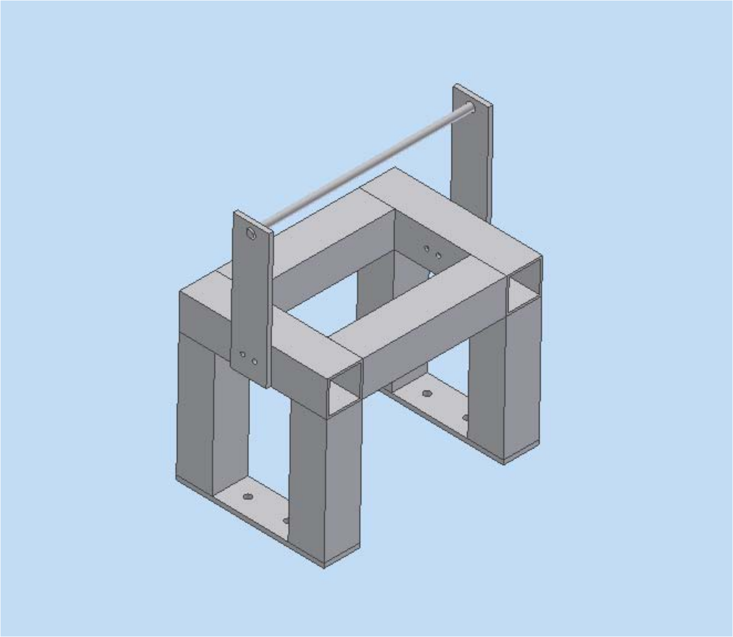


Table I.1 – Tipping bucket parts list.

Tipping Bucket Parts Sheet

Component	Material	Quantity
vertical structural member	2" x 0.125" x 7" square tubing	4
middle structural member	2" x 0.125" x 8" square tubing	2
horizontal structural member	2" x 0.125" x 8.25" square tubing	2
bottom mount	0.125" x 2" x 8.25" bar stock	2
axle mounts	0.125" x 2" x 7.625" bar stock	2
rainfall chamber	19.7" x 23.625" x1/16" steel sheet	1
rainfall chamber divider	5.9" x 17.8" x1/16" steel sheet	1
pivoting axle	3/8" rod	1

Figure I.3 – Middle and vertical member drawings.

