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Sediment Production From Forest Road Surfaces

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Erosion on roads is an important source of fine-grained sediment in streams draining logged basins of the Pacific Northwest. Runoff rates and sediment concentrations from 10 road segments subject to a variety of traffic levels were monitored to produce sediment rating curves and unit hydrographs for different use levels and types of surfaces. These relationships are combined with a continuous rainfall record to calculate mean annual sediment yields from road segments of each use level. A heavily used road segment in the field area contributes 130 times as much sediment as an abandoned road. A paved road segment, along which cut slopes and ditches are the only sources of sediment, yields less than 1% as much sediment as a heavily used road with a gravel surface.

INTRODUCTION

Logging accelerates sediment production in the Pacific Northwest, and excessive sediment loads decrease the survival of anadromous fish [*Anderson*, 1954; *Tagart*, 1976]. It would be advantageous to minimize the effects of logging on streams, but to do so, it is necessary to understand the sources of sediment and their relative importance. Successful sediment control also requires that sediment production rates can be easily monitored once the sources are known.

Erosion of gravel road surfaces is an important source of sediment and is of particular concern both because a high proportion of the eroded sediment is introduced directly to streams and because most sediment from this source is finer than 2 mm; this fine-grained material is the size most harmful to fish and to water quality [*Tagart*, 1976; *Cederholm et al.*, 1981]. While the rate of sediment production from road-related sediment sources such as landslides is easily measured and widely reported, quantitative studies of road surface erosion are rare, and thus there are few data available that allow the evaluation of the importance of this sediment source relative to other logging-related sources. The study discussed here was designed to provide such information using an easily implemented, low-cost, short-term monitoring program and represents a portion of a larger study which compares road surface erosion to sediment production from other sources associated with forest roads [*Reid*, 1981; *Reid et al.*, 1981].

PREVIOUS WORK

Gravel-surfaced roads have long been recognized as an important source of fine-grained sediment. The total erosion rate from road surfaces was first estimated by *Gilbert* [1917], but measured erosion rates were not reported until *Hoover* [1952] described studies of erosion from skid trails and access roads in North Carolina. Successive measurements of cross sections disclosed surface lowering equivalent to a sediment production rate of 1420 m^3/road km per year over a 4-year period. Similar studies in West Virginia [*Weitzman and Trimble*, 1955] concentrated on skid trails and demonstrated that heavily used skid trails were lowered at 4 times the rate of lightly used trails. This method, however, cannot distinguish between surface lowering due to erosion and that due to compaction.

At the same time, multiple regressions of average sediment yield against a variety of basin variables showed that sediment production is positively correlated with road length [*Anderson*, 1954]. *Cederholm et al.* [1981] demonstrated a positive correlation between the proportion of fine sediment in salmon-spawning gravels and the length of roads in a basin.

During the 1960's, results from long-term monitoring of catchments in logged areas began to be reported, but these studies do not isolate the effects of different sediment sources within the monitored basin. In cases where road effects were investigated by delaying logging, all that could be distinguished was the effect of the road construction, since the roads were not subject to traffic until logging began.

More recently, researchers have begun to measure sediment loss from roads directly. *Hafley* [1975] and *Wald* [1975] sampled culvert effluent, Wald showing that average sediment concentration from heavily used gravel roads is higher than that from roads not in use. *Wooldridge* [1979] demonstrated similar results by monitoring sediment concentration in streams above and below inflow from a road culvert. The problems posed by *Gilbert* [1917], however, remain: How much sediment is mobilized by road surface erosion, and how important is this source in relation to other sources of sediment? This paper addresses the first of these questions, and a companion [*Reid et al.*, 1981] addressed the second.

FIELD AREA

Fieldwork was conducted in the central Clearwater basin, which lies between elevations of 50 and 1000 m on the western slope of the Olympic Mountains of Washington State (Figure 1). The 375-km^2 basin is clothed in a dense forest of western hemlock (*Tsuga heterophylla*) and silver fir (*Abies amabilis*) which supports both an important timber industry and spawning grounds for coho salmon and steelhead trout. Hillslopes average 35% in the north part of the basin and 60% in the south and are underlain by Tertiary marine siltstones, sandstones, and graywackes of the Hoh rock assemblage. The soils of the area are inceptisols averaging 50 cm in depth outside of topographic depressions. Textures are locally coarse, with stones larger than 5 mm accounting for 40–90% of the soil material [*McCreary*, 1975]; silts and clays constitute an additional 10–40%. The drainage density is 9.3 km/km^2, as measured from 1:62,500 topographic maps and 1:12,000 aerial photographs, using the method described by *Leopold and Miller* [1956]. Unlike most of the Olympic Pe-

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ninsula, the basin remained largely ice-free during the most recent glacial advances.

Between 1973 and 1978, precipitation averaged about 3900 mm/yr in the study area, falling primarily as low-intensity showers between October and May. Snow is of importance only in the higher parts of the study area, staying on the ground for up to 12 weeks each year. Mean annual runoff for 1973–1978 ranged between 3400 and 3600 mm for three gauged tributaries with drainage areas of 15–25 km^2 (data provided by the Washington State Department of Natural Resources).

About 80% of the basin is managed for timber production on a 60- to 80-year sustained-yield cutting cycle by the Washington State Department of Natural Resources. Logging is carried out using a high-lead clearcutting system which requires only a low density of roads. Road density averaged 1.5 km/km^2 in 1980, when 35% of the Clearwater basin had been logged.

