Results of Road Erosion Studies on the Tongass National Forest

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RESULTS OF ROAD EROSION STUDIES ON THE TONGASS NATIONAL FOREST

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FOREWORD

This report presents the results of road erosion studies conducted in SE Alaska. Studies began in the summer of 1991 and expanded in 1992 and 1993 with cooperation between several offices within the Alaska Region of the USFS, the Juneau Forestry Sciences Laboratory, and the Greens Creek Mine. The studies continued through a FY 1995-1997 cooperative agreement between the Alaska Region and the PNW (Pacific Northwest Research Station) offices of the USFS. The R10 Directors of EAM (Engineering and Aviation Management) and WFEW (Wildlife, Fisheries, Ecology, and Watershed) initiated the continued funding and the resulting cooperative agreement. This information will provide specialists with methods of predicting road produced sediment that are based on measurements of sediment and erosion produced from roads in southeast Alaska.

JUSTIFICATION

Recent work by the Regional Watershed Analysis Team and emphasis on Ecosystem Management have elevated the importance of the effects of roads on watershed function. Sediment produced from the road prism is commonly perceived a major contributor to degradation of streams. There existed very limited measured data to validate this perception for southeast Alaska. Erosion from road prism surfaces and transport of sediment through ditches and culverts needs to be quantified in order to support or repudiate the perception that roads are the major source of sediment. The measured quantities will provide substantiated data for future evaluations of impacts from management activities involving roads.

INTRODUCTION

National environmental concerns, the dictates by forest management legislation, requirements for ecologically sound forest management, and EPA mandates increasingly conflict with the economics of timber harvest and forest road construction. This is a critical problem for all land management organizations which find themselves managing forest resources within strict environmental and budget constraints. One of the principal environmental issues involves identification of the quantity and timing of sediment generation and delivery to channel systems from forest roads and other disturbance sites associated with timber harvest activities.

There exists a need to quantify the environmental effects of road-related management decisions on the Tongass National Forest but little road erosion information has been available for the conditions on the forest. On the undisturbed forest floor in southeast Alaska, little inorganic particle transport (surface erosion) occurs due to the dense, protective organic mat that accumulates as the result of litter fall and large woody debris accumulations from wind throw, death, and slow decay of old-growth trees. Under such conditions bare or sparsely vegetated areas subject to significant surface erosion are rare and primarily limited to local areas of a) uprooting disturbance due to wind throw, b) gully side wall unraveling, and c) denudation caused by occasional landslides and lateral stream cutting during periods of storms. Once bare mineral soils are exposed at such disturbed sites, normal surface erosion processes prevail, resulting in the mass-transfer of individual soil particles by mechanical shifting (freeze-and-thaw; wetting and drying; expansion and contraction); raindrop splash; and by overland flow of water (sheet wash; rilling). The ease with which soils are dislodged and transported is related to characteristics such as particle size, shape, extent of weathering, and degree of compaction. Collectively, these characteristics are determined by type and origin of parent materials.

Forest harvest operations, particularly road construction, accelerate these surface erosion processes through: a) disruption or removal of the stabilizing vegetation cover locally, increasing the areas of bare soil exposed; b) disturbance of the surface soil layers making them more susceptible to surface erosion processes; and c) creation of new surfaces such as cut-banks, fill slopes, and roads where surface erosion processes dominate. The soil particles, once mobilized, are commonly discharged to ditches and transported to the local valley floor and into stream channels where they become incorporated into the sediment load of the stream system. How much sediment is incorporated into the stream system and its final destination is determined by the erosion rate at the point of entry, the transport capacity of the stream and intervening ditches, and the timing of hydrologic events capable of mobilizing sediment movement. If the stream transport capacity is adequate to pass added sediment, for example high flows during major storm periods, the material generally has little long-term impact on water quality or habitat conditions and is usually carried rapidly through the channel system. At low flows or in structurally complex channels or channels with insufficient power, however, the stream may be unable to transport some or all of this increased sediment load producing significant increases in turbidity and in movement and distribution of materials within viable habitat reaches.

Responsible stewardship requires a working knowledge of sediment quantities, transport rates, and routing from roaded areas to the channel system in order to effectively predict and limit impacts of road construction operations on erosion and sedimentation in the forest ecosystem. Integral to this is an understanding of the influence of rainfall intensity, duration, and frequency on sediment source, transport, and delivery to main and secondary channel systems. Such information has been lacking for southeast Alaska. In the past, we did not know: a) what the rates of erosion are from the various types of road surfacing materials; b) how these rates vary for different gradients and levels of precipitation; or c) transport and deposition characteristics of sediment delivered to road ditches and channels. Results of this study provide some of the answers to these areas where information is lacking.

Minimum requirements to acquire this information included: development of a standardized process for data collection and use; and establishment of viable field guidelines for measuring, modeling, and predicting erosion and sediment transport from National Forest roads.

OBJECTIVES

This study was designed to answer basic questions about surface erosion from roads in southeast Alaska, and to provide the land manager with a methodology for predicting the origin and movement of surface-derived sediment from the road right-of-way to the ditch.

The overall objectives of the study were to:

1) identify and quantify sediment generation and delivery to ditches from roads [How does road construction, soil properties, gradient, rainfall, and traffic influence erosion rate and sediment discharge to channels]; and to

2) define characteristics of transport and deposition of road-generated sediments in ditch and outlet channels. [Biological effects of sediment once it gets into the stream channel system is the responsibility of Watershed and Fisheries and should be assessed concurrently.]

The data was collected to compare sediment yield from roads with different surfacing materials and under varying traffic levels, gradient, and rainfall conditions. Results provide quantitative surface erosion and sediment routing information usable by management at both the planning and project levels. This erosion information is also designed to fill a knowledge gap concerning surface erosion in North Pacific coastal rain forests where similar conditions exist.

This information will assist in assuring funds are effectively spent on construction, operation, and maintenance of roads, with the ultimate goal of reducing the large sums spent annually on erosion control in order to stay within acceptable sediment production and transport guidelines. Greater effectiveness of efforts and reduced costs of monitoring are also expected because an inherent part of this project requires the development and testing of field-effective techniques for measuring and assessing sediment generation and transport.

METHODOLOGY

Refer to Appendix A for a literature review of previous road erosion studies and the methods used. Appendix A also describes the methods used for these studies conducted in southeast Alaska. The methods section also describes the site selection criteria used in selection of road study sites and a complete description of the equipment used.

TONGASS NF STUDY SITES AND ANALYSIS TECHNIQUES

Road erosion studies were conducted at four locations on the three USFS Tongass National Forest Administrative Areas (figure 1). The first of the four study sites was instrumented by the Juneau FSL during the summer of 1991 with sample collection beginning in August of that year

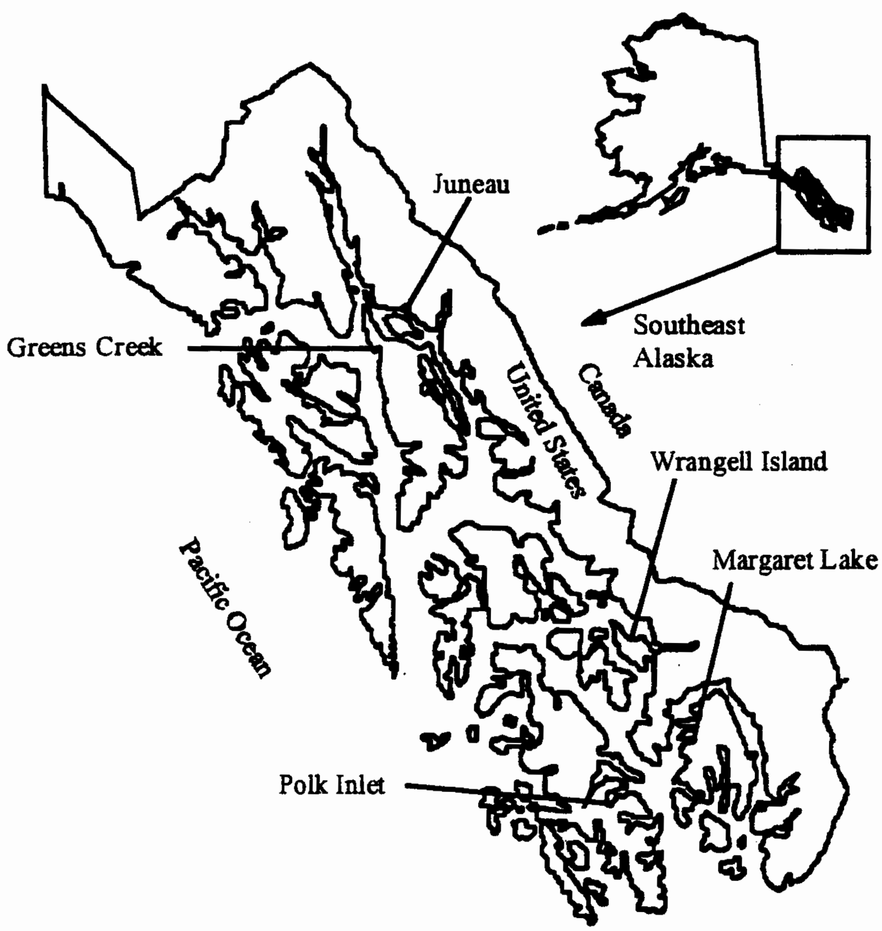

Figure 1. Map of southeast Alaska showing the four locations where data on erosion from forest roads were collected on the Tongass National Forest.

at Polk Inlet on Prince of Wales Island. The Ketchikan Area and the Craig Ranger District were cooperators that facilitated the study. This site was the pilot site used to develop the data collection techniques and instrumentation that were used in later studies. Three subsequent study areas were instrumented at the Greens Creek Mine on Admiralty Island, Earl West Road on Wrangell Island, and Margaret Lake on Revillagigedo Island. Support from R10, PNW, Juneau FSL, Stikine Area, Wrangell District, Chatham Area, Admiralty National Monument, Greens Creek Mining Company, Ketchikan Area, and Ketchikan District allowed these studies to continue up to the present time.

The data for each of the study sites were analyzed separately for the conditions found at the individual site in the traditional "case study" approach. However, the study design required that many of the conditions and variables be common to all the sites in which data were collected. This allowed the results from all sites to be analyzed together in order to determine the important factors related to sediment generated from roads. Pooling the data in this manner strengthens the statistical relationships that determine which variables are most important across all sites. The resulting statistical equations will apply to all sites based on a few important physical parameters (e.g.: road gradient, traffic volume, rainfall, road surface drainage area, surface rock type and quality). If road erosion can be strongly related to physical parameters, the results can be applied to other sites with known physical parameters thus avoiding conducting a case study for every road in southeast Alaska. The results are presented as a case study for each of the sites and then a combined analysis of the four sites is presented that can be applied to all sites with known physical parameters.

A detailed discussion of site conditions at the four study site locations and methods used in analyzing the data are presented in Appendix B (DESCRIPTION OF STUDY SITE CONDITIONS AND METHODS OF ANALYSES).

RESULTS

In the following analyses for each of the locations, many variables were used to develop the best models for predicting sediment production from forest road surfaces. Several of these variables were quantitative precipitation values relating to intensity, duration, and total rainfall. Other variables consisted of physical characteristics of the specific sampling sites such as road gradient, surfacing material, and surface conditions. A qualitative variable representing resurfacing of a study site road surface was used in the analyses for some locations and consisted of either a zero (no resurfacing) or one (resurfacing).

The individual and combined site regression equations for prediction of road erosion include several variables which must be used with the units as defined in the following list. The list defines the variables along with the required units.

- **sed = sediment yield from $4000m^2$ of road (i.e. one kilometer of road with drainage to the ditch that is 4m wide equals $4000m^2$)**
- **rain = rainfall per storm in mm**
- **gradient = road grade of the contributing road segment expressed as a percentage**
- **axles/day = number of vehicle axles passing per day**
- **resurfacing = set equal to (1) if the road has been recently resurfaced or is in equivalent condition; set equal to (0) if the road has not been resurfaced and surface aggregate size is much finer than a resurfaced road.**

The following erosion prediction regression equations presented for each site and for the combined sites should be used for conditions within the range of data shown on the graphs. The graphs may be used directly for prediction of road erosion for the locations where the studies were conducted. When using the equations, the contributing road surface area draining to the ditch must be calculated since the erosion prediction is for an area of $4000m^2$. A typical insloped single lane road with a crown will have about one half of the surface area draining into the adjacent ditch. Therefore a straight 4 meter wide insloped road will have about 2 meters of width draining toward the ditch. In this case, two meters of contributing road surface width which is 2000m long equals $4000m^2$ of contributing area. The quantity of sediment produced per kilometer of road can thus be calculated since management decisions are often made by estimating the quantity of sediment from roads on a weight per kilometer of road basis. In order to better predict sediment yield on a per kilometer basis, an average width including curve widening and turnouts draining to the ditch will need to be used so that the length of road required to contribute $4000m^2$ of surface area can be more accurately calculated.

