APPLICATION OF SEDIMENT BUDGET STUDIES TO THE EVALUATION OF LOGGING ROAD IMPACT

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ABSTRACT

The construction of a partial sediment budget provides a flexible, efficient, and economical means of evaluating changes in sediment production rates generated by changes in land use. Application of the method to a 40% clear-felled area of the northwestern United States demonstrates that landslides are responsible for about 60% of the road-related sediment production. An additional 20% is produced by surface erosion on gravel roads, and about 80% of this value is derived from roads along which logs are being transported. In the terms of the production rate of sediment smaller than 2 mm in diameter, however, the sources are of near-equal importance, and paving the haul roads will result in a 30% decrease in the production rate of fine-grained material.

INTRODUCTION

Geomorphologists are asked with increasing frequency to evaluate the effects of various land management plans on the physical environment. Of particular concern in the north western United States is the impact of forest practices on sediment production, because excessive sediment loads in streams degrade both water and fisheries resources. For example, the Clearwater basin of western Washington, USA, is intensively logged and is an important spawning area for salmon. Salmon stocks have decreased significantly in recent years, and part of the decline is attributed to degradation of the spawning environment by the intrusion of fine-grained sediment into spawning gravels. Statistical correlations between the percentages of fine sediment in stream gravels and the road areas in affected basins further suggest that the presence of roads in the basin is at least partially responsible for the increased sediment loading (Cederholm *et al.*, in press).

Two general types of problems arise frequently. First, changes in sediment production rates wrought by forest practices must be assessed in order to determine whether there is a significant problem. Second, targets for and methods of sediment control must be proposed, and for this purpose one must recognise the sources of sediment and their relative importance.

Paired Basin Studies

Evaluation of changes in sediment production have usually been made using a paired-basin approach: Sediment yields, considered as indices of sediment production rates, are measured at the mouths of basins undergoing different types of land use. Differences in measured yields are then attributed to the differences in land use. Although this approach is useful in identifying general patterns of sediment production, it has several inherent limitations.

First, paired-basin studies are usually designed to provide data only on changes in total sediment yield caused by a particular land use; the contributions from individual sediment sources within a basin cannot be isolated. Secondly, such a study is expensive to support in personnel, funds, and in the amount of land that must be controlled. These factors discourage the use of replicate basins, so the range of applicability of the measured results is unknown. The results thus can not be applied quantitatively to other basins. The small number of sample basins in most paired-basin studies also means that only broad categories of land use can be characterized. In addition, such studies must be carried on for a decade or more before the data assumes a useful form, because in the absence of a direct explanation for variations in sediment yield, the major motivation for their measurement is to determine an average yield over a time period long enough to represent an average distribution of climatic variations. On the other hand, conditions change rapidly in a recently logged basin, making even long-term averages of sediment yield difficult to interpret.

The need for results over a shorter time scale and the practical and financial limitations on the sizes of monitored basins make the results of paired-basin studies extremely susceptible to the occurrence of large, rare events. In small basins the occurrence of a landslide during a short study may cause the over-representation of landsliding as a sediment source and so lead to an over-estimation of average sediment yield, while if no landslide occurs, the source will be under-represented and the estimated average yield will be lower than the actual one. In the north western US, for example, recent paired-basin studies have had to contend with 100-year storms, major landslides, dam failures, and debris torrents. The results of these studies, though interesting, are difficult to interpret quantitatively.

It is evident that paired-basin studies are designed to measure only net changes in sediment yield caused by broadly different categories of land use. The results cannot be used to define the contribution by specific sediment sources, as would be needed to aid in designing sediment control measures, and they cannot be applied quantitatively outside the basins in which they were measured. Finally, the occurrence of large, rare events during the study period can make quantitative application difficult even in the study basin.

Sediment Budgets

The construction of sediment budgets provides an alternative approach to the evaluation of sediment production under various kinds of disturbance. The method was outlined by G. K. Gilbert (1917) and was first implemented using field measurements by Leopold *et al.* (1966). This approach requires that individual sediment sources and transport mechanisms are identified and their rates of sediment contribution measured. The results can then be combined to provide an accounting of sediment flux along the various sediment transport paths in a basin, providing data to assess both the magnitude of changes in sediment production rates and the relative importance of various sources. In its most comprehensive form, such a budget would also include measurements of the residence time of sediment in various storage elements (Dietrich and Dunne, 1978), thus providing data necessary to address the question of long-term impacts. Swanson *et al.* (in press) have constructed a partial sediment budget for an undisturbed forested basin, and the present paper will describe how the approach was used to evaluate the effects of gravel roads on sediment supply to channels in a partially clearcut basin.

