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A Method for Measuring Sediment Production from Forest Roads

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Abstract

Predicting sediment production from forest roads is necessary to determine their impact on watersheds and associated terrestrial and stream biota. A method is presented for measuring sediment originating from a road segment for individual storm events and quantifying the delivery to streams. Site selection criteria are listed to describe the characteristics for efficient data collection and analysis. The method describes equipment used to quantify sediment transport—data loggers, a rain gage, a traffic counter, Parshall flumes with stilling wells, hydrostatic pressure transducers, and water pumping samplers—as well as variables associated with sediment production—road surfacing material, traffic intensity, gradient, age, construction method, and precipitation. A sampling protocol that worked well for the forest roads in southeast Alaska and can be adapted for use in other regions also is described. Examples of data collection and analysis are explained both for sites near the road and downstream sites for sediment delivery quantification. This method can be used to determine the downstream transport of sediment originating from roads and developing regression models or validating existing sediment models.

Keywords: Road erosion, sediment, forest roads, sediment transport.

Introduction

Soil disturbance from forest management and timber production can increase soil erosion on forested watersheds. In the Pacific Northwest, the two main processes that contribute to sediment production are mass failure and surface erosion from forest roads (Fredriksen 1970, Reid and Dunne 1984). In the Clearwater River basin in the State of Washington, as much as 40 percent of the sediment produced in the watershed was attributed to logging roads (Reid 1980).

A method for measuring sediment production from forest roads was developed in southeast Alaska to determine possible impacts of road sediment to fisheries resources. Increases in fine sediments, less than 2 millimeters to streams can cause sedimentation in spawning gravel, which can reduce egg and alevin survival (McNeil 1966, Meehan and Swanston 1977, Sheridan and McNeil 1968). Also, increases in sediment can cause aggradation in streams, which could reduce pool volume and other habitat characteristics necessary for fish survival (Cederholm and Reid 1987). The effects of increased sedimentation in estuaries is another concern in southeast Alaska. Estuaries support spawning and rearing populations of fish, including several species of salmonids: coho (*Oncorhynchus kisutch*), chum (*O. keta*), and pink (*O. gorbuscha*) salmon (Meehan and Bjornn 1991, Thedinga and Koski 1984, Tschaplinski 1987).

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Several studies examining forest road construction techniques provide improved methods to reduce sediment production resulting from both mass failure and surface erosion (Haupt and Kidd 1965, Packer 1967, Sessions and others 1987). The level of sediment reduction in these studies is not quantified, however because no efficient method of measurement existed at the time. Because of recent advances in technology, a feasible method for determining sediment quantity and transport distance from a particular road section has been developed and is presented in this paper. The method includes state-of-the-art equipment and a protocol for sediment data collection.

The objective of this paper is to present a method that can be used to measure (1) sediment production from roads and (2) sediment transport from roads to small streams. The system is designed to sample road sediment discharge during a rainfall event with as little disruption to transport as possible and to simultaneously collect data on several variables that influence the amount of sediment produced: road surfacing material, traffic intensity, gradient, age, construction method, and precipitation. For measuring sediment transport from roads to small streams, the method is designed to sample and compare sediment simultaneously at the road and downslope in small streams. The method can be used to evaluate road erosion to determine the most effective practices for reducing sediment production.

Previous Research

Various 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 altered sediment yield resulting from road construction and timber harvesting (Beschta 1978, Brown and Krygier 1971, Fredriksen 1970). These studies monitored sediment yield at the mouths of the watersheds but did not segregate road surface erosion from yields caused from mass wasting and other sources of sediment. Other studies conducted in the Appalachian Mountains, used Coshocton wheels to take proportional suspended sediment samples from a road section to calculate sediment yield for different road surfacing materials (Kochenderfer and Helvey 1987, Swift 1984b).

Several studies have used simulated rainfall and settling basins to determine sediment production from road plots under varying conditions for simulated storms (Burroughs and others 1991, Foltz and Burroughs 1990). One study measured the distance sediment visibly moved downslope 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 downslope transport rate of sediment (Haupt and Kidd 1965). In the Oregon Coast Range, Black and Luce (1997) used weighing sediment traps to measure sediment production from roads of varying slopes and road segment lengths.

Bilby (1985) sampled suspended sediment and turbidity in a roadside 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 streambed. Duncan and others (1987) analyzed the transport of sediment from roads, through ephemeral stream channels, and into larger fish-bearing streams. Sediment collected in a roadside settling pond was added to the stream during receding flows, and grab samples were separated into three size classes to determine the distance and efficiency of sediment transport. Bilby and others (1989) measured sediment eroded from forest roads using H-flumes and automatic pumping samplers on the downslope side of five cross drain culverts on mainline and secondary road segments. In addition, over 2,000 drainage structures were surveyed in three large watersheds in Oregon and Washington to determine connectivity with first-order or larger streams.