Polk Inlet

A stepwise multiple regression analysis was used to determine that rainfall, gradient, and traffic, are important variables in predicting sediment yield in kilograms from a $4000m^2$ section of road at Polk Inlet. The multiple regression equation is:

$$\log(\text{sed}) = -2.921 + 1.231 \log(\text{rain}) + 0.149 (\text{gradient}) + 0.0062 (\text{axles/day}).$$

A graph of the data used for the multiple regression is shown in figure 2 along with the simple linear regression curves for each of the sampling sites.

Greens Creek Mine Road

A stepwise multiple regression analysis for all the storms at all three sampling sites found that rainfall, gradient of road segment, and resurfacing were significant in predicting the sediment yield for the sites normalized for a $4000m^2$ area. The regression model for erosion at Greens Creek as a result of these data is:

$$\log(\text{sed}) = 1.233 + 1.058 \log(\text{rain}) + 0.152 \text{ (gradient)} - 0.803 \text{ (resurfacing)}.$$

A plot of simple linear relationships for rainfall and sediment is shown in figure 3 with two linear regressions representing before and after resurfacing at "Site 3 Lower".

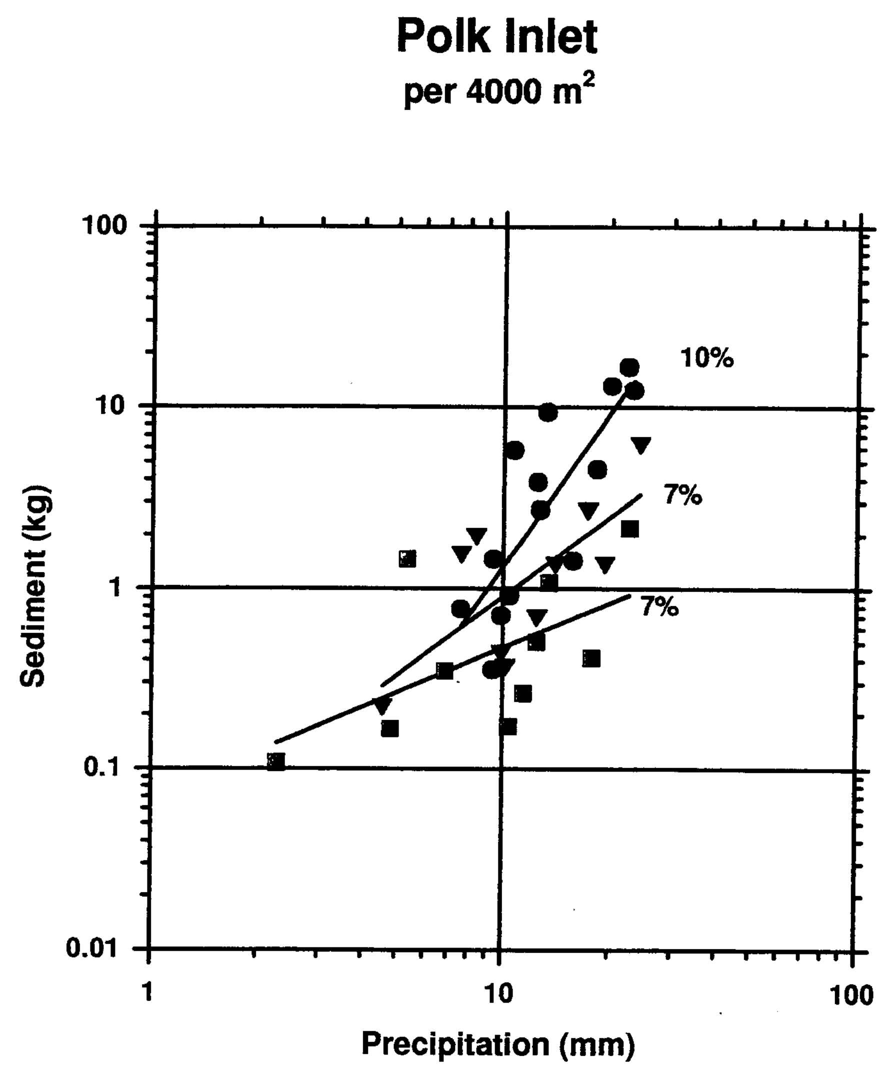

Figure 2. Plot of road sediment versus precipitation data for all 3 sites at Polk Inlet with simple linear regression lines for each of the sampling sites. The circles represent storm data for site 1, triangles for site 2, and squares for site 3. Percentages next to regression lines are road gradients.

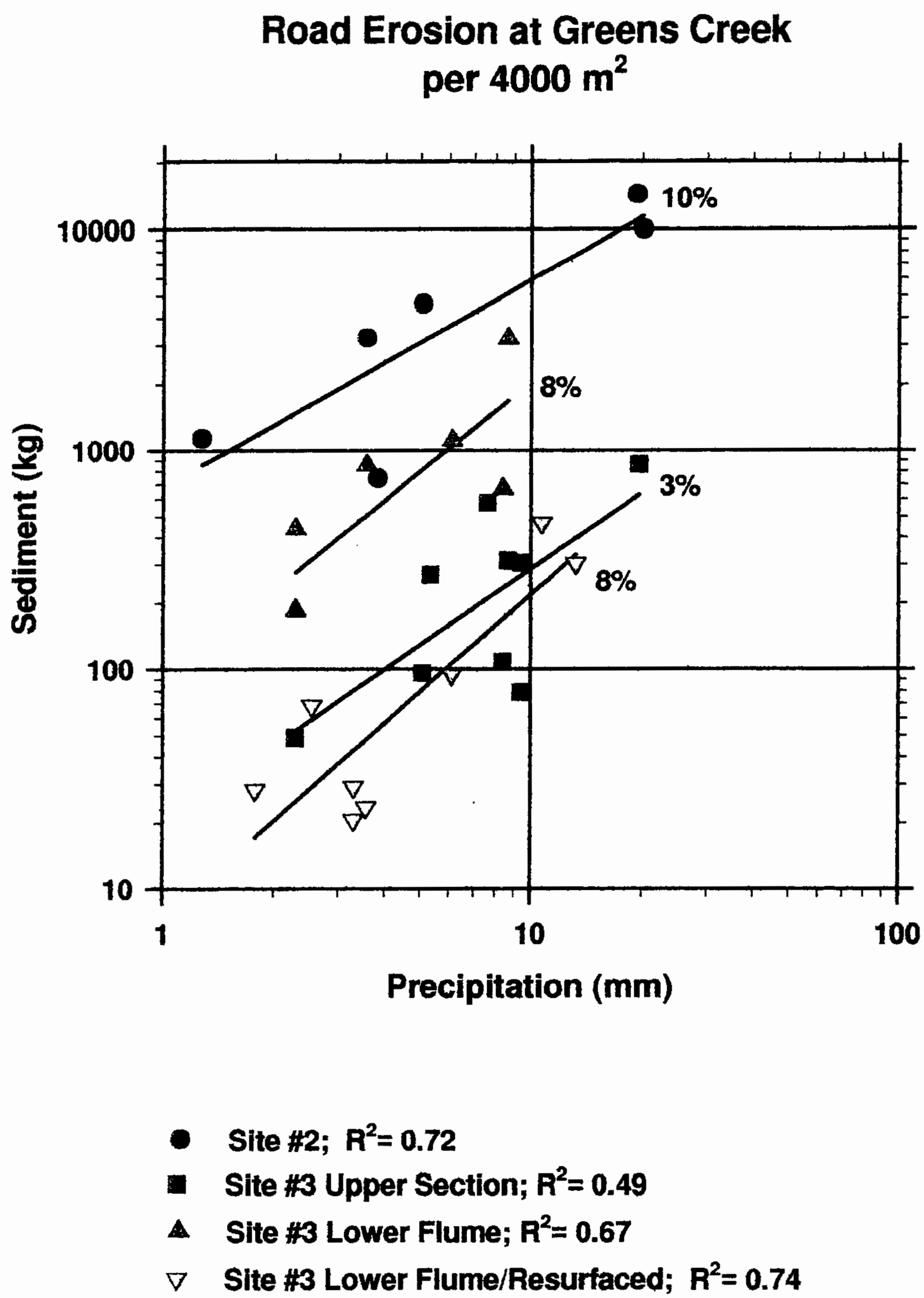

Figure 3. Plot of storm sediment yield versus precipitation for Greens Creek Mine road study sites. Percentages next to regression lines are road gradients for the sampling sites.

Wrangell Island - Earl West Road

The samples were normalized to a 4000m^2 road area and multiple regression was used to determine the most significant variables in sediment production from characteristics found at this study site. Figure 4 illustrates the results of the multiple regression analysis by plotting the simple linear regressions of the storms prior to and after resurfacing on the same graph. The multiple regression equation is:

$$\log(\text{sed}) = -0.194 + 1.760 \log(\text{rain}) - 1.194\ (\text{resurfacing}).$$

Margaret Lake - Revillagigedo Island

Sediment yields for a total of 110 storm events were calculated for the seven sites sampling direct runoff from the road surfaces. The results of the multiple regression equation for sediment yield for a road segment at the Margaret Lake area is:

$$\log(\text{sed}) = -2.630 + 0.183\ (\text{gradient}) + 1.625 \log(\text{rain}).$$

Figure 5 shows the simple linear regression lines for the seven sampling sites on the Margaret Lake road system measuring soil erosion from road surfaces.

Combined Sites

Multiple regression analysis found four variables, traffic, rainfall, gradient, and resurfacing of the road, to be significant in predicting sediment production. The model was developed from 184 calculated sediment yields which represent storm events from over 4000 hourly samples at four locations with a total of 18 sampling sites throughout southeast Alaska. The multiple regression equation for all the sites combined is:

$$\log(\text{sed}) = -3.128 + 0.180\ (\text{gradient}) - 0.291\ (\text{resurfacing}) + 0.011\ (\text{axles/day}) + 1.761 \log(\text{rain}).$$

Figure 6 shows all the study sites plotted on a graph with simple linear regressions for precipitation in millimeters versus sediment in kilograms normalized to a 4000 square meter road segment. Each of the significant variables can be represented by characteristics exemplified on the graph. The sites at Greens Creek and Wrangell have two simple linear regressions representing before and after resurfacing sediment yields. Also, when examining each of the locations with varying road gradients, the effects of steeper gradients are apparent by the position of the regression lines in relation to each other with higher gradients producing higher sediment yields. The volume of traffic is illustrated in color on the lower legend of figure 6 describing the general traffic patterns at each site. The figure clearly shows that heavier traffic volumes produce higher sediment yields.

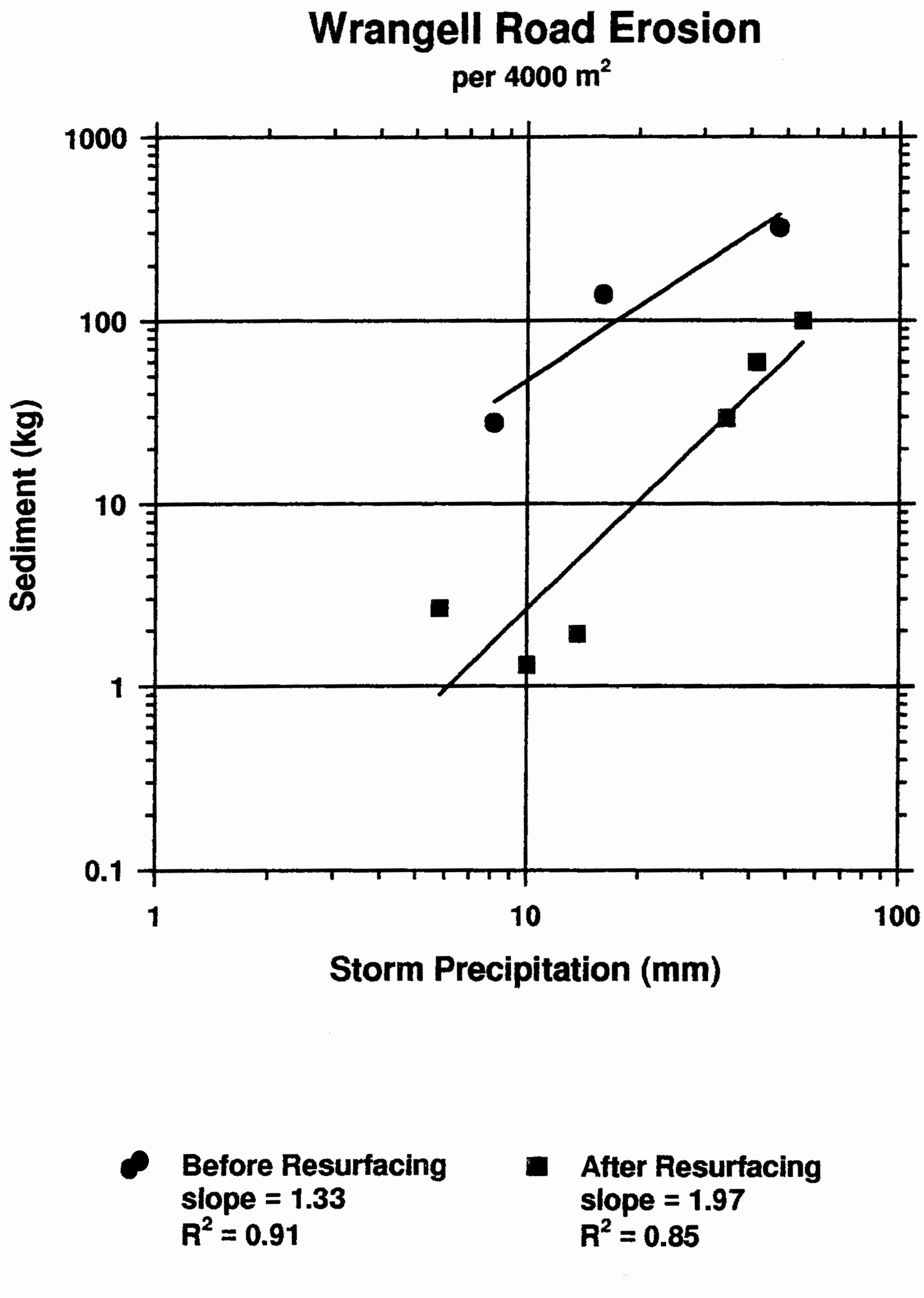

Figure 4. Plot of storm sediment yield versus precipitation for the middle sampling station on the Earl West road on Wrangell Island. The two regression lines represent sediment yields before and after the road was surfaced. The road gradient at this site is 7%.

