AN ABSTRACT OF THE THESIS OF

Keith F. Kahklen for the degree of Master of Science in Forest Engineering presented on December 16, 1993.

Title: Surface Erosion from a Forest Road, Polk Inlet, Prince of Wales Island, Alaska

Abstract approved: Paul W. Adams

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Rainfall, discharge, traffic, and suspended sediment were monitored for a period of 4.5 months at three locations on a secondary haul road at Polk Inlet, Alaska to determine the important processes and variables involved in surface road erosion for this area. Three sites all less than 500m^2 and within 5 kilometers of each other on the same road were chosen to be instrumented for monitoring. The proximity of the sites to each other resulted in the sections all being nearly identical in age, topographical location, aspect, elevation, and construction materials. Also, the sites were subjected to the same traffic amounts of approximately 3 to 4 loaded logging trucks per day plus other light vehicles.

Maps were developed of the sites which helped determine the source areas for each one. The gradients of sites 2 and 3 were approximately 7%, and the gradient of site 1 was 10%. Each study site was equipped with a flume, pressure transducer, datalogger, and pumping sampler to

collect data on discharge and suspended sediment. Sites 1 and 3, had rain gages connected to the dataloggers which recorded 5 minute rainfall intensities. Hourly suspended sediment samples were collected at each site. An infrared traffic counter was used to count the daily traffic amount. An infiltration rate for the road was determined to be 0.9mm/hr using a simple water balance method and also by determining the minimum amount of rainfall to initiate runoff. The infiltration rate was used in development of representative hydrographs for the three sites.

The runoff response of the sites were very similar when normalized to an area of 280 m^2. The precipitation catches for the two gages were very similar with precipitation amounts of 893 mm for site 1 and 975 mm for site 3 during 89 days of record. Several regression analyses were completed for both hourly and storm data to determine which variables and technique would be best for estimating total sediment production. The method that proved to be the best for determining hourly production was to multiply the hourly sediment concentration by the average hourly discharge to obtain a total estimated sediment weight produced for that hour.

During multiple regression analysis, all three sites and the combined model had rainfall as the most important variable. The variable that averaged the number of axles per day since the last runoff event was also found to be significant in the combined model. Qualitative variables were used to determine that timing of the events may have an influence on the sediment production. The total storm sediment production was determined by summing the total hourly sediment weights for a given storm. The regression analyses found rainfall to be the most significant of ten variables for the total storm sediment production.

A comparison of all the different models coefficients was developed. The multiple regression model with total storm rainfall, a qualitative variable for gradient, and axles per day was found to have the best coefficient of determination of 0.66 for the combined data of all the sites. The model for site 3 of axles per day and total storm rainfall was found to have the highest coefficient of determination, $R^2 = 0.85$. The simple linear regression model of log of total sediment yield/km of road to total storm precipitation was used to estimate the annual sediment production from a kilometer of road at Polk Inlet. The annual precipitation data was from a gage located about 16 kilometers northeast of Polk Inlet. The annual road surface sediment erosion estimate is 8.1 tonnes/km of road.

A comparison of other studies shows this to be similar to other locations in the United States and areas of New Zealand. Several assumptions were made and the resulting limitations are described for this estimate. Any use of this estimate or equation for sites without very similar characteristics would not be advised. Future studies are in progress to expand the understanding of some of the other variables not accounted for in this study.

Surface Erosion from a Forest Road,
Polk Inlet, Prince of Wales Island, Alaska

by

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SURFACE EROSION FROM A FOREST ROAD, POLK INLET, PRINCE OF WALES ISLAND, ALASKA

INTRODUCTION

The effects of forest practices and management on soil erosion processes has been and continues to be of great concern to both public and private landowners. The two main processes for accelerated sediment production to forest streams in the Pacific Northwest is mass failures and surface erosion from roads. In areas of unstable ground, mass failures play a major role in sediment production, but surface erosion can also contribute significantly to sediment inputs to streams (Reid 1981). In the Clearwater Basin, Reid (1981) found that roads contribute as much as forty percent of the sediment produced by the basin. Changes in management practices and road construction techniques on forest lands in the last two decades has helped to minimize the frequency and quantities of sediment inputs as a result of timber harvesting activity and road construction (Haupt and Kidd 1965, Packer 1967, and Sessions et al. 1987). Although new measures are being taken to minimize sediment production, roads are still producing sediment at an unknown rate. Investigation into the significant factors involved in the erosion processes and their relationship to the production of sediment is needed to improve land management decisions.

Information on the physical processes and relationships involved in sediment production from forest roads is very limited for southeast Alaska.

The U.S. Forest Service Region 10 is currently revising the Tongass National Forest land management plan. The plan is intended to develop several alternative land management scenarios which would be used to direct management decisions on the Tongass National Forest. At the present, information used to estimate sediment production and erosion from forest roads during management planning is limited to estimates from other areas of the Pacific Northwest (Swanston 1992).

Prince of Wales Island, southeast Alaska is an area where extensive timber harvesting has been occurring for the past fifty years. The island is approximately 2731 square miles with over 2000 miles of logging roads (Alaska Geographic 1987). Studies focusing on logging impacts to streams and fish resources have been continuing since the early 1950's. Difficulties arose in determining whether logging had detrimental effects because of several overlapping variables. The result was the lack of hard evidence for significant logging effects on fisheries resources (Gibbons et al. 1987). Understanding the source areas for sediment production will help separate some of these variables and attempt to determine which are significant. At this time, data on surface erosion rates for the Polk Inlet area on Prince of Wales Island does not exist. This is indicative for nearly all of southeast Alaska. The objective of the study is to examine the variables and processes which are important in the production of sediment solely from selected road surfaces. This information will be necessary to develop methods for sediment routing and construction of sediment budgets for the Polk Inlet area as well as other locations in southeast Alaska. This will be one component of several involved in the routing and budgeting of sediment for southeast Alaska.

LITERATURE REVIEW

Studies in Southeast Alaska

The information available on erosion processes and sediment movement in southeast Alaska is limited to natural disturbance processes and sediment movement in the larger streams and their effects on salmonid fish species. In the late 1950's and entire 1960's, several studies were initiated on Prince of Wales Island to examine the impacts that logging may have on salmon spawning success (McNeil 1966, Sheridan et al. 1966, and Smedley 1968). One of the major concerns was the effects of increased sediment supplied to spawning gravel as a result of timber harvesting activities in watersheds. Several studies found increases in sediment in spawning gravel on several of the streams in which logging had occurred (Smedley et al. 1970, Sheridan and McNeil 1968). The source of the sediment increases were attributed to logging activities which included an increase in landslides, sediment from harvesting activity in streams or tributaries, and sediment from roads. Smedley et al. (1970) states there was an observed increase in sediment produced from the road surface at 108 Creek during periods of rainfall and log haul traffic. The sediment amounts were observed to decrease after log hauling stopped even during continued rainfall.

In the early 1980's, other studies were conducted at Trap Bay on Chichagof Island to study the natural sediment transport processes and quantities for an undisturbed watershed (Campbell and Sidle 1985, Sidle and Campbell 1985, Estep and Beschta 1985). An estimate, by Sidle and Campbell (1985), of suspended sediment yield for Bambi Creek drainage (154 ha) in the Trap Bay watershed was 20 $t/km^2/yr$. The Kadashan watershed which is adjacent to Trap Bay also had been the focus of several studies since the early 1960's to study the impacts of timber harvesting and road building (Gibbons et al. 1987). It was several years until any activity occurred in this watershed and the activity that did occur was much less than planned and limited to a few miles of road building.

In 1984, road building occurred in the Kadashan watershed in which information was collected on sediment production (Paustian 1987). Sediment traps were constructed on three first order streams that were crossed by the roads. The sediment traps were located approximately 300 meters below the road. Each trap had a pumping sampler at the outlet to sample suspended sediment passing over the sediment basins. Short-term increases in suspended sediment occurred immediately following road construction, then dropped back to pre-road construction levels. Sediment in the settling basins showed an increase for two years of 0.5 to 4 tons which represents a 20 to 66 percent increase in sediment yield for the three first order watersheds. Also part of the same study, bedload and suspended sediment concentrations were collected for Indian Creek which experienced a harvest of 8 percent of the watershed. Four years of data collection with two years prior to harvest and road construction and two years after harvesting activities resulted in no apparent change in sediment yield for the fourth order watershed. Paustian (1987) concluded, the high in-channel storage of sediment for the Kadashan and Indian Rivers would attenuate the effects of short-term limited disturbance in these larger watersheds.

Watershed Studies and Road Building Effects

For several decades, watersheds of varying sizes have been studied to assess the effects of timber harvesting and road building on sediment production and yield (Haupt and Kidd 1965, Fredriksen 1970, Brown and Krygier 1971, Beschta 1978, and Packer 1967). These studies quantified the effects of various management activities on the total sediment production for a watershed. Many used the timing of activities over an extended period to separate contributions of sediment from each activity (Fredriksen 1970, Brown and Krygier 1971, and Beschta 1978, and Harr and Fredriksen 1988). Fredriksen (1970) used a paired watershed approach to examine the effects of road construction and timber harvesting methods in the steep slopes of the Cascade Mountains in Oregon. The study found an increase in suspended sediment of approximately nine times that expected for an undisturbed watershed several weeks after road construction. The elevated sediment concentrations persisted for the next two years at two to three times higher than that expected for an undisturbed watershed. Brown and Krygier (1971) also used the paired watershed approach in the Oregon Coast Range to study the amount of sediment production from different harvesting methods and road construction. A two-fold increase in sediment production resulted following road construction and prior to timber harvesting.

Studies on Sediment from Roads

The evidence that roads are major contributors of sediment by many of the previous watershed studies prompted new studies focusing directly on road erosion and its contribution to total sediment yield in disturbed watersheds (Megahan and Kidd 1972, Reid 1981, Rothwell 1983, Swift 1984a, and Fahey and Coker 1989). Several studies attempted to determine the total contribution from the entire road section that included the cut and fill slopes as well as the road surface. In the Idaho Batholith, an area with highly erodible granitic soils, erosion from logging roads has been shown to increase 770 times more than in undisturbed areas. Thirty percent of this increase is attributed to surface erosion and the rest to mass erosion (Megahan and Kidd 1972). In a separate study in Idaho, Megahan (1974) measured a seven year range of 0.9 to 22.8 t/km^2/day with an average of 8.2 t/km^2/day of annual road erosion for the Silver Creek watershed. Observations during these studies noted that most of the material resulting from surface erosion was coming from the steep road fills. Subsequent studies focused on this portion of the road prism in an effort to determine the relationship of various vegetative treatments and to understand the erosional processes on road fills (Megahan 1978, King 1979).

A study by Reid (1981) in the Clearwater Basin in Washington, addressed the different sources as well as the processes involved in sediment production from forest roads. Surface erosion from the gravel surfaced roads in the Clearwater basin were responsible for more than 40% of the fine (< 2mm) sediment produced above background levels and the remaining percentage was a result of landslides caused by roads and any resulting erosion of the landslide surface. The calculated sediment yield for several road sections with various traffic levels range from 440 t/km/yr for heavy use roads to 3.4 t/km/yr for light use roads. The road cut-slope contribution was included in the road portion and the fill-slope was included in the landslide portion.

In North Carolina, at the Coweeta Hydrologic Laboratory, further study of the significance of each component on sediment production from a forest road was completed (Swift 1984a). The cut and fill slopes were found to be the largest producers of sediment during different times of the year. The cut-slopes experienced the highest erosion rates during the winter months due to frost heaving and dry ravel and the fill-slopes erosion primarily occurred during heavy rainfall of the first spring following construction. The road surface was found to produce more sediment than the other two sources during a period which log haul traffic was occurring. The study concluded that each component of the road section, cut, fill, and road surface, will have temporal and erosional process differences. Also, the study illustrates various methods for controlling some of these processes with surfacing and vegetation.

New Zealand has several forested areas which are currently being harvested or are in second growth maturing to harvest size. A study by Fahey and Coker (1989) in the northwestern part of the South Island in New Zealand was undertaken to determine the erosion rates for newly constructed and preexisting roads on steep granitic slopes. The study consisted of six sites on two different roads with four of the sites on one road undergoing grading of the cutbank and road surface prior to the study initiation and the other two left at their present state. The grading was an attempt to simulate surface conditions just after road construction. One site on the graded road separated the road surface and cutbank contributions while all other sites combined the total sediment yield for both road and cutbank. All road sections were surfaced with gravel but only three of the six were open to traffic. However, little if any traffic occurred during the study. An average annual sediment yield of 0.9 kg/m^2 was measured for the road surface alone at the one site with average annual sediment yields for the combined road and cutbank at the other sites ranging from 1.6 to 11.3 kg/m^2. The authors estimate 2 kg/m^2/yr for the road and cutbank sections not graded and 3 to 4 kg/m^2/yr for the graded road and cutbank sections. These estimates are for highly erodible granitic soils on average road gradients of 3.5 to 7.5 percent and experiencing minimal traffic.

The Variables of Road Surface Erosion

Several of the previously mentioned studies have found numerous variables to be important to road surface erosion. Many other studies focused on specific variables in an attempt to determine which were most important for sediment production from road surface erosion.

In the 1960's, Packer (1967) conducted a study of 720 road segments in the northern Rocky Mountain Region to determine which road and watershed characteristics influenced rill development and sediment transport on forest roads. A total of 14 variables were used in a multiple regression equation to determine the distance water traveled on the road before cutting a 25 mm rill.

Five of the fourteen variables chosen for regression analysis were determined to be significant with two accounting for more than 80 percent of the total variance explained by the regression equation. The proportion of soil surface aggregates greater than 2mm in diameter had the greatest influence, with 19 percent of the variance, on the distance water traveled before developing rills 25 mm deep. The effect of road grade explained 16 percent of the variance in the regression analysis of the variables for distance until erosion. From these results, recommendations for cross-drainage spacing to prevent rill development and erosion were developed for various road surfacing materials and gradients.

Other researchers examined the effects of surfacing gravel on sediment production from forest roads (Swift 1984b, Burroughs and King 1985, and Kochenderfer and Helvey 1987). A study comprising of six surfacing material treatments was conducted by Swift (1984b) at the Coweeta Hydrologic Laboratory, North Carolina. One section was left with bare soil, one with 20 centimeters of large stones, two with 5 centimeters of crushed rock, and two with 15 centimeters of crushed rock. In the first 8 months after road construction and with light traffic use, the bare soil road surface had a cumulative loss of over 200 t/ha with the rocked surfaces only having cumulative losses of less than 35 t/ha. However, after logging traffic occurred on the roads for 4.5 months, an increase in sediment loss occurred over all of the six sections. The sections with the greater gravel depth experienced a slight increase as compared to the other surfacing treatment, with one exception. Swift (1984b) found that the sub-grade soil type is important to sediment production as well. The two gravel treatments of 5 and 15 centimeters on a sandy clay loam soil sub-grade produced between 50 to 100 t/ha of soil more than those on a sandy loam sub-grade soil over the period of active logging.

Another study in the Appalachian Mountains focused on surfacing materials and the effects of traffic and construction standards (Kochenderfer and Helvey 1987). The treatments consisted of three surfacing replications on a minimum standard road of 7.5 cm clean gravel, 7.5 cm crusher-run gravel, and ungraveled. The higher standard road received 2.5 cm crusher-run gravel on two sites. The results of the four year study were a significant difference between the roads surfaced with gravel and those sections not surfaced. The annual sediment yields for the four treatments were 1.3 kg/m^2 for the 7.5 cm clean gravel minimum standard road sections and the same for the 2.5 cm crusher-run gravel on the higher standard road. The 7.5 cm crusher-run gravel treatments on the minimum standard road resulted in an average of 2.3 $kg/m^2/yr$ and the ungraveled treatments averaged 10.6 kg/m^2 of sediment yield annually. These sediment yields are from both the road surface and the cutbank for the newly constructed minimum standard roads; conversely, the higher standard road had stable cutbanks with established vegetation which prevented significant sediment input from these areas. Much of the sediment yield from the higher standard road was attributed to the heavy logging traffic and rutting of the surface which occurred during the study period. Storm intensity and total precipitation appear to significantly influence the quantity and timing of the sediment yield. A majority of the sediment production occurred during eleven percent of the storms which exceeded 25 mm total rainfall and an annual average of 5.2 storms with intensities greater than 12.5 mm/hr. Also, the study found that for the gravel surfaced roads more than half of the sediment yield was a result of suspended sediment transport. The researchers suggest with the gravel surface, much of the energy for moving the larger soil particles is absorbed by the large gravel substrate, thus, reducing the ability to move the larger particles and resulting in suspended sediment as a major contributor to sediment yield.

Burroughs and King (1985) used simulated rainfall on road surfaces in Idaho with and without gravel surfacing material. The results were sediment yields of 0.24 kg/m^2 and 1.08 kg/m^2 per 2.54 cm of rain. This is about a 79 percent reduction in sediment yield as a result of gravel surfacing. Several other studies mention the variation observed in sediment production as a result in differences in surfacing materials and construction methods; but, do not give specific details or quantities attributable to the surfacing materials because the studies were addressing other variables thought to be more significant (Reid 1981, Bilby et al. 1989, Fahey and Coker 1989, Foltz and Burroughs 1990, and Haydon et al. 1991).

Another variable that has been shown to be significant to sediment production and yield from road surfaces is the surface condition or topography of the road surface (Swift 1984b, Kochenderfer and Helvey 1987, Fahey and Coker 1989, Foltz and Burroughs 1990, Burroughs et al. 1991, and Haydon et al. 1991). Wheel ruts concentrate flow on road surfaces which results in more energy for dislodging and transporting larger particles and higher quantities of sediment particles. In the study by Swift (1984b), one site developed ruts as a result of moist conditions and heavy traffic. This road section with only 5 centimeters of crushed gravel produced as much sediment as the ungraveled sections. Kochenderfer and Helvey (1987) had a similar occurrence with the two replications on the higher standard road developing rutting as a result of heavy logging traffic. The sediment production at this time nearly doubled for these two sites. Foltz and Burroughs (1990) used simulated rainfall and rutting to determine the effect of wheel ruts on sediment production. The simulations were conducted at one site in Idaho and the other in Colorado resulting in a ratio of rutting to no rutting for sediment production of over 2:1 and nearly 5:1, respectively. The differences in the two sites were primarily attributed to differences in soil types and site conditions. Both sites' wheel rut plots experience a decrease in sediment runoff following successive simulations because of the limited supply of sediment. The same result was not observed for the overland flow plots in which the supply did not appear to be limited. On a separate study by Burroughs et al. (1991), a rainfall simulator was used to compare sediment production for a road section with reduced tire pressure and one with normal tire pressure. The result was nearly a two fold increase in sediment production on the section with normal tire pressure over the section with reduced tire pressure.