Several variables have been found 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). Two of the most important were gradient and road surface material particle size. Studies in the Appalachian Mountains found depth, composition, and size of surfacing material to be significant in controlling the production of sediment (Kochenderfer and Helvey 1987, Swift 1984a).

Traffic intensity and vehicle characteristics affect many of the physical parameters that have been shown to be significant to sediment production from road surfaces (Bilby and others 1989, Reid 1981, Reid and Dunne 1984, Swift 1984b). Traffic breaks down surfacing material resulting in finer surface gradation and increased sediment transport from the road surface. Traffic also can produce wheel ruts on road surfaces, thereby increasing sediment erosion and transport (Fahey and Coker 1989, Foltz and Burroghs 1990, Haydon and others 1991). The concentration of water in wheel ruts increases energy available 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 and others 1991). Grading of the road surface to eliminate runoff concentrations in rills and ruts can reduce sediment production; however, grading also can disturb hardened or armored surfaces and increases quantities of loose erodible material available for transport. Other variables that can significantly affect sediment production include precipitation intensity and duration, vehicle tire pressure, and erosion of cut and fill slopes (Kochenderfer and Helvey 1987, Megahan and Kidd 1972, Powell and Brunette 1991, Reid 1981).

Site Selection

The following is a list of several important site selection criteria that should be considered when using this method to determine sediment delivery from a road:

1. A road section with a uniform gradient is required to determine the effect of slope.

2. A road surface that has a well-defined source area is necessary to accurately calculate sediment production per unit area.

3. To quantify the sediment produced primarily from the road surface, the road section should have cut slopes and a ditch with stable, erosion-resistant surfaces. Heavily vegetated or rocky cut slopes and ditch are ideal for isolating the source of sediment to the road surface. Where cut slopes or the ditch are important sources of sediment, sampling sites should be set up to determine sediment contributions from these sources. Reid (1981) sampled paved road segments to isolate the amount of sediment produced from cut slopes and ditches.

4. If effects of traffic are being studied, the road must have active hauling during the study period and during precipitation events.

5. Minimal interception of off-site surface and subsurface water by the ditch at the road study section will greatly simplify interpretation of results; this can be difficult, however, in mountainous terrain. The methods for analysis described later help account for the intercepted surface and subsurface water.

6. The road section must be located close to a stream if tracking sediment delivery into streams is a goal.

Figure 1–Topographic survey of a measured road segment and the instrumentation used for sampling road surface erosion.

7. The study site chosen should be representative of the construction methods and materials used for that area. A topographic survey of the road surface is not required but is useful for calculating average road gradient and determining the source area contributing surface runoff and sediment (fig.1). This source area includes the road surface from the drainage divide (crown) to the ditch.

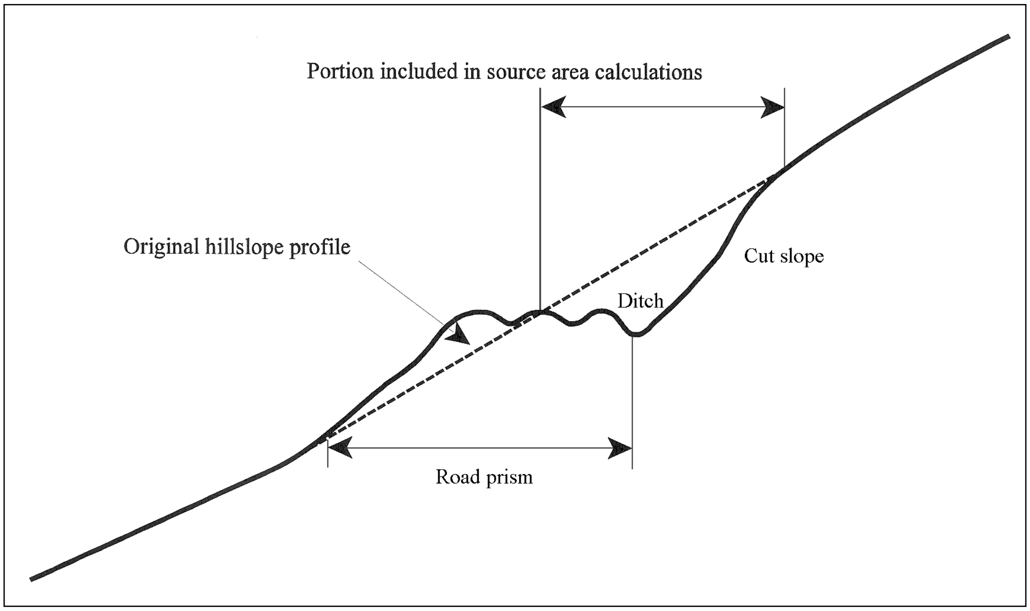

Figure 2—Cross section of a typical crowned road prism and the road surface area that typically contributes runoff to the inside ditch. Note the wheel ruts resulting from traffic use.