The sediment budget approach avoids most of the limitations described for paired-basin studies. The results of sediment budget measurements are in a form which allows consideration of several kinds of problems because sediment sources are monitored independently. The isolation of individual sources also makes possible the evaluation of each sediment production process over a time and space scale applicable to its distribution and frequency irrespective of the confines of a single basin. Thus, in the present study, landslides are observed over a 40 km^2 area, while road surface erosion is monitored intensively on ten road segments. Separation by sediment source also allows the identification and measurement of factors controlling sediment production rates. If the controls on production rates are understood, then the measured sediment production rates can be applied to any basin in an area by determining the distribution of the controlling variables in that basin. In the present study, for example, sediment production from gravel road surfaces is found to be directly related to the use level of the road. This relation is defined quantitatively, so by knowing the distribution of road types and usage levels in an area it is possible to calculate an expected sediment production rate from those road surfaces for a basin.

For some processes sediment production rates may be related directly to climatic variables such as rainfall intensity, allowing the calculation of an average sediment production rate from a long-term climatic record. For landslides and other rare, large processes, datable evidence of an erosion event remains long after it has occurred, allowing the calculation of event frequency over a relatively long time span from a single season's fieldwork. A combination of these two methods generally allows the calculation of sediment production rates reflecting an average distribution of climatic variables after a relatively short period of study. Finally, if the relation between production rates and controlling variables is understood quantitatively, then the effects on sediment production of proposed changes in management practices can be estimated on the basis of the effects of the changes on the controlling variables. A sediment budget, in other words, can be used to assess the effects of hypothetical changes in real basins.

A complete sediment budget would require quantification not only of sediment production rates but also of transport rates and storage times. In this form the results could be compared directly with those from paired basin studies. In the more abbreviated form described in the present paper, however, only sediment production rates — that is, the rates of transfer of sediment from hillslopes to stream channels — are measured. Because the volume of sediment in storage is likely to change as a basin is disturbed, sediment production rate within a basin does not necessarily equal sediment yield from the basin in any particular time period.

In summary, even incomplete sediment budget studies provide a quick and relatively inexpensive way of generating the kinds of data necessary to determine the magnitude of the impact of various land use policies, to specify the sources of sediment generating the impact and their relative importance, and in some cases to outline the factors determining sediment production rate from a source and thus to facilitate the recognition of efficient methods of sediment control. The remainder of this paper will describe a study in which the sediment budget approach was used to evaluate the significance of sediment production from gravel-surfaced logging roads.

STUDY AREA

The Clearwater River drains 375 km^2 of the western slope of the Olympic mountains in coastal Washington, USA (Figure 1). Elevations in the study area range from 50 to 1,000 m. Drainage density measured from 1 : 12,000 aerial photographs averages 9.3 km/km^2, and slopes are straight and steep averaging 2° in the north west part of the basin and 30° in the south east. Soils in the area vary between 25 and 130 cm in depth and are dominated by stony silt-clay-loams derived from the marine sandstones, shales, and greywackes of the Hoh lithic assemblage.

Precipitation averages about 3900 mm/yr and falls mostly as low-intensity showers during October through May. Mean annual runoff in the area is 3550 mm, with instantaneous stream discharges varying between 0.011 m^3 s^{-1} km^{-2} and 13.9 m^3 s^{-1} km^{-2} in a 20 km^2 sixth-order basin.

Eighty percent of the basin is managed by the Washington State Department of Natural Resources and is being clearcut on a sustained yield cutting plan implemented in the mid-1960's and now 35% complete. Logs are yarded using high-lead towers, permitting the relatively low road density of 1.5 km/km^2; final density is expected to be about 2.5 km/km^2. Most road use in the area of interest takes place on 4-m wide, gravel-surfaced maintained roads and on narrower logging spur roads which are abandoned between cutting cycles.

