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Long-Term Patterns of Sediment Production Following Road Construction and Logging in the Oregon Coast Range

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Suspended sediment production after road construction, logging, and slash disposal was significantly increased ($P = 0.95$) on two watersheds in Oregon's Coast Range. A 25% patch-cut watershed showed increases during 3 of 8 posttreatment years. These increases were caused primarily by mass soil erosion from roads. Monthly sediment concentrations before the occurrence of the annual peak flow were increased more than those following the annual peak. Surface erosion from a severe slash burn was the primary cause of increased sediment yields for 5 posttreatment years on a watershed that was 82% clear-cut. Monthly sediment concentrations were generally increased throughout the winter runoff period on this watershed. The flushing of suspended sediment in Oregon Coast Range watersheds is apparent from seasonal changes of suspended sediment rating curves.

INTRODUCTION

The effects of timber harvesting upon sediment production are important to land managers in the Pacific Northwest. In western Oregon, first-, second-, and third-order streams drain more than 80% of the commercial forest land area [*Harr,* 1975]. Many of these second- and third-order coastal streams are spawning and rearing areas for both resident and anadromous fish species. Increased sedimentation in small mountain streams may have a detrimental impact on fisheries by clogging gravels and reducing survival rates following spawning. Indirect effects may be an alteration of invertebrate populations, of primary productivity, or of channel characteristics (habitat). The effects of increased sedimentation upon fish and other organisms have been reported by *Brusven and Prather* [1971], *Koski* [1972], *Gibbons and Salo* [1973], *Moring and Lantz* [1974], and *Iwamoto et al.* [1978]. Timber-harvesting practices which alter the stream environment through increased sedimentation can directly affect the biological components of the stream system as well as downstream water quality and beneficial uses.

Forest operations, such as road building, timber yarding, and slash disposal, can have a major impact on erosion in mountainous terrain. On steep hillslopes of the Pacific Northwest, mass soil movement is the dominant mechanism of sediment transport to stream channels. Road construction, in particular, may cause marginally stable slopes to fail. For example, *Swanston and Swanson* [1976] found that debris avalanche erosion associated with roads was 25–340 times greater than debris avalanche erosion in unroaded, forested areas. The removal of forest vegetation may cause a reduction in rooting strength and alter the hydrologic regime of a site. Yarding and slash disposal may also significantly affect surface soil characteristics and increase surface erosion rates. Although not all forest-harvesting operations accelerate erosion, the potential often exists in steep terrain.

THE ALSEA WATERSHED STUDY

The Alsea watershed study began in the fall of 1958 and continued for 15 years. Three experimental watersheds about 25 km southeast of Newport, Oregon (Figure 1), ranged in size from 75 ha (Needle Branch) to 304 ha (Deer Creek). Flynn Creek, the control watershed, covered 202 ha.

Logging roads were constructed into Deer Creek and Needle Branch between March and August 1965. Logging began the following year in March and was completed by November 1966. Approximately 82% of Needle Branch was clear-cut, of which 5% was in roads and landings. No buffer strip was left along the stream channel, and no effort was made to protect the stream during yarding activities. Deer Creek was 25% patch-cut, including 4% (11 ha) for roads and landings. The three patch-cut units on Deer Creek were about 25 ha in size. High-lead cable yarding was used on both watersheds, although some tractor skidding was done on the lower portions of Needle Branch. Buffer strips of overstory forest vegetation extending 15–30 m from the stream were left on the two lower patch-cut units in Deer Creek to provide shade to the stream and to prevent changes in water temperature. A secondary benefit was the prevention of channel and soil disturbance along the stream during logging activities. Slash on Needle Branch and the lower patch-cut unit of Deer Creek was burned in October 1966. The two upper patch-cut units of Deer Creek remained unburned. The lower Deer Creek burn was light, but the slash burn on Needle Branch was severe, exposing mineral soil throughout much of the watershed. A more detailed description of watershed characteristics and treatments is given by *Brown and Krygier* [1971] and *Moring and Lantz* [1975].