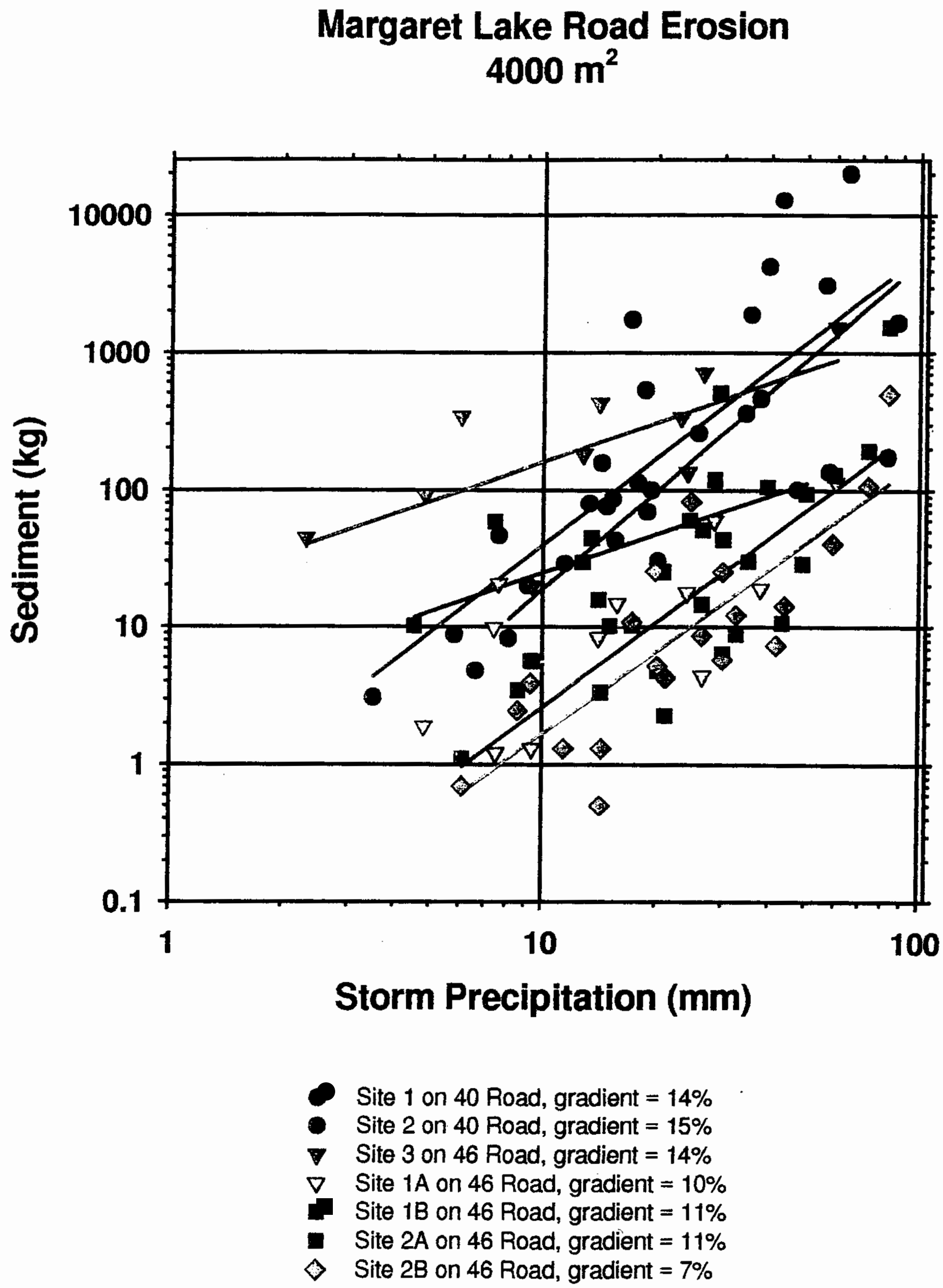

Figure 5. Plot of storm sediment versus precipitation data for the seven sampling sites on the Margaret Lake road system on Revillagigedo Island, Alaska. Percent slope for each of the sampling site road segments are given in the legend.

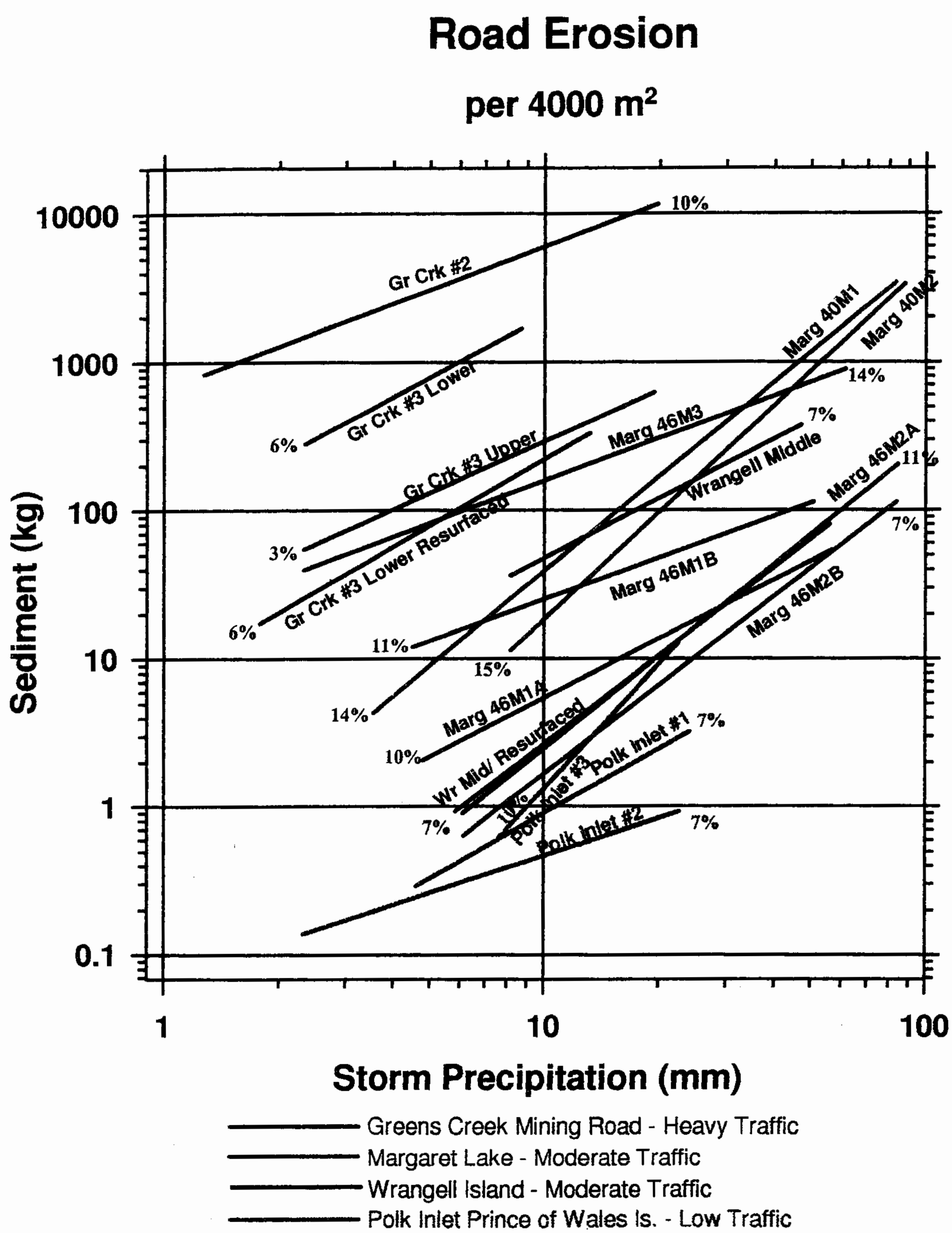

Figure 6. Simple linear regressions for all 4 locations in which road erosion studies were conducted in southeast Alaska. The numbers next to the lines are percent slope for each study section. Each of the locations are represented by a different color.

APPLICATIONS

Sampling Equipment and Monitoring Protocols

There are several applications for this sampling and monitoring technique. The most important is meeting requirements of laws requiring monitoring the effects of management activities such as logging and recreation and the associated roads. Information on road erosion should become part of a management data base to indicate the amount of sediment a road would produce resulting from measurable characteristics at the road location (precipitation, traffic levels, surfacing materials, gradient, ditch condition, and maintenance). The monitoring technique will allow collection of road sediment data related to these variables as well as discharges from ditches and small streams into which runoff is routed. Comparing the data between the roadside sites with the downstream sites will be useful in determining the transport of sediment to larger streams. Combining road study data into a data base from many different National Forests roads with different variables could be used to develop more accurate models for predicting road sediment production and routing.

Road Erosion Prediction Equations

The road erosion prediction equations presented herein can be used as a first step for prediction of sediment produced from road surfaces in southeast Alaska. The equations for the individual sites will be most accurate for the sites where the data was collected. The equation for the combined sites can be used as a more general prediction method but it must be understood that the equation is based on limited data. The equations and graphs can be used to make decisions which will avoid road construction projects with high erosion potential and identify existing roads with potential high erosion hazard. Both the equations and the graphs show that steep road gradient, high traffic level, and poor road surfacing produce much larger quantities of sediment. These are variables over which management has control and decisions on effective spending of public funds to reduce erosion need to be made based on this information. Rainfall is an important variable over which management has no control, however control of traffic and maintenance during high rainfall periods is under management control. Use of the data and equations is intended to be an additional resource tool for the land manager and technical specialist. As additional data from other geographic areas is collected, a means of checking the reliability of these erosion prediction equations and graphs, and the need for modifications will become apparent.

Example of Sediment Yield per Storm Estimate :

Estimate the sediment delivered to the ditch from one kilometer of road for a storm with 20 mm of rainfall, the road gradient was 6%, and 3 logging trucks made 2 round trips per day (Each truck made 2 trips loaded with 3 axles on the road and 2 trips unloaded with 2 axles on the road for a total of 10 axles per day for each truck. Since three trucks were operating this is a total of 30 axles/day.). The road is insloped with a centerline crown resulting in two meters of road width draining toward the ditch. The road location is not at one of the study sites, therefore use general equation for southeast Alaska.

Solution: $\log(sed) = -3.128 + 0.180\ (6) + 0.011\ (30) + 1.761 \log (20)$.

$\log(sed) = 0.573$

$(sed) = 10^{0.573} = 3.74$ kg

The estimated sediment delivered to the ditch from a 20 mm storm is 3.74 kilograms for a $4000m^2$ section of road with a road gradient of 6% and 30 axles per day of traffic. One kilometer of road area is 2 meters by 1000 meters which equals $2000m^2$. Therefore, the sediment yield to the ditch per kilometer equals 3.74/2 = 1.87 kg.