Maintenance is also a significant factor in the topography and condition of the road and can severely disturb the road surface. Effective maintenance can reduce rutting and prevent concentration of water on road surfaces and decrease sediment production. Haydon et al. (1991) conducted a study in Victoria, Australia on unsurfaced forest roads to determine the effect vehicle use and road maintenance has on surface erosion. High and low levels of maintenance and traffic were examined for a road built from highly erodible soils without surfacing material. High levels of traffic were more than 30 vehicles per week and low traffic were 4 vehicles per week. The maintenance levels were defined as: grading on average one time in 16 weeks plus weekly culvert cleaning for low maintenance; and high maintenance consisting of grading when deemed necessary, using cut-off drains on the road surface to divert water, cleaning of table drains, and cleaning of culverts. Total sediment load estimates for combinations of traffic and maintenance levels were; high use/high maintenance 52 t/ha/yr, low use/low maintenance 56 t/ha/yr, and high use/low maintenance 77 t/ha/yr. The researchers noted that events following grading produced very high sediment yields. This is a concern that may need to be considered to determine the frequency of maintenance.

Traffic levels have been determined to be a significant variable in the production of sediment from road segments, as well as, precipitation intensities and runoff as a means of transport (Reid 1981, Reid and Dunne 1984, Swift 1984b, Kochenderfer and Helvey 1987, and Bilby et al. 1989). Traffic levels can influence several of the variables already discussed by breaking down the surfacing material, causing rutting and concentrating flow, and increasing the maintenance frequency for a road. Reid and Dunne (1984) determined traffic to be the primary variable in road surface sediment production from forest roads for the Clearwater Basin, Washington. Sediment rating curves were developed for six different road types based on usage. The calculated annual sediment yield for the heavy traffic (>4 loaded log trucks/day) was 500 t/km of road per year and for light use (only light vehicle traffic) was 3.8 t/km of road per year. These estimates include cutbank, ditch, and road surface erosion; however, estimates of contributions from cutbanks and ditch erosion were 2.0 t/km/yr of the totals for all use levels. A similar study in southwestern Washington by Bilby et al. (1989) also found traffic to be the most significant variable for the production of sediment from five road sections. The cutbank and ditch contributions were included into the total sediment estimates for the three secondary road section; but, the two mainline road sections did not have cutbanks. The average sediment yield for all sites was 2.41 kg/m^2 over the 23 week study period. The sediment production rates for the two road classifications were 10 t/km for the secondary roads and 26 t/km for the mainline roads over the 23 week period. The precipitation at the two sites during the study differed considerably with the secondary road sites receiving 1580 millimeters and the mainline site receiving 630 millimeters. Traffic appears to be a significant variable in those studies which have quantified its effects, as well as, several other studies in which researchers have made qualitative observations of the influence of traffic.

Other variables that may effect the sediment yield from roads are age, topographic location, aspect, rainfall intensity, discharge, and disturbance during road construction. Many of these variables have been addressed or referred to in several studies, but most studies have focused on other variables deemed more significant. The difficulty in studying road erosion lies in the determination of significant variables for that particular location and the methods of quantifying the contributions from each variable.

Sediment Effects on Fish/Habitat and Estuaries.

A primary concern in southeast Alaska is the possible impacts increases in sediment may have on fisheries resources. Increases in sediment discharge into forest streams can have an adverse effect on fish (Cederholm and Reid 1987, and Scrivener 1987a). Concerns for the increases in sediment discharge, from disturbed forested areas, has led to a substantial amount of information on the impacts of sediment on fish. It has been shown that increases in fine sediments to a stream can cause increases in sedimentation of coarse gravel in which many fish spawn (Smedley 1968, Scrivener 1987a). The increases of sediment entrained in spawning gravel can cause a decrease in survival of eggs and alevins resulting from a decrease in water flow through these gravel (McNeil 1966, Sheridan and McNeil 1968, Meehan and Swanston 1977). Also, these increases of sediment may prevent fry emergence from the gravel due to a cementing effect (Meehan and Swanston 1977). Other effects of sediment increases, may be an aggradation of sediment in the stream and a reduction in pools and other habitat which may have an effect on survival (Cederholm and Reid 1987).

Another concern in southeast Alaska which has not been studied a great deal is the effects of accelerated sediment production on estuaries. Estuaries are used by several species of salmonid fish to spawn and rear juveniles (Tschaplinski 1987, Thedinga and Koski 1984). Increases in small gravel and sand in estuary spawning gravel has been observed at Carnation Creek, British Columbia (Scrivener 1987b). An increase in sedimentation in estuaries could cause an aggredation of sediment in many of the sloughs and off-channel areas which many fish use to forage for food (Tschaplinski 1987). Southeast Alaska has an enormous number of streams which flow into estuaries which support spawning and juvenile salmon.

JUSTIFICATION

The expected result of this study is to provide some initial data for developing local relationships between precipitation and traffic levels to sediment discharge from road surfaces. The present plan by the USFS Pacific Northwest Research Station is to conduct similar studies at other locations on Prince of Wales Island and southeast Alaska to collect more data on the variables important to forest road erosion processes to be used to develop a method for determining estimates for road erosion throughout southeast Alaska. The variables which are to be focussed on are surfacing material, maintenance, traffic, and gradient, with total rainfall, intensity, and discharge being the transport mechanisms.

Information from this study will provide local land managers with methods for identifying the quantities of sediment yield that can be expected from forest roads. With a better understanding of the erosion process of forest roads, local land managers will be able to make decisions that can be more cost effective and have the least environmental impacts. Without this information, future regulations may not be adequate or may be too restrictive.

METHODS

Site Selection and Location

The location of the study sites were at Polk Inlet 55°20′ latitude, 132°30′ longitude, on Prince of Wales Island, Alaska (figures 1 and 2). This site was chosen because there was available lodging less than 17 kilometers from potential study site locations which had active log hauling occurring throughout the study period of June to October, 1993. Also, support from the USFS Ketchikan Area Office and Area Hydrologist, in the form of equipment and lodging, was available. Three acceptable sites were located on haul road 2150-000 paralleling the beach at approximately 30 meters above sea level. The road had been constructed five years earlier (USDA FS 1986). The criteria used to determine the suitability of sampling sites were very important in reducing the amount of variables that would need to be accounted for in the subsequent analysis. In doing so, the age of the road, the rock type used in construction, and the type of vehicle traffic, would be the same. As a result, the road construction material was a gabbro rock and had come from two rock pits within a few kilometers of each other. The gabbro was fairly hard and resistant to breakdown from weather and traffic. The elevation, aspect, and rainfall were all very similar.

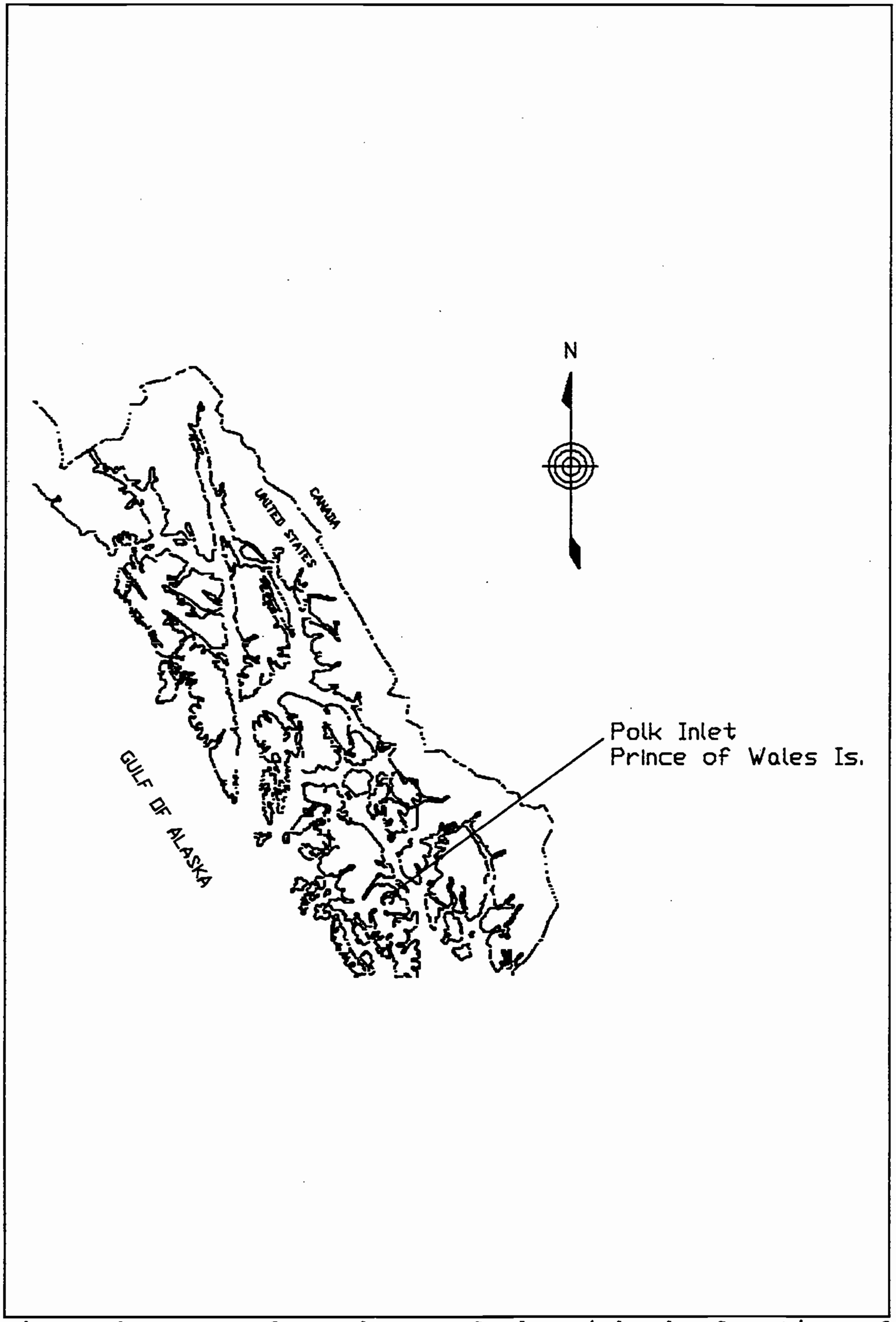


Figure 1. Map of southeast Alaska with the location of Polk Inlet, Prince of Wales Island.

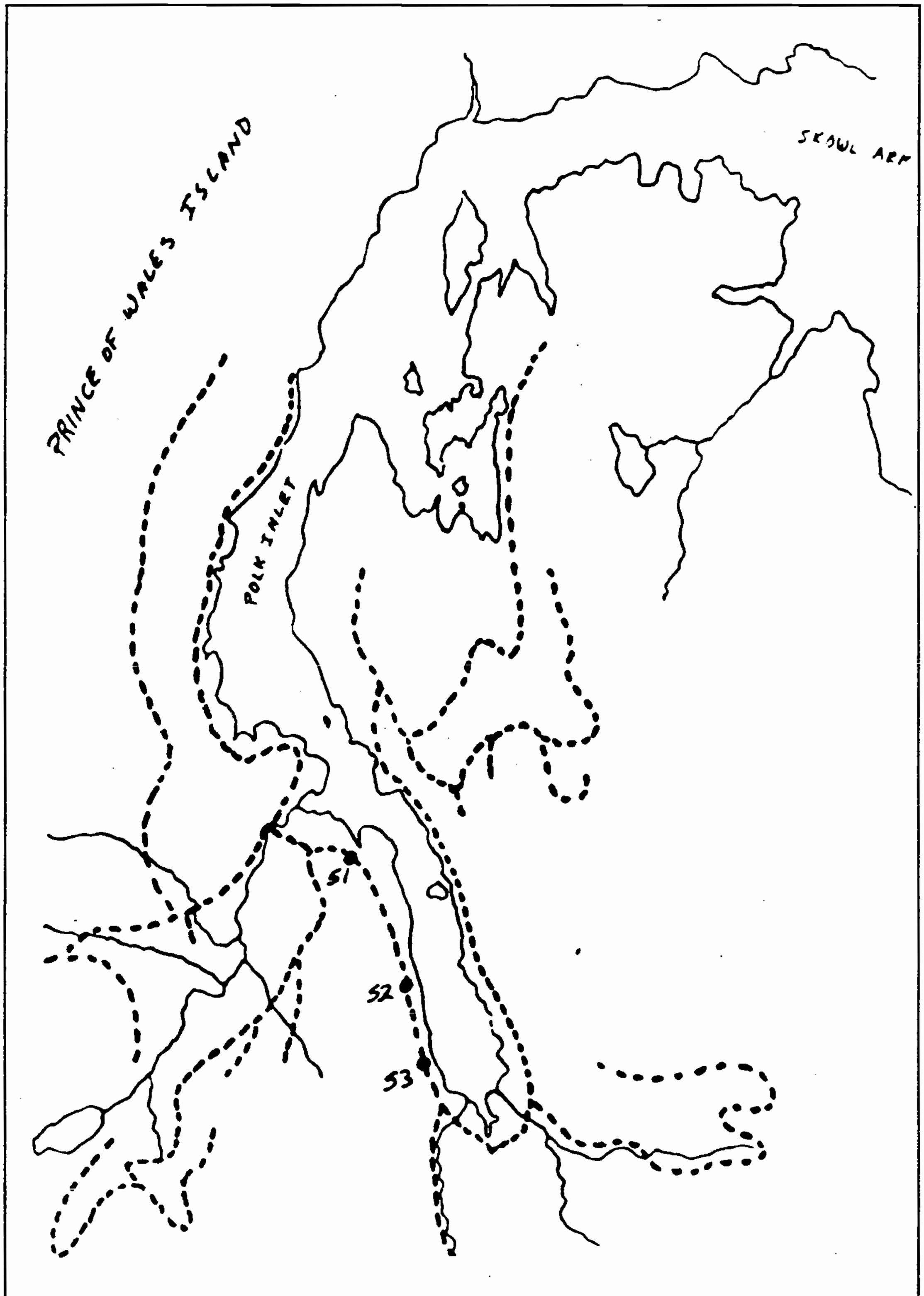


Figure 2. Map of Polk Inlet study site. The dotted lines are roads and filled circles are approximate locations of study sites. The scale is approximately 0.5 km per centimeter.

Also important in site selection was to isolate sediment from road surfaces through the elimination or reduction of contributions of sediment from the cutslope and ditch so that any of these contributions would be considered insignificant. Initially, the cutslopes were to be covered with burlap to stabilize the soil and reduce or stop any erosion; but, shortly after equipment installation and prior to any significant rainfall events the cutslopes were hydroseeded by a contractor which resulted in a well vegetated and stable cutslope. Erosion pins were established in the ditch with the steepest gradient that appeared to be the most susceptible to erosion. Measurements during the study and one year later did not show any change in height at which the pins were initially established indicating little if any erosion in the ditch. Also, personal observations of the cutslopes and ditches during the larger storms were used to determine if erosion from these sources were evident. During all the storms observed, there didn't appear to be any significant contribution from the cutslopes and ditches.

The road segments that were chosen for this study are representative of the type of logging roads found in the Polk Inlet area as well as much of the Tongass National Forest. A windshield survey of 55 kilometers of logging roads in the Polk Inlet vicinity had an average gradient of approximately 6 percent with over 35 percent of the ditches draining into stream channels. Also, most of the cutslopes were hydroseeded to reduce erosion. Hydroseeding cutslopes and bare soil areas is a practice that is at the discretion of the Ranger District personnel and is used on several districts on the Tongass National Forest.

Source Areas

In order to determine sediment yield for a road section, a map of the general slope, layout, and contributing source area was produced for each of the three study site road surfaces. The information necessary for these maps were collected using an engineers level, compass, and cloth tape. At each of the road sections, "rebar" was driven into the shoulder of the road across from each other and used as pins for cross section measurements. The pins were placed approximately one to two meters apart along the entire study section. A control survey was completed on all the pins using a compass measuring to the nearest degree and tape to the nearest centimeter. The control survey data was input into a program and reduced to X and Y coordinates. Next, a level loop was run on all the pins to be used for determination of the height of the instrument to the nearest 3 mm with respect to an established bench mark. The height of the instrument is used to relate cross-section elevations to each other. A program developed at the Juneau Forestry Sciences Laboratory was used to compile the cross-sectional data and the control survey data for development of X, Y, and Z coordinates for all the data points surveyed on the road section.

The data set was then loaded into a mapping program, to generate topographic maps of the road surfaces (figures 3, 4, and 5). There were approximately 1700 data points for the largest site and 700 data points for the smallest site used in generating the maps. The elevations at each point were read to the nearest 3 mm. The elevations on the maps are relative elevations and not true elevations with respect to sea level. The maps show the possible source areas contributing to the runoff in the ditch. The possible source area was noted in the survey notes which mainly consisted of the area between the two berm resulting from road grading. The estimated sediment source area for the ditch discharge was developed from the maps and visual observations during storms. A centerline was noted during the survey and is displayed on the maps. The intersection of the elevation lines and the centerline can be used to determine the direction the road surface is sloping. With the use of both the maps and the personal observations and measurements, an estimate of the source areas for the three study sites has been made.