Although about 20% of the road length in the basin has been paved, most of this length is along the main valley. The area of concern to this study comprises the 15- to 25-km^2 tributary basins, where most roads are gravel-surfaced "management standard" roads, which average 4–5 m in width and are built with a 40-cm-thick bed of compacted gravel ballast and a maximum gradient of 16%. Roads built to provide access to single clearcuts are generally narrower and steeper but are built with a similar design; these roads are abandoned between successive harvests, and culverts are replaced by cross ditches. Gravels used on the road surfaces are well-indurated sandstone and graywacke pebbles found in glaciofluvial terraces of the Clearwater and neighboring basins. Fine sediments eroded from road surfaces are probably derived both from breakdown of the surfacing material and from the forcing upward of fine-grained sediment from the road bed as traffic pushes the surfacing gravels into the bed. Topographic surveys of road segments and observations during storms show that 16% of the runoff generated on a typical road surface in the Clearwater basin is diverted off the outer side of the road as sheet flow, while the rest eventually flows into an inboard ditch, whence it flows through a culvert, into a flume, and, in 75% of the cases, into a stream. The incidence of flumes is unusually high in the Clearwater basin as a result of intensive efforts to prevent drainage-related landslides. The other 25% of the culverts empty their outflow directly onto the hillslope below the road, where the runoff infiltrates. Flow is often continuous in ruts on the bearing surface of the road for 100–200 m.

Most road segments in the study area have an associated cutbank holding an angle of 55–70° with an average height of about 3.4 m, of which 72% is covered by a coarsely armored debris mantle. The rocks of the debris mantle are derived from bedrock exposed in the cutbank, and they generally range in diameter from about 1 to 50 mm in areas of siltstone and up to 200 mm at sites underlain by sandstone. Armoring is generally absent only where no bedrock is exposed in the roadcut. Fine-grained sediment is present in layers within the debris mantle and appears to originate from the thin soil mantle exposed atop the cutbank. Roadside ditches are partially filled with gravel from the cutbanks, but resting on the coarse ditch material are bars of sand or silt, which represent the grain size of the bedload in transport in the ditches. Ditches are usually cleaned out during road maintenance operations, with ditch-fill material being spread onto the road surface.

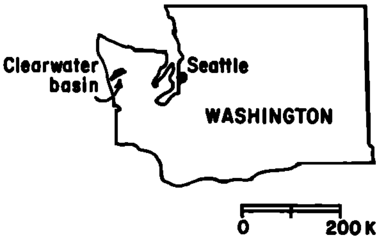

Fig. 1. Location of the study area.

APPROACH AND FIELD METHODS

The goal of the 1-year field study was to develop a simple and inexpensive method of determining average sediment production rates from road surfaces of a variety of characters. The method developed during the study can be used in other regions to measure sediment loss and study its controlling factors and does not require expensive equipment or permanent installations. Continuous monitoring of surface erosion was not possible for our purpose both because of budgetary and personnel constraints and because a given length of road did not undergo the same level of use for extended periods of time. Instead, a more flexible monitoring program was designed which provided for data collection from a number of sites which could be selected according to the level of road use occurring during a particular storm.

The study was based upon the sampling of rainfall, discharge, and sediment concentration in the catchments of road culverts. If a relationship could be constructed between the storm hyetograph and the hydrograph from a road segment, then a long-term rainfall record could be used to reconstruct a series of hydrographs for the road surface. If a relationship could also be constructed between discharge and sediment concentration, then the hydrographs could in turn be used to reconstruct a long-term record of sediment discharge. Integration of the sediment discharge curve would then provide the sediment yield from the road segment during the period of interest. This procedure allows the calculation of sediment yield averaged over the duration of the rainfall record and thus avoids producing results relevant only to the specific storms during which runoff was sampled.

Ten segments of road older than 5 years were selected for monitoring. Each segment consists of the drainage basin of a single culvert and was chosen to avoid any component of surface flow from springs or natural channels intercepted by the roadside ditch. Cutbanks were not observed to generate overland flow, and the ditches carried no base flow between storms, suggesting that subsurface flow was generally not present. Cutbank area is thus not included in the culvert catchment for the purposes of hydrologic calculations. The segments were selected to represent a variety of road types and intensities of traffic (Table 1). On gravel roads the traffic levels which we sampled were heavy (more than four loaded logging trucks per day), moderate (one to four trucks), light (no logging trucks but some light vehicles), and abandoned. Roads that had been heavily used until 2 days before measurements fell into a category referred to as temporary nonuse. Two segments of paved roads were also monitored in order to evaluate erosion rates from ditches and cutbanks. The number of trucks using a road segment during a day was determined by counting load receipts filed with the Department of Natural Resources for each logged unit.

TABLE 1. Description of Road Segments Monitored for Culvert Discharge and Sediment Concentration

Segment	Gradient, %	Ditch Length, m	Category*	Days Sampled	Number of Measured Hydrographs	Hydrographs Used in Construction of Unit Hydrographs: No.	Hydrographs Used in Construction of Unit Hydrographs: Category*
1	12	123	H, T, L	27	11	4	H
2	8	173	H, L	14	11	2	L
3	10	96	L	7	0		
4	9	187	T, L	8	12	2	T
5	8	204	M, L	10	9		
6	13	132	M, L	9	0		
7	9	176	P	10	1		
8	10	171	P	6	3	2	P
9	14	56	A	4	0		
10	15	64	A	11	3	2	A

*H, heavy use; T, temporary nonuse; M, moderate use; L, light use; P, paved; A, abandoned.