There generally will be additional criteria to be considered depending on the site conditions and management factors. Meeting the previously mentioned criteria exactly may limit the number of potential sites significantly; therefore some flexibility and judgement is advised in the selection process.

Most roads in southeast Alaska, where this method was developed, are crowned with a ditch on the uphill side. The crown of the road acts as a surface drainage divide, which results in half of the road contributing runoff to the inside ditch (fig. 2).

Instrumentation

Data Logger

The main controller and data collector for each of the sample sites consists of a data logger in a weatherproof enclosure. Each of the enclosures contains a circuit board (“termination strip”) to which several sensors and relay switches can easily be connected. The data logger controls the timing and frequency of sampling during storm events. Loggers are set up to scan the pressure transducers on a 5-second interval and log the total or average readings every 15 minutes. For these studies, Unidata loggers[1] were used, which have a memory capacity between 64 and 128 kilobytes depending on the model. This allows a maximum logging period of 200 to 400 days at a typical sampling site. More frequent downloading, however, allows determination that all the sensors are working correctly. The data loggers have the capability to monitor several instruments simultaneously as well as activate sampling equipment based on readings from other sensors. Data are downloaded via a serial cable connected between the data logger and a palmtop, laptop, or desktop computer. This allows an on-site visual check of the raw data to determine if equipment is working and whether changes to the sampling program need to be made. Plotting the data on a portable computer by using spreadsheet software provides a quick review in the field.

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Rain Gage

A 15.2-centimeter diameter tipping bucket rain gage with a 0.25-millimeter bucket is connected to the data logger, which records the total rainfall for 15-minute intervals. According to the manufacturer, Unidata, the gage has an accuracy of 1 percent up to 50 millimeters per hour. Storm intensity and duration is derived from the sampling protocol for rainfall as discussed below. A similar protocol for the collection of sediment samples also is discussed below.

Traffic Counters

Two different types of traffic counters are used to determine traffic levels for the study sections. Both systems are unable to distinguish between light or heavy vehicles; on-site sample counts of traffic distribution, however, can be used to estimate the relative frequency of light and heavy traffic. One type is a pneumatic road traffic counter that counts axle passes through a connection to a data logger that records total axles during 15-minute intervals. The pneumatic pressure sensor is connected to a rubber tube laid across the road that 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. A difficulty with this type of traffic counting system is wear on the rubber tubing, which can develop leaks and fail. 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.

Alternatively, a traffic counter (Compu-Tech TR-41P) with a passive infrared sensor (Compu-Tech PIR-70) also was found to be effective. This counter can detect movement or heat in a narrow 60- by 120-centimeter detection zone up to 30 meters away. When an object is detected, the sensor sends a signal to a counter that keeps a cumulative total and relays the same signal to the data logger where counts also are 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, which 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 are reliable.

Parshall Flume and Hydrostatic Pressure Transducer

For convenience and accuracy, a prefabricated fiberglass Parshall flume is installed at each of the sampling sites. Each flume is leveled and secured in the ditch with sand bags, which also direct the flow into the inlet (fig. 3). The Parshall flume is preferred for this study because the head drop causes turbulence and mixing of water passing out of the flume. This permits collection of a more representative sediment sample and reduces the potential for sediment settling in the outlet, thereby reducing the effectiveness of the flume. Prefabricated Parshall flumes range in throat size from 2.54-centimeters up to several meters. The capacities and range of the 5.1- and 7.6-centimeter Parshall flumes work best for discharges encountered in roadside ditches and small streams. The stage discharge equations for these two flumes are $Q = 5.778 H^{1.55}$, where Q is water discharge in liters per minute, and $Q = 8.566 H^{1.547}$, respectively. H is stage height measured in centimeters. Each flume has a staff gage molded into the sidewall opposite the outlet to a stilling well (fig. 3). The staff gage has depth increments for measuring stage height visually. The stilling well is constructed from 5.1-centimeter ABS or PVC pipe and fittings.

A hydrostatic pressure transducer is clamped in the stilling well at the elevation of the flume floor and connected to the data logger. The transducer used has an accuracy of 4-millimeters after calibration and a resolution of at least 1 millimeter. The data logger program or “scheme” is set up to scan the pressure transducer every 5 seconds, average those readings every 15 minutes, and record that average as the stage height. Data are downloaded into a spreadsheet, and the discharge is calculated by using the appropriate equation.