SEDIMENT SOURCES

Preliminary fieldwork disclosed five major sources of sediment from roads. Landslides are commonly initiated in roadfill or sidecast material, and since they are frequently caused by drainage concentration from the roads, much of the resulting sediment is introduced into streams. Some of the road-related landslides mobilize sediment in storage in stream channels, initiating debris flows which can scour sediment from valley walls and strip channel deposits for lengths of up to 1.5 km. Sediment sidecast from the roadbed during construction provides another source of unstable debris; where such deposits are near streams, erosion processes such as dry ravel and rainsplash may succeed in moving the debris to the channel. Road surfaces constitute a continually renewed source of fine sediment if they are in use: traffic not only abrades and fractures the surfacing gravels but also forces the gravels into the substrate, pumping the fine matrix to the surface whence it is removed by overland flow generated on the road. Finally, roadcuts shed sediment into roadside ditches, where it is also susceptible to transport by road-generated runoff. In each case the value of concern to the present study is the amount of sediment transferred from hillslope to stream channel; it is this transfer that is here referred to as sediment production.

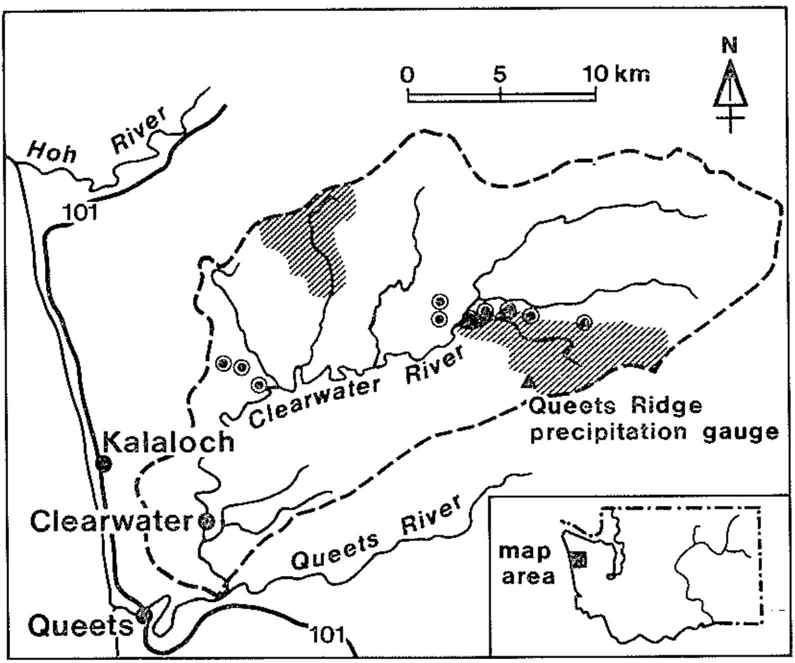

FIGURE 1—Map of Clearwater basin. Circles indicate locations of monitored road segments, and hachured area is that in which road-related landslides and debris flows have been mapped.

Road-related Landslides, Debris Flows, and Associated Disturbances

Aerial photographs were used to map and measure areas of road-related gullies, landslides, and areas of sidecast erosion over a 40 km² area; field measurements verified the measurements of surface area and estimates of landslide depth and the proportion of sediment reaching streams. These data could then be used to calculate the total sediment volume delivered to streams by the processes; use of sequential photographs permitted coverage dating from the initiation of logging in the area in the mid-1960's.

Landslides continue to produce sediment by processes such as sheetwash, rilling, and rainsplash long after the initial failure has occurred. Erosion due to rilling on road-related landslide scars was calculated from field measurements of rill volumes, and erosion pin networks were monitored over a 16-month period to provide information on other process rates.

Debris flows incorporate sediment from three sources: the initial landslide (considered above), stored channel debris (already introduced into the stream channel by other processes), and slope deposits on the valley walls, which are undercut by the debris flow. This last item is the only primary source of sediment from the flows. Debris-flow size, frequency, and distribution, were measured from aerial photographs; these data were combined with field measurements of erosion depth on valley walls to calculate sediment production from this source.

The results of these calculations (Table 1) demonstrate that landslides are the most significant of the sources considered thus far, contributing 5.6 times as much sediment as valley-wall erosion from debris flows and 10.4 times as much as the secondary erosion processes active on landslide scars. The length of time over which the secondary processes are active is not yet known; most of the observed landslide scars remain largely unvegetated 10 years after the initial failure occurred.

TABLE 1—Sediment production from road-related landslides and associated sediment sources.