The gradients and lengths of the selected segments (Table 1) are typical for secondary roads in 10- to 25-km^2 catchments in the Olympic Mountains and range between 8 and 15% and 56 and 240 m, respectively. The values for the segments studied show a rough inverse correlation between length and gradient, in keeping with the road construction policies of the Department of Natural Resources. In the Clearwater basin the average road gradient is 10% with a corresponding culvert spacing of 165 m. We did not have the resources to document fully the individual effects of road gradient and segment length on erosion, but a multiple regression of measured sediment loss against discharge, road use, segment length, and gradient demonstrated the overwhelming importance of road use compared to length or gradient over the range of gradients sampled: Discharge alone explained 10% of the variance, use explained an additional 68%, and length and slope together explained 3% (Table 2). The equation used is of the form

$$C = UQ^pL^qS^r \tag{1}$$

where C is measured concentration, Q is discharge, L is road segment length, S is gradient, and U is a dummy variable representing road type. This formulation results in the following equation for regression:

$$\begin{aligned}\ln C = {} & a + \alpha_1 U_1 + \alpha_2 U_2 + \alpha_3 U_3 + \alpha_4 U_4 + \alpha_5 U_5 + b \ln Q \\ & + \beta_1 U_1 \ln Q + \beta_2 U_2 \ln Q + \beta_3 U_3 \ln Q + \beta_4 U_4 \ln Q \\ & + \beta_5 U_5 \ln Q + c \ln L + \gamma_1 U_1 \ln L \\ & + \gamma_2 U_2 \ln L + \gamma_3 U_3 \ln L \\ & + \gamma_4 U_4 \ln L + \gamma_5 U_5 \ln L + d \ln S \\ & + \delta_1 U_1 \ln S + \delta_2 U_2 \ln S \\ & + \delta_3 U_3 \ln S + \delta_4 U_4 \ln S + \delta_5 U_5 \ln S\end{aligned} \tag{2}$$

TABLE 2. Statistical Results of Multiple Regression of Measured Sediment Concentration Against Discharge, Road Segment Length, Gradient, and Road Type

Variable, in Order of Entry	Cumulative r^2	Overall F
$\ln Q$	0.10	27
U_i $U_i \ln Q$	0.78	167
$\ln L$	0.79	150
$U_i \ln L$	0.82	94
$\ln S$	0.82	87
$U_i \ln S$	0.82	not entered: not significant

Here the symbols a, b, c, d, α_i, β_i, γ_i, and δ_i represent regression parameters. The appropriate dummy variable (U_i) takes on a value of 1 according to the road type that a sample represents: U_1 for heavy use, U_2 for moderate use, U_3 for temporary nonuse, U_4 for light use, and U_5 for paved. In each case, all other dummy variables are set equal to zero. In the case of samples from abandoned roads, all dummy variables are set to zero. Because the relation between concentration and discharge was determined using covariance analysis for several of the road types (discussed later), the α_i terms serve as known constraints once the discharge variable enters the equation. The equation produced by regressing 244 data points is

$$\begin{aligned}\ln C = {} & U_1(0.76 \ln Q - 0.86 - 0.037 \ln L) \\ & + U_2(0.76 \ln Q + 16.3 - 4.07 \ln L) \\ & + U_3(0.78 \ln Q + 2.81 - 1.34 \ln L) \\ & + U_4(0.44 \ln Q + 15.2 - 3.89 \ln L) \\ & + U_5(0.72 \ln Q + 245 - 49.1 \ln L) \\ & - 10.9 + 2.52 \ln L - 2.24 \ln S\end{aligned} \tag{3}$$

The coefficients of determination and overall F for the included variables are shown in Table 2. The unexpectedly low importance of length and slope for predicting sediment loss is an indication of the extent to which decreasing road-segment length compensates for increasing slope. We thus designed our study to focus upon the effect of traffic intensity, the dominant control on sediment loss. Variations in slope and segment length merely add slightly to the variance of the relationships defined here for different categories of road use. In regions where road standards are less stringent, road gradient and segment length are expected to be more important controls on sediment loss, and the methods described in this paper could be used quickly to quantify their effects on sediment production.

Discharge at the mouth of each culvert was measured with a bucket and stopwatch during rainstorms. Measurements were made at 1/2- to 5-min intervals, and replicate samples show that discharge is reproducible to ±5% over the range of values measured; some of this uncertainty reflects real variations in discharge between the replicate samples. Water samples of 0.5–1 L were collected at 1- to 10-min intervals for filtering and gravimetric determination of sediment concentration, with sampling most frequent during rapid changes in discharge. On abandoned roads from which culverts had been removed, discharge was measured either by capturing the channeled flow where it dropped over a natural lip or by measuring the width, depth, and velocity of the flow. Rainfall intensity was monitored at each sampling location by measuring the volume of rain in a plastic gauge. Rainfall measurements were timed to correspond to noticeable changes in rainfall intensity, and durations varied between 1 and 25 min. Replicate measurements demonstrate that values are reproducible to ±5% for the average sampling interval. Drainage patterns on the road surfaces were mapped during the storms, and the topography of each road segment was surveyed with a tape and level.

Sediment yields measured at the mouths of culverts contain contributions both from road surfaces and from cutbanks and roadside ditches. As discussed later, these components may be evaluated using data from the monitored paved roads.