APPENDIX A

A METHOD FOR MEASURING SEDIMENT PRODUCTION FROM FOREST ROADS

INTRODUCTION

Soil disturbance from forest management and timber production can increase the potential for accelerated soil erosion on forested watersheds. In the Pacific Northwest, the two main processes which contribute to sediment production resulting from forest management activities are mass failure and surface erosion from forest roads (Fredriksen 1970, and Reid 1981). In the Clearwater River Basin, as much as forty percent of the sediment produced in the watershed could be attributed to logging roads (Reid 1981). Several studies examining road construction techniques for forest roads have resulted in improved methods to reduce the quantity of sediment production resulting from both mass failure and surface erosion (Haupt and Kidd 1965, Packer 1967, and Sessions et al. 1987). Although the results of these studies provided methods which can reduce sediment production, the level of sediment reduction was not quantified because efficient measurement methodology was not available. Due to recent advances in solid state technology a feasible method for determining the quantity of sediment produced from a particular road section and the distance transported to a fish bearing stream has been developed and is presented herein. The methodology includes not only state-of-the-art equipment but also a protocol for sediment data collection.

Several variables are known to influence the amount of sediment produced from logging road surfaces. A study in the Northern Rocky Mountain Region of the United States examined 14 different variables to determine which had the most influence on development of rills on the road surface (Packer 1967). Particle size and gradient of the road surface were the two variables which were found to have the most influence on rill development on the road surface. This study indicates the surfacing material of the road is important to sediment production. Studies in the Appalachian Mountains focused on the depth, type, and size of surfacing material applied to a forest road surface (Swift 1984a, and Kochenderfer and Helvey 1987). The results found road surfacing to be significant in reducing the production of sediment. These two studies reinforce the factors used in the Universal Soil Loss Equation (USLE) which is based on more than 10,000 plot-years of data (Brooks et al. 1991). Traffic is another variable which has been shown to be significant in sediment production from road surfaces (Reid 1981, Reid and Dunne 1984, Swift 1984b, and Bilby et al. 1989). Traffic levels and vehicle type affect many of the physical parameters that have been shown to be significant to sediment production. Traffic breaks down surfacing material resulting in finer surface gradation which increases sediment transport from the road surface. Traffic can also produce wheel ruts on the road surfaces which have been shown to increase sediment erosion and transport (Fahey and Coker 1989, Foltz and Burroughs 1990, and Haydon et al. 1991). Particle size and linear surface depressions are also very important factors as well in the generally accepted USLE methodology. The concentration of water in wheel ruts increases energy for eroding and transporting larger sizes of particles and transporting higher total quantities of sediment. The frequency of road maintenance can either increase or decrease the amount of sediment production from a road surface (Haydon et al. 1991). Grading of the road surface to eliminate runoff concentrations in rills and ruts that have formed will reduce sediment production; however, grading that is not needed to maintain uniform road surface drainage can disturb hardened or armored surfaces and increase quantities of loose erodible material available for transport. There are many other variables which can effect sediment production that have not been mentioned but may be as significant.

Possible impacts to fisheries resources is the primary concern from accelerated sediment production in southeast Alaska. Increases in fine sediments, less than 2 millimeters, to streams can cause sedimentation of spawning gravel and a reduction in egg and alevin survival (McNeil 1966, Sheridan and McNeil 1968, and Meehan and Swanston 1977). Also, increases in sediment can cause an aggradation of sediment in streams which could reduce the pools and other habitat necessary for fish survival (Cederholm and Reid 1987). Another concern in southeast Alaska is the effects that can occur from increased sedimentation in estuaries due to the large number of streams with estuaries supporting spawning and rearing populations of fish. Several species of salmonid fish, coho (*Oncorhynchus kisutch*), chum (*O. keta*), pink (*O. gorbuscha*) salmon, use estuaries to spawn and rear juveniles in the Pacific Northwest (Meehan and Bjornn 1991, Tschaplinski 1987, and Thedinga and Koski 1984).

Several different methods have been used to determine the impacts of roads on sediment production and to quantify the amount of erosion attributable to forest roads. Watersheds of various sizes have been studied to determine the association of increased sediment yield resulting from road construction and timber harvesting (Fredriksen 1970, Brown and Krygier 1971, and Beschta 1978). These studies monitored sediment yield at the mouths of the watersheds but did not segregate the yields resulting from road surface erosion from yields due to mass wasting and other sources of sediment. Coshocton wheels were used to take proportional suspended sediment samples of discharge from a road section to allow calculation of sediment yield for different road surfacing materials (Swift 1984a, and Kochenderfer and Helvey 1987). Several studies have used simulated rainfall to determine the amount of sediment produced from a road with different variables and conditions. These studies collected the cumulative sediment from the plots in settling basins for each simulated storm (Foltz and Burroughs 1990, and Burroughs et. al. 1991). One study measured the distance sediment has visibly moved down slope to develop a model for predicting the travel distance of sediment from fill slopes, rock drains, and culverts (Megahan and Ketcheson 1996). Others have used settling basins a distance below the road in small ephemeral stream channels to measure the transport of sediment down slope (Haupt and Kidd 1965). Bilby et. al. (1989) measured sediment eroded from forest roads using a sampling method which minimally disrupted the sediment discharge process and then combined his results with several other studies in southwestern Washington to determine the fate of sediment produced by roads and transported to larger streams. One of these studies examined the transport of sediment originating from roads through small ephemeral stream channels at different levels of flow in order to determine the ability of these channels to transport sediment from roads to larger fish bearing streams (Duncan et. al. 1987). A previous study by Bilby (1985) had sampled suspended sediment and turbidity in a road side ditch and sampled stream gravel for fine sediment content above and below the stream crossing to determine whether there was a significant difference in fine sediment deposited in the stream bed. This study found that 80 percent of the material by weight that was transported to the stream was finer than 0.04 millimeters and the sediment was deposited into the stream bed during low flow periods but were flushed from the gravel at moderate flows.

The objective of this Appendix is to present a methodology to measure sediment production and movement from roads and also present a methodology that can be used to measure quantities of road sediment transported in small streams. The methodology includes the equipment and measurement protocols that can be used to evaluate road erosion in order to determine the most effective practices for reducing sediment production. The downstream sediment transport methodology is designed to sample sediment simultaneously at the road and down slope in small streams. The system is designed to sample sediment discharge with as little disruption to transport as possible in order to accurately determine the quantities transported downstream. The use of equipment and protocols described in the following will allow collection of information on several of the variables that have been shown to influence the amount of sediment produced and also allow tracking of sediment transported down slope from a road.

METHODS

Site Selection

There are several important site selection criteria in the following list that should be considered when using this method for determining sediment delivered from a road surface.

1. A road section with a uniform gradient is required to determine the effect of slope.
2. A road surface which has a well defined source area in order to accurately calculate the sediment production on a per unit area of road basis is necessary.
3. The road section should have cut slopes which are stable, erosion-resistant surfaces. Heavily vegetated or rocky cut slopes would be ideal for isolating the source of sediment to the road surface. Where cut slopes are important sources of sediment, determination of these sediment contributions would be an additional requirement of the study.
4. The road ditch must be stable and armored with no apparent scouring. Grassed or rocky ditches would be ideal.
5. Where the affects of logging is the focus of the sediment study, the road must have active log hauling traffic during the study period.
6. Minimal surface and subsurface water interception by the ditch associated with the road study section will greatly simplify interpretation of results.
7. An additional criteria required when tracking delivery of sediment into streams requires the road section be located close enough to a stream to allow tracking of the sediment movement from the road to a viable stream. This additional criteria, coupled with the first six, limits the possible sites significantly.

Meeting these criteria completely is difficult and some compromises will likely have to be made. There will always be additional criteria to be considered depending on the site conditions and management factors.

The study site that is chosen should be representative of the construction methods and materials used for that area. A survey of the road surface is not necessary but can be useful in development of a topographic map of the road surface for determination of the source area contributing to surface runoff and erosion (figure 7). The calculated sediment source area includes the portion of the road surface from the drainage divide to the ditch.

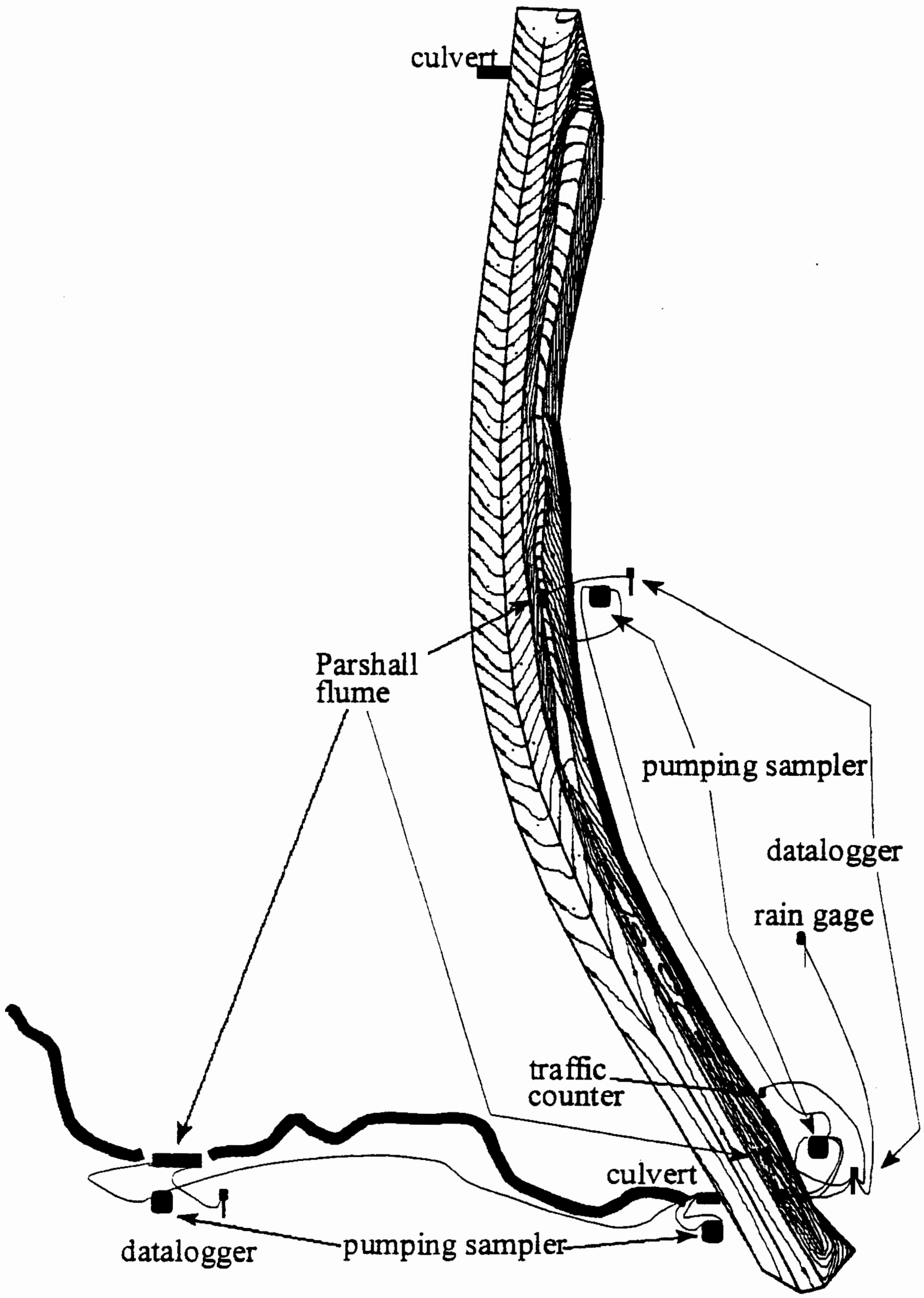

Figure 7. Topographic survey of Earl West road segment on Wrangell Island and the instrumentation used for sampling road surface erosion.

A majority of roads in southeast Alaska are crowned with a ditch on the uphill side. The crown of the road and the presence of wheel ruts act as a surface drainage divide which results in half of the road contributing runoff to the inside ditch (figure 8).

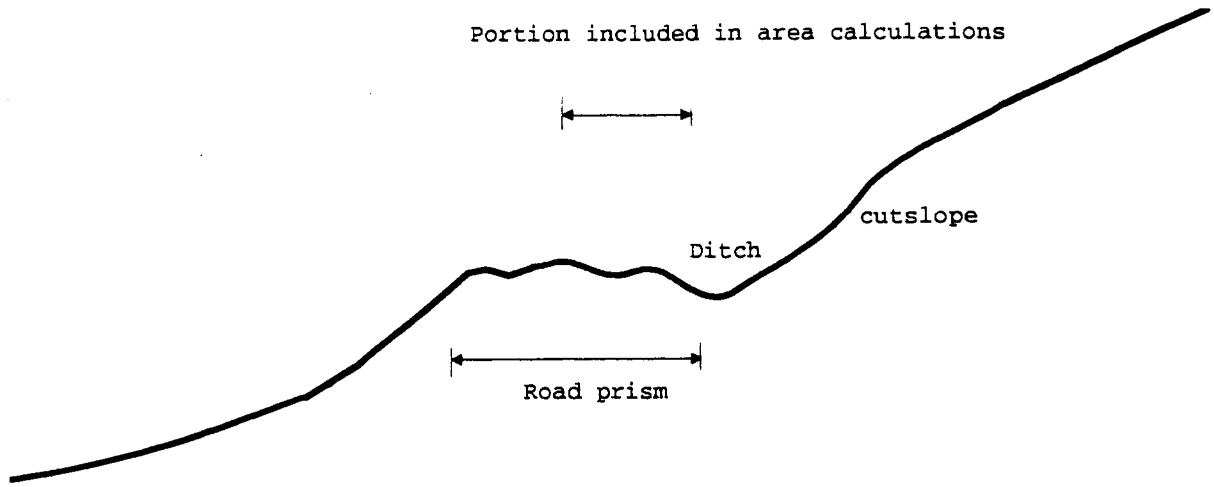

Figure 8. Cross-section of a typical road prism and the area that typically contributes runoff to the inside ditch.