Source	Sediment production (t (road-km)$^{-1}$ yr^{-1})
Landslides	61
Gullies	0.6
Sidecast ravel	1.1
Secondary surface erosion on slide scars	4.5
Rilling of slide scars	1.4
Debris flows (valley wall erosion)	11
TOTAL	80

Road Surface and Backcut Erosion

Ten road segments which drained to single culverts and received no drainage from upslope were selected for intensive monitoring. Because road-building standards are designed to make culvert spacing compensate for increasing gradient, road segments were selected to correspond to the average segment length and gradient in the basin. The road segments chosen fall into six categories: abandoned roads, which have not been subjected to truck traffic for more than a year; light-use roads, used only by light vehicles; moderate-use roads, which carry fewer than four logging trucks per day; heavy-use roads, which carry more than four trucks per day; paved roads with unpaved ditches and backcuts; and heavy-use roads which are temporarily not being used (measurements in this last category were generally made on weekends). In all cases the roads had been constructed more than three years before the measurements were made.

Each road segment was monitored during a series of rainstorms occurring between January and October, 1978. Discharge at the culvert mouth was measured with a bucket at ½- to 5-minute intervals, and water samples were collected periodically for later filtering and gravimetric determination of sediment concentration. Meanwhile, rainfall was measured by determining the volume of rain in a plastic gauge at intervals of 3 to 20 minutes, allowing construction of a hyetograph.

The hyetographs and culvert discharge hydrographs were used to construct 15-minute unit hydrographs (Figure 2), and the sediment measurements were used to define sediment rating curves (Figure 3) for each segment. The rainfall intensity and runoff measurements also allowed an estimate of average infiltration capacity for each segment.

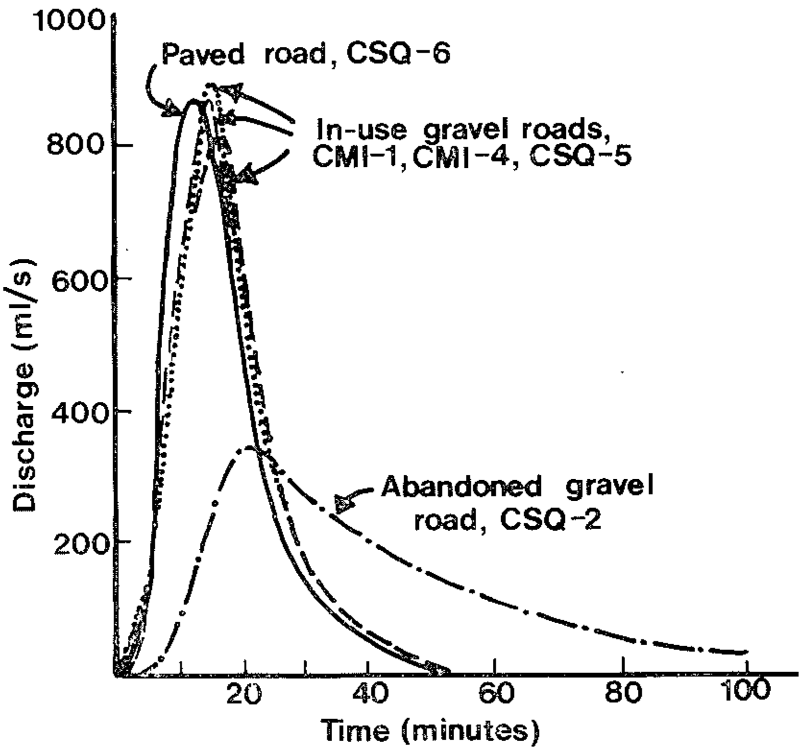

FIGURE 2—Unit hydrographs from each road type, normalized by catchment area. Hydrographs used to construct unit hydrographs for in-use gravel roads include those measured during periods of heavy-, light-, and temporary non-use.