CULVERT DISCHARGE AND UNIT HYDROGRAPHS

Of the 46 measured hydrographs, only 12, representing seven storms, were generated by periods of relatively uniform rain intensity, and these were used to construct unit hydrographs for five of the roads (Table 1), providing the necessary relationship between rainfall intensity and culvert discharge. In some cases where the hydrograph peak due to the isolated burst of rain was not naturally isolated, isolations could be made by subtracting a constant "baseflow" generated by a low-intensity, background precipitation during which the high-intensity burst occurred. In other cases, an exponential curve could be fitted to the falling limb and extended beneath the next peak to separate discharge from two bursts of rain, and in one case the average value of the exponent for a road segment was used to construct a falling limb.

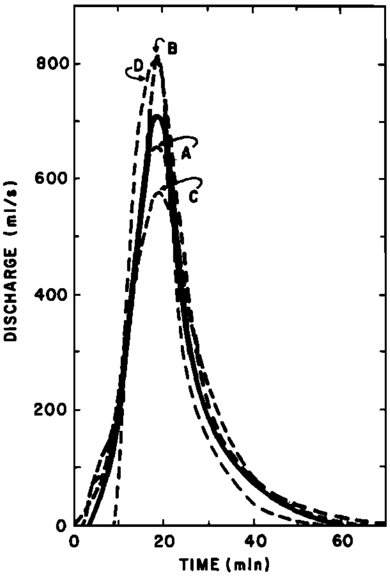

Fig. 3. Measured (dashed lines) and average (solid line) unit hydrographs for a heavily used road. Peaks A and B result from rain durations of 14–16 min, while peaks C and D are constructed by the addition of two 7-min hydrographs.

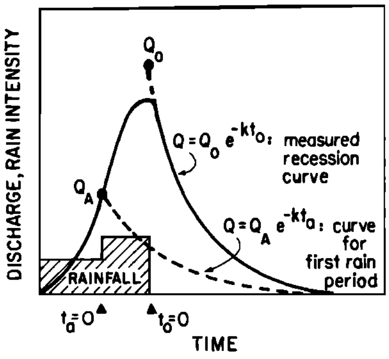

Fig. 2. Separation of a complex hydrograph into component simple hydrographs resulting from periods of uniform rainfall. The component hydrograph resulting from the second rainfall intensity is constructed by subtracting the ordinates of the constructed recession curve from those of the measured hydrograph. See text for an explanation of how the recession curve is constructed.

Once isolated, the hydrographs in most cases still exhibit the effects of changes in rain intensity during the rainfall peak. Where rainfall intensity and duration were well documented, the isolated complex hydrographs could be further separated into the component simple hydrographs resulting from each intensity. Standard methods for such separation were difficult to apply to runoff from the road catchments because of the variable duration of rainfall measurements. Instead, an iteration technique was developed which is based on the characteristics of runoff from the road segments. The falling limbs of the measured hydrographs are well fitted by exponential curves, and falling limbs from isolated rain bursts on the same road segment have similar exponents, as would be expected if a unit hydrograph could be constructed for the catchment. An exponential curve can be expressed as the sum of two-component exponential curves, each with the same exponent as the original curve. A provisional falling limb for the first period of uniform rain intensity was thus constructed using the expression

$$Q = Q_a e^{-kt_a} \tag{4}$$

where Q is the calculated discharge at any time t_a after the end of the first rain period (Figure 2) and k is the exponent of the falling limb of the measured complex hydrograph. The discharge at the time of initiation of the falling limb for the first hydrograph component is Q_a, and this value initially is selected from the rising limb of the measured hydrograph at the beginning of the second burst of rainfall ($t_a = 0$ in Figure 2). The volumes of runoff in the component hydrographs resulting from the constuction of the separating limb are then measured from the areas above and below the dashed curve in Figure 2 and are compared to the rain volumes generating them. If the ratios of runoff to rainfall are not equal, a new value of Q_a is selected at $t_a = 0$ and the process repeated until the ratios agree. If the durations of the rain intensity periods are equal, then the resulting simple hydrographs may be transformed to represent the same runoff volumes by using standard unit hydrograph manipulations, and the technique may be checked by comparing peak discharges, lags to peak, and forms of the rising limbs. Where comparisons were made, lags to peak agreed to within 2.5 min and peak discharges to within 12%.

The 12 isolated single-intensity hydrographs were generated by rain periods ranging from 6.5 to 14 min, but in order to be used in calculations, the hydrographs all had to represent the same storm duration. Hydrographs were thus adjusted to a 15 ± 1 min storm duration by subdividing the hydrographs by using the method described above and illustrated in Figure 2. Subdivided components could then be offset and added to each other or to the original hydrograph until a storm duration of 14–16 min was obtained. If the duration of the storm generating the hydrograph was 7–8 min, then the entire hydrograph was offset by that duration and added to the original. Hydrographs adjusted for storm duration by using these techniques agree quite closely with those measured for a full 14- to 16-min storm, as demonstrated by Figure 3.

The resulting hydrographs provide two or more samples from each of five road segments. Those from each segment were then normalized to a unit volume and superimposed to construct an average form, the unit hydrograph for a 15-min storm. When the unit hydrographs from each of the road segments are normalized by the area of the road segment and superimposed, all but that from the abandoned road are seen to agree closely (Figure 4). On this basis, two general unit hydrograph forms were used in subsequent calculations: one (based on eight measured hydrographs) for paved roads and gravel roads which are in use, and a radically different one (based on two measured hydrographs) for gravel roads which have been abandoned. The unexpected correspondence between hydrograph forms for paved roads and used gravel roads is probably due to the similarity in flow character between these roads. In both cases the flow is quickly channelled, either into the roadside ditch on paved roads or into road surface ruts on gravel roads. On the abandoned roads, however, the ditches are largely filled by debris, and the flow moves as a dispersed sheet over the well-armored, unrilled road surface.