Although the determination of changes in sedimentation after logging was a major objective of the Alsea watershed study, other hydrologic and biologic impacts have been reported. These include stream temperature [*Brown and Krygier,* 1970], low flows [*Harr and Krygier,* 1972], nutrient losses [*Brown et al.,* 1973], and peak flows [*Harr et al.,* 1975]. *Moring and Lantz* [1975] summarize the biological studies. The effects of forest-harvesting operations on several of these variables have been further summarized by *Brown* [1972], *Harris* [1973, 1977], and *Moring* [1975*a*, *b*].

A classical paired watershed study assessed changes in hydrologic and biologic conditions on the treated watersheds. The effects of road construction and logging upon sediment production for the first 4 water years (WY) after treatment (1966–1969) have been previously reported by *Brown and Krygier* [1971] and *Harris* [1973]. These preliminary assessments show significant changes in annual sediment yields as a result of treatment. An additional 4 years of posttreatment data have provided further insights concerning the temporal patterns of sediment production from wild land watersheds. The purpose

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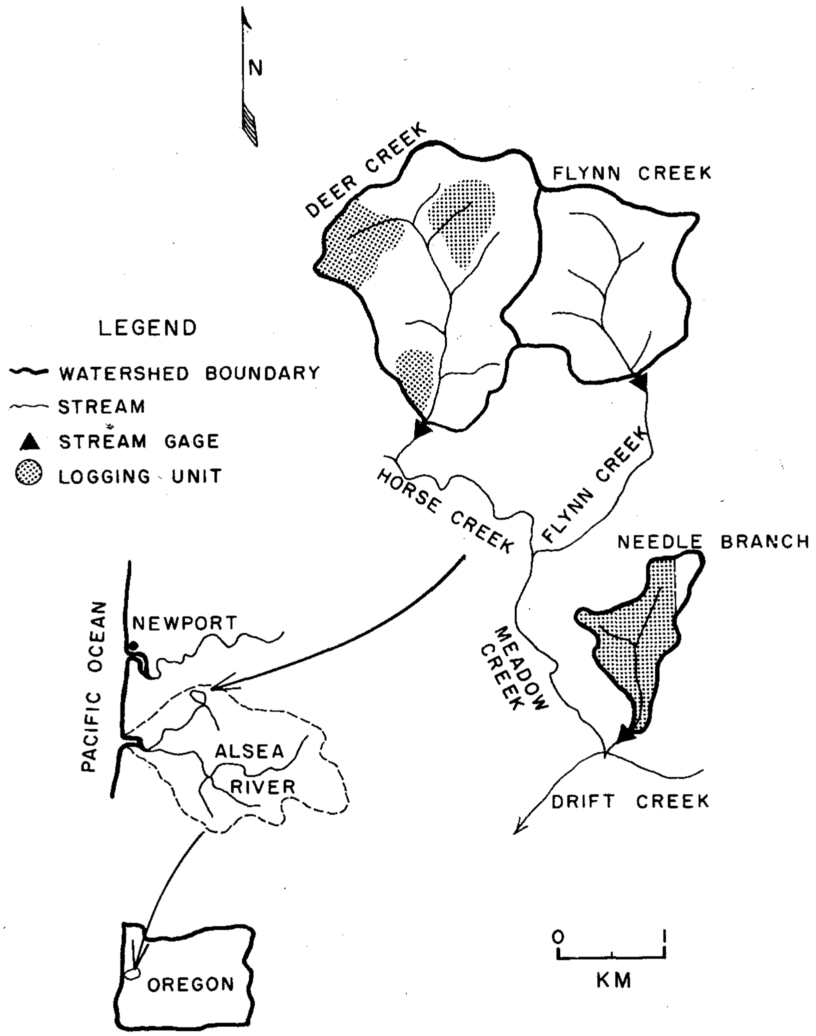

Fig. 1. Location of the study watersheds in western Oregon.

of this paper is to identify and evaluate from posttreatment data both annual and seasonal changes in sediment production. A long-term perspective is fundamental to evaluating impacts and to understanding the relative importance of various erosional processes.