Instrumentation

The main controller and data collector for each of the sample sites consists of a data logger and weatherproof enclosure. Each of the enclosures contains a termination strip in which several sensors and relay switches can easily be connected. The data loggers are setup to scan the instruments on a 5 second interval and log the total or average readings every 15 minutes. The data loggers have between 64 and 128 kilobyte memory capacity depending on the data logger model, which allows logging 200 to 400 days at a typical sampling site. However, it is preferred that data is downloaded as frequently as possible to determine if all the sensors are working correctly. The data is downloaded via a serial cable connected between the data logger and a palmtop, laptop, or desktop computer. This allows a visual check of the raw data to determine if the equipment is working or whether changes to the sampling program need to be made. Plotting the data on a portable computer using spreadsheet software provides a quick method of reviewing the data in the field.

A 6 inch diameter tipping bucket rain gage with a 0.25mm bucket is connected to the data logger and the total rainfall for 15 minute intervals is recorded by the logger. According to the manufacturer, Unidata, the gage has an accuracy of 1% up to 50mm/hr. Storm intensity and duration is derived from the sampling protocol for rainfall. A similar protocol was used for collecting sediment samples and will be discussed later.

Two different types of traffic counters have been used to determine traffic levels for the study sections. A pneumatic road traffic counter that counts axle passes can be connected to a data logger that records total axles during 15 minute intervals. The pneumatic pressure counter is connected to a rubber tube laid across the road which sends a pulse to a transducer when a vehicle passes over it. For every axle on the vehicle, one pulse is sent to the data logger; therefore, larger vehicles with more axles will produce more axles counts. This system is not able to distinguish between light or heavy vehicles, however samples of traffic distribution can be used to estimate the volume of light and heavy traffic. A difficulty with this type of traffic counting system is wear on the rubber tubing which can develop leaks and stop counting traffic. This is a significant problem on gravel roads surfaced with pit run rock or crushed gravel which tend to have angular shapes that can cut the rubber tubing from vehicle traffic.

Another traffic counter which has been found to be very effective is a passive infrared traffic counter. This counter uses an infrared sensor which can detect movement or heat in a narrow 60 by 120 centimeter detection zone up to 30 meters away. Once an object is detected moving through the detection zone, the sensor sends a signal to a counter that totals the counts and in turn sends a signal to the data logger that is totaled for the set recording interval (typically 15 minutes). The sensor has a 3 to 4 second delay before it will activate again to prevent double counts. The infrared sensor is powered by three "AA" batteries and should last an entire season. The counter unit is powered by four "D" cell batteries which also last a full season. Both the sensor and counter have been very reliable.

A fiberglass Parshall flume was installed at each of the sampling sites, as shown in figure 9. The flume is leveled and secured in the ditch with sand bags which also direct the flow into the inlet. The Parshall flume was chosen for this study because of the head drop which occurs after the throat which causes turbulence and mixing of the water passing out of the flume. This permits the collection of a more representative sample and reduces the potential for sediment settling in the outlet and reducing the effectiveness of the flume. Prefabricated Parshall flumes range in size from a 1" (2.54cm) throat up to several feet. The capacities and range of the two and three inch Parshall flumes have worked the best for discharges encountered in road side ditches and small streams. The stage discharge equations for the two flumes are:

$Q = 8.566\ H^{1.547}$ with Q in (l/min) liters per minute, for the 3" (7.6cm) Parshall flume and

$Q = 5.778\ H^{1.55}$ with Q in (l/min) liters per minute, for the 2" (5.1cm) Parshall flume,

with H = stage height measured in centimeters.

For this study, liters per minute (l/min) discharge was used because the flows are small and it is easier to use these units to convert discharge and concentration to sediment discharge estimates.

Each flume had a staff gage molded into the side wall opposite of a prefabricated stilling well outlet for connecting a 5.1 centimeter (2" nominal) threaded pipe for measuring stage height. The staff gage had markings in tenths of feet and inches for measuring head visually. A stilling well can be constructed from 5.1 cm (2" nominal) ABS or PVC pipe and fittings and a clamp for securing the pressure transducer. A hydrostatic pressure transducer was mounted in the stilling

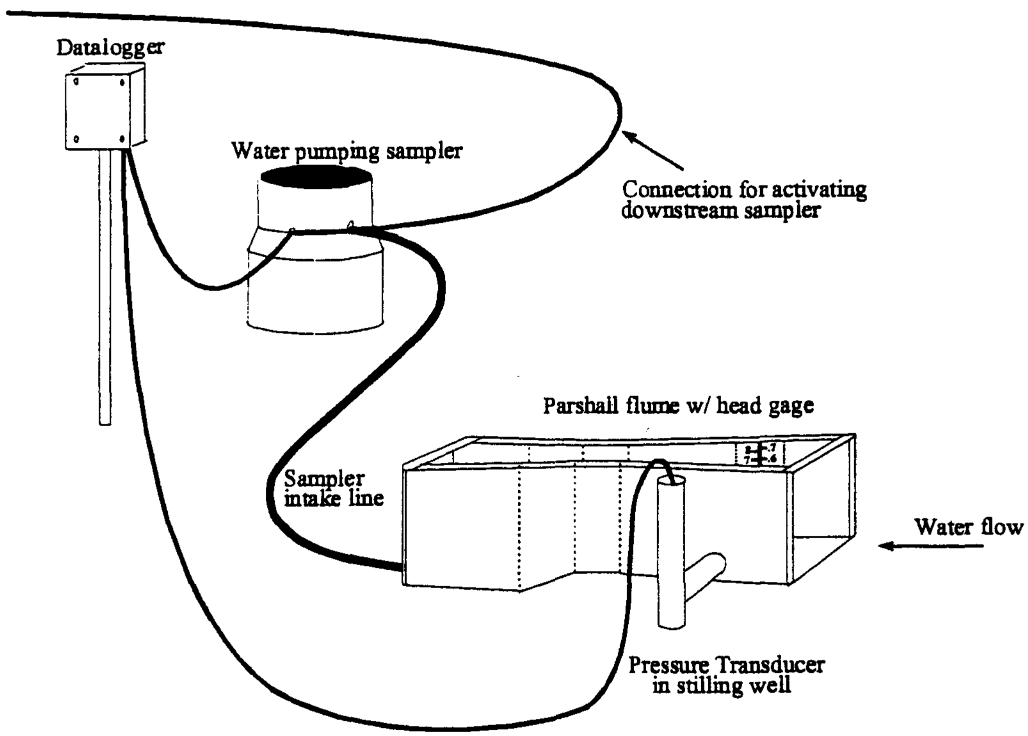

Figure 9. Instrumentation used to collect road erosion samples and discharge measurements from the road surface in roadside ditches.

well at the elevation of the flume floor and connected to the data logger. The hydrostatic pressure transducer has an accuracy of 4 mm after calibration and a resolution of at least 1 mm. The data logger can be setup to scan the pressure transducer every 5 seconds and average those readings every 15 minutes and record that average as the stage height. The logging interval and scan rate is set by the person developing the data logger scheme. Once the data is downloaded, it is put into a spreadsheet and the discharge is calculated using the appropriate equation.

Each of the sampling sites was equipped with a water pumping sampler located next to the flume to take water samples under programmed control of the data logger (figure 9). The lead sampler, which activates the other samplers down slope once it samples, is connected to the data logger via a cable which receives a pulse produced by the data logger when the water level in the associated flume reaches a designated height. The pulse is produced from a relay switch that is soldered to the termination strip inside the weatherproof enclosure. The data logger program sends a signal to the relay switch which in turn sends a pulse to the sampler every ten seconds after the designated stage height has been reached. The relay switch stops sending pulses when the water level drops below the designated height. The pumping samplers are programmed to sample when the pulse total reaches 90 which is every 15 minutes. If the samplers are being used in series as shown in figure 7, a signal splitter is used to connect a wire from the first sampler in the series to the other samplers. The first sampler is programmed to send a signal to a second sampler in series which is also known as the slave sampler. The splitter allows the sampler to receive the pulses from the data logger relay switch and send out a signal for one or two additional samplers. This configuration is referred to as a master/slave setup. The second sampler in the above example can also use a splitter to send a signal to other samplers within seconds of the initiation of the first sampler. The samplers were programmed to collect composite samples consisting of four 15 minute samples pumped into one bottle to obtain a one hour sample. The samplers have a capacity of 24 one hour composite samples which consists of 96 fifteen minute sub-samples. There are many options in the sampler program to set the frequency, size, whether to composite or not, and a combination of discrete and composite samples. As described in the previous example, setting up samplers connected in a series downstream enables an estimation of the transport of sediment from a road to a larger stream.

The pumping samplers have a microprocessor which contains the necessary software programs to set up a sampling scheme. Also, the samplers have a liquid detector which detects liquid in the tubing at a specific point so that it will sample a consistent volume each time. One problem experienced with this system is the stage does not always stay above the designated height on exactly one hour intervals; therefore, some of the composite samples are from different rainfall events. This is mainly a problem during short rainfall events which last less than 24 hours or with low intensity storms with intermittent rainfall. However, the pumping samplers keep a record of when each sample is taken by date and time that can be reviewed during sample collection. The samples which are found to be composites of two distinctly different rainfall events are not included in the analysis for that storm. This is necessary and some data is lost; but, the amount of information lost is small and unavoidable at the present time. This problem does not happen often because most of the storms recorded in southeast Alaska produce enough runoff to sample for the entire 24 hour period. Also, little information is lost since the samples near the end of the recession limb on the hydrograph usually contain little if any sediment. Other geographical areas with shorter duration storms will require more frequent sampling schemes for data collection.

Another consideration with the samplers is power consumption as they require battery recharging frequently when the internal rechargeable Nicad batteries are used. Some storms can be missed if the batteries are not charged regularly. A solution to this problem is to use deep cycle marine or RV batteries and a cable with battery clips to power the samplers. The samplers have taken over 500 samples during a field season without requiring a recharge and are much more cost effective than the Nicad batteries sold by the manufacturer. The disadvantages of the automotive batteries are the weight, transportation, potential for theft, and hazardous material contained in lead acid batteries.

After the composite samples are collected and the bottles removed from the sampler, gravimetric analysis can be performed to calculate the amount of sediment passing through the flume during the one hour sampling period. The standard method of analysis for total suspended sediment can be used to determine the total sediment for each sample (APHA 1985). The calculated sediment concentration from the gravimetric analysis is combined with the average discharge calculated from the data recorded on the data logger for the same time interval to determine the total sediment discharge for that time interval. The hourly sediment discharge can then be summed to determine the estimated total sediment discharge for the storm event. The data collected for the same time period for traffic, precipitation, and site specific variables such as gradient, surfacing material, and ditch condition are recorded to be used during regression analysis to predict hourly and total storm sediment discharge.

A sample of the surfacing material is collected to be sent to a materials testing laboratory for testing. Road surfacing material gradation and durability are important factors in development of prediction equations of sediment produced from roads. Gradation size analysis and the Los Angeles Abrasion test are conducted to determine the hardness of the road surface aggregate.

Expected Uses for the Resulting Sediment Data

There are several expected results of this sampling and monitoring technique. The first is to determine the amount of sediment a road will produce based on measurable characteristics of the road. Some of these characteristics or variables are, but not limited to, precipitation, traffic levels, surfacing materials, gradient, ditch condition, and maintenance. This monitoring technique will collect data on these variables as well as discharges from ditches and small streams in which runoff is routed. Comparing the data between the roadside sites with the downstream sites will be useful in determining the transport of sediment to larger streams. The data could also be used to calibrate and validate the Water Erosion Prediction Project (WEPP) model for roads associated with localized conditions. Combining data from several different road study sections with different variables could be used to develop a regression model for predicting sediment production and routing for a more diverse set of conditions.

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APPENDIX B

DESCRIPTION OF STUDY SITE CONDITIONS AND METHODS OF ANALYSIS

Road erosion studies were conducted at four locations on the three USFS Tongass National Forest Administrative Areas (figure 1). The first of the four study sites was instrumented and samples collected beginning in August, 1991 at Polk Inlet on Prince of Wales Island. Three subsequent sites were located at the Greens Creek Mining Road on Admiralty Island, Wrangell Island, and Margaret Lake on Revillagigedo Island, in the following years and up to the present time, 1998. The data for each of the study sites were analyzed separately for the conditions found at that site, however, many of these conditions and variables were common to all the sites in which data were collected. The results will be presented for each of the sites and then a combined analysis of the four sites will be presented.