The source area measurements for sites 1 and 2, mainly consist of the surface area of the road approximately from the centerline to the inside ditch. The apex of the crown of the road was the dividing line for the drainage of the road surfaces. The contributing source area for site 1 is

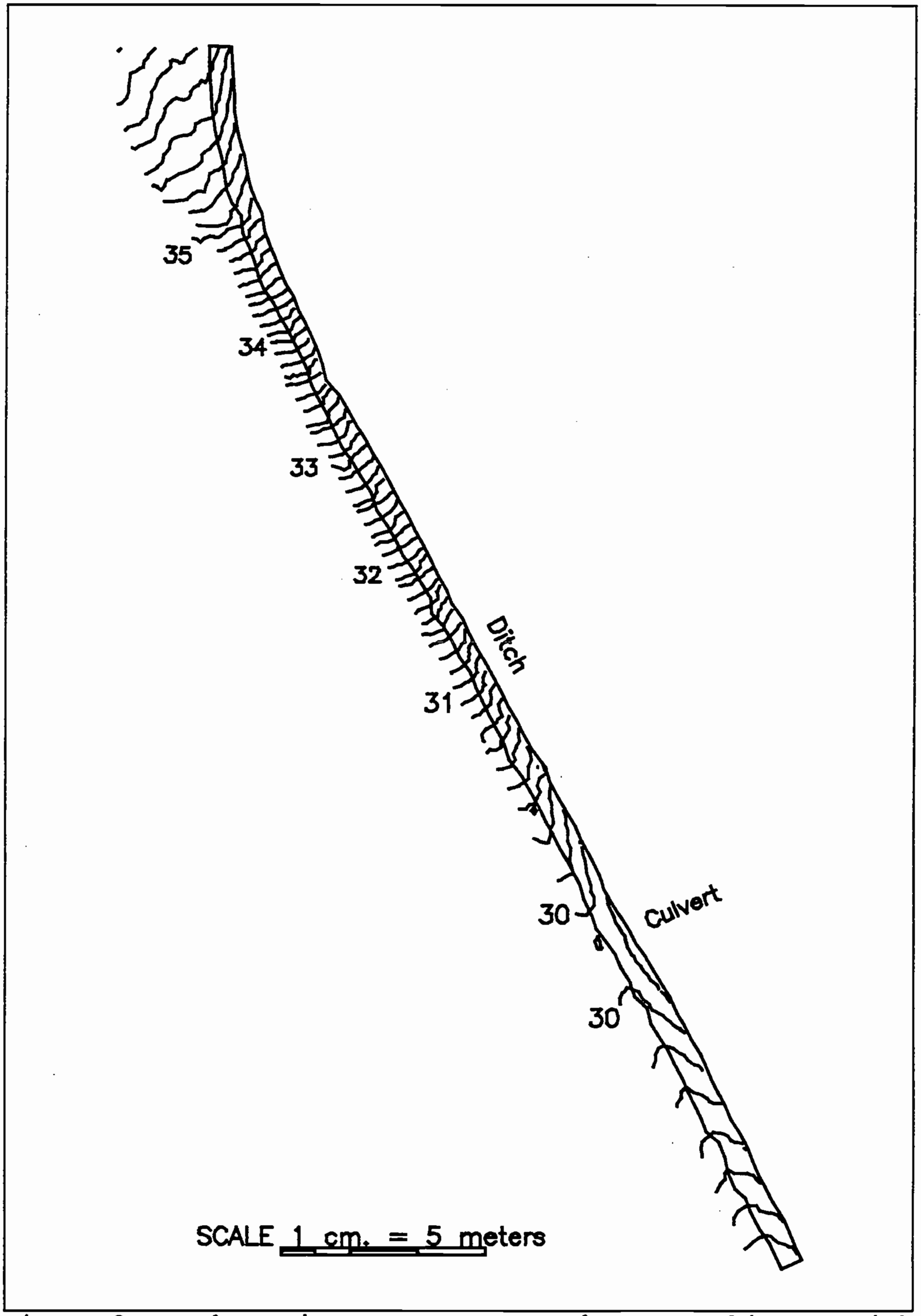


Figure 3. Road erosion source area and topographic map with a relative elevation interval of 0.1 meter for the road surface for site #1, Polk Inlet, Alaska.

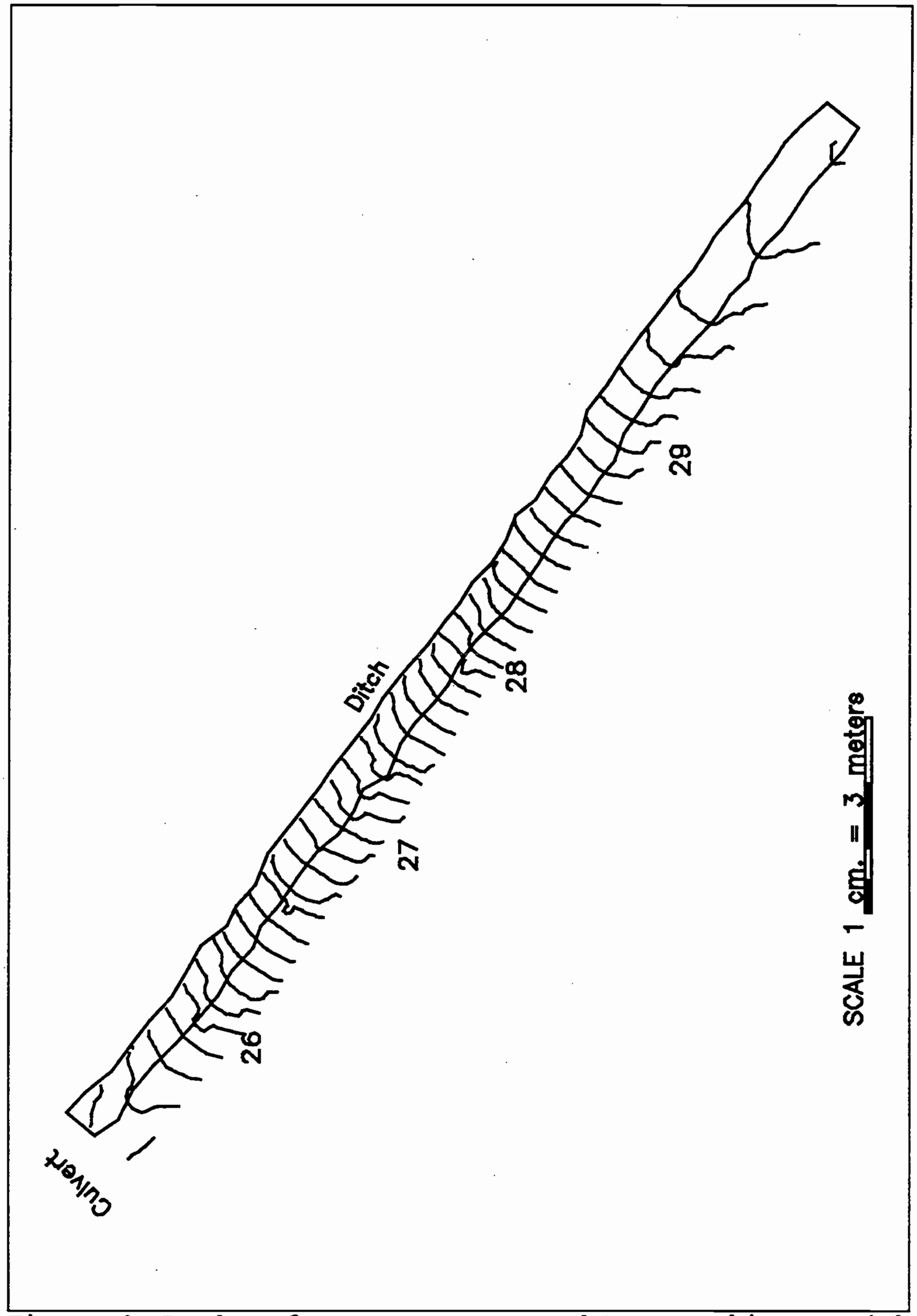


Figure 4. Road surface source area and topographic map with a relative elevation interval of 0.1 meter for site #2 at Polk Inlet, Alaska.

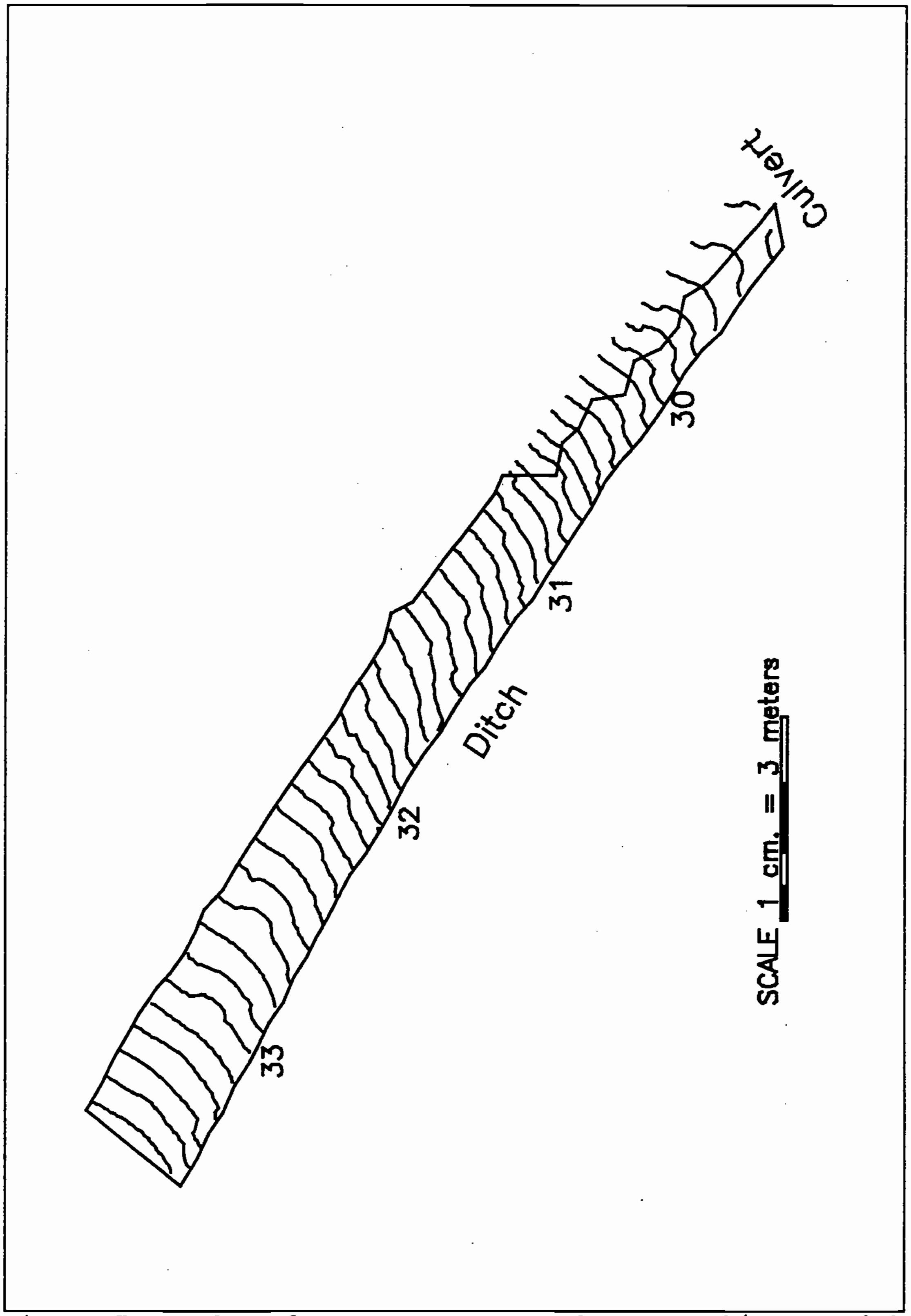


Figure 5. Road surface source area and topographic map with a relative elevation interval of 0.1 meter for site #3 at Polk Inlet, Alaska.

251m^2 with an average 10% gradient. The area for site 2 is 98m^2 with an average 7% gradient. Site 3 had a different drainage pattern than the other two sites. The road sloped inward on a slight curve in the road and was enough to result in most or all the drainage of the upper section of the entire road surface to drain to the inside ditch. The contributing source area for site 3 is 283m^2 with an average 7% gradient. These calculated areas were used to determine the area of runoff for the total sediment production estimates and the estimates of total runoff and infiltration during representative hydrograph synthesis.

Runoff, Precipitation, and Sediment

At each road segment chosen for a study site (figure 6), a "large 60° V trapezoidal flume" was installed either in the ditch prior to the cross drain culvert or at the outlet of the culvert. These are critical depth flumes in which the head is measured at a designated point in the entrance of the flume which can be used in the equation:

$$Q_{cfs}=1.55\times H^{2.58}$$

with H measured in feet, to determine the instantaneous discharge. The capacities of these flumes were 0.25 cfs. The head was measured using a 1 psig pressure transducer with an accuracy of 0.3% of full scale. Full scale is 2.31 feet, therefore, the accuracy of the transducer was ±0.0069

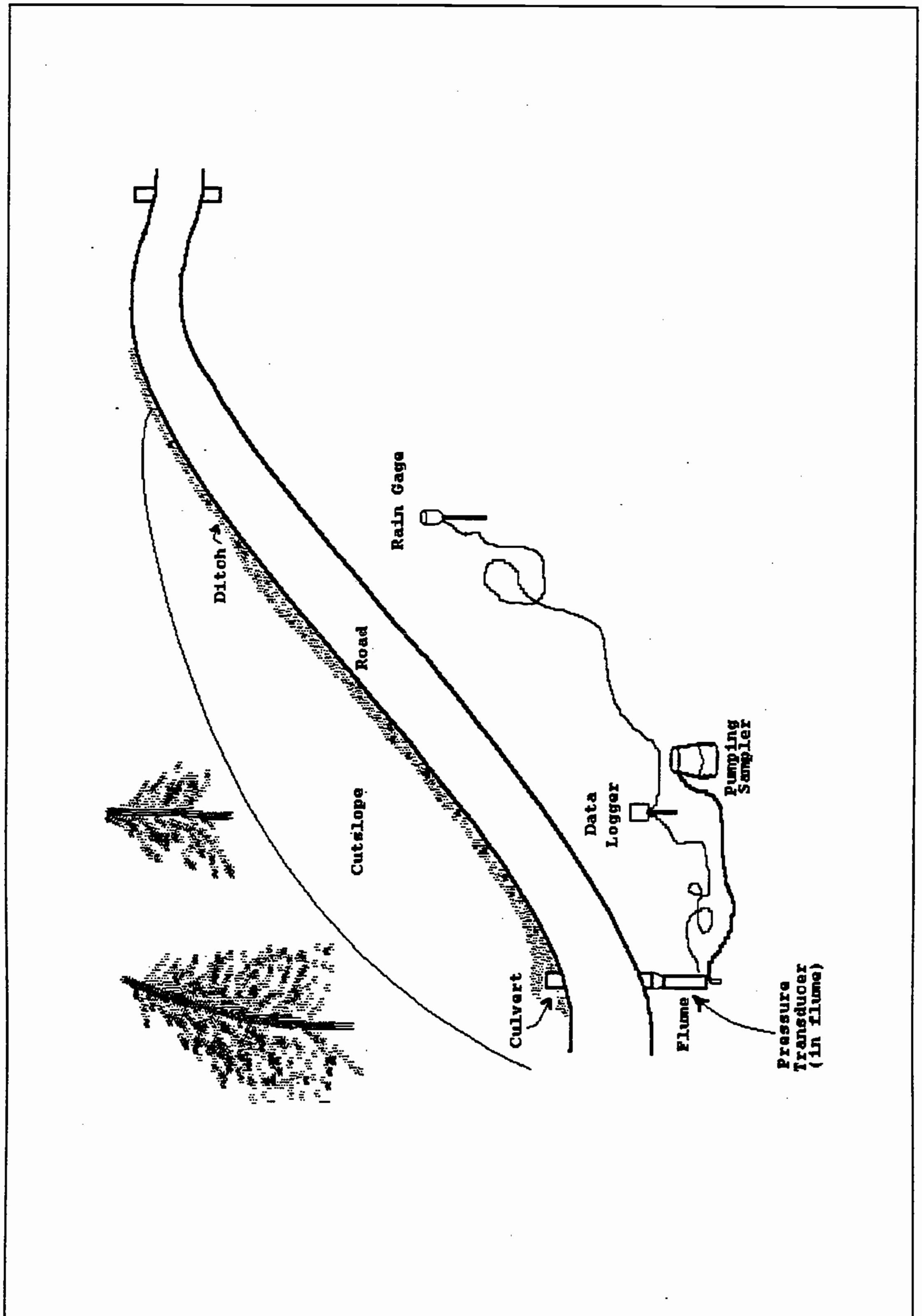


Figure 6. The instrumentation of the typical road section for the study sites at Polk Inlet, Alaska.

feet. The pressure transducers were connected to datalogger with 64 kilobyte data storage packs. The logger scan rate was set at a 5 minute interval so that it logged an instantaneous measurement of head, then recorded it to the data storage pack.

Two tipping bucket rain gauges were used to determine the amount of rainfall and the intensities at which it occurred. The rain gauges were calibrated to tip every 0.25 mm of rainfall and was recorded by a data logger for five minute intervals. The rain gauges were located at sites 1 and 3, approximately three miles apart. Each gauge was set in the best location to allow for optimal capture of precipitation for the two sites.

Each site was equipped with a pumping sampler to sample the water as it discharged from the flume. The sampler intake was located in a small pool formed by two sand bags just below the flume to ensure the water was deep enough to cover the intake. The area of the ditch below the flume outfall was armored with rock to reduce any possible erosion resulting from the 2.5 cm drop out of the flume. The sampler was activated by a liquid level actuator that activates the sampler once the water level reached the set height. Once actuated, the sampler would sample every 15 minutes with 4 of these 15 minute samples compositing into one sample bottle to give a 1 hour composite sample of the sediment discharge during that time. The samplers have a capacity of 24 to 28 composite samples depending on the sampler model. Once a rainfall event occurred, samples bottles were collected and taken back to a field lab for filtering.

The samples were filtered following the Standard Methods for examination of water and wastewater for suspended solids (APHA 1985), with a micropore filtering apparatus at Polk Inlet. The filters used were 1.2 micron glass fiber filters which were oven dried and preweighed at the lab in Juneau and stored in Whirl Pack sample bags with the weight noted on the bag. Once filtering was complete, the filter was folded in half and briefly dried in a microwave oven and placed back into the sample bag to be taken back to Juneau and completely dried and reweighed to the nearest 0.1mg on the same scale previously used. During the filtering process, the total volume of the sample was determined prior to filtering using a 500ml graduated cylinder.

Traffic

An infrared traffic counter was set up about 50 meters prior to the first sampling site on the logging road. The counter would give a total count of traffic that passed between the counter and reflector. Once the beam was broken a mechanical counter would register one count. A reading of the counter was taken late in the evening to get a total of number of vehicles using the road during the day. If days were missed, a reading was made and an average was calculated for the total days missed. Also, when at the sampling sites, notes were kept on the type of traffic, frequency, and totals during the period at the site to corroborate the count from the traffic counter. Also, the timber sale administrator was asked the number of loaded logging truck trips were made per day to supplement the traffic data collected. Daily traffic counts were converted to axle counts by counting five axles for a loaded log truck and 3 for an unloaded log truck with the rest of the traffic having two axles unless noted in the daily notes.

The data collected on the data loggers were summed or averaged into an hourly format to correspond to the four 15 minute suspended sediment samples which were composited into one hour samples. The samples were analyzed both as hourly samples and entire storm amounts.