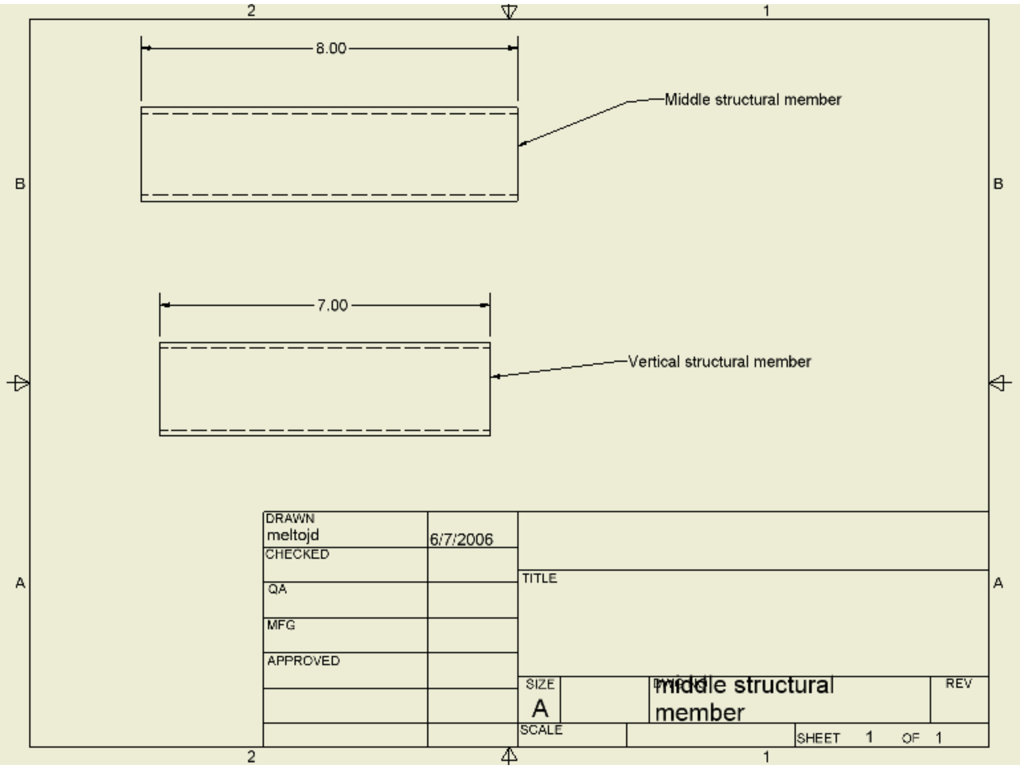
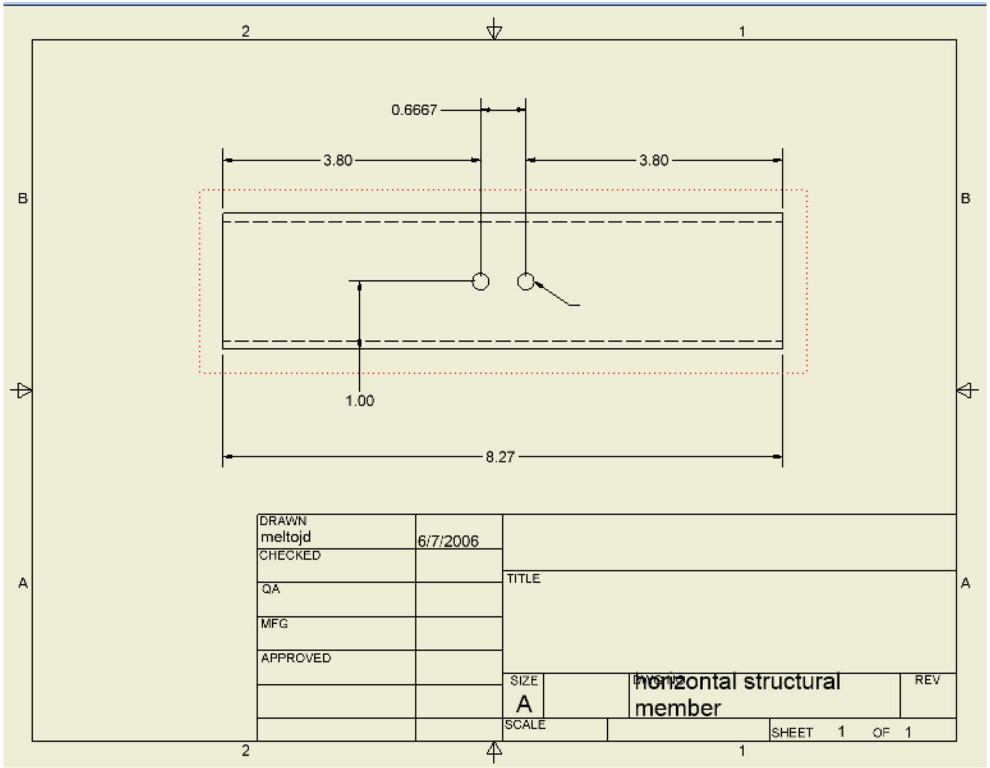


Figure I.4 – Horizontal member drawing.



DRAWN meltojd 6/7/2006
CHECKED
QA
MFG
APPROVED
TITLE
SIZE A
DWG NO horizontal structural member
REV
SCALE
SHEET 1 OF 1

Figure I.5 – Bottom mount drawing.