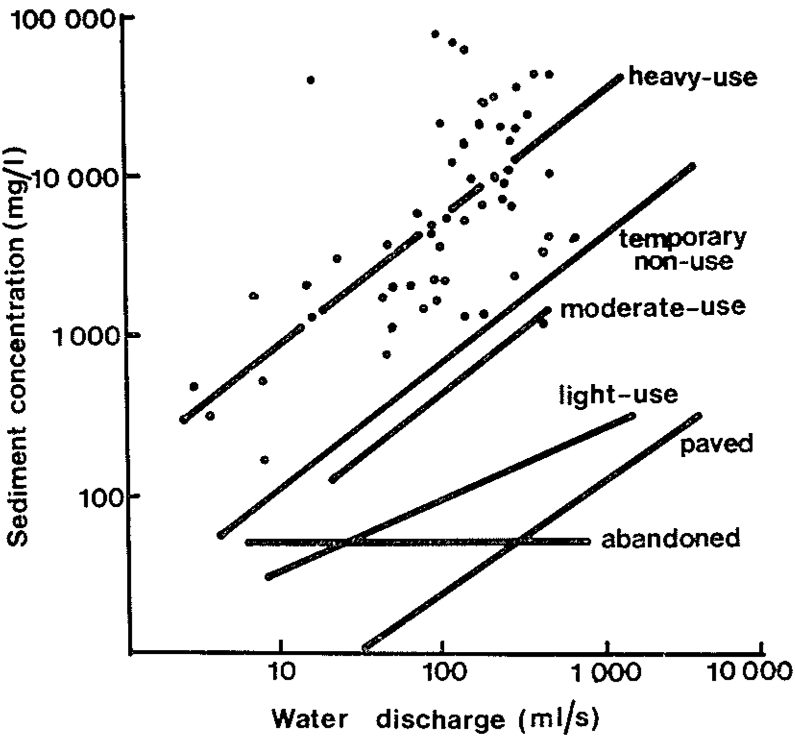

FIGURE 3—Concentration versus discharge curves for six road types. Data points are indicated for heavy-use segments to give indication of scatter.

The infiltration capacity and unit hydrographs were then used, together with a record of 15-minute rainfall intensities from the recording rain gauge on Queets Ridge (Figure 1) during the 1977-78 water year, to construct hydrographs at each culvert for each storm during the year. The hydrographs and sediment rating curves were then combined to calculate the total annual sediment yield from each road catchment. Details of the calculation procedure are given by Reid (1981).

The long-term average sediment yield by water erosion could have been calculated by the same method through the use of a long record of rainfall intensities. However, the following simpler method also appears to work well. For the 1977-78 water year a strong correlation was observed between total precipitation and sediment yield during a storm (Figure 4). This relation allowed the calculation of annual sediment yields from records of storm precipitation for 12 additional years, and these values were averaged to calculate long-term averages for heavily-used, moderately-used, and temporarily non-used road segments (Table 2).

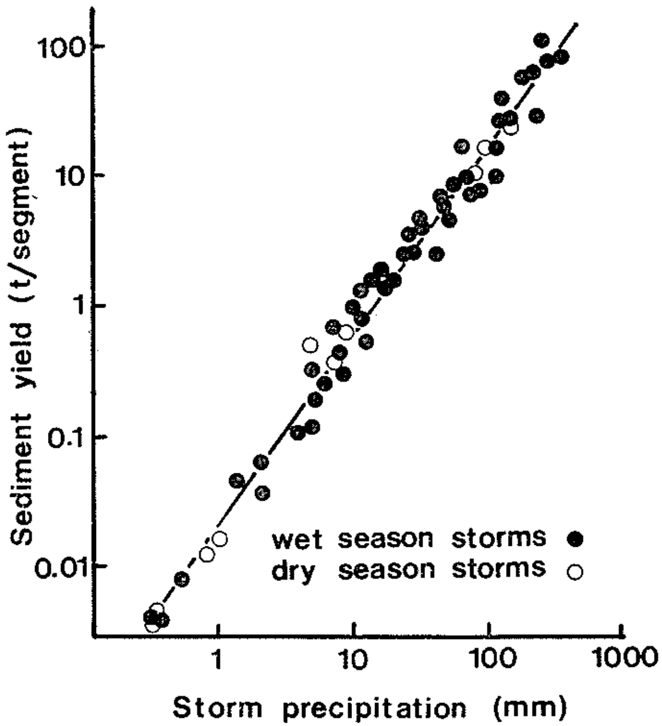

FIGURE 4—Sediment yield during storms versus corresponding storm precipitation for a heavily-used road segment.

TABLE 2—Calculated average sediment yield from road surfaces undergoing different intensities of use, and from backcuts.

Road type	Sediment yield at culvert mouth (t (road-km)$^{-1}$ yr^{-1})	Sediment production from road surface (t (road-km)$^{-1}$ yr^{-1})
Heavy-use	664	662
Temporary non-use	89	87
Moderate-use	55	53
Light-use	5.1	2.7
Abandoned	0.6	
Paved	2.8	0
Backcut on gravel road	2.4	

The sediment yield measured at the culvert represents contributions from two sources: road surface and backcut. On paved roads, however, the backcut is left as the only source. If the sediment yield from a road segment is calculated using the sediment rating curve and unit hydrograph measured on paved roads combined with the infiltration rate from in-use gravel roads, the result is an estimate of the sediment production rate from backcuts on gravel roads· Backcuts are thus calculated to account for 0.4% of the sediment load measured from heavy-use roads and about 50% of that from light-use roads. The yield from abandoned roads is very low; roads built to be abandoned are generally narrow, so backcuts are generally smaller than those of maintained roads and are partially vegetated.