In the following analyses for each of the locations, many variables were used to develop the best models for predicting sediment production from forest road surfaces. Several of these variables were quantitative precipitation values relating to intensity, duration, and total rainfall. Other variables consisted of physical characteristics of the specific sampling sites such as road gradient, surfacing material, and surface conditions. A qualitative variable representing resurfacing of a study site road surface was used in the analyses for some locations and consisted of either a zero (no resurfacing) or one (resurfacing).

The individual and combined site regression equations for prediction of road erosion include several variables which must be used with the units as defined in the following list. The list defines the variables along with the required units.

- **sed = sediment yield from $4000m^2$ of road (i.e. one kilometer of road with drainage to the ditch that is 4m wide equals $4000m^2$)**
- **rain = rainfall per storm in mm**
- **gradient = road grade of the contributing road segment expressed as a percentage**
- **axles/day = number of vehicle axles passing per day**
- **resurfacing = set equal to (1) if the road has been recently resurfaced or is in equivalent condition; set equal to (0) if the road has not been resurfaced and surface aggregate size is much finer than a resurfaced road.**

The following erosion prediction regression equations presented for each site and for the combined sites should be used for conditions within the range of data shown on the graphs. The graphs may be used directly for prediction of road erosion for the locations where the studies were conducted. When using the equations, the contributing road surface area draining to the ditch must be calculated since the erosion prediction is for an area of $4000m^2$. A typical insloped single lane road with a crown will have about one half of the surface area draining into the adjacent ditch. Therefore a straight 4 meter wide insloped road will have about 2 meters of width draining toward the ditch. In this case, two meters of contributing road surface width which is 2000m long equals $4000m^2$ of contributing area. The quantity of sediment produced per kilometer of road can thus be calculated since management decisions are often made by estimating the quantity of sediment from roads on a quantity per kilometer of road basis. In order to better predict sediment yield on a per kilometer basis, an average width including curve widening and turnouts draining to the ditch will need to be used so that the length of road required to contribute $4000m^2$ of surface area can be more accurately calculated.

Polk Inlet

Polk Inlet on Prince of Wales Island was chosen to develop a methodology for the study of surface erosion from logging roads in southeast Alaska. This study was initiated by the PNW

Research Station, Juneau FSL, with support from the Ketchikan Area and Craig Ranger District to develop a methodology and begin quantifying forest road surface erosion rates and determine the variables which influence erosion from forest roads in southeast Alaska.

The study consisted of three road sections on the same secondary haul road. The road ditches were equipped with fiberglass flumes and pressure transducers for measuring runoff water discharge, a pumping water sampler for collecting sediment samples from the flumes, and rain gages at two of the three sites for measuring precipitation. An infrared traffic counter was also installed on the road to count the number of vehicles that traveled the road during the study period. All three road segments received the same amount of traffic which consisted of one to two logging trucks making three to four trips a day. The rainfall measured at the two rain gages were very similar during the study period with an average of 934 millimeters from the middle of June to October, 1991. Road surface drainage areas contributing sediment were calculated for the three road segments based on surveys and observations of drainage patterns during rainfall events.

Hourly sediment samples were collected at the three sites during rainfall events. These samples were filtered and weighed to calculate the concentration of sediment in milligrams per liter of runoff water discharge. Discharge, rainfall, traffic, and other physical parameters and conditions that could influence sediment production from road surfaces were recorded. Regression equations were used to develop sediment rating curves with water discharge as the independent variable and sediment concentration as the dependent variable. The sediment rating curves indicated a slightly negative relationship and were irregular from storm to storm. The reason this occurred was due to the limited source of sediment which resulted in an initial flush of sediment at the beginning of an event which became depleted as the discharge increased. Also, as the rainfall event progressed, runoff from upslope increased and had the effect of diluting the sediment concentrations. These observations show that sediment produced from gravel roads is supply limited and simpler sediment rating curve techniques used in agricultural fields and sediment rich streams cannot be used for gravel roads. Available erodible sediment supply limits the amount of sediment produced from roads, but this is not accounted for and is a shortcoming in many models including the WEPP model.

Since the sediment rating curve approach was not appropriate for road erosion in this case, an alternate approach was used. The hourly sediment concentrations were discharge weighted by multiplying the hourly sediment concentration by the discharge to calculate a sediment discharge weight for the one hour sampling periods. The discharge weighted samples eliminate the dilution effect on sediment concentration from increased runoff interception from upslope and reduces the hysteresis effect observed in the relationship between sediment concentration and discharge. Various multiple regression models were used to test which variables were significant in predicting hourly sediment amounts but these models had limited success in predicting sediment yield on an hourly basis.

As a result of the limitations for predicting hourly sediment discharge rates, total sediment yields from the storms sampled were calculated by summing the hourly sediment discharge rates to calculate a total sediment yield per storm. The total sediment yields for the storms was used to determine the variables which had the most influence on sediment yield and develop regression equations on a per storm basis for each road segment and for all segments combined. A stepwise multiple regression equation found that rainfall, gradient, and traffic were important variables in predicting total sediment yield from the road segments at Polk Inlet on a storm basis.
The multiple regression equation is:

$$\log(\text{sed}) = -2.921 + 1.231 \log(\text{rain}) + 0.149 (\text{gradient}) + 0.0062 (\text{axles/day}).$$

A graph of the data used for the multiple regression is shown in figure 2 along with the simple linear regression curves for each of the sampling sites. The model for the three segments combined had a R-squared of 0.66 which suggests the variables account for 66 percent of the total variation in the model. A simple linear regression model with total rainfall in millimeters during a storm event as the independent variable and total sediment yield in kilograms per 4000 square meters of road as the dependent variable was used to calculate an annual sediment yield for a 4000 square meter section of road at Polk Inlet (figure 2). The daily precipitation measured at Hollis for 1991 was used to represent the precipitation for Polk Inlet since it was the closest location with an annual precipitation record. The Hollis data was within ten percent of total precipitation recorded at Polk Inlet during the study period and was therefore considered representative. An annual sediment yield of 0.6 tonnes/4000m^2/yr was estimated for the Polk Inlet road during the 1991 calendar year.

Several assumptions were made to develop the annual estimated sediment yield for this site. These include: 1) all the precipitation that fell at the Hollis gage was in the form of rain; 2) The Hollis gage accurately represents the precipitation characteristic found at the Polk Inlet sites; 3) the logging traffic was constant throughout the year; and 4) the regression relationship holds beyond the limits of the data collected. Other limitations with this study as well as a more in depth examination of the data can be found in Kahklen (1993). Some of these limitations and assumptions were the initiative for subsequent studies in southeast Alaska.

In order to substantiate the results observed on the test road sections, rainfall simulator erosion plots were used on the same test road sections. The simulator consisted of 61 cm wide x 61 cm long x 2.5 cm thick plastic tank with 242 evenly spaced 23 gage stainless steel tubes which produce drop sizes of approximately 2.87 mm. A flow meter and valve was used to control the flow rate and intensity of the simulated rainfall. Simulated rainfall intensities of 12.7, 25.4, and 51.0 mm/hr were applied to the plots and the resulting sediment was measured as it eroded off the surface of the wheel track at the test road sections on the road system. Figures 10-12 show the concentration in mg/l of the sediment measured in the collection trough versus time of rainfall application. The effect of traffic on sediment production can be seen in all three graphs of varying intensities. The test plot gradients, indicated on the graphs, show the influence of slope on the amount of sediment eroded from the road surface. The results from the rainfall simulations substantiate the results of the tests on the full scale road sampling locations. Both show that precipitation, traffic, and gradient are major contributing factors to erosion from roads and sediment yield. The Polk Inlet site, being the first study area, served to: develop the

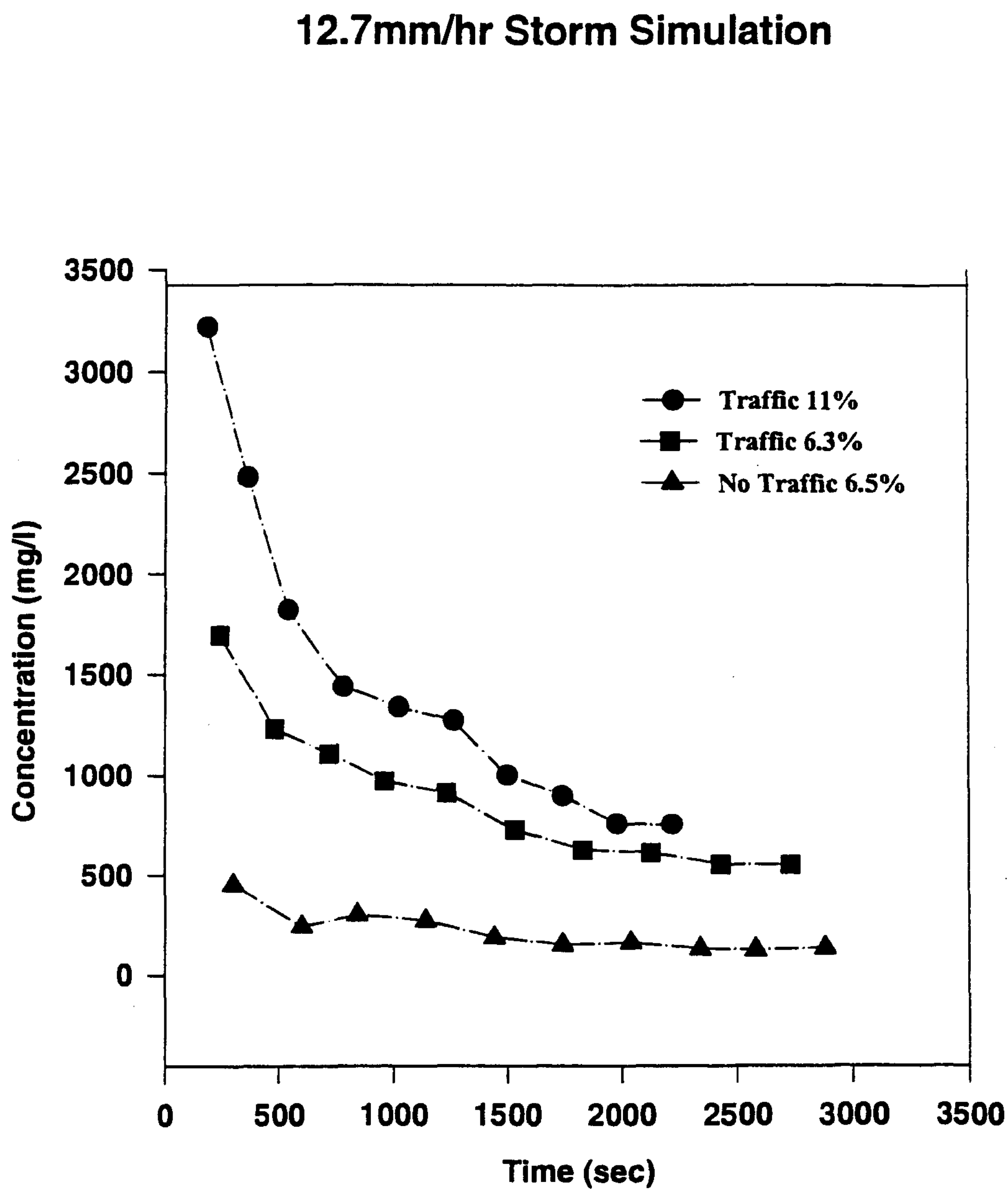

Figure 10. Three rainfall simulations of 12.7 mm/hr (0.5 in/hr) for the Polk Inlet road. Two of the simulations were conducted on roads with active haul and one with no haul traffic for over a year. Percent slopes of each plot are given.