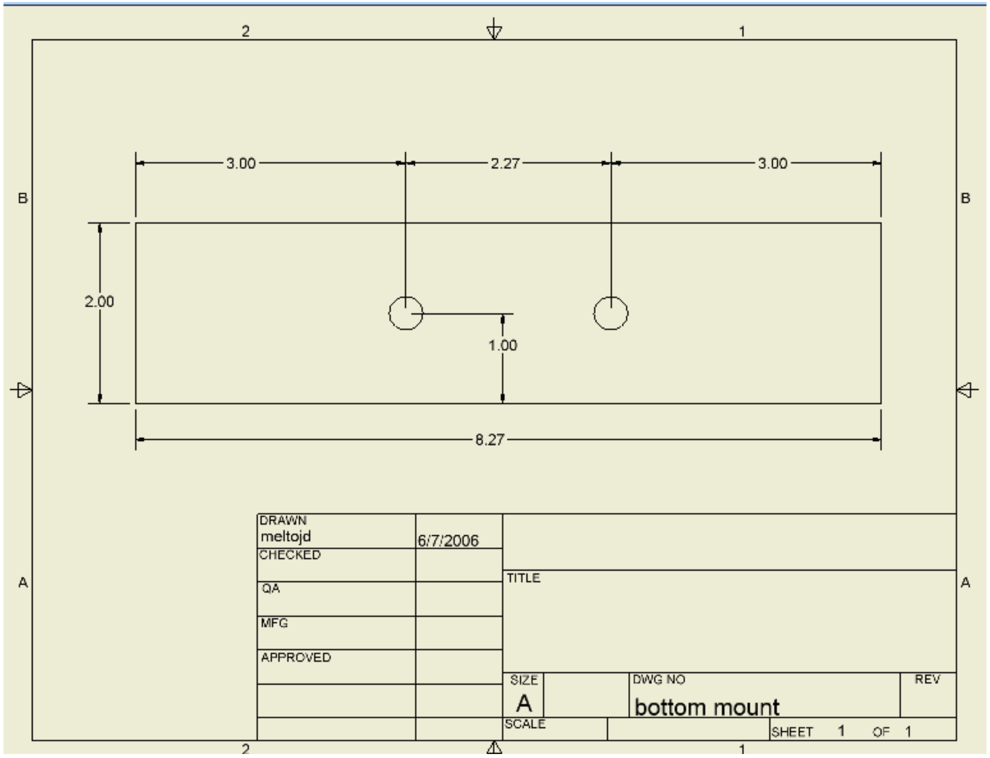


Figure I.6 – Tipping bucket axle mount drawing.

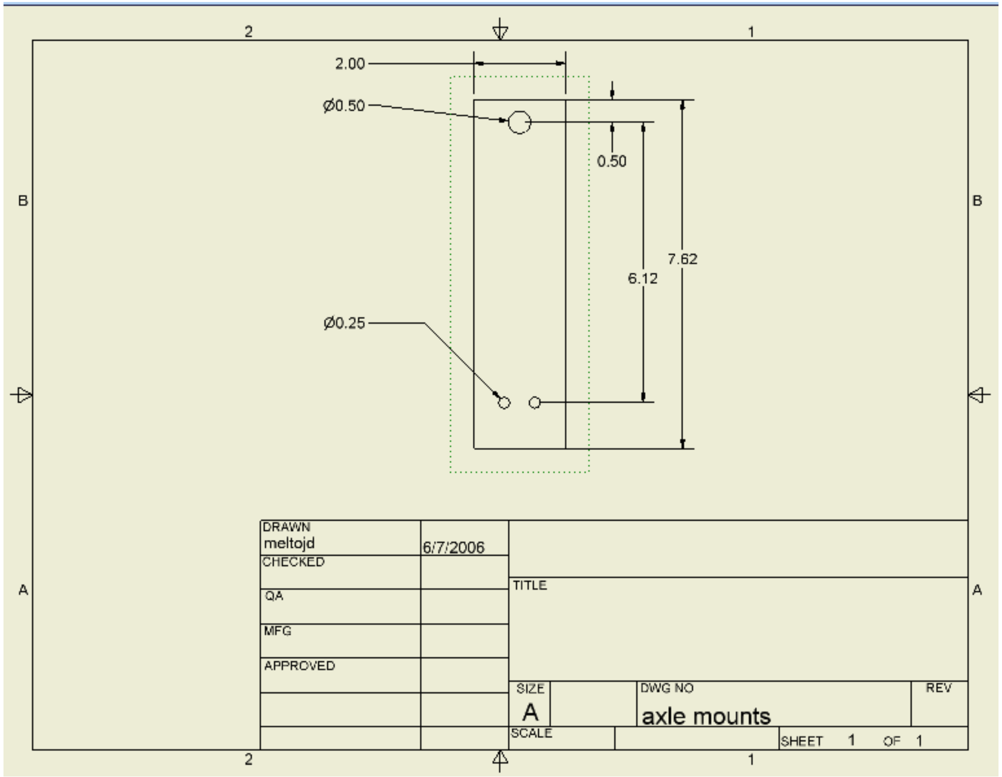


Figure I.7 – Rainfall chamber drawing.