Excess precipitation in the unit hydrograph computations was calculated as the difference between rainfall intensity and infiltration capacity, which was estimated from three sets of measurements on the gravel roads. First, the maximum rainfall intensities which generated no runoff were compared with the minimum intensities for which runoff occurred, and it was found that all storms with intensity greater than 0.5 mm/h generated runoff and five of six storms of lesser intensity did not. Second, total precipitation was compared with total runoff for four well-defined storms. This method produced an average infiltration rate of 0.8 mm/h over the duration of the storm, with a standard error of ±0.1 mm/h. Rainfall simulation experiments show stabilization of infiltration rates on these roads within the first 3–5 min of precipitation, so this value is expected to represent the average infiltration capacity. A third estimate was obtained by comparing culvert discharge with rainfall intensity for 11 periods of uniform rain intensity and constant discharge; this method indicates an average infiltration capacity of 0.3 ± 0.1 mm/h. Thus even the gravel roads are almost impermeable during winter storms, and an infiltration capacity of 0.5 mm/h was selected for use on the gravel-surfaced roads that had not been abandoned. Because the range of estimated values is so low in relation to the rainfall intensities generating most of the erosion, the uncertainty of the selected value has very little effect on the following calculations; temporal variation in infiltration rate is also expected to be unimportant in relation to storm intensities. In addition, because the first estimate is based on observations of the road surface, while the second and third estimates include the effects of infiltration on the shoulder and in the ditch, the agreement between the values suggests that infiltration rates are similar throughout the culvert catchment. If infiltration rates on the shoulder and ditch were substantially higher than those on the road surface, infiltration rates calculated using the second and third methods should increase as a function of rain intensity. No such relation exists.

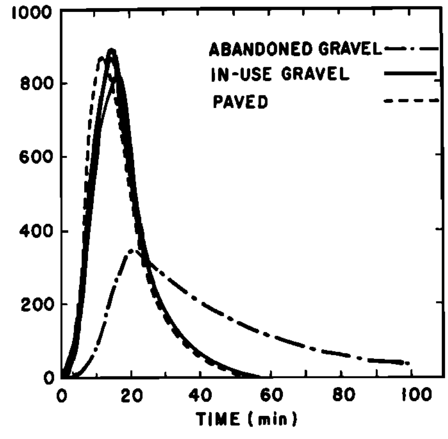

Fig. 4. Unit hydrographs from each road type, normalized for a catchment area of 850 m^2.

The bearing surface on paved segments is considered impermeable, and the remainder of the culvert catchment consists of a ditch and shoulder. If the estimated average infiltration capacity for gravel roads is assumed to apply to the off-road area, then the weighted average over the ditch, shoulder, and bearing surface of the paved road segment is 0.2 mm/h.

Qualitative observations show that surfaces on abandoned gravel roads are more permeable than those on roads which are still in use, but measurements from which infiltration capacities could be inferred were few. Comparison of total runoff to total precipitation for an 8-hour storm provided an approximate average infiltration rate of 0.7 mm/h, and an infiltration capacity of 1.0 mm/h is assumed for abandoned gravel roads during subsequent calculations.

Excess precipitation may now be estimated for any storm by subtracting infiltration capacity from rainfall intensity. This is considered a valid approximation, both because the duration of runoff after the end of a storm is generally quite short in relation to the length of the storm and because once the rain ends, the area available for infiltration decreases to just that of the flowing channels. Excess precipitation may now be used in conjunction with the unit hydrographs to construct a continuous culvert hydrograph from any precipitation record measured at 15-min intervals. A more complete discussion of the above procedure is available in the work by *Reid* [1981].

SEDIMENT CONCENTRATION AND SEDIMENT RATING CURVES

The sediment rating curves constructed for the 10 road segments demonstrate that data from different levels of road use on a single road segment plot in different fields (Figure 5*a*), while measurements from the same use level on different segments plot in the same field (Figure 5*b*). On this basis, data were grouped by intensity of road use, and a sediment rating curve was constructed for each type of road. In the case of the heavy use roads, samples represent a relatively wide range of traffic loads of between 16 and 32 trucks per day, and a simple regression of the pooled data did not provide a fit that corre-

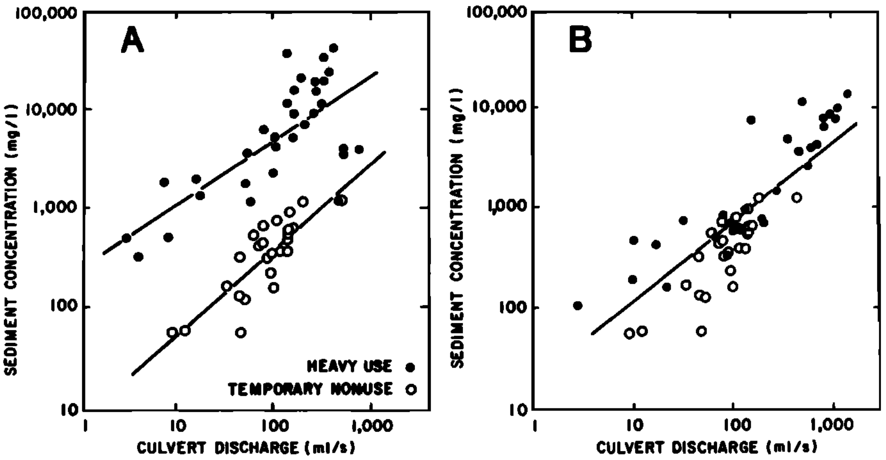

Fig. 5. (*a*) Relations between sediment concentration and discharge for a single road segment on adjacent heavy use and temporary nonuse days. The four heavy use samples falling within the temporary nonuse field were taken during the afternoon of a half-day holiday, and road use may have already ended for the day. (*b*) Relations between sediment concentration and discharge for two temporarily nonused roads (roads distinguished by symbols). Samples plotted with open circles are the same set plotted in Figure 5*a*.