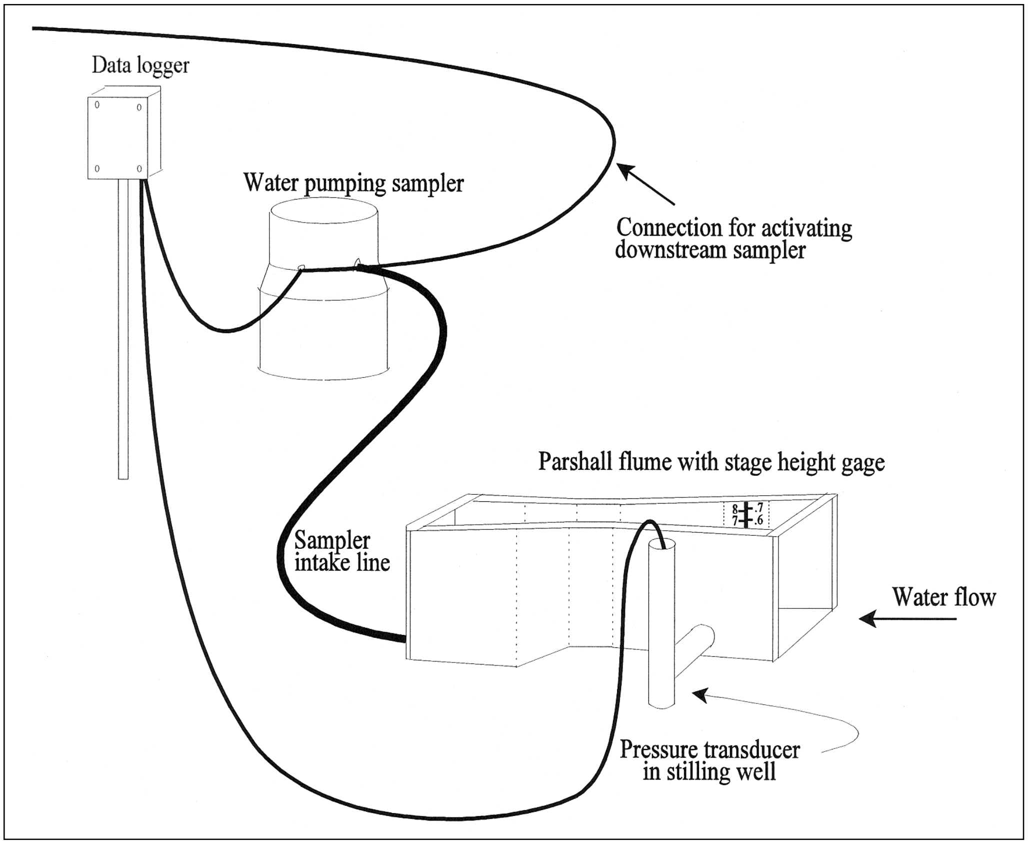

Figure 3—Instrumentation used to collect road erosion samples and discharge measurements from the road surface in roadside ditches.

Pumping Sampler

Suspended sediment samples were collected by using American Sigma pumping samplers, which have a microprocessor with the necessary software programs to set up a sampling scheme. These samplers detect liquid in the tubing so that a consistent volume is sampled each time. In addition these samplers can:

- Be configured with 24 polypropylene 1 liter sample bottles
- Record time, date, and any errors in sampling
- Be programmed to sample based on time intervals or flow proportions
- Sample by using composite or discrete modes with either samples per bottle or bottles per sample options
- Have the option for a signal splitter for setting up samplers in series. This allows the sampler to receive pulses from the data logger relay switch or from other samplers and send a signal out to one or two additional samplers.
- Offer many other features and configuration possibilities not discussed here, which may be useful for specific applications or locations. There are many options in the sampler program for setting sampling frequency, size, and options to create a composite sample, including combinations of discrete and composite sampling.

For these studies, the intake for the samplers were mounted to the bottom of the flume after the head drop and near the outlet. The head drop increases the velocity and enhances the mixing of transported sediment, providing a well-mixed sample. The samplers located on the small streams used a bent, free-swinging rod with the intake attached as described by Beschta (1980) but with a different triggering mechanism to initiate sampling.

The samplers were programmed to collect 1-hour composite (or multiplexed) samples consisting of four 200-milliliter subsamples pumped at 15-minute intervals into one bottle. With this composite sampling scheme, the samplers have a capacity of twenty-four 1-hour composite samples, a total of ninety-six 15-minute subsamples. The composite method of sampling has some advantages and disadvantages. One advantage is being able to extend the sampling duration to sample long-duration precipitation events that may start with low intensities and increase several hours into a storm. Another advantage is that it reduces the number of sample filtration analyses. A disadvantage of compositing samples can occur when rainfall events are less than 1 hour long, which can lead to two different events being combined into one sample bottle. Another disadvantage is that the sediment discharge curve may not be characterized as well as it would with discrete samples and shorter duration sampling intervals. With small source areas, the limited sediment may be flushed rapidly from the ditch and stream, which may be a cause of some of the variability found in the sediment concentration and discharge relation described later.