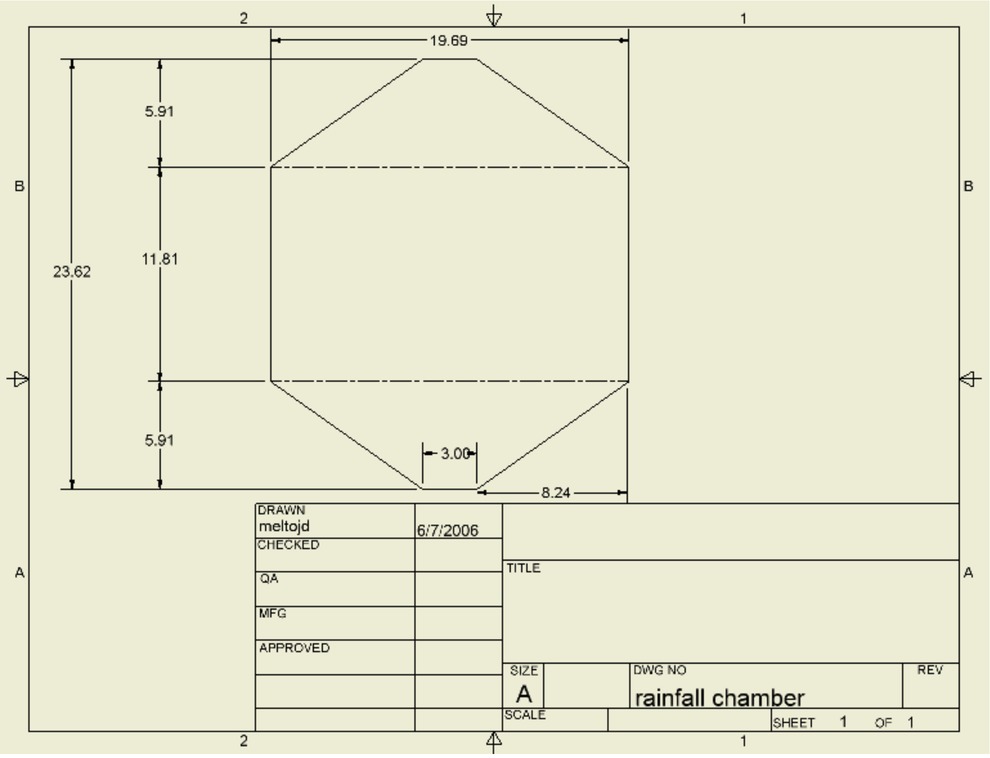


Figure I.8 – Rainfall chamber divider drawing.