sponded with the well-defined and near-equal slopes of the component data sets. We thus used covariance analysis to calculate the slope of the sediment rating curve. Data from temporarily nonused roads also represent a wide variety of road conditions due both to the varying length of time (i.e., 6–36 hours) since road use was discontinued and to the range of antecedent traffic levels. A sediment rating curve for these roads was thus constructed using the same method as for heavily used roads, and slopes of the relation agree within ±2% for the two road types.

In the case of the moderately used roads the few available data points represent a small range of discharges and thus are not sufficient to define a valid rating curve, although they plot in a well-defined field between those for heavily and lightly used roads and overlap with neither (Figure 6). An estimated rating curve could be constructed, however, using a slope constrained to equal the average shared by the two road types which were most similar to the moderate use category, the heavily used and temporarily nonused roads. The resulting slope is not significantly different from that indicated by a standard regression.

The observations that fields of data points are well segregated by use level and that variation within a single category of road use also appears to reflect traffic loads suggest that more detailed sampling may eventually allow the definition of a direct relationship between the number of vehicles using a road segment and the sediment yield from that segment.

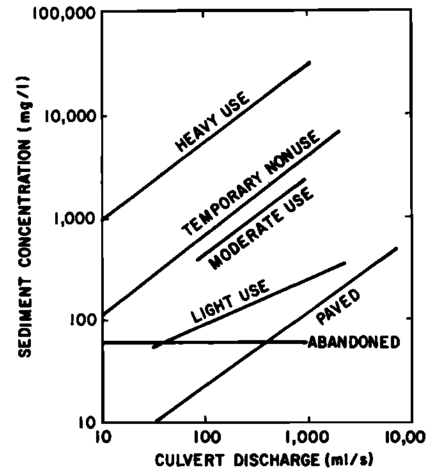

Fig. 6. Relations between sediment concentration and culvert discharge for six road types.

Curves showing sediment concentration as a function of water discharge were defined for six road types (Figure 6 and Table 3). Regressions for the slopes of these curves are significant at the 0.01 level in every case except those of the moderately used road (described above) and the abandoned road. The latter road type represents a condition of extreme sediment starvation because sediment of the size that may be transported by road surface flows is no longer being replenished by traffic. The higher level of the regression line for paved roads than that for abandoned roads reflects the increased importance of cutbank erosion on these roads; roads built to be abandoned are generally narrower and so have lower cutbanks, and once they are abandoned, road maintenance activity no longer keeps the cutbanks active.

SEDIMENT YIELD FROM ROAD SURFACES

A recording rain gauge with a record resolvable to 15 min has been maintained in the Clearwater basin since 1973. Fifteen-minute average rainfall intensities were read from the most complete record, that for the 1977–1978 water year, and were used with the unit hydrographs to construct a continuous culvert hydrograph for a road segment of average length and gradient. The computed annual runoff record was then used in conjunction with the appropriate sediment rating curve to calculate sediment discharge at 1-min intervals through the year for the road segment under the six different conditions of road use and surface type. Integration of the resulting curves provided a value for the year's sediment yield from a typical segment for each road condition (Table 4).

In regions with good rainfall records the computation of annual sediment loss can be repeated for other years, but in the Clearwater basin the precipitation record is not complete enough to extend the record of 15-min rainfall intensities to allow calculation of the long-term average sediment yield. Instead, a relation was sought which would allow calculation of sediment yield from longer, more complete records which can be resolved only to daily rainfall. We therefore defined a storm

TABLE 3. Data Used to Define Sediment Rating Curves

Road Type	Type of Regression	Number of Samples	Number of Roads	Number of Sampling Days	Regression Equation: *a* Coefficient	Regression Equation: *b* Exponent	Regression Equation: Correlation Coefficient
Heavy use	covariance	54	2	11	161	0.76	0.29*
Moderate use	constrained slope	13	2	3	13	0.76	0.48*
Temporary nonuse	covariance	55	2	5	18	0.78	0.73*
Light use	standard	41	5	15	12	0.44	0.28*
Abandoned	standard	29	2	17	70	0.00	0.04
Paved	standard	50	2	10	0.83	0.72	0.48*

Equation for rating curve: Concentration = $a \times (\text{discharge})^b$.
*Correlation coefficient significant at 0.025 level or higher.

to be a period of rain bounded by calendar days with precipitation of less than 0.5 mm. We used the record of 15-min intensities to calculate sediment yield from each storm during the 1977–1978 year and regressed sediment yield against storm precipitation for each road type (Figure 7). That the relationships are so well defined is an indication that the character of the storms is similar throughout the year. Storms at this west coast site are the result of fronts moving in from the north Pacific; orographic storms are virtually absent, and dry season storms are seen to plot on the same line as wet season storms. Daily rainfall records at a nearby weather station were then used to compute precipitation from each storm during a 17-year period. From storm precipitation we calculated sediment yield for each road type during each storm, and results were summed to calculate annual yields. Rainfall at this station is 15–20% lower than in the field area, so annual sediment yield was regressed against precipitation, and the resulting relation was used to estimate sediment yields in the field area and to compute average yields for the typical segments over a 34-year period (Table 4). In the Clearwater basin the average amount of sediment reaching streams from such road segments is 25% less than the values tabulated, since 25% of the culverts in the area do not contribute flow directly to streams.