Depending on the sediment load, pumping samplers may not sample all sediment produced by roads and transported as bedload. In these studies, sediment traps were not chosen to track the sediment movement downstream from the road. The samples collected by the pumping samplers were considered to be representative of the sediment transported through the ditch and stream. The method discussed in this paper is designed to sample erosion and transport with little disruption to the flow in order to track downstream sediment movement. To determine the bedload contributions in areas where pumping samplers may not adequately sample bedload, the method by Megahan and Ketcheson (1996) that measured sediment volumes below fills, rock drains, and culverts could be combined with this method to track both suspended and bedload sediment downstream without disrupting the transport process.

An important consideration with these samplers is power consumption, as they require frequent battery recharging when internally mounted rechargeable Nickel-cadmium (Nicad) batteries are used. Data from 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. These provide power for over 500 samples during a field season without requiring a recharge and are much more cost effective than the Nicad batteries. The disadvantages of the marine batteries are the weight, transportation difficulties, potential for theft, and hazardous material contained in lead acid batteries.

Sampling Protocols

Depending on the objectives of the sampling project, various sampling protocols and site installations can be used. Two different sampling installations were used to collect road erosion data at these study sites. The first, referred to as “road erosion sites,” collects data for a road segment by sampling ditch flow directly downstream of the contributing road surface. The second, referred to as “downstream transport sites” adds additional sampling stations located in the ditch and in small ephemeral or perennial streams for tracking road-generated sediment to larger streams (fig. 4).

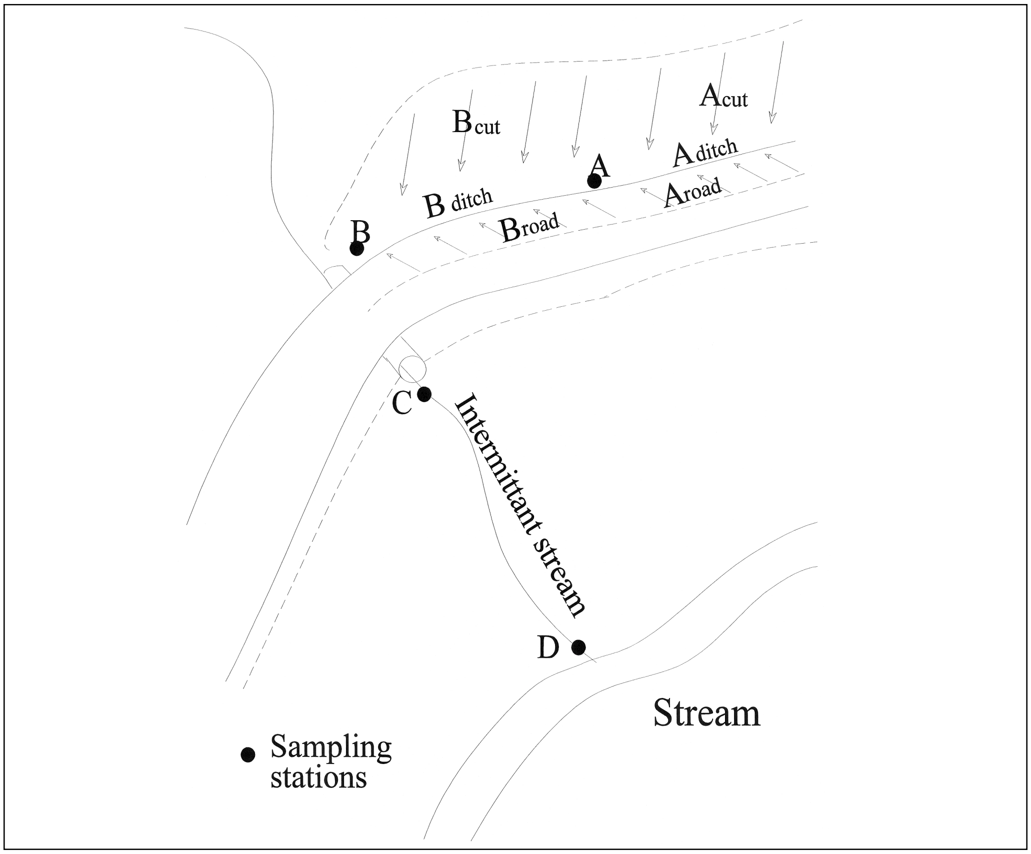

Figure 4—Diagram of samplers setup in series to determine the amount of sediment produced from a road segment and transported downslope to a larger stream. In segments A and B, sediment is delivered from the road cut to the ditch and sampled at stations A, B, C, and D.

Road Erosion Sites

This method is used to quantify surface erosion on road sections with known site characteristics to determine the most important site characteristics that contribute to erosion. At these sites, only the amount of sediment from the contributing road segment is measured in the adjacent ditch. At least three separate sampling sites are installed on three nearby road segments with similar prism and material characteristics to define the relation between suspended sediment load and independent variables such as slope, traffic, and precipitation. The typical sampling site is equipped with a pumping sampler, Parshall flume, hydrostatic pressure transducer, and data logger (fig. 3). A rain gage is located at one or more of the sampling sites, as needed for representative measurements.