Infiltration

The infiltration capacity for the road surfaces were determined to develop a representative hydrograph for the roads by completing a simple water balance for the drainage area. The volume of water resulting from a short duration rainfall event onto the surface area of the road and ditch should be the same as the volume of water discharged through the flume plus the infiltration into the road and ditch. This reasoning was the basis of the method for determining the infiltration capacities of the road surfaces.

The first method used for determining infiltration rates for the study sites was an examination of short duration rainfall events which did produce runoff and compare the volume of rainfall to the resulting volume through the flume. The difference between the two would be estimated to be the loss due to infiltration at the study area. During the representative hydrograph development, the five minute average discharges would be converted to a total volume and compared to the total volume of rainfall for that event. The difference between the rainfall volume and discharge volume was the estimate of the infiltration capacity of the road and ditch. The results were the same as those of the previous method of 0.8 mm/hr to 1.0 mm/hr. These estimates of infiltration capacity are for both the road surface and the ditch together. It is probable that the infiltration capacities of the road surface and ditch are different due to the differences in compaction of the surfaces, but for this study the interest is the amount of runoff reaching the culvert. Therefore, the infiltration capacities of both the ditch and road surface must be reached to produce runoff in the ditch and result in sediment transport and separation of the two is not necessary.

With the other method, the rainfall and discharge records were examined to determine the amount of rainfall required to initiate a runoff response through the flume. This assumed that any runoff response was due to excess rainfall above the infiltration capacity of the road and ditch. Many different events under different antecedent conditions over the five month study period were examined to determine the infiltration rate of the study areas. As a result, the infiltration rates for the study sites were between 0.8 mm/hr and 1.0 mm/hr; therefore, the rate of 0.9 mm/hr will be assumed for the three sites. Some of the loss of water may have come from evaporation; however, loss from evaporation is probably insignificant during rainfall events due to the high humidity and lower temperatures found in southeast Alaska.

Representative Hydrograph Method

In an attempt to determine the important variables associated with sediment production from roads, a necessity arose to develop a method for separating the road surface runoff and any other runoff intercepted by the ditch. This was necessary to minimize the dilution effect caused by the intercepted water and to develop a theoretical concentration and discharge for use with statistical methods in determining the relationships between sediment production and several independent variables and their significance in predicting total sediment discharge. Also, the representative hydrograph was used to compare the runoff responses for the three sites.

The original plan for the study was to choose sites in which inputs of sediment from the cutslope and ditch were negligible. Three sites were chosen using this criteria. The cutslopes and ditches did not contribute significant amounts of sediment to the runoff because the ditches were well armored and, as a result of hydroseeding by the USFS, the cutslopes well vegetated. Also, sites were chosen in which surface and subsurface flow from above the cutslope appeared to be minimal so that the primary runoff in the ditch was from the road surface. During the site selection process, the ditches did not have water flowing in them even though it had been raining lightly for several days. It was approximately three weeks after site selection that there was enough precipitation to cause any runoff to occur in the ditch. It was then observed that flow originating upslope in ephemeral streams were being intercepted by the road ditch and routed to the culvert. The flow from these small ephemeral streams were variable depending on the amount of rainfall and the length of time it had been raining. The water from these streams were observed not to contain sediment during the runoff period. As a result, the water from the ephemeral streams would dilute the concentration of sediment coming from the road surface runoff.

The method used for representative hydrograph development for this project is similar to that discussed by Chow (1964). To be able to use a representative hydrograph method several assumptions must be satisfied which include:

a. The rainfall is of short duration and is evenly distributed during the associated time period.

b. The rainfall is evenly distributed over the entire area of the drainage basin.

c. The time period in which runoff occurs is constant for an effective amount of rainfall.

d. The principle of superposition can be used with the representative hydrograph because the direct runoff is directly proportional to the amount and duration of the effective rainfall.

e. The runoff from a specific event for the specific drainage area accurately reflects the normal runoff pattern due to the physical characteristics of that drainage area.

Each of the assumptions are addressed to illustrate that it is appropriate to use the technique with the Polk Inlet study sites: (a) Five minute intervals were used to record rainfall amounts for the study sites which helped in separating the short duration events; however, the storms in southeast Alaska are commonly frontal storms that last for several hours or days. This made it moderately difficult to separate storms that were short duration and were evenly distributed through time. To find events that could be used in the development of representative hydrographs, the technique of baseflow separation was used during periods when there were short rainfall bursts during the longer frontal events.

(b) The area of the drainage basins were very small (>400m^2) so the rainfall is likely to be evenly distributed over the entire area. A precipitation gauge was not set up at the middle site, however, the other two sites were a mile or less away and examination of the two rainfall records show consistency between the two. Therefore, it is assumed that the rainfall is the same for this site as was recorded for the other two.

(c) Examination of several short duration events demonstrated that the time period for runoff on each of the sites was constant for an effective amount of rainfall. The runoff time for a five minute duration rainfall event was approximately 35 to 40 minutes for all three sites.

(d) Several comparisons between the actual hydrograph using baseflow separation and the representative hydrograph show that the amount and duration of rainfall is directly proportional to both hydrographs; therefore, the principle of superposition can be assumed.

(e) The runoff response for the events in which the representative hydrographs were developed were representative of the normal runoff events due to the physical characteristics of the drainage area. Some minor modifications may have occurred to the road surface from vehicle traffic or road maintenance, but not enough to cause any change in the runoff response at any of the sites.

Incorporating the assumptions previously mentioned, a representative hydrograph was developed by examining the hydrograph and rainfall records of each of the sites and choosing a period containing a short duration rainfall event and runoff response. Representative hydrograph development for sites 1 and 2 were very difficult, primarily because of the intercepted flow originating upslope. For the development of representative hydrographs for these two sites, the discharge and rainfall records were compared to find isolated rainfall bursts with resulting spikes on the hydrograph. The spikes were assumed to be the direct result of rainfall onto the road surface and ditch. Baseflow separation was used to separate the runoff from the rainfall burst and the flow originating from the ephemeral streams resulting from previous rainfall.

The baseflow separation was completed by determining the approximate time required for the complete runoff of an effective amount of rainfall. Then, an equation was developed for a line from the point on the hydrograph where the rainfall first occurred to the point on the hydrograph that corresponds to forty minutes after the last effective rainfall (figure 7). From the line, the baseflow can be determined and subtracted from the hydrograph to get the

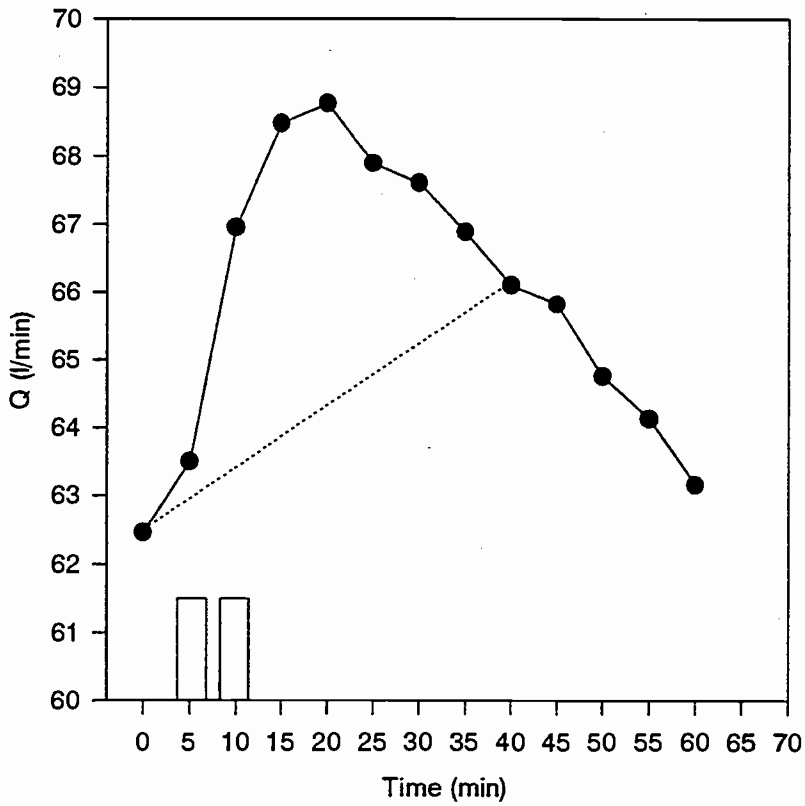


Figure 7. Representative hydrograph with baseflow separation for site 1. Bars are 0.51mm rainfall amounts and the dotted line is used for the baseflow separation of the runoff.

discharge resulting from the burst of rainfall. The hydrograph resulting from the baseflow separation is the representative hydrograph for the effective amount of rainfall. To check the validity of the representative hydrograph, a simple water balance is used to compare the representative hydrograph volume discharge to the total volume of precipitation less infiltration. The average five minute discharges are summed and multiplied by five to get a total volume discharged. Then, the rainfall minus the infiltration of 0.9 mm/hr ± 0.1 mm/hr is multiplied by the area of the study site to determine the volume of precipitation. The total volume of the representative hydrograph discharge is compared to the total volume of rainfall with a 0.9 mm/hr ± 0.1 mm/hr infiltration rate to see if they are within the 0.1 mm/hr volume.

Example: Site 3, Simple Water Balance

- Area = 280 m^2,
- Infiltration rate 0.9 mm/hr ± 0.1 mm/hr,
- Total discharge volume representative hydrograph = 100 liters,
- Total precipitation 1.02 mm,
- Time = 40 minutes,

Volume of Precipitation

$$1.02mm * 280m^2 * \frac{1m}{1000mm} * \frac{1000l}{1m^3} = 286l$$

Infiltration

$$0.9\frac{mm}{hr}*40\text{min}*\frac{1hr}{60\text{min}}*280m^2*\frac{1m}{1000mm}*\frac{1000l}{1m^3}=168l$$

Rainfall 286 liters - infiltration 168 liters = 118 liters, both occurring over a 40 minute period. The ± 0.1 mm/hr infiltration is approximately ± 19 liters for the 40 minutes of runoff. Therefore, the seventeen liter difference between the representative hydrograph and the precipitation minus infiltration is within the ± 0.1 mm/hr infiltration range.

RESULTS AND DISCUSSION

Precipitation and Representative Hydrographs

Representative hydrographs were developed for all three study sites to compare the runoff responses from rainfall and determine whether different site characteristics had significant effects on the runoff and sediment yield. The representative hydrographs in figure 8, illustrate that all three sites have similar runoff responses which enabled an analysis that combined all samples into one model as well as examined differences other than runoff for the three sites which may not have been initially addressed. The intent was to develop a relationship between total suspended sediment and or total sediment yield with discharge from the road surface for each site. From these relationships, it would be possible to calculate total sediment yield for roads with these characteristics from precipitation records.

It was assumed that all suspended sediment was a result of surface erosion from the road surface. The ditches and cutslopes on these sections were armored and stable. The catchment and sediment contributing areas used in the calculations were the surface areas of the road sections mapped and the associated ditches with exception of site 3. After the initial mapping at site 3, it was observed that an additional 22 meters up the road needed to be included into the total contributing source area. This

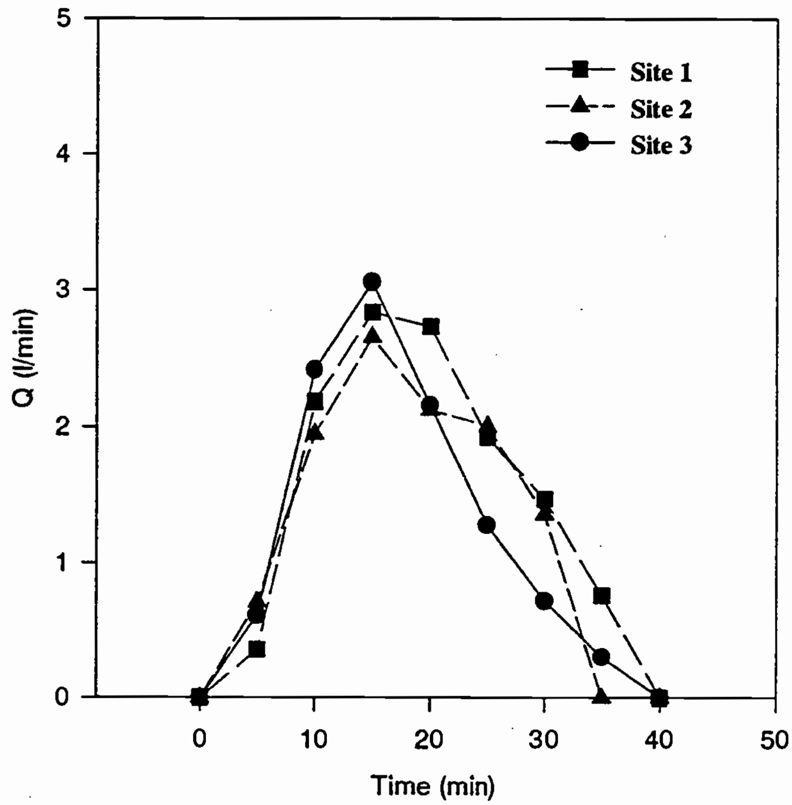


Figure 8. Representative hydrographs for the three study sites normalized to $280 m^2$ road surface area.

was a result of road maintenance in which a berm developed at the ditch edge that routed the water down the road instead of to the ditch and upper culvert.

A comparison of the precipitation records of the two gauges showed a tendency for the gauge at site 3 to have a slightly higher total daily precipitation amount than the gauge at site 1. The precipitation totals for the gauges at site 1 and 3 during the 89 total days which data was recorded at both sites were 893 mm and 975 mm, respectively. This amounts to approximately an 8.5 percent difference in precipitation amount for the two gauges less than three miles apart. The differences between the two may be partially due to the influence of trees near the gauge at site 1. The gauge at site 3 was located in a clearcut area allowing for unobstructed catch of all precipitation.

Due to a malfunction of the datalogger at site 3, rainfall and discharge were not recorded for the days of August 29, and September 11-22. The regression equation, Site 3 rain = 1.071(Site 1 rain) + 0.006, shown in figure 9, was used to estimate the rainfall for site 3 during those missing days. A similar method was used to estimate the discharge for site 3 except the discharge relationship required two equations. One equation was used when the discharge at site 1 was less than 50 liters per minute and a different one for discharges over 50 liters per minute.

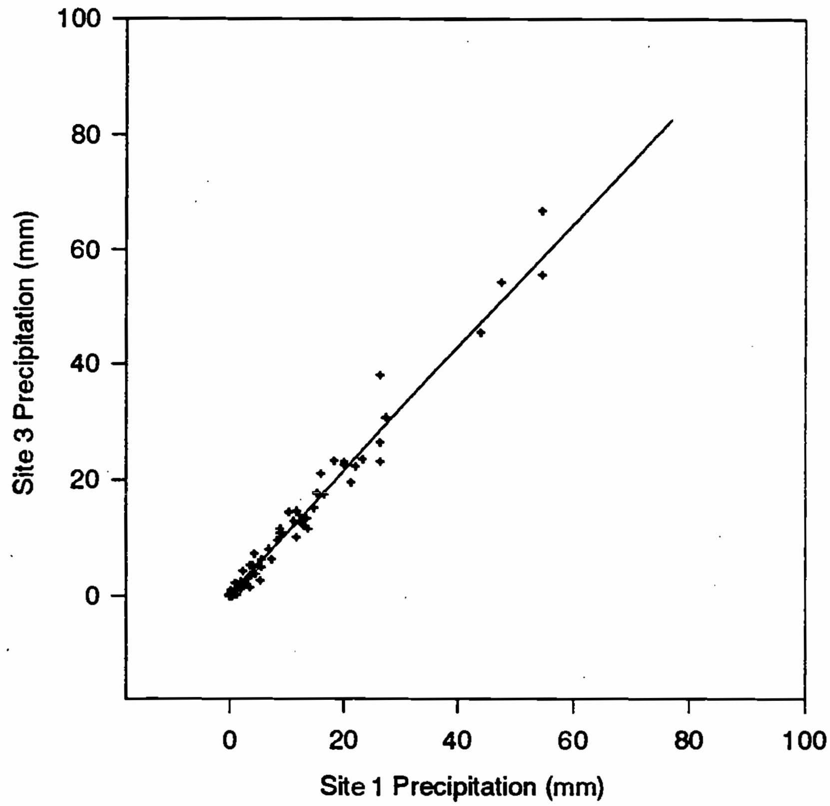


Figure 9. The regression equation of $y = 1.071x + 0.006$ with $R^2 = 0.98$, for the daily precipitation catches for the two rain gages located at sites 1 and 3.

Figures 10 and 11 show the daily rainfall amounts for the rain gage at site 1 and the days which sampling and grading of the road surface marked. The frequency of the largest storms sampled, 25.4 mm to 76.2 mm, from June to October are estimated to occur on 6 percent of the days during this period.

Hourly Suspended Sediment Concentration

This portion of the analysis was primarily conducted to determine the importance of the independent variables in explaining the variation in sediment production from forest roads. The samples collected at each site were normalized to an area of 280m^2 and analyzed on an hourly basis using both sediment concentration and sediment weight as the dependant variable. The use of sediment concentration as the dependant variable would permit the development of a sediment rating curve using discharge as the independent variable. A sediment rating curve would allow estimates of sediment production on five minute intervals corresponding to the discharge record.