The monthly and annual suspended sediment concentrations and water discharges used in this analysis were obtained from published U.S. Geological Survey data. Depth-integrated samples had been collected at daily or more frequent intervals during periods of high flow. Simple linear regression techniques were used to develop pretreatment prediction equations and 95% upper confidence limits (95% CL) about the regression [*Ostle,* 1963]. Posttreatment regression equations were not computed and tested against pretreatment relationships because of posttreatment time trends in the response of a watershed to forest harvesting. Increases in sediment yields (as well as other hydrologic responses) resulting from a land treatment usually decay toward pretreatment levels with time. Thus a comparison of pretreatment and posttreatment equations may not indicate significant changes throughout the entire posttreatment period.

Results

During the 15-year study, annual suspended sediment yields from the untreated Flynn Creek watershed ranged from 18 to 433 t km^{-2} and averaged 98 t km^{-2}. Average annual sediment yields for each watershed are shown in Table 1. During the pretreatment period, average sediment yields from Needle Branch were approximately one-half those from Flynn Creek or Deer Creek. Annual sediment yields, however, do not fully illustrate the variability of yield from watersheds of Oregon's coastal mountains. For example, instantaneous peak flows

TABLE 1. Average Annual Sediment Yields of the Alsea Study Watersheds

Period	Water Years	Flynn Creek Untreated, t km^{-2}	Deer Creek 25% Patch-Cut, t km^{-2}	Needle Branch 82% Clear-Cut, t km^{-2}
Pretreatment	1959–1965	102	97	53
Posttreatment	1966–1973	95	136	146

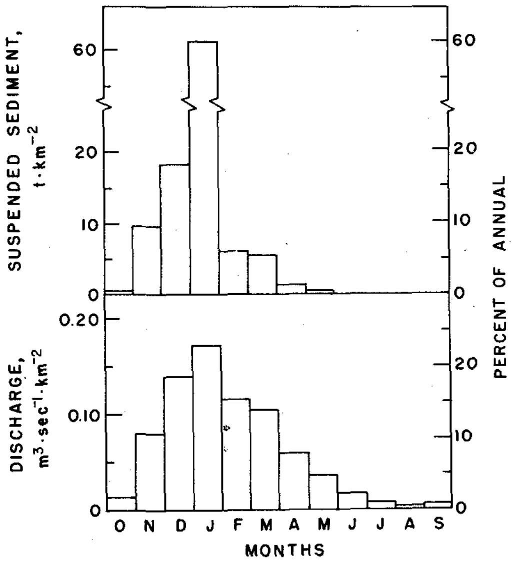

Fig. 2. Average monthly suspended sediment yield and water discharge of the untreated Flynn Creek watershed over a 15-year period (1959–1973 WY).

from the two largest storms recorded on Flynn Creek, on January 28, 1965, and January 11, 1972, were 3.9 m^3 s^{-1}. During the 3-day period of high flows associated with the 1965 and 1972 storms, 308 and 224 t km^{-2} of suspended sediment, respectively, were transported out of the watershed. Together, these two storms account for 36% of the total 15-year suspended sediment yield from the Flynn Creek watershed and over one half of the average suspended sediment yield for January. The distributions of average monthly sediment yield and water discharge are illustrated in Figure 2. The influence of the two large January storms is apparent. Precipitation averages 250 cm annually on these watersheds, nearly 90% occurring from November through May.

Posttreatment sediment yields for Deer Creek, in relation to the undisturbed Flynn Creek watershed, are shown in Figure 3. Water years 1966, 1967, and 1972 have significantly increased sediment yields (95% CL). The large response in 1966 is primarily a result of road construction and a subsequent mass failure into the headwaters of Deer Creek [*Brown and Krygier,* 1971]. The significant increase in 1967 may be a result of sediment that had been deposited in the channel the previous year. In 1972, several road-associated mass failures occurred within the uppermost patch-cut unit of Deer Creek. In addition, another road-caused mass failure occurred on an uncut portion of the watershed, and several smaller nonroad failures occurred within the cut unit located in the northeastern portion of the watershed (Figure 1). A large proportion of the increases shown for the 1972 WY occurred during the large January storm.