TOTAL ROAD-RELATED SEDIMENT PRODUCTION

In order to compare sediment production rates from road surfaces and backcuts to sediment production from the other road-related sources it is necessary to consider the distribution of road-types in a basin. This was done by using clear-cutting records to reconstruct the percentage of road length undergoing various use levels for basins in the area. The resulting percentages were then applied to a hypothetical 20 km^2 basin modelled using an average of conditions present in the central part of the Clearwater basin. This basin is considered to have a road density of 2.5 km/km^2, corresponding to that of a 40% clearcut basin. On average, 6% of this road length is heavily-used, 5% moderately-used, 39% lightly-used, and 50% abandoned.

TABLE 3—Calculated road-related sediment production in a hypothetical 20 km^2 basin with road density of 2.5 km/km^2 and average distribution of road uses.

Source	Sediment Total (t km^{-2} yr^{-1})	Production < 2 mm (t km^{-2} yr^{-1})
Landslides	155	40
Debris flows (valley wall erosion)	26	6.6
Gullies	1.2	0.4
Sidecast erosion	2.8	2.8
Secondary surface erosion on slide scars	12	12
Rills on slide scars	3.2	3.2
Backcuts*	(4.0)	(4.0)
Road surface and backcut		
Heavy-use	36	36
Temporary non-use	5.2	5.2
Moderate-use	5.2	5.2
Light-use	3.7	3.7
Abandoned	0.6	0.6
TOTAL	251	116

* Backcut contribution is included in road surface production but is listed separately here to allow comparison.

All calculated erosion rates have been transforemd to the unit of tonnes per square kilometer of basin per year, allowing comparison of erosion rates by diverse processes (see Table 3). Landslides are seen to account for most of the sediment production from roads, contributing 62%, and debris flows account for an additional 10%. Erosion from road surfaces, producing 19% of the road-related sediment, is the second most important source, with 81% of the road surface and backcut sediment being derived from heavily-used and temporarily non-used roads.

A topic of major concern is the role of logging in increasing the production rate of suspendible sediment. This is the sediment size that increases stream turbidity and infiltrates into salmon spawning riffles, decreasing fish survival. Published analyses of soil textures can be used to calculate the production rate of fine-grained sediment from the sources considered in this study. Landslides and debris flows produce sediment that has the textural characteristics of the soil since most of the sediment moved is soil, but samples collected from culvert wash indicate that sediment produced from road surfaces consists overwhelmingly of fine-grained material. If just the component of sediment smaller than 2 mm is considered (Table 3), road surfaces and landslides are of nearly equal importance as sediment producers. Breakdown of coarse sediments during transport will increase the relative significance of landslides as producers of fine sediment, however.

CONCLUSION

This study provides only a first step toward the construction of a sediment budget for logged basins. In order to quantify the sediment budget fully it will be necessary to measure sediment production from sources related to clearcuts and undisturbed areas to measure changes in the volume of sediment in storage in stream channels and floodplains; the rates of sediment transport and of the breakdown of sediment during transport must also be measured. It is only when these factors are measured and understood that the long-term effects of sediment production in logged basins can be evaluated.

In the meanwhile, however, a partial sediment budget has been demonstrated to provide quickly available information on sediment production rates, which can then be used to determine the magnitude of sediment contribution from roads. The most important sources are immediately evident, and it is possible to predict the effects of a changing distribution of road uses. The sediment budget method also makes possible a quick evaluation of various methods of sediment control. It becomes evident, for example, that paving all roads in a typical 40% logged basin will decrease the production rate of fine-grained sediment by over 30%. Similarly, an analysis of sediment production by landslides of various sizes indicates that if more sophisticated engineering geology analyses and roadbuilding techniques succeed in preventing the average largest land-slide in a basin, total road-related sediment production will decrease by about 15% (Reid, 1981). The construction of sediment budgets is thus seen to be a useful method for the evaluation of management impacts on sediment production.

ACKNOWLEDGEMENTS

The Washington State Department of Natural Resources provided funding for the study; the National Science Foundation provided additional support in the form of a 3-year graduate fellowship. Blake Harrison and Patricia Irle assisted with fieldwork, and William Dietrich and Lee Fairchild provided helpful critiques of an earlier draft of the manuscript.

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