Using the sediment rating curves, it was anticipated that a more precise estimate could be made for sediment yield from hourly data than developed from a storm basis. However, the coefficients derived from the regression analyses using these data were negative which is contrary to the established positive influence the variables would be expected to generate. Figure 12 illustrates the

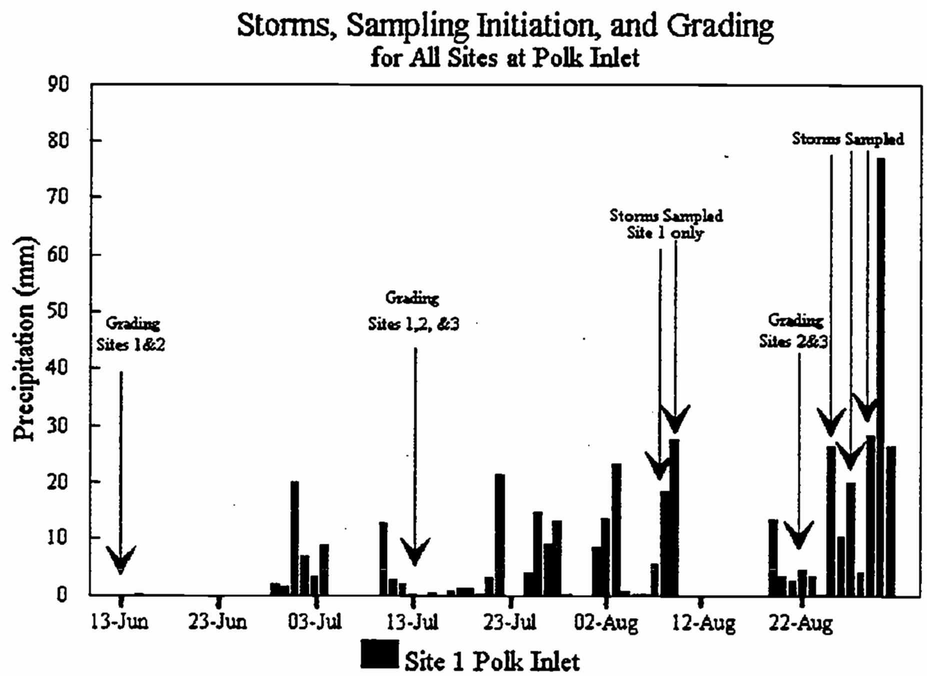


Figure 10. Daily rainfall for site 1, Polk Inlet from June 13 to August 31, 1991, marking the days that storms were sampled and the road sections graded.

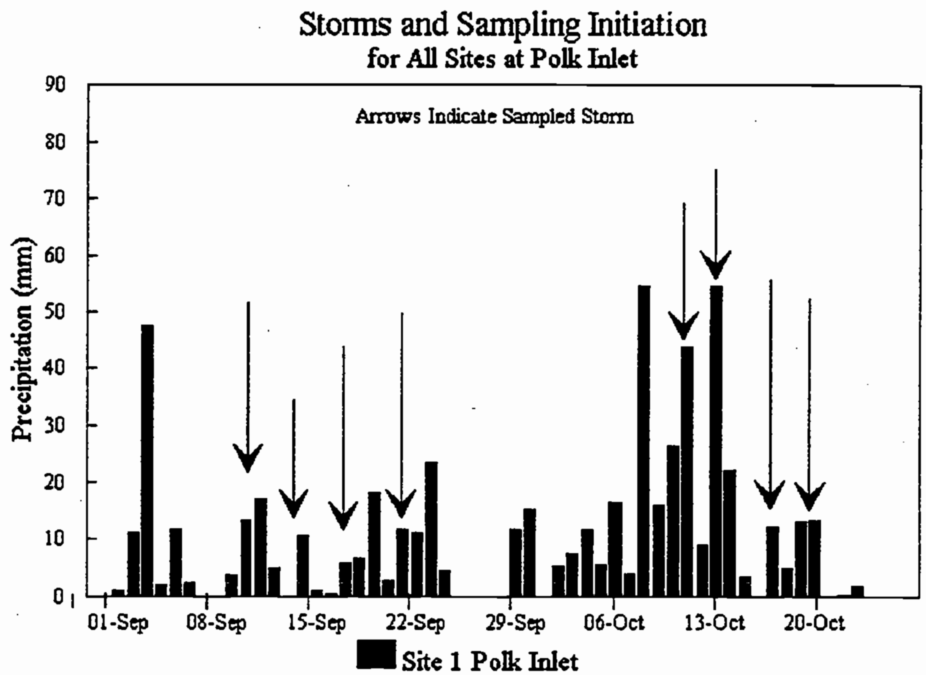


Figure 11. The daily rainfall for site 1, Polk Inlet from September 1 to October 25, 1991, marking the days that storms were sampled and no grading occurred at any of the sites.

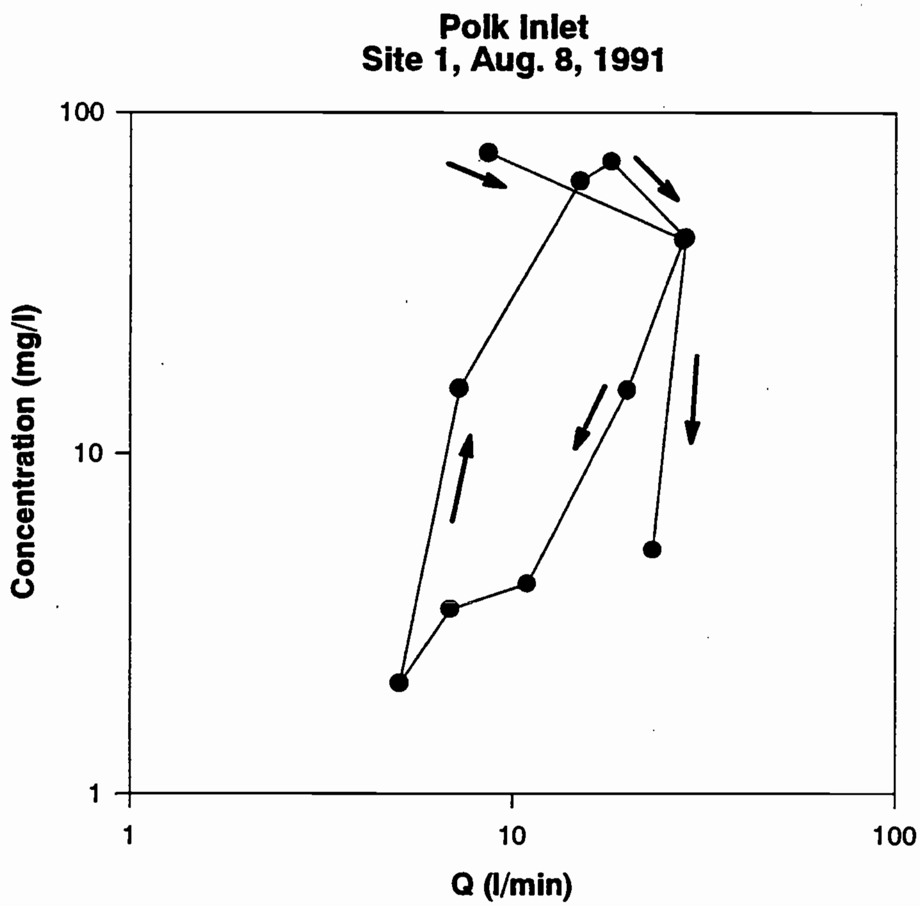


Figure 12. The effect of hysteresis illustrated by one set of hourly sample data. Two samples with rain, followed by two without, and finally seven samples with rain. The arrows depict the order the samples were taken.

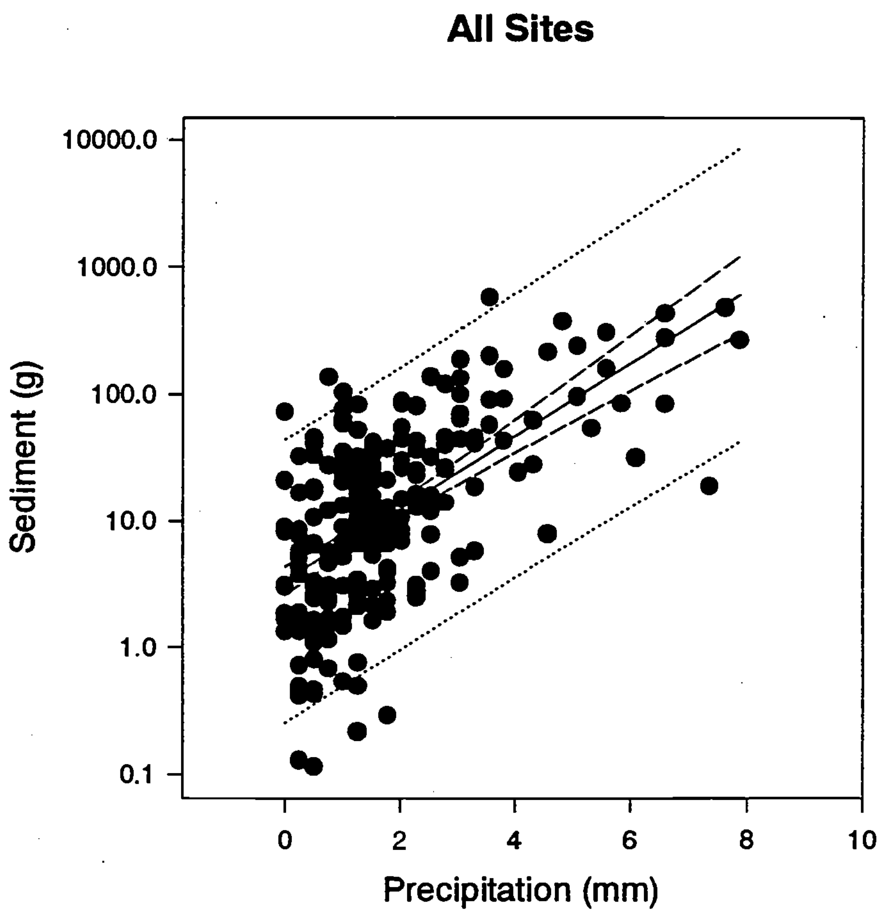
hysteresis effect encountered during development of a rating curve using sediment concentration and discharge for only one storm. After several manipulations and analyses of the representative hydrograph and sediment data for all three sites, it was apparent that an isolation of the road surface runoff from the water intercepted by the ditch originating above the cutslope and a reduction of the hysteresis effect would not be possible. Therefore, a dependent variable which combined both discharge and concentration was used to reduce the dilution effect the intercepted water produced. This variable is sediment weight.

Hourly Sediment Weight

The following analysis for the hourly data involved using sediment weight as the dependant variable. It was calculated by multiplying the average hourly discharge and the hourly composites concentration together for an estimated sediment yield for a one hour interval. All sediment in the sample concentrations were assumed to be from the road surfaces and ditches, not from cutslope erosion. This method proved to be the best technique for determining which variables may be most important in the production of sediment from road surfaces for the Polk Inlet area. Discharge was not used as a variable in any of the regression procedures because it was used to develop the dependant variable sediment weight.

A stepwise multiple regression procedure was used in the analysis with the dependant variable total hourly sediment produced and the independent variables total hourly rainfall, highest five minute intensity, total number of axles since the last runoff, axles per day, cumulative rainfall since the storm began, and indicator or qualitative variables representing the month the samples were collected. Also, several interactive variables were tried in the regressions and rejected because they did not increase the significance of the models. Tables 1-4, show the regression results of the models for each site and the combined model used in the multiple regression analysis. The model for site 2 had very poor correlation with any of the variables which may be a result of the site having a very small source area. The small source area at site 2 produced a smaller amount of sediment from a narrow range of concentrations compared to the other two sites that were two to three times as large. This made it difficult for to find a trend in the data since the range was limited; however, this was not thought to be a good enough reason to remove the data from the analysis for the combined model.

Rain was found to explain a large percentage of the variance in three of the four models. Rainfall was entered into the regression in three different forms. The first was hourly rainfall which is significant in all four models. Figure 13, shows a simple linear regression for



ANALYSIS OF VARIANCE

Source	DF	Sum of Sqs.	Mean Sq.	F Value	Prob>F
Model	1	43.643	43.643	136.07	.0001
Error	230	73.770	0.321		
C Total	231	117.413			

R^2 0.3717

Regression Equation

log Sediment (g) =0.521 + 0.287 Precipitation (mm)

Figure 13. The simple linear regression and analysis of variance for hourly sediment yield in grams vs. hourly precipitation in millimeters for all sites combined.

Table 1. The analysis of variance for the multiple regression model describing the sediment yield in grams per 280 m^2 of road for the combined hourly samples of all three sites.

ALL SITES

Dep. Var. : LNORMSED

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	5	60.9644	12.1929	48.816	0.0001
Error	226	56.4488	0.2498		
C Total	231	117.4132			

Root MSE	0.4998	R-square	0.5192
Dep Mean	1.0303	Adj R-sq	0.5086
C.V.	48.5095		

Parameter Estimates

Variable	DF	Parameter Estimate	SE	T for H0: Par.=0	Prob>|T|
INTERCEP	1	-2.3746	0.5023	-4.7270	0.0001
RAIN	1	0.1662	0.0304	5.4650	0.0001
AUG	1	0.3738	0.0810	4.6150	0.0001
LAXPDAY	1	1.4108	0.2640	5.3430	0.0001
TWOHR	1	0.0598	0.0142	4.2150	0.0001
OCT	1	0.3789	0.0999	3.7920	0.0002

Summary of Stepwise Procedure for Dependent Variable LNORMSED

Step	Var. Ent.	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F
1	RAIN	1	0.3717	0.3717	67.35	136.07	0.0001
2	LAXPDAY	2	0.0668	0.4385	37.96	27.23	0.0001
3	AUG	3	0.0269	0.4654	27.31	11.48	0.0008
4	TWOHR	4	0.0232	0.4886	18.38	10.32	0.0015
5	OCT	5	0.0306	0.5192	6.00	14.38	0.0002

Table 2. The analysis of variance for the multiple regression model describing sediment yield in grams per 280 m^2 of road for site 1.

Site 1

Dep. Var. : LNORMSED

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	5	32.4742	6.4948	44.725	0.0001
Error	86	12.4886	0.1452		
C Total	91	44.9628			

Root MSE	0.3811	R-square	0.7222
Dep Mean	1.1982	Adj R-sq	0.7061
C.V.	31.8051		

Parameter Estimates

Variable	DF	Parameter Estimate	SE	T for H0: Par.=0	Prob>|T|
INTERCEP	1	-1.2380	0.5527	-2.24	0.0277
RAIN	1	0.0952	0.0474	2.011	0.0475
TWOHR	1	0.1277	0.0272	4.697	0.0001
LAXPDAY	1	0.8177	0.2979	2.745	0.0074
AUG	1	0.2688	0.1009	2.663	0.0092
OCT	1	0.2476	0.1183	2.093	0.0393

Summary of Stepwise Procedure for Dependent Variable LNORMSED

Step	Var. Ent.	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F
1	TWOHR	1	0.6397	0.6397	23.57	159.78	0.0001
2	LAXPDAY	2	0.0404	0.6800	13.07	11.23	0.0012
3	RAIN	3	0.0148	0.6948	10.49	4.26	0.0420
4	AUG	4	0.0133	0.7081	8.38	3.96	0.0498
5	OCT	5	0.0142	0.7222	6.00	4.38	0.0393

Table 3. The analysis of variance for the multiple regression model describing sediment yield in grams per 280 m^2 of road for site 2.

Site 2

Dependent Variable: LNORMSED

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	1.3640	1.3640	4.916	0.0313
Error	49	13.5944	0.2774		
C Total	50	14.9584			

Root MSE	0.52672	R-square	0.0912
Dep Mean	1.03275	Adj R-sq	0.0726
C.V.	51.00224		

Parameter Estimates

Variable	DF	Parameter Estimate	SE	T for H0: Par.=0	Prob>|T|
INTERCEP	1	0.8322	0.1167	7.13	0.0001
RAIN	1	0.1083	0.0488	2.217	0.0313

Table 4. The analysis of variance for the multiple regression model describing sediment yield in grams per 280 m^2 of road for site 3.

Site 3

Dependent Variable: LNORMSED

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	5	32.4943	6.4989	27.41	0.0001
Error	83	19.6791	0.2371		
C Total	88	52.1734			

Root MSE	0.4869	R-square	0.6228
Dep Mean	0.8553	Adj R-sq	0.6001
C.V.	56.9318		

Parameter Estimates

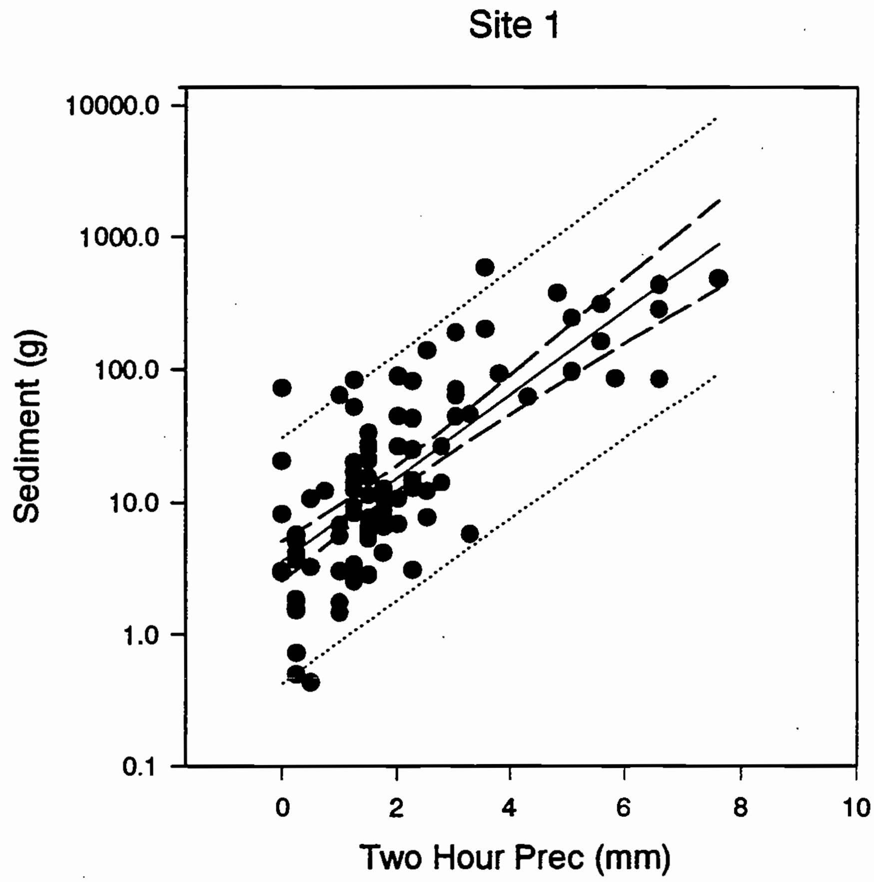
Variable	DF	Parameter Estimate	SE	T for H0: Par.=0	Prob>|T|
INTERCEP	1	-4.8103	0.9228	-5.212	0.0001
RAIN	1	0.1715	0.0484	3.542	0.0007
LAXPDAY	1	0.6136	0.1348	4.553	0.0001
TWOHR	1	2.5717	0.4767	5.395	0.0001
OCT	1	0.0820	0.0187	4.379	0.0001
AUG	1	0.6443	0.1703	3.783	0.0003

Summary of Stepwise Procedure for Dependent Variable LNORMSED

Step	Var. Ent.	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F
1	RAIN	1	0.3332	0.3332	61.74	43.37	0.0001
2	AUG	2	0.1388	0.4720	33.19	22.61	0.0001
3	LAXPDAY	3	0.0461	0.5181	25.04	8.14	0.0054
4	TWOHR	4	0.0397	0.5578	18.31	7.53	0.0074
5	OCT	5	0.065	0.6228	6.00	14.31	0.0003

hourly precipitation versus hourly sediment yield in grams for the combined model. The variable for hourly rainfall for site 1 does not appear to be very significant in the multiple regression analysis of variance shown in table 2. However, if hourly rainfall is used as the only independent variable for sediment yield, it is shown to explain more than 50 percent of the variance (figure 14). The next variable was two hour rainfall, which is the sum of the rainfall one hour prior to the sampling period and the rainfall during the sampling period. This variable was very significant in the model for site 1 explaining nearly 64 percent of the variance (figure 15). Either of the two rainfall variables do reasonably well in predicting the amount of sediment a 280m^2 section of road might produce. The last form of the rainfall variables is a cumulative rainfall variable, which summed the rainfall from the beginning of the storm to the sampling period. This last variable did not show up in any of the final stepwise regression models as significant.