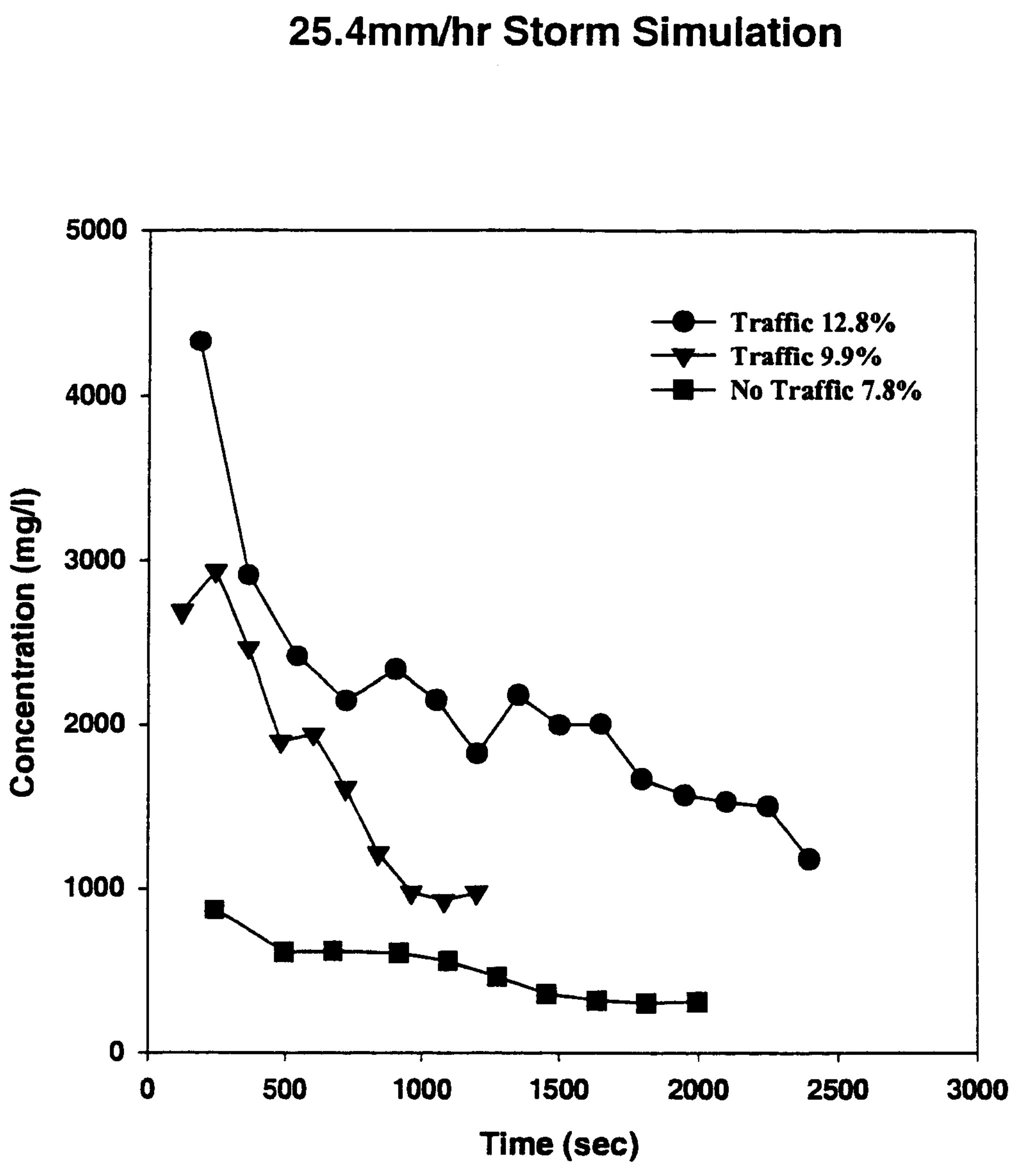

Figure 11. Three rainfall simulations of 25.4 mm/hr (1 in/hr) for the Polk Inlet road. Two of the simulations were conducted on roads with active haul and one with no haul traffic for over a year. Percent slopes of each plot given.

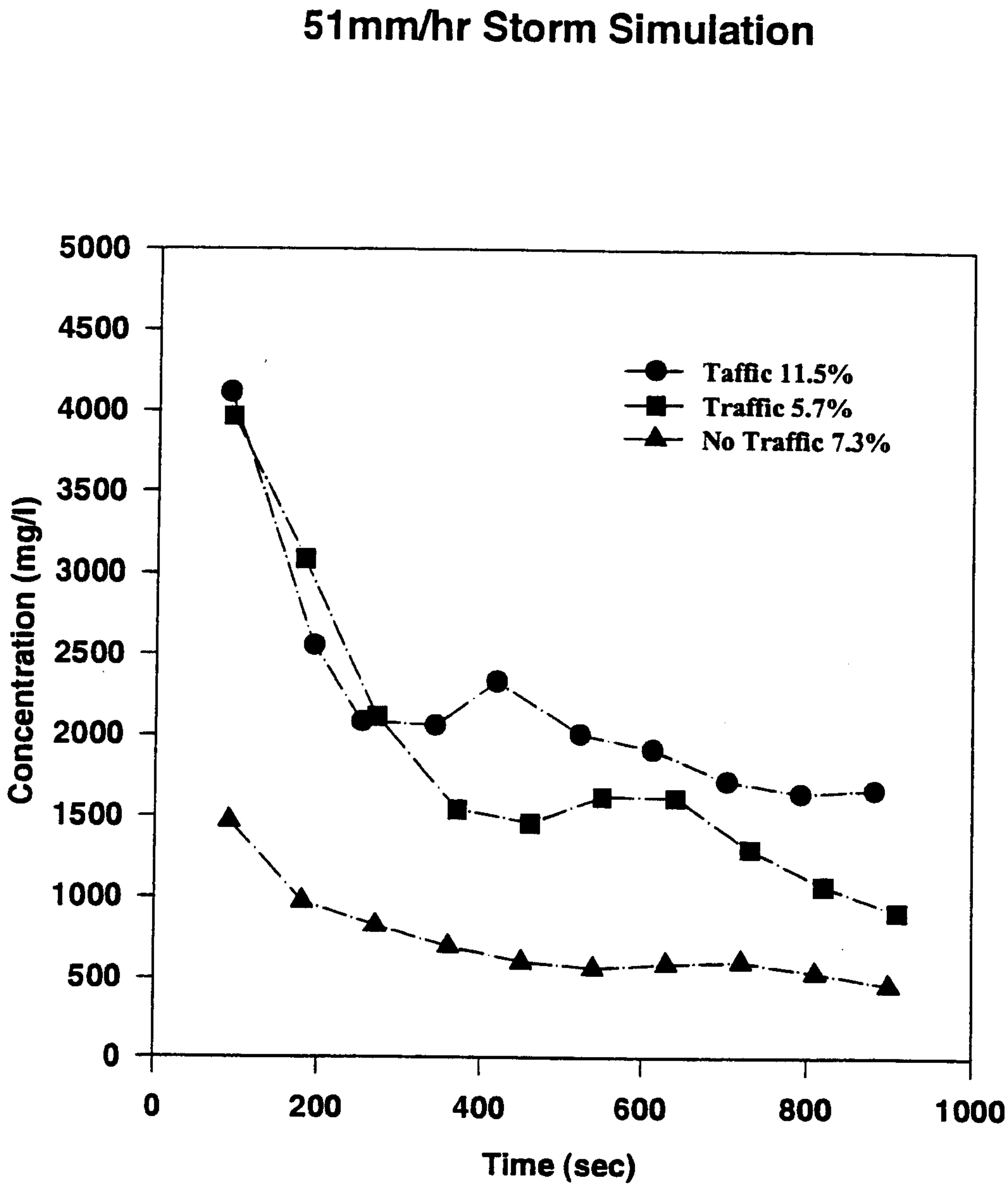

Figure 12. Three rainfall simulations of 51 mm/hr (2 in/hr) for the Polk Inlet road. Two of the simulations were conducted on roads with active haul and one with no haul traffic for over a year. Percent slopes of each plot are given.

methodology, begin quantifying forest road surface erosion rates, and determine the variables which influence erosion from forest roads in southeast Alaska.

Greens Creek Mining Road

The B road at the Greens Creek Mine is on Admiralty Island approximately 15 miles west of Juneau, Alaska. This site was chosen as the next site for quantifying erosion from forest roads and the variables which influence this process. The site selection criteria was very similar to those used for the study conducted at Polk Inlet and the methodology used is described in Appendix A. Three road segments were chosen in the fall of 1992 to be surveyed and instrumented. The first of the three chosen segments was not instrumented due to construction occurring along that road segment. The second site chosen was a straight segment with a 10 percent grade and a source area of 260 m^2. This site was instrumented at the culvert outlet. The third site selected was located on a section of road with a slight S curve. The site was approximately 150 meters long with the top 50 meters having a 3 percent grade and the lower 100 meters with an 8 percent grade. This site was split into two sites by placing an additional sampling site near the break in slope, 50 meters from the top of the segment, sampling a source area of 185 m^2. A sampling site was installed as planned at the outlet of the culvert draining the entire 150 meter segment with a source area of 465 m^2.

Samples were collected at the three sampling sites during the fall wet season. During this period, the mine was operating 24 hours a day with an average of over 300 vehicle passes a day. The traffic consisted of large ore hauling trucks, buses, and freight trucks as well as light vehicle traffic. The traffic on the mine road was much higher than what would be found on a typical forest road, but, provided an opportunity to illustrate the influence of traffic on sediment production from roads. During the sampling period, the road was resurfaced at two of the three sample plots with aggregate barged in from the Lena Point rock quarry located 16 miles north of

Juneau. The Admiralty Island local rock source was not of sufficient durability to withstand the traffic, therefore, the Lena Point rock source was used.

A total of 30 storms were sampled during the study period at the three sampling locations on the main haul road. The methods for calculating the sediment yield on a storm basis at each sampling site is the same that was used for the Polk Inlet data. Sediment production rates from these sites were very high. The normalized erosion estimates and simple linear regressions for the Greens Creek sites are shown in figure 3. The graph shows four linear regression relationships because the data for "site #3 lower" flume sampling site was separated into samples collected before and after resurfacing. Only three samples were collected at the upper flume site after resurfacing, therefore these were not separated into two different plots. Site 2 was not resurfaced by the company because the road surface template was in good condition.

A stepwise multiple regression analysis for all the storms at all three sampling sites found that rainfall, gradient of road segment, and resurfacing were significant in predicting the sediment yield for the sites all normalized for area. A qualitative variable representing resurfacing of the road within the last two months was used in the multiple regression analysis to account for the reduction in sediment yield. The regression model for erosion at Greens Creek as a result of these data is:

$$\log(\text{sed}) = 1.233 + 1.058 \log(\text{rain}) + 0.152 (\text{gradient}) - 0.803 (\text{resurfacing}).$$

A plot of simple linear relationships for rainfall and sediment is shown in figure 3 with two linear regressions representing before and after resurfacing at "Site 3 Lower" flume.

An annual estimate of sediment yield for $4000 m^2$ of road was calculated using the precipitation records for the Juneau International Airport. An estimate of 302 tonnes/$4000 m^2$/yr was calculated for a 4000 square meter road section at Greens Creek Mine that has an average gradient of six percent and experienced the high traffic levels that occurred during full production. A road with the same characteristics as the previous except that had been resurfaced frequently would yield 48 tonnes/$4000 m^2$/yr. Many assumptions similar to those for Polk Inlet were made in order make an annual estimate. Others assumptions that pertain specifically to the Greens Creek site are the samples were collected only two months after resurfacing, therefore, the frequency of resurfacing to maintain the 48 tonne estimate is not known, and erosion during snow melt was not accounted for as well as maintenance effects on sediment yields.

Wrangell Island - Earl West Road

The Earl West road on Wrangell Island was the third road study location chosen to collect data in order to continue to quantify sediment production from forest roads. The road was carefully chosen in order to quantify and track the sediment eroded from the road surface into a ditch relief culvert and then to a viable fish stream. The road was scheduled to be resurfaced in the fall with a new rock source that was considered to be more durable. This new source came from a pit known as the "garnet pit" at 5.6 mile on road 6265. Both sources of aggregate used to surface the road originally and the new surface consists primarily of schist. The "garnet pit" source had been found to be one of the more durable rock sources on Wrangell Island and was being used to resurface most of the National Forest roads in the area.

The road section was surveyed with a total station to develop a topographic map of the road surface for determination of the source area contributing to surface runoff and erosion (figure 7). In figure 7, the contour lines on the road surface show that only the inner half of the road contributes flow to the ditch which is typical for most forest roads in southeast Alaska. As in the previous studies, the sediment yield estimates for this site are calculated by normalizing to a 4000 square meter area so sediment yield comparisons with sites previously sampled can be made.

Sampling at the Earl West site occurred over a two year period. During the sampling period, traffic consisted of two logging trucks making five or six trips a day over the road study section. Figure 7 shows a diagram of the three sampling sites for the road segment. It was designed to collect sediment samples approximately halfway down the road segment, close to the ditch relief culvert, and 25 meters down slope from the road. A class one stream was approximately 45 meters further down slope than the last sampling site. There were only four precipitation events that initiated runoff in the first three months prior to resurfacing with three of these being sampled at the middle sampling site. Due to problems with batteries, minor vandalism, and difficulties with the stage activation sensors, the middle sampling site was the only one that collected consistent samples over the entire study period.