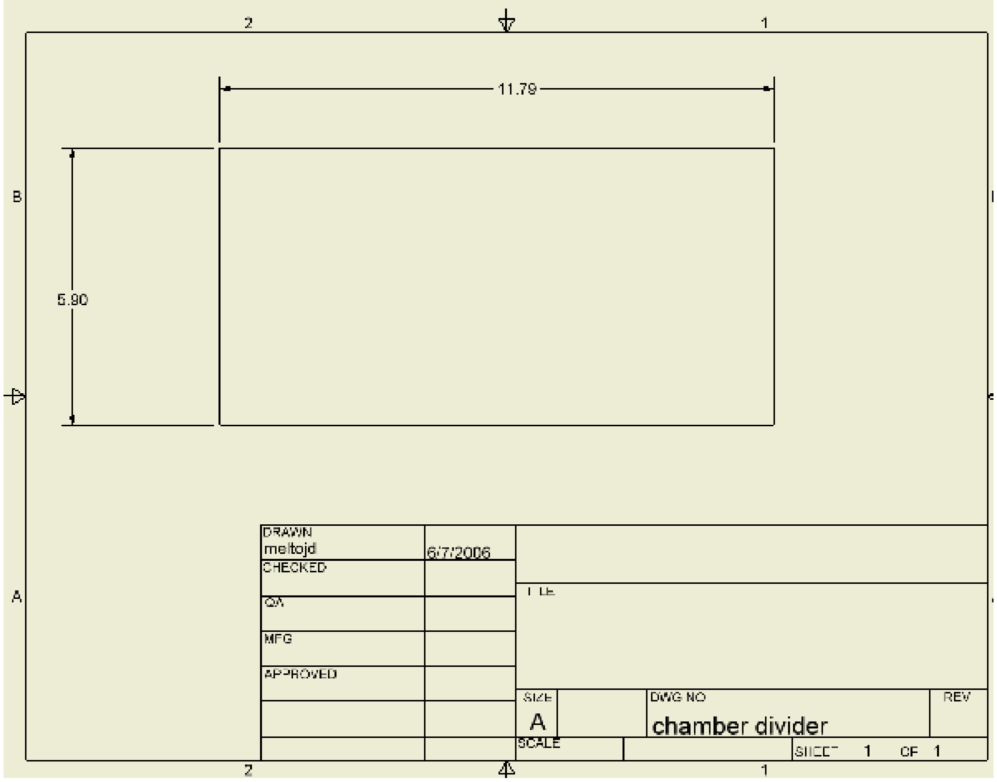
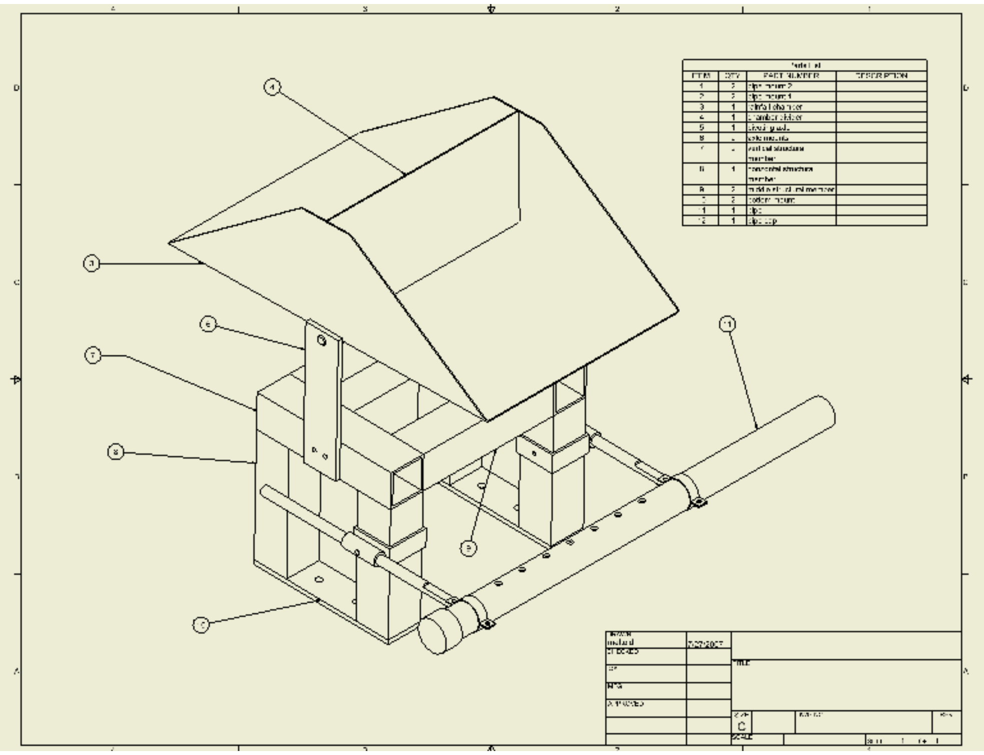


Figure I.9 – Tipping bucket design and parts location.



Parts List			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	2	pipe mount 2	
2	2	pipe mount 1	
3	1	rainfall chamber	
4	1	chamber divider	
5	1	[illegible] guard	
6	2	side mounts	
7	2	vertical structure member	
8	1	horizontal structure member	
9	2	middle vertical member	
10	2	bottom mount	
11	1	pipe	
12	1	pipe cap	

APPENDIX J

Water Diversion Spacing

Table J.1 -- Recommended spacing for water diversion structures.

Recommended Water Diversion Structure Spacing	
Slope (%)	Spacing (ft)
2	85
4	45
6	30
8	20
10	15
12	13
14	10

Table J.2 -- Water diversion spacing developed by Brodbeck.

Recommended Diversion Structure Spacing developed by Brodbeck	
Slope (%)	Spacing (ft)
4	46
6	36
8	33
10	29
12	27
14	22
18	19

Table J.3 -- Recommended distances between water bars on skid trails and logging roads after logging is complete (Brinker, 1995).

Recommended Distances Between Water Bars On Skid Trails and Logging Roads After Logging Is Complete.	
Road Grade	Spacing (feet)
2	250
5	135
10	80
15	60
20	45
25	40
30	35
40	30

Table J.4 – Water bar and broad-based dip spacing as recommended by the Alabama BMP Manual for Forest Operations.

% Slope	Distance Between Water Bars (feet)	Distance Between Broad-base Dips, Turnouts (feet)
3%	200	235
5%	135	180
10%	80	140
15%	60	125
20%	45	NA
30%	35	NA
40%	30	NA