The traffic patterns were very consistent throughout the study period. Two logging trucks each made three to four loaded trips a day on six of the seven days of the week. The only traffic variable which was found to be significant in the multiple regression models was the log transformed axles per day variable for the models for site 1, 3, and the combined sites. The transformed axles per day variable explained from 0 to 6.7 percent of the



ANALYSIS OF VARIANCE

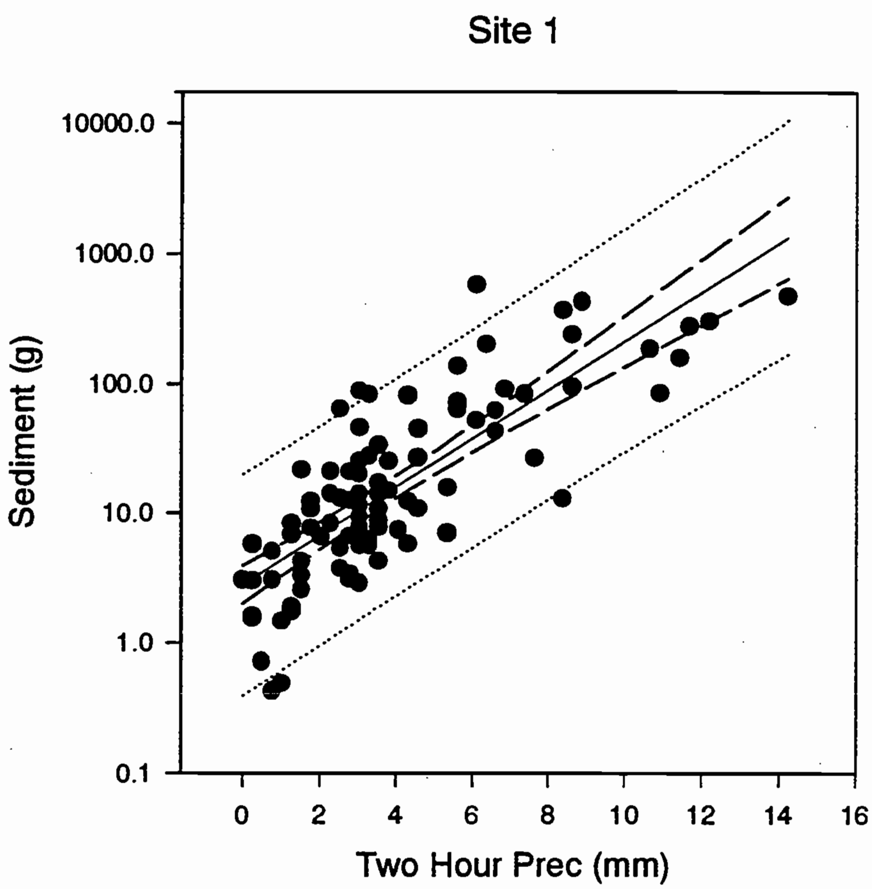
Source	DF	Sum of Sqs.	Mean Sq.	F Value	Prob>F
Model	1	25.436	25.436	117.24	.0001
Error	90	19.527	0.217		
C Total	91	44.963			

R^2 0.5657

Regression Equation

log Sediment (g) =0.556 + 0.313 Precipitation (mm)

Figure 14. The simple linear regression and analysis of variance for hourly sediment yield (grams) vs. hourly precipitation (mm) for site 1.



ANALYSIS OF VARIANCE

Source	DF	Sum of Sqs.	Mean Sq.	F Value	Prob>F
Model	1	28.762	28.762	159.78	.0001
Error	90	16.201	0.180		
C Total	91	44.963			

R^2 0.6397

Regression Equation

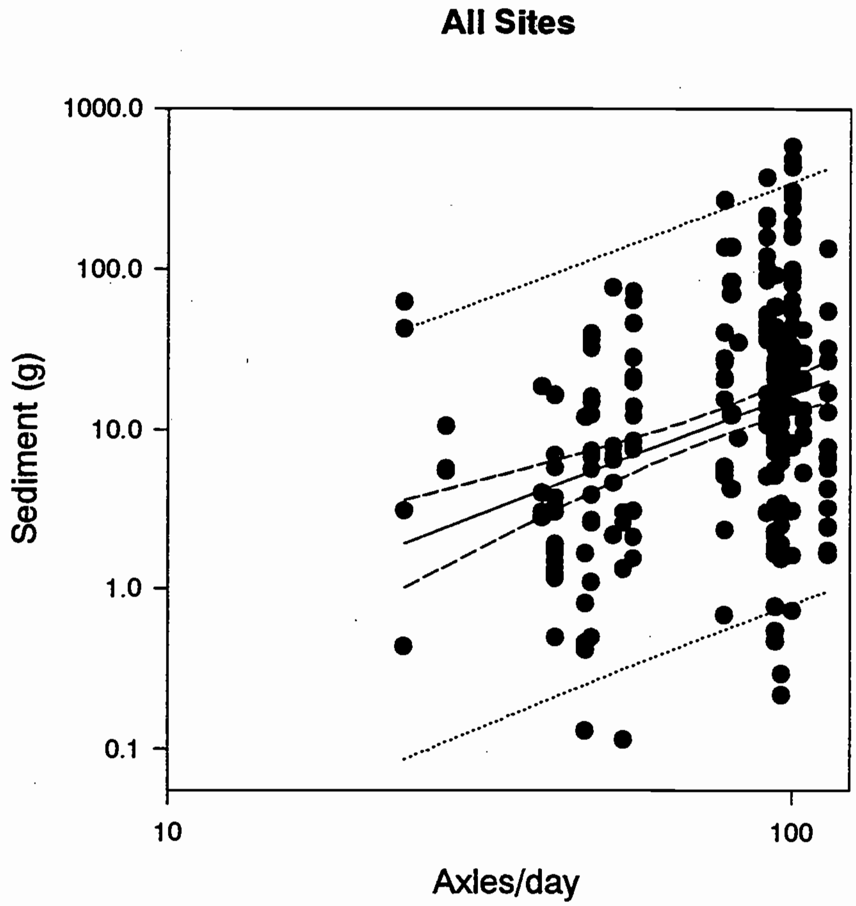
log Sediment (g) =0.443 + 0.188 Two Hour Prec. (mm)

Figure 15. The simple linear regression and analysis of variance for hourly sediment yield (grams) vs. two hour precipitation (mm) for site 1.

variance in the four multiple regression models. Simple linear regression was used to examine the axle per day variable's relationship with hourly sediment yield alone for the three models (figures 16, 17, and 18). These regressions show that without the other variables, traffic does have a minor influence on sediment yield.

A study site which experienced a wider range of traffic amounts over the study period may be able to develop a much better relationship between the two variables (Reid 1981, and Bilby et al. 1989). The variable for total accumulated axles was not found to be significant in the model as was in the study by Bilby et al. (1989), because at the Polk Inlet sites runoff was produced nearly every day and the total axle counts were so similar for almost all the storms. However, the axles per day counts were not as similar for each storm sampled because some samples were collected on or following the day in which no logging traffic was occurring.

The indicator variables August, September, and October were used to determine whether during one month there were site characteristics different than the other months that were not quantifiable. Beschta (1987) found in Oregon that as the storms progressed into the wet season and the seasonal peak discharge was reached a seasonal decline was observed in sediment concentrations for flows similar to those prior to the peak flow. This indicated the sediment was supply limited for the watersheds he studied. The



ANALYSIS OF VARIANCE

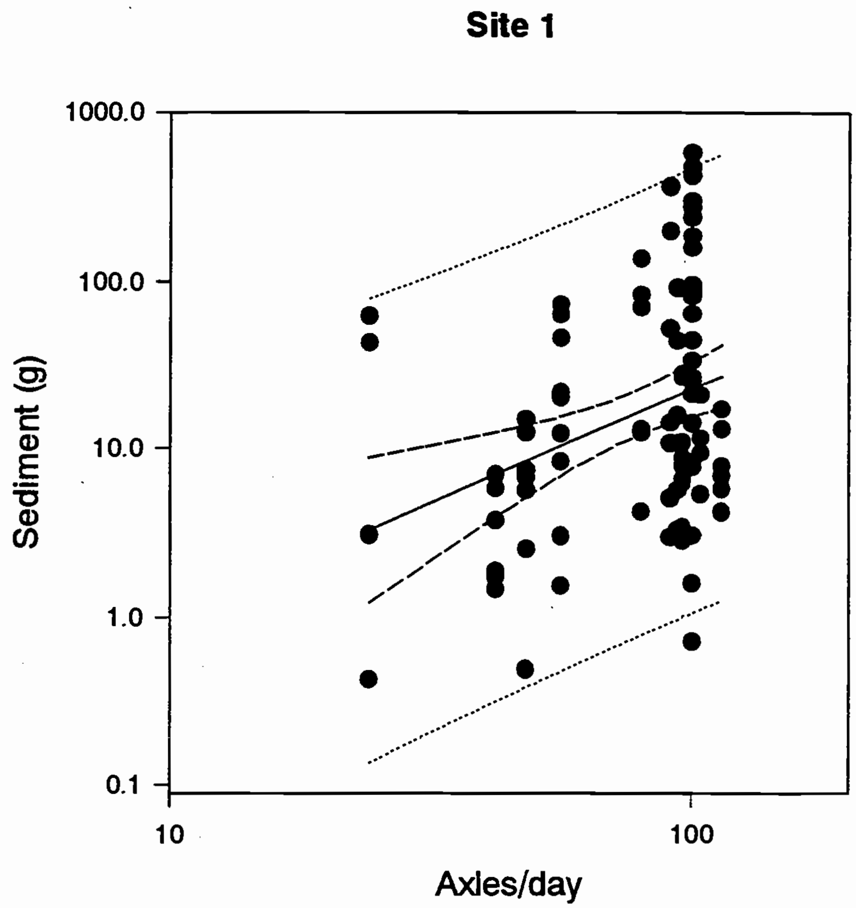
Source	DF	Sum of Sqs.	Mean Sq.	F Value	Prob>F
Model	1	14.504	14.504	32.42	.0001
Error	230	102.909	0.447		
C Total	231	117.413			

R^2 0.1235

Regression Equation

Sediment (g) =0.015 Axles/day$^{1.523}$

Figure 16. The simple linear regression and analysis of variance for hourly sediment yield (grams) vs. axles per day for all sites combined.



ANALYSIS OF VARIANCE

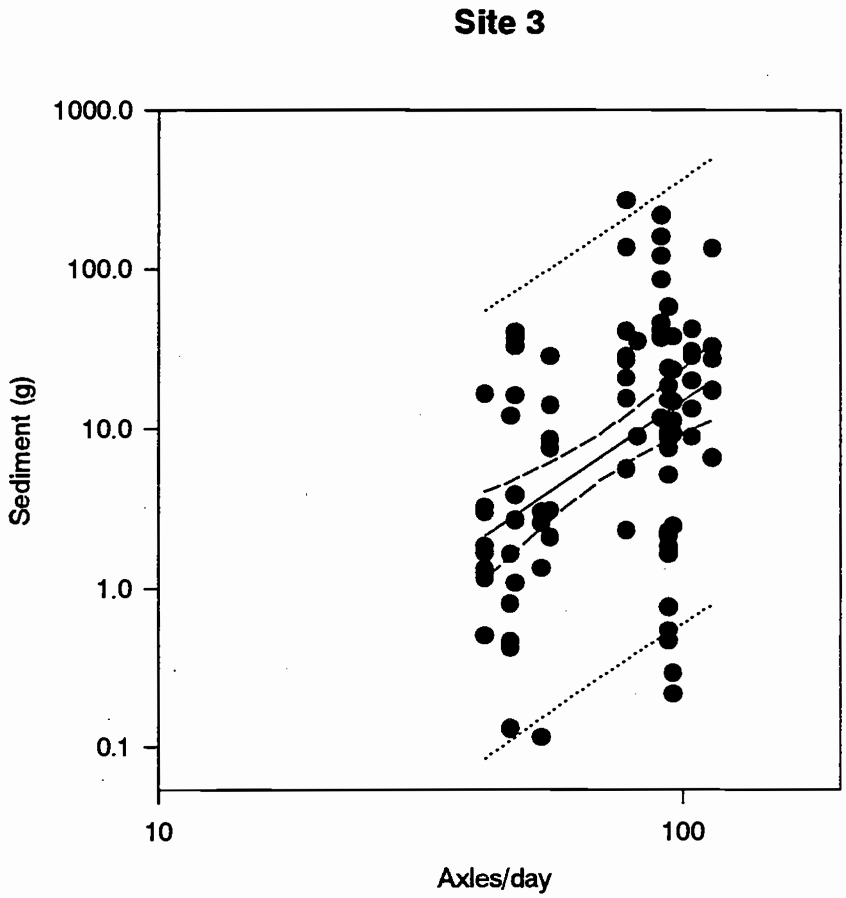
Source	DF	Sum of Sqs.	Mean Sq.	F Value	Prob>F
Model	1	4.958	4.958	11.15	.0012
Error	90	40.005	0.445		
C Total	91	44.963			

R^2 0.1103

Regression Equation

Sediment (g) =0.046 Axles/day$^{1.343}$

Figure 17. The simple linear regression and analysis of variance for hourly sediment yield (grams) vs. axles per day for site 1.



ANALYSIS OF VARIANCE

Source	DF	Sum of Sqs.	Mean Sq.	F Value	Prob>F
Model	1	9.894	9.894	20.36	.0001
Error	88	42.279	0.586		
C Total	89	52.173			

R^2 0.1896

Regression Equation

Figure 18. The simple linear regression and analysis of variance for hourly sediment yield (grams) vs. axles per day for site 3.

indicator variables used in the regression analysis for this study were used to evaluate whether the same condition may exist for the road surfaces at Polk Inlet.

The stepwise regression analysis results in tables 1, 2, and 4, of the dependant variable sediment weight show both the qualitative variables August and October were considered significant to a p-value of <0.05 for the regression models for sites 1 and 3, as well as the model for samples for all three sites. The regression for the model of all the samples shows that variables August and October both explain approximately 3 percent of the variance in the model. In the analysis of site 1, the two variables account for slightly more than 1 percent each. However, the analysis for site 3 shows that the variable August explains nearly 14 percent and October 6.5 percent of the variance in the model.

These results of the regression analyses do not appear to be due to seasonal effects of supply limitation because the coefficients for the October indicator variable are positive. This indicates during the month of October there may be an unaccounted variable having a positive effect on the amount of sediment yield from the road sections. One reason the October variable accounted for 3 to 6.5 percent of the variance in the model may be a result of the storms of greater intensity occurred later in the fall.

The other indicator variable August, also appears to be significant in describing the model relationship. One possible explanation is best illustrated at site 3, which shows the August variable to explain a considerable amount of variance which may be a result of grading on August 22 at sites 2 and 3. The three storms sampled in August at site 3 occurred on August 25, 26, and 27 less than a week after grading occurred (figure 10). Disturbance of the road surface from grading would likely increase the short-term supply of sediment and is a probable factor involved in sediment production. Site 1 did not receive grading prior to the storm runoff and resulted in the August indicator variable only explaining slightly more than 1 percent of the variance as compared to nearly 14 percent for site 3.

The model with the samples from all three sites combined resulted in a multiple regression equation with five independent variables. The equation is as follows:

$$\log(\text{sed (grams)}) = 0.166(\text{rain (mm)}) + \log(1.411)(\text{axles/day}) + 0.374(\text{Aug}) + 0.06(\text{twohr (mm)}) + 0.379(\text{Oct}),$$

with R^2=0.52. This indicates that the above equation only explains a little more than 50 percent of the variance in sediment production.

Storm Sediment Yield Multiple Regression Models

Southeast Alaska has very few precipitation gaging sites in which detailed and consistent precipitation records are reported. As a result, daily precipitation totals at sea level for scattered locations are the only data that can be found for most of the region. Precipitation in southeast Alaska is primarily a result of large frontal storms moving westward across the Gulf of Alaska and running into the coastal mountain range. The storms that are produced are several hours to several days in duration and can have numerous fronts associated with them. The analysis of storm sediment yield is designed to use daily rainfall records to estimate sediment yield for roads with the same site characteristics at Polk Inlet, Alaska. The dependant variable sediment per kilometer of road is the amount of sediment in kilograms per kilometer of forest road four meters wide or $4000m^2$.

Individual Sites

Stepwise multiple regression was used to analyze the data for each site independently of the others. The ten quantitative independent variables used in the analyses were a function of rainfall, traffic amounts, or interactive variables of those two. Also, three qualitative variables were used to represent the months the storms occurred to determine if timing was significant; however, none of these were found to be significant in any of the models. Also, none of the interactive variables were significant. The criteria for a variable entry into the model was the 0.15 significance level and the criteria for keeping the variable in the model was the 0.05 significance level. The results of these analyses were different for each site.

Stepwise multiple regression analysis for site 1 resulted in a model containing only the total rainfall variable (figure 19). The coefficient of determination or R^2 is 0.62 for the simple linear regression of the log of total sediment per kilometer to total rainfall. The coefficient for the explanatory variable is 0.079 with a standard error of 0.018. The stepwise multiple regression analysis for site 2 resulted in none of the variables meeting the criteria of 0.05 significance level. However, using simple linear regression, both axles per day and total rain had p-values of 0.0555 and 0.069, respectively. Figure 20, shows the simple linear relationship for total kilograms of sediment per kilometer and total storm precipitation for site 2.