ISOLATION OF ROAD SURFACE EROSION

As mentioned above, sediment yields calculated for culvert mouths include components from the erosion of road surfaces, cutbanks, and ditches. Road surface erosion can be isolated using the results from the paved roads because on these roads the cutbank and ditch are the only sediment sources. Table 4 indicates that sediment yield from the typical segment, if paved, is only 0.4% of that from the segment if it is gravel surfaced and heavily used, demonstrating that the contribution of sediment from the off-road sources is small compared to that from an active road surface. Even this value overestimates the significance of cutbank and ditch erosion both because the paved roads generate more runoff than gravel roads and because paved roads are generally wider and so have higher cutbanks. If sediment yield from the paved segment is recalculated assuming that the infiltration capacity is the same as on a heavily used gravel road, the estimated sediment yield from cutbank and ditch is reduced by 11% to 1.8 tonnes/yr per kilometer of road (road km).

These results may seem surprising in view of the large area of erodible sediment that cutbanks appear to provide. In the Clearwater basin, however, an average of 72% of the cutbank area represents an accumulation of coarse debris derived from the eroding face above; the actual eroding area of the cutbank represents on average only 960 m^2 of the 3410 m^2/road km of roadcuts. Seventeen erosion pins located on eroding faces indicate an average loss of 16 mm over a year, with a standard error of 4 mm; this is equivalent to an annual sediment yield of 15 tonnes/road km. A second estimate of the rate of cut face erosion results from measuring the depth of root exposure on datable vegetation growing on the faces. Sixteen measurements on 5- to 16-year-old plants indicate an average bank

TABLE 4. Calculated Sediment Yield per Kilometer of Road for Various Road Types and Use Levels

Road Type	Sediment Yield, 1977–1978 tonnes/km/yr	Average Sediment Yield, tonnes/km/yr
Heavy use	440	500
Temporary nonuse	58	66
Moderate use	36	42
Light use	3.4	3.8
Paved	1.9	2.0
Abandoned	0.43	0.51

Roads are 4 m wide, have an average gradient of 10%, and are drained to an average of six culverts per kilometer. The 16% of the road surface that does not contribute runoff to the inboard ditch is not included in this tabulation.

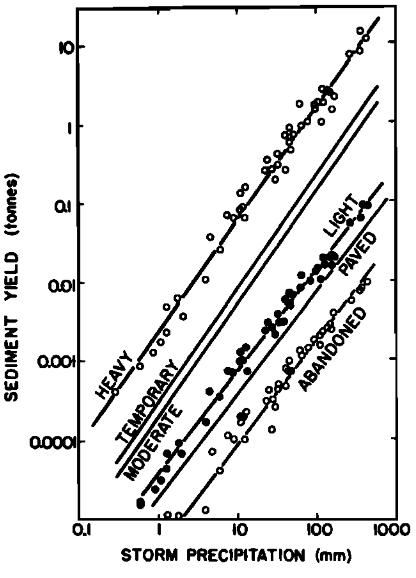

Fig. 7. Relation between the calculated sediment yield during a storm and the corresponding storm precipitation for 850-m^2 road segments of various types. The values defining the regression lines are shown for heavily used, lightly used, and abandoned roads.

retreat rate of 15 ± 2 mm/yr, agreeing well with the erosion pin data. Data from 44 additional erosion pins located on the coarsely armored debris mantles indicate that these are currently areas of net aggradation, and the data, though widely scattered, suggest that aggradation is of the same order as the erosion rate. The ditches, too, appear to undergo net aggradation: Most of the 58 erosion pins located in ditches were first buried by coarse debris from the cutbank and then removed by grading of the ditches during road maintenance. The measurements thus suggest that only a small proportion of the sediment produced from the actively eroding part of the roadcut is transported beyond the accumulating debris mantle, which itself protects the lower part of the cut from erosion. Of the sediment that is transported as far as the base of the slope, most appears to be trapped in the ditch. Only twice during the field season were discharges in ditches observed to be high enough to mobilize the armoring gravel, and each of these events was short lived.

TABLE 5. Relative Importance of Sediment Production From Different Categories of Roads

Sediment Source	Percent of Time in Category	Percent of Total Road Length	Average Sediment Yield as Percent of Total
Surfaces of active roads			
Heavy use	48	6	70.8
Temporary nonuse	52	6	9.9
Moderate use	100	5	9.8
Light use	100	39	3.8
Cutbanks, ditches of active roads		50	4.5
Abandoned roads*		50	1.2

Roads are in a 20-km^2 basin having a typical distribution of road uses: 50% abandoned, 39% lightly used, 6% heavily used, and 5% moderately used; paved roads are generally not present in tributary basins. Road density averages 2.5 km/km^2.

*Value includes sediment from road surface, cutbank, and ditch.