Equipment is installed, programmed, and tested before the samplers are set for activation by the data logger. The logger monitors and records the stage height measured by the pressure transducer in the stilling well until a preset discharge is reached. Then, the logger begins sending pulses at 10-second intervals to the sampler. The sampler is programmed to begin sampling after a total of 90 pulses. The depth at which activation of pulses occurs is set small, about 2-centimeters, to capture the initial flush of sediment at the beginning of a storm event. Gravimetric analysis is performed, by using standard methods (APHA and others 1985), on composite samples to calculate the total amount of sediment passing through the flume during the 1- hour sampling periods. Data collected for traffic, precipitation, and site-specific variables, such as gradient, surfacing material, and ditch condition are recorded for the same period for use in multiple-regression analysis to relate these independent variables to hourly and total-storm sediment discharge.

Although the purpose of this paper is to report methodology, some data are presented to illustrate analysis procedures. Data collected during three field seasons show the highly variable relation between suspended sediment concentration and the hourly-averaged discharge (fig. 5). Bilby and others (1989) explain the low correlation between concentration and discharge for road surface erosion to be the result of supply limitation. To reduce the variability found in this relation, sediment concentration (milligrams per liter) is multiplied by the average discharge (liters per minute) to calculate the hourly sediment discharge (milligrams per minute converted to grams per hour).

These data are made more useful by examining sediment delivery for entire storm events. Storm events were defined by examining the precipitation and discharge data to determine events with sufficient intensity and runoff to initiate erosion. In our studies, storm events were between 3 and 24 hours long. The hourly sediment discharge (grams) can be summed to determine the estimated total sediment delivery for the storm event. To compare among sampling sites, total sediment delivery is normalized to a square-meter area by dividing by the size of the contributing area. Precipitation total in millimeters for the storm is plotted versus storm sediment in grams per square meter (fig. 6). Other information for the road segment such as ditch condition and road grading or other maintenance is noted in field notebooks. The average gradient of the road segment is calculated by using the topographic survey.

Composite samples found to be from two different rainfall events are not included in the analysis. This situation results from a drop in stage below the activation threshold of the sampler, followed by a stage increase during the subsequent event. This can be a problem with short rainfall events, which last less than 1 hour, or with low-intensity storms with intermittent rainfall. Neither scenario is common because most of the storms recorded in southeast Alaska produce enough runoff to sample for the entire 24-hour period. Furthermore, the problem is easily detected because the pumping samplers keep a record of when each sample was taken by date and time, which can be compared to precipitation records. Other geographical areas with shorter duration storms will require more frequent data collection during the brief sampling periods.

Downstream Transport Sites

Connecting samplers in a downstream series enables an estimation of the transport of suspended sediment from a road to a larger stream (fig. 4). Discharge and sediment load contributed from each sampling site can be calculated by using the equations listed in appendix A. Once sampler A (fig. 4) samples, activated in the same manner as at the single sampling site, it is programmed to send a signal through a signal splitter box to the next sampler in the series. Sampler B (fig. 4) is set up to sample after one pulse so it samples immediately after sampler A. After sampler B samples, a signal is sent through the signal splitter box to samplers C and D (fig. 4), the other two samplers in the series, which are also programmed to sample at one pulse. Sampler A continues to count 10-second pulses until a total of 90 are reached, reinitiating the sampling sequence.

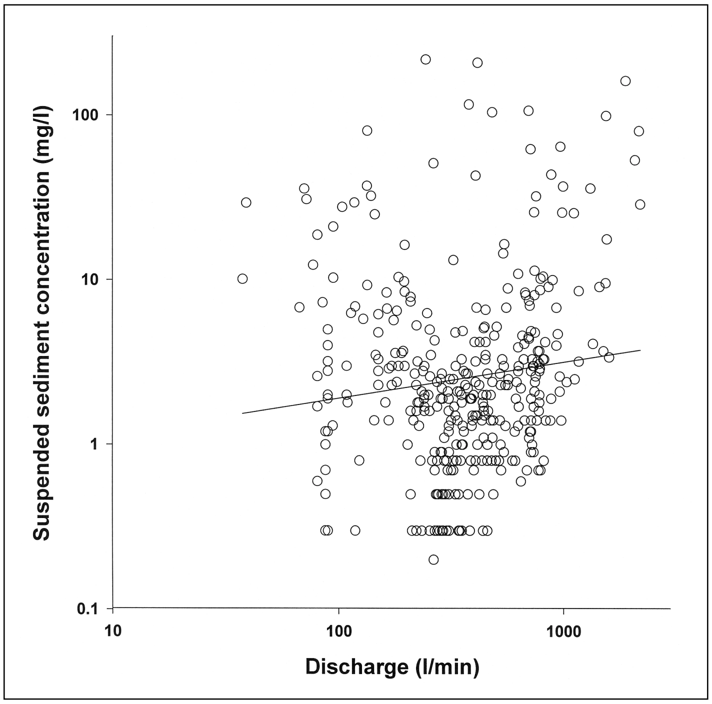

Figure 5—Average discharge versus suspended sediment concentration for 1-hour samples at one sampling site collected for field seasons 1995-97. A least-squares linear regression fit for the data also is shown.