Site 3 was the only site in which the stepwise multiple regression analysis resulted in more than one explanatory variable significant to the 0.05 level. For site 3, axles per day was first into the model with a partial R^2 of 0.54 and total rain next with a partial R^2 of 0.30 with both significant to the 0.05 level. When total rain was the only explanatory variable used for the site 3 data, the regression produced a model and variable coefficient both significant to 0.05 and a R^2 of 0.54 (figure 21). A comparison of all three sites and the

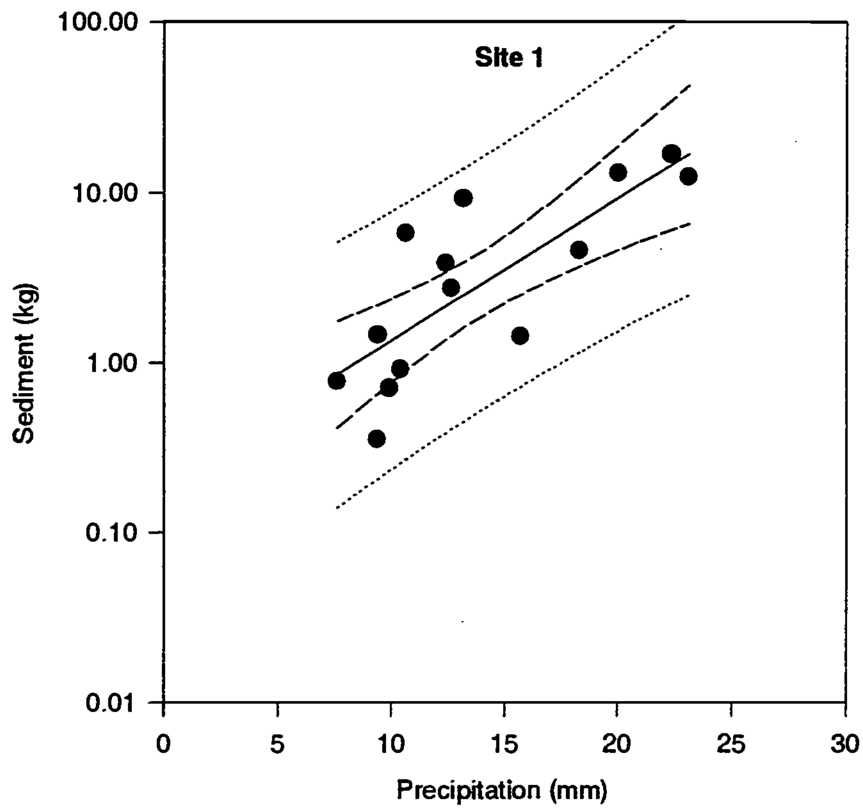


Figure 19. The simple linear regression for total sediment in kg/km of road vs. total storm precipitation in mm for site 1. See table 5 for regression model and statistics.

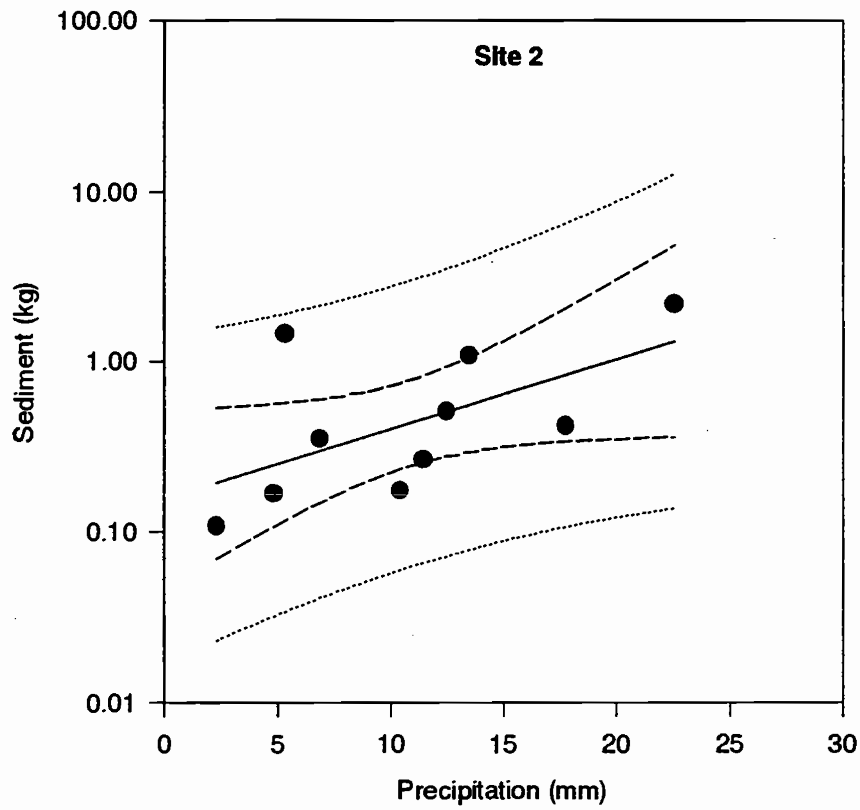


Figure 20. The simple linear regression of total sediment in kg/km of road vs. total storm precipitation in mm for site 2. See table 5 for regression model and statistics.

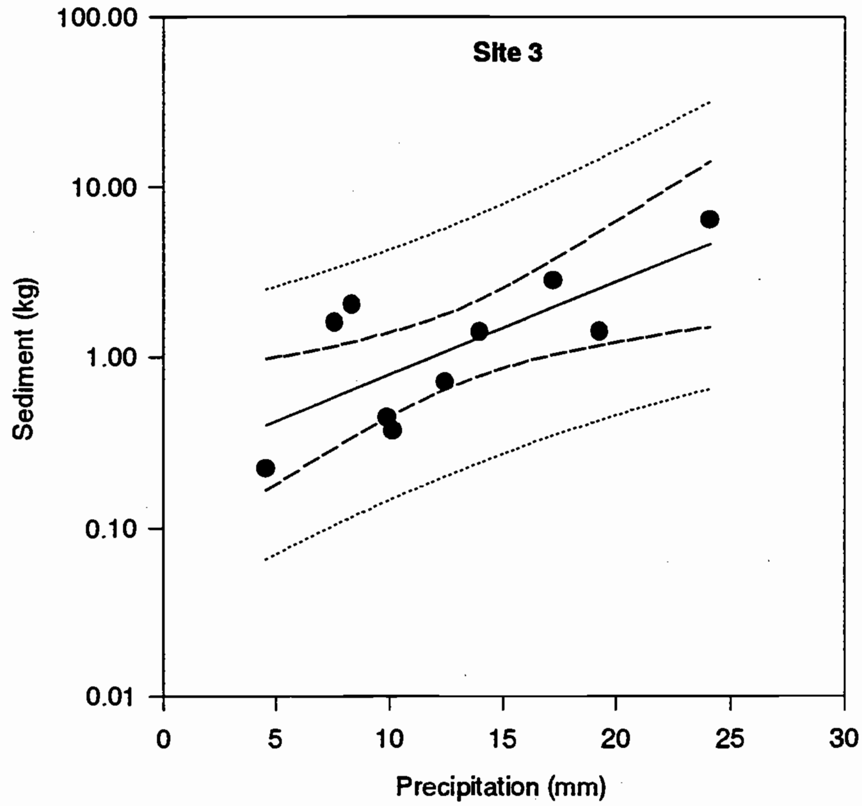


Figure 21. The simple linear regression for total sediment in kg/km of road vs. total storm precipitation in mm for site 3. See table 5 for regression model and statistics.

resulting regression model coefficients and statistics are given in table 5.

All Sites Combined

An analysis of the combined data from all three sites was completed using stepwise multiple linear regression with 10 variables. As in the analyses for the individual sites, the variables were both quantitative and qualitative. However, another qualitative variable was developed to test the gradient differences between site 1 and sites 2 and 3 of 10 percent and 7 percent, respectively. This variable was entered into the storm data as a 1 if the gradient was 10 percent or a 0 if the gradient was 7 percent. This qualitative variable was used to illustrate the possible influence that gradient may have on sediment yield for these sites. Packer (1967), found gradient to be one of the most important factors in rill development and erosion of road surfaces. Gradient was one of the most obvious differences between site 1 and the other two sites, but, length of the section or some other unknown site difference could be significant. Site 1 had a total length of 84 meters, while sites 2 and 3 had total lengths between 50 to 65 meters.

The results from the analysis were similar to the analyses for the individual sites (table 5). The analysis once again had total rainfall as the most important variable in the production of sediment from the road

Table 5. Comparison of the analyses variables and models that were significant to a 0.05 significance level for each individual site and the combined site data for storm sediment production in kilograms per kilometer of road.

SITE	MODEL TYPE	VAR.	COEFF.	SE	PART. R^2	MODEL R^2
1	Simple	Total rain mm	0.079	0.018		0.624
2	Simple*	Total rain mm	0.041	0.020		0.356
2	Simple*	Axles per day	0.009	0.004		0.385
3	Simple	Total rain mm	0.054	0.018		0.528
3	Simple	Axles per day	0.012	0.004		0.543
3	Mult.	Axles per day	0.010	0.003	0.543	0.543
3	Mult.	Total rain mm	0.042	0.011	0.303	0.846
All	Simple	Total rain mm	0.069	0.013		0.468
All	Mult.	Total rain mm	0.054	0.011	0.468	0.468
All	Mult.	% Slope	0.415	0.128	0.135	0.603
All	Mult.	Axles per day	0.006	0.002	0.061	0.664

* Denotes the model significant to 0.10 level significance.

- Bracketed statistics are multiple regression models and the model R^2 is for all variables combined in order of significance and entrance into the model.

surface. The main difference in the multiple regression model for all sites is the significance the qualitative variable gradient had on the entire model. The gradient variable was the second most influential variable for the combined storm sediment yield data. This suggests that gradient may be a significant factor in the amount of sediment produced from road surfaces. However, it must be noted that other differences between site 1 and the other two sites exist and the qualitative variable could reflect any one of these. The two variables previously mentioned, gradient and section length, are strong candidates. Further study accounting for these variables would be needed to determine which if any of the variables discussed is important in sediment production from road surfaces. The variable axles per day which explained approximately 6 percent of the variability was considered significant for inclusion into the multiple regression model for the combined data. The total model is:

$$\log(\text{Totsed kg/km}) = -1.196 + 0.054(\text{Total rain (mm)}) + 0.415(\text{Gradient } \{0{=}7\% \ \& \ 1{=}10\%\}) + 0.006(\text{Axle/day}),$$

with an R^2 of 0.664. the coefficients for the two variables found in some of the other models for the individual sites were similar.

Figure 22, shows a simple linear regression for total rainfall versus sediment production for all three sites.

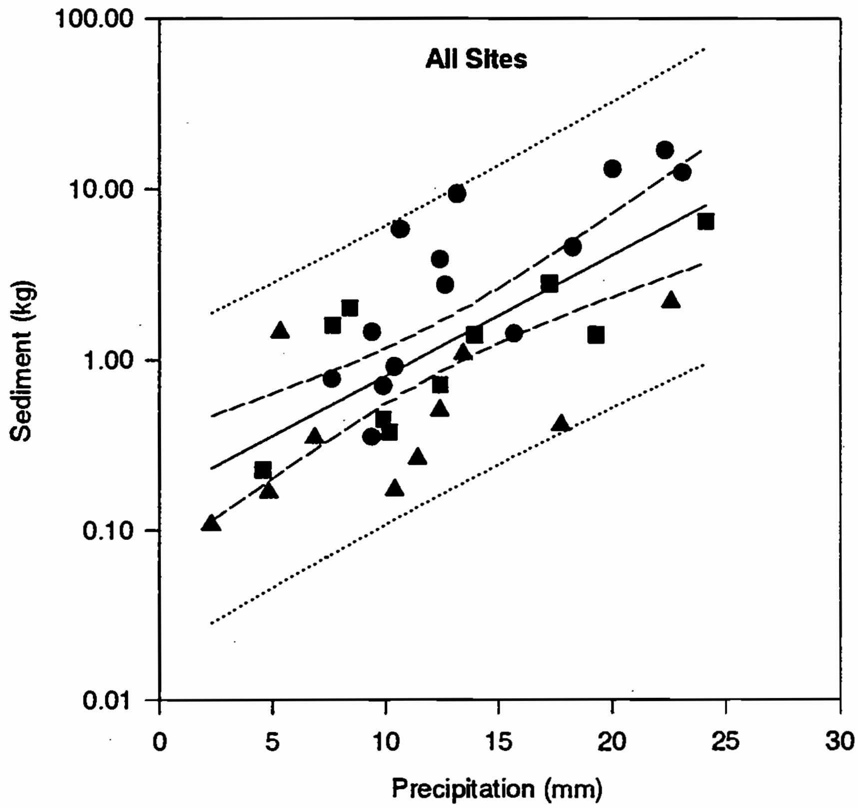


Figure 22. The simple linear regression for total sediment yield in kg/km of road vs. total storm precipitation in mm for all three sites combined. The symbols ● = site 1, ▲ = site 2, and ■ = site 3.

The model estimates total sediment production per kilometer solely from total precipitation amounts during the period in which samples were collected. The results of the regression are shown in table 5.

Total Annual Sediment Production Estimates

Assumptions

Several assumptions were made when developing the models in figures 19-22, and calculating the total sediment production estimates for the Polk Inlet area. The first was all the precipitation that fell at the Hollis gage was in the form of rain, which is not probable. However, a majority of it was rainfall, with approximately 25 mm of the total annual precipitation coming as snow. Also which should be noted, is five of the six stations in southeast Alaska with data on departures from the mean show the annual precipitation for 1991 to be 10 to 60 percent above normal, therefore, the sediment yield estimate is likely to be higher than normal. Another assumption was that the Hollis gage accurately represents the amount of precipitation that fell in the Polk Inlet area. A comparison of the rainfall data for the two precipitation gages at the study site and the Hollis gage were similar in total rainfall during the study period. The Hollis gage reported approximately a 10 percent lower precipitation catch than the average of the two study precipitation gages.

Another major assumption was that the road sections were subjected to the constant amount of axles from two logging trucks making 3-4 trips a day plus other light vehicle traffic during the entire year. The assumption that the logging traffic occurred throughout the entire year clearly represents a much higher level of road use than has occurred in the past. The logging traffic only lasted until the harvest crews were done on the units these roads accessed and shut down during periods when snow made it dangerous for hauling.

The last and a critical assumption is that the regression relationship still holds beyond the largest sampled storm. This problem could be addressed with more sampling of larger storms to extend the regression line to these points; but, at the present time the information is not available. Therefore, the limitations of the equations and estimates need to be taken into account when they are applied to any sediment budgeting estimates.

Individual Sites

The regression equations, from figures 19-21, for the three individual study sites were used to estimate the total sediment produced from each of the study sections on an annual basis using the precipitation data from Hollis. The total precipitation for the gage at Hollis in 1991 was

3002 mm. The estimates from the regression equations for the three study sites for the total sediment produced from a kilometer of road during 1991 were 37.6 tonnes, 0.4 tonnes, and 2.0 tonnes, for sites 1, 2, and 3, respectively. These estimates assume the same amount of erosion measured from the study sections would occur over an area of a road 4 meters wide and 1 kilometer long. These estimates do not imply all the sediment eroded is transported to the inside ditch. The sediment may be transported off the other side of the road depending on the micro-topography of the road surface.

All Sites Combined

A model which combined the data from all three sites was use to estimate the total annual sediment produced from a 1 kilometer length of road (figure 22). The equation for the model is:

$$\underset{\text{(kg per kilometer)}}{\log(\text{Tot. annual sediment})} = (-0.775) + (0.07)\underset{\text{(mm)}}{\text{Total rain}}$$

$R^2 = 0.47$, with a standard error for the intercept and total rain coefficient, 0.180 and 0.013, respectively. Using this model, the calculated total annual sediment yield from a kilometer of road in the Polk Inlet area experiencing traffic levels of 2 loaded logging trucks making three to four trips a day plus other light vehicles is 8.14 tonnes.

A comparison of the results from this study and those of other studies conducted at several other locations is given in table 6. The estimate of 8.1 t/km/yr is comparable to the estimates from Bilby et al. (1989) and Reid and Dunne (1984) for areas in the Pacific Northwest. The estimates by Fahey and Coker (1989) from New Zealand are similarly close when calculated for a road section of 4 meters wide. The result were 8 to 16 t/km/yr for the ungraded and graded road sections in their study. Similarly Kochenderfer and Helvey (1987) have graveled road sections with erosion estimates near 8 t/km when they are calculated on a kilometer of road length measurement. However, an important factor that needs to be taken into account is the amount of precipitation each study location receives on an annual basis. Some locations have as much as three times the amount of precipitation as others which would enhance the possibility for erosion. Also, the precipitation intensities are during storms are probably different for the various study locations listed.

This study had several limitations that were not previously addressed and will be addressed now. The first is the limited amount of variables which were chosen to be recorded or measured. The regression analyses have shown that only 40 to 60 percent of the variability could be explained by these variables. Also, the study is very site specific and in essence is a case study for that particular road at Polk Inlet. Another limitation is that all

Table 6. A comparison of erosion estimates for forest logging roads in several locations in the United States and in New Zealand.

Location	Notes	Erosion Estimate	Total Precip.	Time Period	Author
South.* Wash.	2ndary	10 t/km	1580 mm	23 weeks	Bilby et al. (1989)
South. Wash.	Mainline	26 t/km	630 mm	23 weeks	" "
New * Zealand	Graded Section	12-16 t/km	1307 mm average	Annual	Fahey & Coker (1989)
New * Zealand	Ungraded Section	8 t/km	1307 mm average	Annual	" "
Appal.* Mnts.	Graveled	9.2 t/km	1320 mm to 1524 mm	Annual	Kochend-erfer & Helvey (1987)
Appal.* Mnts.	Not graveled	42.4 t/km	1320 mm to 1524 mm	Annual	" "
Olympic† Pen. WA	Heavy traffic	500 t/km	3900 mm average	Annual	Reid and Dunne (1984)
Olympic† Pen. WA	Light traffic	3.8 t/km	3900 mm average	Annual	" "
North Carolina	Bare soil lt.traf.	80 t/km	Approx 1400 mm	8 months	Swift (1984)
North Carolina	Graveled lt.traf.	14 t/km	Approx 1400 mm	8 months	" "
Polk Inlt. Ak	Graveled	8.1 t/km	3002 mm	Annual	This study

* Denotes the estimates include cutslope contribution.