Significance of Traffic Intensity

The calculated sediment yields from the road surfaces and cutbanks demonstrate that road surface erosion is extremely sensitive to traffic levels (Table 4). For example, on weekdays the typical heavily used segment loses sediment at 7.5 times the rate measured on weekends and other days on which it is temporarily not being used. If the period without heavy use is extended beyond 2 days (i.e., if the road is classified as "light use," average sediment production eventually decreases to 0.8% of that from the heavily used road) and if use and maintenance are completely discontinued, the contribution drops by an additional factor of 10. Sediment production on the heavily used road is undoubtedly influenced by the frequency of road maintenance and grading, but this factor was not isolated during this study. Because maintenance activities were carried out during the field season, their effects show up as an increase in variance on the sediment rating curves. The extent to which maintenance operations influence sediment production rates could be determined using the methods employed by this study, and this represents a useful area for future work.

The importance of road use was demonstrated by a second series of road surface measurements. Sediment concentration in a 200-m-long road surface rut was measured at intervals before and after passage of a logging truck. Rainfall intensity and discharge in the rut varied little through the period, while concentration increased from a value of 4500 mg/L 17 min after the previous truck passed to a peak of 31,000 mg/L before declining to the original level 20 min later when the next vehicle passed (Figure 8). During this time, at least 1.7 kg of sediment in excess of the background level were introduced into the culvert discharge from this and the adjacent rut, equivalent to a production rate of at least 9 kg/road km for a single truck during a rainstorm with an intensity of only 1.5 mm/h. Continued traffic made it impossible to measure the actual background level of sediment production. During the wet season, traffic is distributed over a 10-hour period each day, so a use level of 16 loaded trucks per day would result in an average of 19 min between passes if the unloaded return trips are also considered.

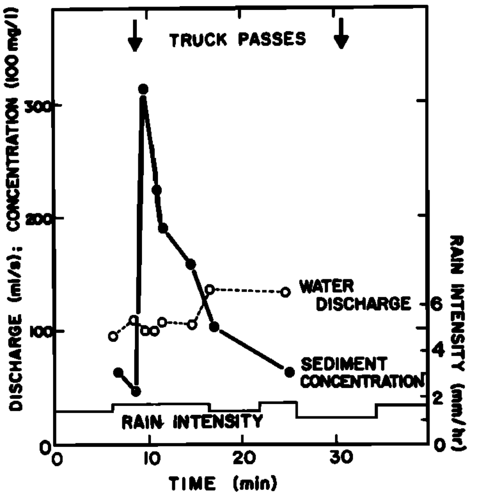

Fig. 8. Short-term effect of truck traffic on sediment concentration for road surface flow.

Relative Significance of Road Types in a Basin

The overall significance of a specific road type as a sediment source is determined both by its rate of sediment production and by the length of that road type in a basin. Measurements in the Clearwater area indicate that in a 40% clearcut, 20-km^2 basin under the current management plan, an average of 50% of the road length is abandoned, 39% is lightly used, 6% is heavily used, and 5% is moderately used at any one time. Road density in such a basin averages 2.5 km/km^2. In addition, a road that is being used heavily during the week generally falls into the temporary nonuse category on weekends and at night; sediment production is expected to fall to levels characteristic of temporary nonuse roads approximately 6 hours after the day's use ends (K. Sullivan, Weyerhaeuser Co., personal communication, 1979). Under these assumptions a heavily used road falls into the temporary nonuse category for 52% of the time.

Because a single road segment is likely to fall into several categories during a year, the distribution of road gradients and culvert spacings is assumed to be similar for heavy use, temporary nonuse, moderate use, and light use roads. If ratios between rates of sediment production from different road types are similar over the range of road gradients present in a basin, as suggested by the results of the multiple regression described in Table 2, then the relative importance of different road types can be calculated for a typical 20-km^2 basin in the field area (Table 5). These results demonstrate that although roads subjected to heavy use on weekdays account for a relatively small proportion of the road length in a basin, 71% of the total amount of sediment from road surfaces is produced from these roads during periods of use and an additional 10% comes from the same roads during temporary nonuse periods.

CONCLUSION

Although the technology exists for precise measurement of hydrologic variables in small catchments, such equipment is costly and vulnerable to vandalism, requires relatively permanent installations and continued maintenance, and restricts the observer to a few study sites. Although suitable for long-term research projects, installations for continuous monitoring lack the flexibility needed by land managers and are not always appropriate or necessary even for research applications. The monitoring program described above provided data of sufficient precision not only to demonstrate that the rate of erosion from the surfaces of gravel roads is extremely sensitive to the traffic intensity but also to quantify the magnitude of the effect in the Clearwater basin. During a period of heavy traffic, here considered to be a traffic load of more than four loaded trucks per day, monitored roads in the study area contribute sediment at 7.5 times the rate of the same roads on days when they are not being used. If traffic on the roads is restricted to occasional light vehicles, the sediment loss from the road surface decreases to 0.8% of the value for heavily used roads. The measurements also demonstrate that sediment production from roadcuts in the field area is relatively minor compared to that from the road surfaces, accounting for approximately 5% of the combined production rate for a 20-km^2 basin with a road density of 2.5 km/km^2. These values pertain to the well-surfaced, relatively well-maintained roads and armored cutslopes characteristic of the Clearwater basin.

Rates of sediment production were calculated using relationships constructed from measurements of rainfall intensity, culvert discharge, and sediment concentration. Once the necessary relationships are constructed for roads in an area, additional measurements of the same type would provide a quick and inexpensive means of monitoring the effectiveness of conservation measures designed to decrease sediment production rates from road surfaces. Such methods could also be used to predict the sediment influx to streams that would result from a variety of planning options for road distribution, traffic pattern, and maintenance practices. The method is attractive because it yields results quickly and inexpensively, but it needs to be tested on rural roads in a wider range of environments, and the separate effects of catchment length and gradient need to be examined.

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