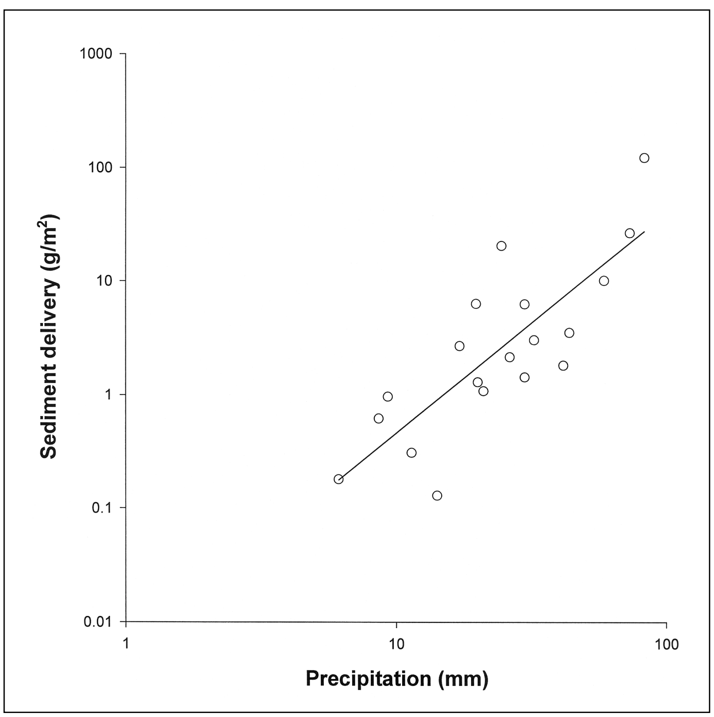

Figure 6—Storm precipitation total versus storm sediment delivery total per square meter. A least-squares linear regression fit for the data also is shown. Data represent storms over the three field seasons 1995-97.