† Denotes cutslope contribution included, with estimated cutslope contribution at 2.0 t/km/yr.

sediment yield amounts were based on 15 minute grab samples composite into 1 hour samples. The problem is that this probably does not accurately sample the runoff to best represent the sediment movement from the road surfaces. Samples of smaller time intervals as runoff begins and longer intervals later into the storm would give a better representation of the sediment discharge from these road surfaces. The last limitation that will be discussed is the problem of using daily rainfall records with the storm regression equation. Many of the storms may extend longer than a day or may begin late and carry over to the next day which would reduce the magnitude when entered into the regression equation. All of these limitations should be considered when using the equation or the estimate for the Polk Inlet study.

The issue of sediment production from forest road surfaces is important primarily because of the possible detrimental impact the sediment may have once delivered to larger streams. Two of the three study sites had their drainage enter a small ephemeral stream. A windshield survey of 55 kilometers of road in the area found over 35 percent of the ditches drain into streams of various sizes. Culvert spacing in the area is quite frequent, between 50 to 100 meters, due to the many small streams draining the steep slopes.

A study by Bilby et al. (1989) addresses the issue of transport of road sediment from the ditch to the stream by synthesizing several studies completed in central Washington. The delivery of sediment to larger streams is primarily dependant on the efficiency of the smaller perennial and ephemeral streams to transport the sediment from the road ditch to the larger streams. Duncan et al. (1987) found that more than 65 percent of the sediment introduced into the stream at the road was stored in the ephemeral stream channel and is a function of the channel characteristics. Paustian (1987) found that it may take years for larger particles from roads to move 300 meters or more down stream in many of these small headwater streams.

The findings in the previous studies must be considered when examining the results of the study sites at Polk Inlet. The delivery of the sediment from the road to a stream was not determined by the Polk Inlet study and no estimates can be made as to the quantity that may have been transported to the larger streams. Studies are in progress attempting to answer these questions for several areas of the Tongass National Forest.

CONCLUSION

The purpose of this study was to attempt to understand the physical processes and development of some relationships for sediment production from forest roads for the Polk Inlet area in southeast Alaska. The analyses of the hourly samples provided some evidence as to which variables are the most influential in estimating sediment production from road surfaces. Rainfall prior to and during the sampling period proved to be most significant of the variables which were collected. Axles per day were also significant contributors in explaining the variability in the sediment production relationship, but, at a significantly less amount. The other variables in the final regression equation for the hourly samples were qualitative variables which helped explain a small percentage of the variation in the relationships. Qualitative variables, present difficulties in interpreting what specific influence they represent, but can be used to explore possible ideas for new variables in future studies.

The analysis of sediment production from total storm data resulted in a relationship between precipitation and sediment yield for a kilometer of road surface. The analysis found two other variables to be significant as well as total precipitation. The traffic variable once again appeared as a significant variable for explaining sediment yield. The last variable was a qualitative variable developed just for the storm data analysis. The variable tested the differences in gradients between site 1 with 10% and sites 2 and 3 with 7%. There appears to be a relationship between sediment production and gradient (or some other unknown difference between site 1 and the other two sites); however, a study focusing on gradient differences is necessary to examine that possibility.

Also, something important to note is the road sections were approximately five years old when the study was conducted and it is expected this road and others would produce much more sediment following the initial construction in the first year or two (Megahan and Kidd 1972). This is a key reminder that if one influential variable such as road age is changed it can have a major effect on the amount of sediment ultimately produced from road surfaces.

The estimate of total sediment yield for the study sites at Polk Inlet with the site characteristics mentioned in the study is approximately 8.1 tonnes/km/yr. This amount is only attributable to the Polk Inlet road in which the study was conducted, but, expansion of the study to other sites in southeast Alaska is currently in progress. These other studies will try to determine how much of the sediment produced from the road surfaces reaches the streams which is a vital consideration which is not addressed by this study project.

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APPENDIX

Polk Inlet, Site 1 data for houly samples during storm precipitation.

DATE	TIME	Q (l/min)	RAIN (mm)	CONC (mg/l)	TSED (g/hr)
Aug-8	06:03	8.63	2.03	76.12	39.42
Aug-8	07:03	28.22	2.29	42.46	71.89
Aug-8	08:03	20.07	0.00	15.43	18.57
Aug-8	09:03	10.95	0.00	4.11	2.70
Aug-8	10:03	6.85	0.25	3.45	1.42
Aug-8	11:03	5.05	0.25	2.10	0.64
Aug-8	12:03	7.25	1.52	15.62	6.79
Aug-8	13:03	15.06	1.02	62.87	56.80
Aug-8	14:03	18.17	2.03	71.68	78.14
Aug-8	15:03	28.58	1.27	42.94	73.63
Aug-8	16:03	23.44	0.00	5.19	7.30
Aug-9	02:03	16.10	2.29	12.90	12.46
Aug-9	03:03	50.02	6.60	126.82	380.60
Aug-9	04:03	99.52	5.59	45.22	270.06
Aug-9	05:03	120.01	2.03	3.25	23.40
Aug-9	06:03	166.07	1.52	2.97	29.55
Aug-9	07:03	174.39	1.52	2.13	22.34
Aug-9	08:03	178.09	2.29	2.08	22.27
Aug-9	09:03	181.42	1.27	1.14	12.40
Aug-25	15:28	8.52	2.79	24.39	12.47
Aug-25	16:28	35.85	3.56	82.76	177.99
Aug-25	17:28	60.44	4.83	90.45	327.99
Aug-25	18:28	35.76	1.27	21.56	46.26
Aug-25	19:28	21.95	0.51	7.19	9.47
Aug-25	20:28	17.26	0.25	4.33	4.48
Aug-26	13:08	11.10	2.54	10.32	6.87
Aug-26	14:08	17.98	1.02	5.57	6.01
Aug-26	15:08	19.72	0.25	3.15	3.72
Aug-26	16:08	21.39	1.27	11.71	15.03
Aug-26	17:08	37.47	2.29	5.09	11.45
Aug-26	18:08	35.88	0.25	2.35	5.05
Aug-29	14:23	33.33	6.60	37.03	74.05
Aug-29	15:23	66.93	1.78	2.82	11.34
Aug-29	16:23	57.66	1.78	1.08	3.74
Aug-29	17:23	85.49	2.54	2.12	10.86
Aug-29	18:23	114.63	3.05	9.07	62.38
Aug-29	19:23	158.13	2.54	12.79	121.35
Sept-11	18:33	39.06	1.52	7.85	18.39
Sept-11	19:33	38.95	1.27	3.54	8.28
Sept-11	20:33	44.32	1.52	1.77	4.71
Sept-11	21:33	60.51	1.52	2.78	10.11
Sept-14	15:33	5.38	3.30	15.75	5.08
Sept-14	16:33	16.98	2.03	6.00	6.11
Sept-14	17:33	16.91	0.25	3.25	3.30
Sept-14	18:33	12.40	1.02	1.75	1.30
Sept-14	19:33	15.33	0.25	1.75	1.61
Sept-14	20:33	17.10	1.02	1.50	1.54
Sept-14	21:33	18.73	0.25	1.48	1.67
Sept-19	00:48	10.80	3.05	60.54	39.24
Sept-19	01:48	41.26	3.81	32.78	81.14

Polk Inlet, Site 1 data for houly samples during storm precipitation.

Sept-19	02:48	38.79	1.52	5.95	13.84
Sept-19	03:48	48.82	2.03	3.24	9.50
Sept-19	04:48	74.50	1.02	1.11	4.97
Sept-19	05:48	89.00	0.51	0.54	2.89
Sept-19	07:48	86.64	0.51	0.56	2.89
Sept-21	17:48	6.11	1.78	15.75	5.77
Sept-21	18:48	8.06	1.78	16.00	7.74
Sept-21	19:48	14.45	2.79	27.16	23.55
Sept-21	20:48	27.67	1.78	5.75	9.55
Sept-21	21:48	33.50	1.52	2.75	5.53
Sept-21	22:48	33.67	1.52	1.25	2.53
Sept-21	23:48	40.06	1.27	1.25	3.00
Sept-22	00:48	51.20	1.78	2.25	6.91
Sept-22	01:48	70.96	1.52	5.75	24.48
Oct-11	09:43	273.26	5.08	13.01	213.31
Oct-11	10:43	423.47	6.60	9.72	247.02
Oct-11	11:43	697.13	7.62	10.14	424.17
Oct-11	12:43	821.10	3.05	3.36	165.60
Oct-13	09:13	396.03	3.56	21.64	514.30
Oct-13	10:13	473.48	5.08	2.97	84.46
Oct-13	11:13	613.67	5.84	2.03	74.57
Oct-13	12:13	761.91	5.59	3.09	141.39
Oct-17	16:03	8.73	0.25	0.83	0.44
Oct-17	17:03	10.05	1.27	3.75	2.26
Oct-17	18:03	13.23	1.52	7.43	5.90
Oct-17	19:03	25.35	2.29	8.62	13.11
Oct-17	20:03	31.59	1.78	3.44	6.52
Oct-17	21:03	32.63	1.52	2.55	4.98
Oct-17	22:03	37.78	1.27	4.85	10.99
Oct-19	04:03	22.43	0.51	0.28	0.38
Oct-19	05:03	26.88	2.29	1.69	2.73
Oct-19	06:03	61.78	4.32	14.86	55.08
Oct-19	07:03	59.73	2.29	10.57	37.89
Oct-20	10:03	25.38	0.25	0.90	1.36
Oct-20	11:03	26.12	1.02	1.71	2.69
Oct-20	12:03	30.90	1.27	3.94	7.31
Oct-20	13:03	30.50	0.76	5.92	10.83
Oct-20	14:03	35.26	1.52	8.93	18.90
Oct-20	15:03	43.18	1.27	6.86	17.77
Oct-20	16:03	49.53	3.30	13.68	40.65
Oct-20	17:03	84.37	3.05	11.14	56.41
Oct-20	18:03	84.49	0.00	12.68	64.26

Polk Inlet, Site 2 data for hourly samples during storm precipitation.

Date	Time	Q (l/min)	Rain (mm)	Conc (mg/l)	Sed (g/hr)
Aug-25	17:44	43.94	3.56	11.93	31.46
Aug-25	18:44	43.90	1.02	13.70	36.09
Aug-25	19:44	48.59	0.51	5.47	15.93
Aug-25	20:44	46.60	0.25	2.09	5.85
Aug-26	13:24	34.87	2.03	9.11	19.06
Aug-26	14:24	33.15	0.76	0.43	0.86
Aug-26	15:24	32.38	0.51	0.43	0.84
Aug-26	16:24	35.52	1.78	0.52	1.11
Aug-26	17:24	39.42	1.52	0.24	0.57
Aug-27	14:59	35.24	0.76	0.11	0.23
Aug-27	15:59	35.66	1.02	0.84	1.79
Aug-27	16:59	37.01	1.27	3.31	7.35
Aug-27	17:59	38.01	1.52	0.89	2.03
Aug-29	14:39	35.50	7.11	7.82	16.65
Aug-29	15:39	33.00	1.27	0.69	1.37
Sept-19	00:19	17.12	2.79	8.72	8.96
Sept-19	01:19	23.48	4.06	6.00	8.45
Sept-19	02:19	21.38	1.52	1.95	2.50
Sept-19	03:19	21.89	1.52	5.50	7.23
Sept-19	04:19	24.15	1.27	6.50	9.42
Sept-19	05:19	29.07	1.02	11.71	20.42
Sept-19	06:19	33.14	0.51	5.85	11.64
Sept-19	07:19	35.12	0.25	5.37	11.31
Sept-19	08:19	36.45	0.51	2.93	6.40
Sept-21	18:09	18.68	1.78	6.59	7.39
Sept-21	19:09	22.34	2.03	2.05	2.74
Sept-21	20:09	24.38	2.54	3.00	4.39
Sept-22	00:09	30.35	1.27	3.15	5.73
Sept-22	01:09	34.34	1.78	1.36	2.81
Sept-22	02:09	36.75	1.52	3.37	7.43
Sept-22	03:09	38.36	1.27	0.45	1.05
Sept-22	04:09	39.00	0.76	0.23	0.53
Oct-11	10:04	81.56	6.10	2.26	11.08
Oct-11	11:04	167.33	7.37	0.66	6.58
Oct-11	12:04	307.15	5.33	1.03	18.90
Oct-11	13:04	273.98	3.81	0.91	14.94
Oct-11	14:04	225.28	3.05	2.56	34.66
Oct-14	09:29	42.16	2.29	0.41	1.05
Oct-14	10:29	45.35	2.54	0.51	1.38
Oct-14	11:29	54.20	3.30	2.00	6.50
Oct-15	11:04	34.74	1.27	1.75	3.65
Oct-15	12:04	33.78	0.76	0.98	1.98
Oct-15	13:04	33.06	0.25	0.97	1.92
Oct-20	10:29	26.12	0.76	1.03	1.61
Oct-20	11:29	26.41	1.27	1.43	2.26
Oct-20	12:29	26.11	0.51	1.43	2.24
Oct-20	13:29	26.33	1.27	0.47	0.75
Oct-20	14:29	27.52	1.78	1.45	2.39
Oct-20	15:29	27.49	1.02	16.19	26.71
Oct-20	16:29	32.47	4.57	1.40	2.72

Polk Inlet, Site 3 data for hourly samples during storm precipitation.

Date	Time	Q (l/min)	Rain (mm)	Conc (mg/l)	Sed (g/hr)
Aug-25	10:32	21.08	2.03	67.20	85.01
Aug-25	11:32	24.88	2.79	30.28	45.21
Aug-25	12:32	35.04	2.79	56.77	119.36
Aug-25	13:32	39.02	1.78	15.89	37.21
Aug-25	14:32	35.79	1.52	5.39	11.57
Aug-25	15:32	43.47	3.30	15.58	40.63
Aug-25	16:32	56.99	3.81	46.06	157.51
Aug-25	17:32	80.38	4.57	44.36	213.95
Aug-25	18:32	73.68	1.52	8.21	36.30
Aug-26	13:32	36.16	3.05	61.65	133.75
Aug-26	14:32	30.70	0.51	9.31	17.14
Aug-26	15:32	29.18	0.51	3.75	6.57
Aug-26	16:32	37.97	2.54	14.13	32.18
Aug-26	17:32	39.98	1.02	11.23	26.94
Aug-27	15:12	16.84	0.76	27.44	27.73
Aug-27	16:12	17.86	1.02	19.03	20.40
Aug-27	17:12	23.40	2.54	10.99	15.43
Aug-27	18:12	25.24	0.51	26.54	40.20
Aug-27	19:12	22.45	0.25	4.12	5.55
Aug-27	20:12	24.08	1.78	1.60	2.31
Aug-27	21:12	32.01	1.52	13.66	26.23
Aug-27	22:12	76.05	7.87	58.21	265.60
Aug-27	23:12	87.23	0.76	25.91	135.60
Sep-11	16:18	12.08	1.52	57.62	41.77
Sep-11	17:18	15.09	0.76	30.80	27.89
Sep-11	18:18	18.19	2.03	27.56	30.08
Sep-11	19:18	19.36	1.27	16.85	19.57
Sep-11	20:18	21.19	1.02	10.44	13.28
Sep-11	21:18	28.36	1.78	5.19	8.83
Sep-14	14:28	2.47	1.27	3.33	0.49
Sep-14	15:28	2.46	3.05	21.80	3.22
Sep-14	16:28	7.89	2.29	34.61	16.38
Sep-14	17:28	8.84	0.25	3.15	1.67
Sep-14	18:28	6.25	0.76	3.08	1.15
Sep-14	19:28	7.52	0.51	6.59	2.97
Sep-14	20:28	8.43	0.76	3.26	1.65
Sep-14	21:28	9.38	0.51	2.20	1.24
Sep-15	22:28	9.26	0.25	2.39	1.33
Sep-17	11:48	1.18	0.25	6.38	0.45
Sep-17	12:48	1.69	2.54	117.89	11.95
Sep-17	13:48	1.47	0.51	18.54	1.63
Sep-17	14:48	1.40	0.25	5.26	0.44
Sep-17	15:48	1.10	0.25	6.25	0.41
Sep-17	16:48	1.44	0.51	9.26	0.80
Sep-17	18:48	0.73	0.25	2.95	0.13
Sep-18	16:28	1.22	0.76	31.06	2.26
Sep-18	17:28	1.26	0.00	24.19	1.83
Sep-18	19:28	1.43	1.52	24.55	2.11
Sep-18	20:28	1.48	0.00	18.41	1.64
Sep-18	21:28	1.41	0.51	5.45	0.46
Sep-18	22:28	1.59	1.02	5.62	0.53

Polk Inlet, Site 3 data for hourly samples during storm precipitation.

Sep-18	23:28	1.62	1.27	7.78	0.76
Sep-19	00:28	2.86	3.05	29.66	5.09
Sep-19	01:28	18.07	3.56	52.53	56.94
Sep-19	02:28	18.48	2.03	13.41	14.87
Sep-19	03:28	20.74	1.52	7.78	9.68
Sep-19	04:28	33.81	1.02	4.40	8.93
Sep-19	05:28	43.19	1.02	9.01	23.35
Sep-19	06:28	45.11	0.51	6.74	18.24
Sep-19	07:28	43.85	0.25	2.86	7.52
Sep-19	08:28	42.45	0.25	3.33	8.48
Sep-21	17:23	2.70	1.27	1.32	0.21
Sep-21	18:23	3.63	1.78	1.32	0.29
Sep-21	19:23	5.24	2.29	7.78	2.45
Sep-21	20:23	11.63	2.29	32.97	23.00
Sep-21	21:23	15.71	1.78	39.56	37.30
Sep-21	23:23	18.75	1.52	9.89	11.13
Sep-22	00:23	22.36	1.52	6.88	9.23
Sep-22	01:23	31.82	1.52	7.66	14.63
Oct-17	16:02	3.18	0.51	5.62	1.07
Oct-17	17:02	5.83	1.27	7.64	2.67
Oct-17	18:02	7.88	1.78	8.14	3.85
Oct-17	19:02	14.54	2.54	18.28	15.95
Oct-17	20:02	17.23	2.79	38.44	39.75
Oct-17	21:02	19.27	2.29	31.40	36.30
Oct-17	22:02	21.42	1.27	25.25	32.45
Oct-20	12:32	5.86	0.25	21.23	7.47
Oct-20	13:32	7.84	1.27	4.42	2.08
Oct-20	14:32	11.83	1.52	19.55	13.88
Oct-20	15:32	11.51	2.03	12.21	8.43
Oct-20	16:32	27.70	4.32	16.82	27.95
Oct-20	17:32	27.76	0.76	1.84	3.06