Resurfacing of the Earl West road segment occurred in the fall of the first year of the study. Three samples of the road surface were collected which included samples prior to, one week after, and one year after resurfacing was completed on the road segment. The samples were oven dried and particle size analysis completed with a mechanical shaker and sieves. The result of the analysis are shown in figure 13. Prior to resurfacing, the samples contained over 47 percent by weight of sand size particles or less (< 2 mm). One week after resurfacing, sand size or less particles constituted nearly 16 percent by weight of the surface aggregate. For the last samples taken nearly one year after resurfacing, the less than 2 mm size fraction consisted of 29 percent of the total weight. The graph illustrates the change in the particle size distributions for the three sets of samples as a result of resurfacing and traffic. The increase in fines one year after resurfacing may be a result of traffic wear and weathering breaking down the larger particles or the weight of the traffic compacting the larger particles into the old road surface thus bringing the finer material to the surface. Hourly sediment samples were collected at the middle sampling site using the same method as mentioned at previous sampling sites and described in Appendix A. The hourly samples were summed to calculate a total sediment yield for the storm and then normalized for an area of 4000 square meters of road. After the samples had been normalized to a $4000 m^2$ road section, multiple regression was used to determine the most significant variables in sediment production with characteristics found at this study site. Figure 4, illustrates the results of the multiple regression analysis by plotting the simple linear regressions of the storms prior to and after resurfacing on the same graph.

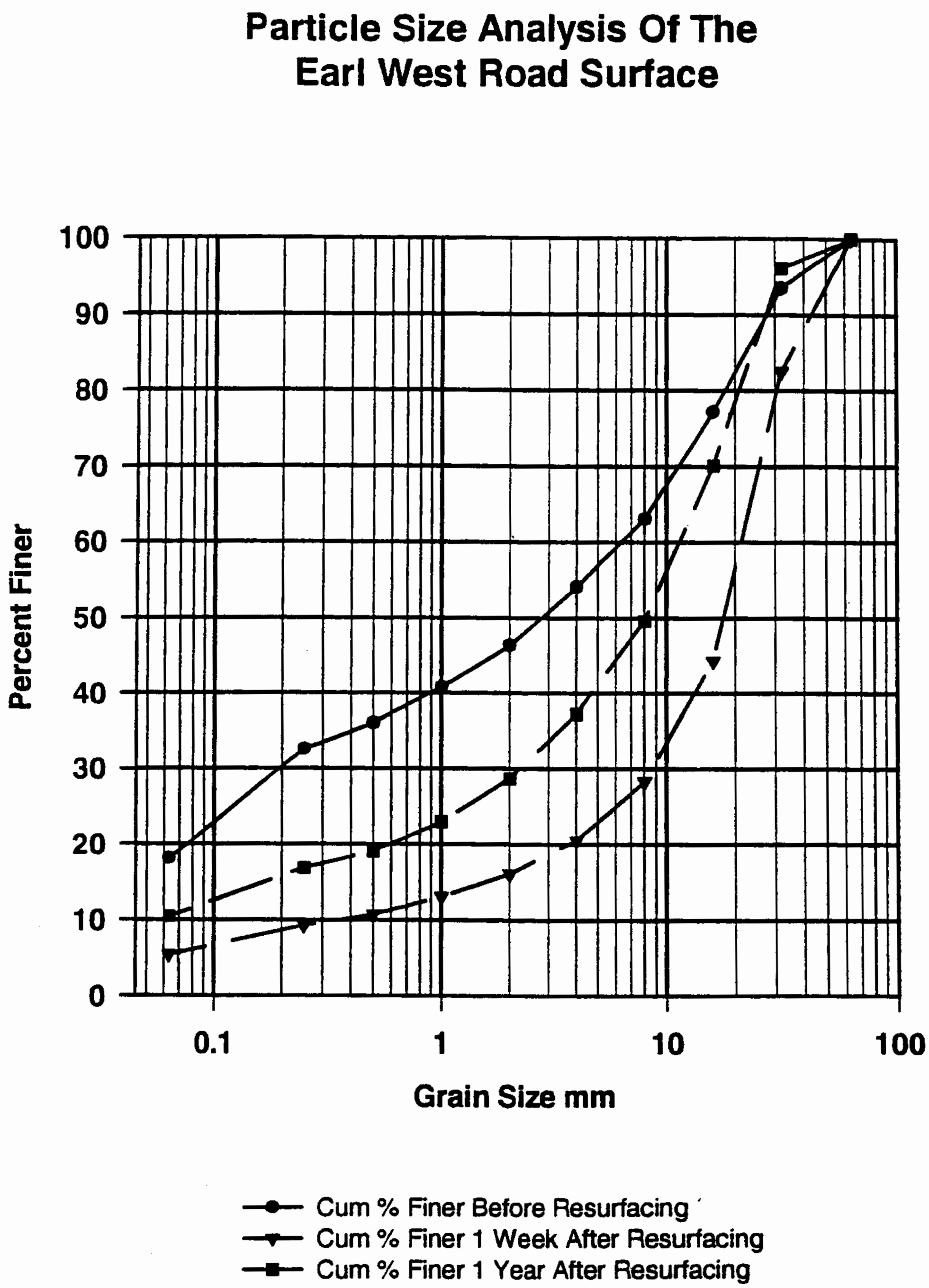

Figure 13. Road surface gradation curves for samples prior to resurfacing, one week following resurfacing, and one year following resurfacing. Size fraction of < 2mm as a percentage of the total sample for road surfacing material during each period are approximately 47%, 16%, and 29%, respectively.

The multiple regression equation is:

$$\log(sed) = -0.194 + 1.760 \log(rain) - 1.194 (resurfacing)$$

These results show that precipitation and resurfacing are important variables in predicting the amount of erosion from a logging road subjected to traffic. In the regression equation, a qualitative variable for resurfacing was used to represent the effects on sediment production as a result of resurfacing. The results show that resurfacing reduces sediment production by an order of magnitude on road surfaces at this location. An annual estimated sediment yield was calculated for $4000 m^2$ road sections prior to and after resurfacing using the equation shown above. The annual estimated precipitation for the site is 2448 mm/yr using a relationship between data collected for precipitation at the study site and the Wrangell Airport precipitation records. Using daily precipitation records an annual sediment yield for a $4000 m^2$ road section prior to resurfacing is 18.1 tonnes/yr and 1.2 tonnes/yr for a road after resurfacing occurred.

Margaret Lake - Ravillagigedo Island

The Margaret Lake area on the southern end of southeast Alaska was chosen as the next location to study erosion from forest roads and the transport of sediment down slope. The equipment was installed on two roads in the Margaret Lake area that would be subjected to haul traffic and road construction equipment for an estimated two years. One of the roads was constructed in the late 1980's on the south side of the lake running parallel to a class 1 and 2 stream. On this road, sampling stations were installed similar to those described in the previous study locations and in Appendix A. However, on this section of road four samplers were installed in series to determine the quantity of sediment eroded from the road and transported to a larger stream (figure 14). Two separate segments of road received this type of setup of four samplers in series. Three other sampling sites were instrumented on other road segments in the basin to quantify the sediment yield from the road surface to the culvert to supplement the surface erosion data collected on the other sections. Samples at the 11 sampling locations were collected over a two and a half year period during the spring through fall months.

Hourly samples were summed for each precipitation event to calculate the sediment yield for each of the sampling sites consistent with the methods previously used at the other sites. The seven sampling sites sampling direct runoff from the road surfaces produced 110 calculated sediment yields for over 25 separate storm events during the two and a half season sampling period. The results of the multiple regression equation for sediment yield for a road segment at the Margaret Lake area is:

$$\log(\text{sed}) = -2.630 + 0.183 \text{ gradient} + 1.625 \log(\text{rain})$$

Figure 5 shows the simple linear regression lines for the seven sampling sites on the Margaret Lake road system measuring soil erosion from road surfaces. The sediment estimate is in kilograms for 4000m^2 of road with gradient measured in percent slope and rainfall in millimeters. An annual sediment yield of 4.3 tonnes/4000m^2 for roads in the Margaret Lake area was calculated using daily rainfall data for Ketchikan for 1995 and assuming a road segment with a gradient of 11 percent. The total precipitation for the Ketchikan station was 2253 millimeters during 1995.

Combined Sites

The total sediment yield for 4000m^2 of road per storm for all four study locations were combined and analyzed to develop a model that contained the variables that have the most influence on sediment production from forest roads in southeast Alaska. Multiple regression analysis found four variables, traffic, rainfall, gradient, and resurfacing of the road, to be significant in predicting sediment production. The model was developed from 184 calculated sediment yields which represent storm events from over 4000 hourly samples at four locations with a total of 18 sampling sites throughout southeast Alaska. The multiple regression equation for all the sites combined is:

$$\log(\text{sed}) = -3.128 + 0.180 \text{ gradient} - 0.291 \text{ resurface} + 0.011 \text{ axles/day} + 1.761 \log(\text{rain}).$$

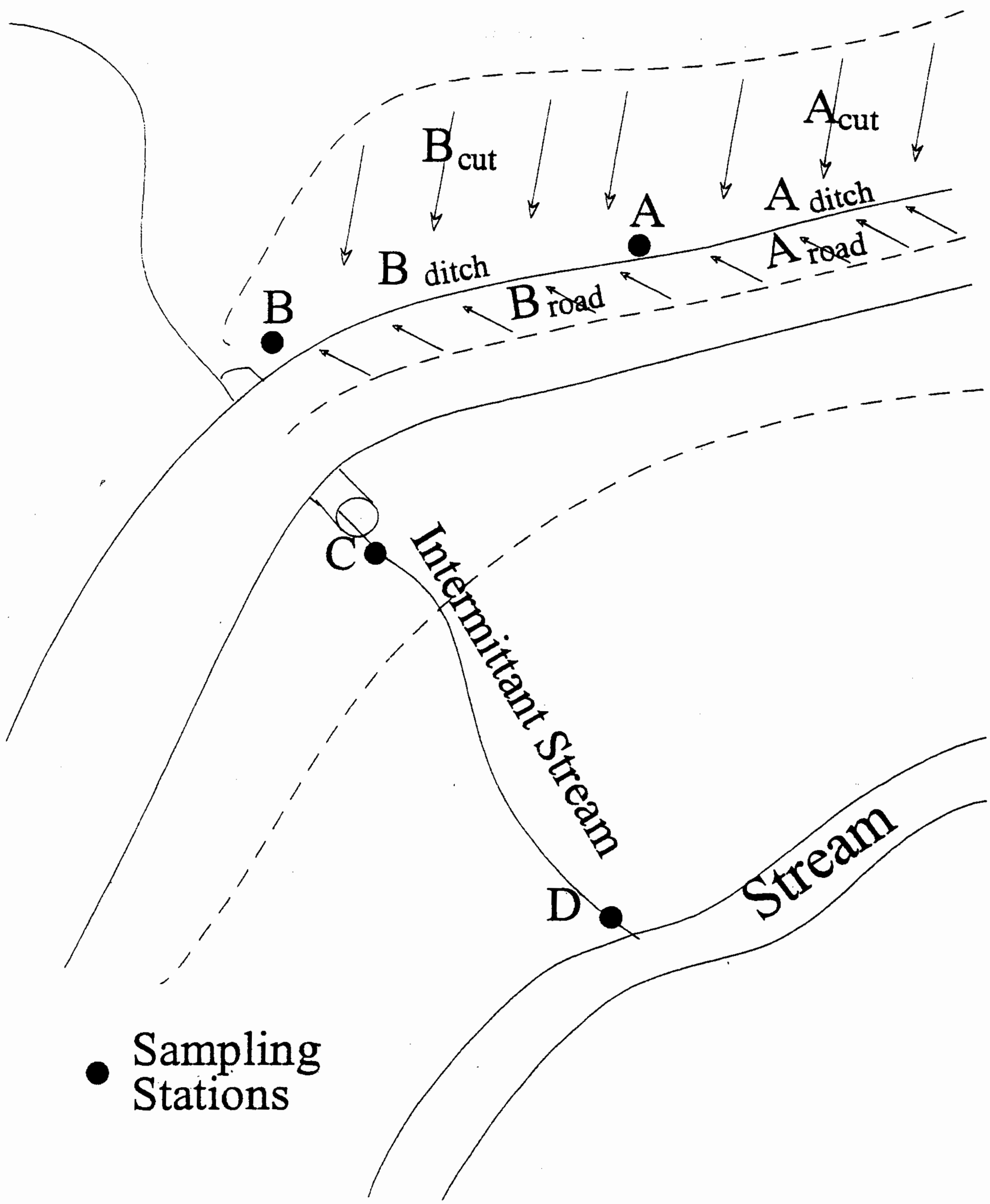

Figure 14. Diagram of samplers setup in series to determine the amount of sediment produced by a road segment and transported downslide to a larger stream. Two road segments had this type of sampling setup at Margaret Lake on Revillagigedo Island..

gure 6 is a graph with all the study sites plotted on a graph showing simple linear regressions precipitation in millimeters versus sediment in kilograms normalized to a 4000 square meter ad segment. Examining the graph, each of the significant variables can be represented by aracteristics exemplified on the graph. The sites at Greens Creek and Wrangell have two fferent simple linear regressions representing before and after resurfacing sediment yields. so, examining each of the locations with more than one sampling site, the effect of steeper adients are apparent by the position of the regression lines in relation to each other. The fects on sediment production of traffic are apparent by comparing traffic levels illustrated in lor on the lower legend describing the general traffic patterns at each site.

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