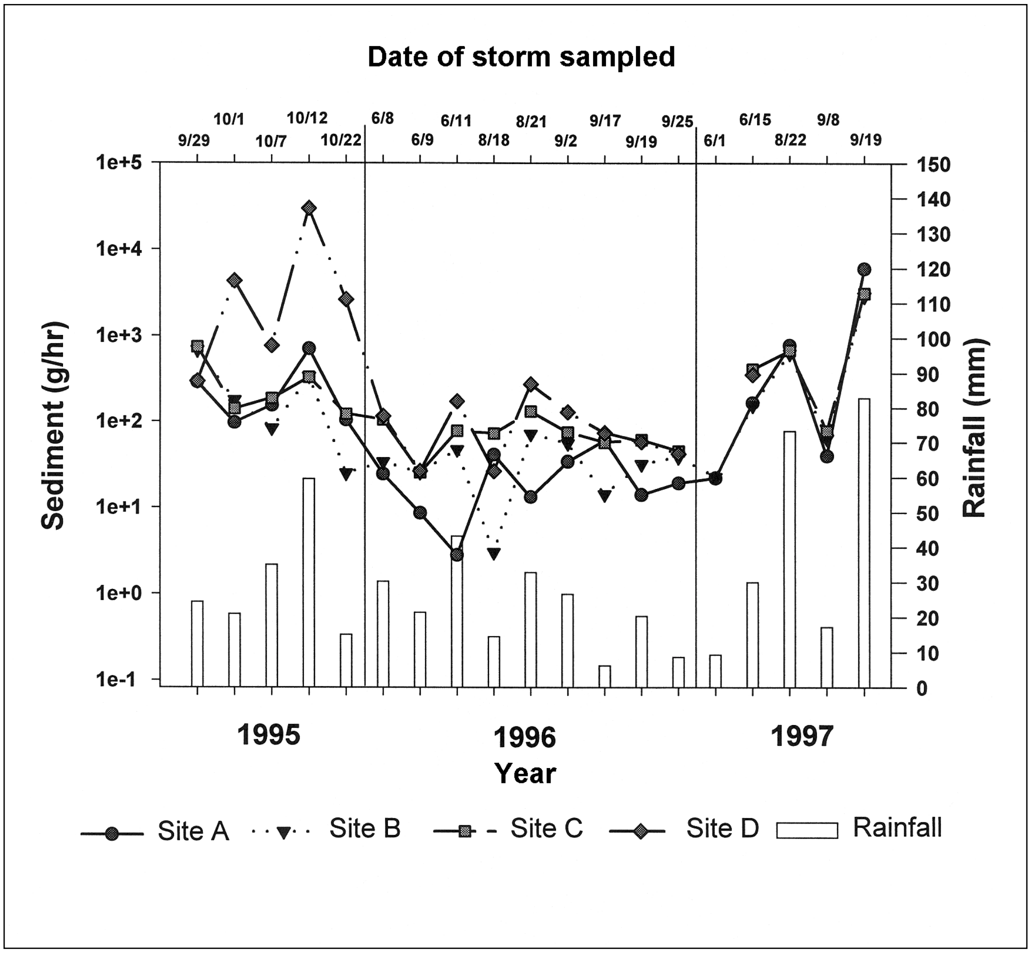

Figure 7—Average hourly sediment discharge for 19 storms sampled during 1995-97 for sampling stations A-D (fig. 4). Precipitation totals for the storms also are given. During 1997, only one event was sampled at site D because black bears (*Ursus americanus*) disrupted equipment.

All sediment samples are analyzed by using the same procedure described above for single sampling stations (see the appendix). Hourly sediment discharge is calculated as well as hourly totals for traffic and precipitation. Other site-specific variables are noted for use in a more indepth analysis by using multiple regression. Total sediment discharge (grams per hour) from the road sampling sites (A and B) is compared to that in the small stream (sites C and D) (fig. 7) by using equations in the appendix to calculate the quantity of sediment transported from the road to the larger stream. Using sediment discharge eliminates the dilution effect that would be evident if concentrations (grams per liter) were used for direct comparisons.

Surfacing Material Testing

Samples of the surfacing material are collected and sent to a materials laboratory for testing gradation and durability by using standard gradation size analysis and the Los Angeles Abrasion test (LAR AASHTO T-96). These are important factors in development of prediction equations for sediment produced from roads. Gradation indicates the proportion of fine particles that are easily eroded from the road surface during precipitation events. The Los Angeles Abrasion test indicates how easily the road surface materials are reduced to a transportable size because of traffic volume and vehicle characteristics.

Expected Uses for the Resulting Data

There are several expected uses of the data from this sampling and monitoring technique. Comparing roadside to downstream data will be useful in determining the transport of sediment to larger streams. Furthermore, sediment production can be predicted from precipitation data based on measurable road characteristics. These characteristics or variables include, but are not limited to, traffic intensity, surfacing and ditch material quality and grain size, road ditch and stream gradient, ditch condition, and road and ditch maintenance. Combining data from several different road study sections could be used to develop a regression model for predicting sediment production and routing for a more diverse set of conditions. The data also could be used to calibrate and validate other models such as the water erosion prediction project model (Elliot and others 1994) for localized conditions.

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Appendix

Runoff and Sediment Quantification

$q_{\text{cut A}}$ = discharge contribution from cut slope for area A shown on figure 4.

Q_A = total discharge for all contributions for area A shown in figure 4.

$s_{\text{cut A}}$ = sediment load contribution from cut slope for area A shown on figure 4.

S_A = sediment load total for all contributions for area A shown in figure 4.

Σq_i = other runoff, surface and subsurface interception

Σs_i = other sediment inputs

<u>Discharge</u>

<u>Station A</u>

$$q_A = q_{cutA} + q_{ditchA} + q_{roadA}$$

$$Q_A = q_A + \Sigma q_i$$

<u>Station B</u>

$$q_B = q_{cutB} + q_{ditchB} + q_{roadB}$$

$$Q_B = q_B + (q_A + \Sigma q_i)$$

Since, Q_B and Q_A will be measured:

$$q_B = Q_B - Q_A$$

<u>Sediment load</u>

<u>Station A</u>

$$s_A = s_{cutA} + s_{ditchA} + s_{roadA}$$

$$S_A = s_A + \Sigma s_i \pm \Delta storage$$

<u>Station B</u>

$$s_B = s_{cutB} + s_{ditchB} + s_{roadB}$$

$$S_B = s_B + (s_A + \Sigma s_i) \pm \Delta storage$$

Since, S_B and S_A will be measured:

$$s_B = S_B - S_A \pm \Delta storage$$

Station C

$$q_C = q_{channelC}$$

$$Q_C = q_C + q_B + (q_A + \Sigma q_i)$$

______ $q_C = Q_C - [q_B + q_A + \Sigma q_i]$

______ $q_C = Q_C - Q_B$

Station D

$$q_D = q_{channelD} = Q_D - Q_C$$

Station C

______ $s_C = s_{channelC}$

$$S_C = s_C + s_B + (s_A + \Sigma s_i)$$

______ $s_C = S_C - [s_B + s_A + \Sigma s_i]$

______ $s_C = S_C - S_B \pm \Delta storage$

Station D

$$s_D = s_{channelD} = S_D - S_C \pm \Delta storage$$

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