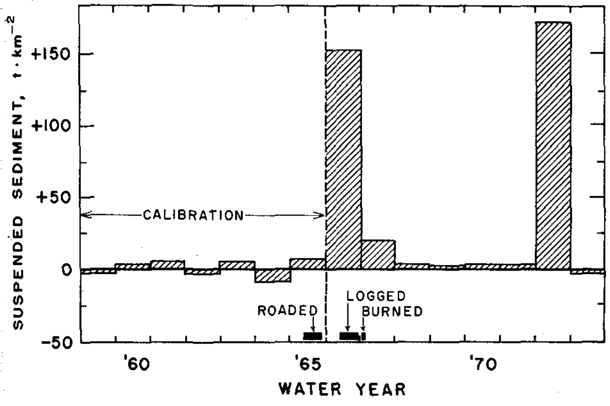

Fig. 3. Increases in annual suspended sediment yield after road building and 25% patch-cut logging on Deer Creek watershed.

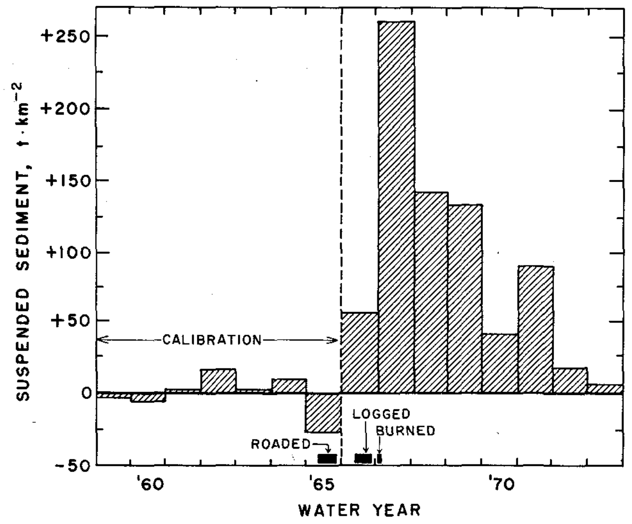

Fig. 4. Increases in annual suspended sediment yield after road building and 82% clear-cut logging on Needle Branch watershed.

The pattern of increases in annual suspended sediment yield after treatment is considerably different for Needle Branch (Figure 4). An apparent increase in sediment yield for Needle Branch in the 1966 WY (the first year after road construction) is not a significant change (95% CL) from the pretreatment relationship. However, significant increases did occur during the next 5 years (1967–1971 WY). A fivefold increase in sediment yield was measured in the 1967 WY, the first year after logging and burning of slash. Although much of this increase has been attributed to the severe slash fire and exposure of mineral soil [*Brown and Krygier,* 1971], the effects of logging along the channel are another possible cause of increased sedimentation. During successive years, sediment yield increases show a general decline toward pretreatment levels. The response of Needle Branch to the January 1972 storm was much less than that of Deer Creek.

Annual streamflow increases of 3% for Deer Creek and 26% for Needle Branch were measured during the posttreatment period. Because sediment yields are computed as the product of two variables (water discharge and suspended sediment concentration), the increased streamflow after treatment, particularly for Needle Branch, may have caused the increase in annual sedimentation yields without significantly affecting concentrations. To test this hypothesis, annual discharge-weighted concentrations of suspended sediment were computed for each watershed by dividing total sediment yield by total discharge for each year. A comparison of pretreatment regression equations with posttreatment data for Deer Creek showed that the same 3 years that had significant increases in yield (1966, 1967, and 1972) had significant increases (95% CL) in mean concentrations (Figure 5). Similarly, those years that showed significant yield increases on Needle Branch (Figure 4) also showed significant concentration increases (Figure 6), with a single exception. In the 1970 WY the mean concentration showed no significant change, but the annual suspended sediment yield did.

The temporal variability of sediment production resulting

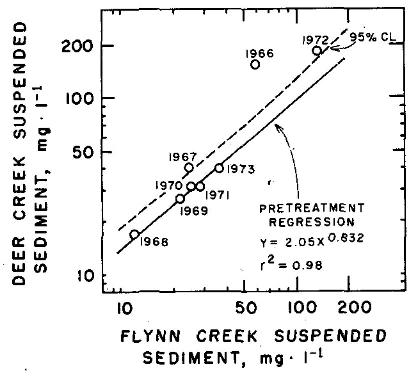

Fig. 5. Annual discharge-weighted suspended sediment concentrations after 25% patch-cut logging on Deer Creek watershed.

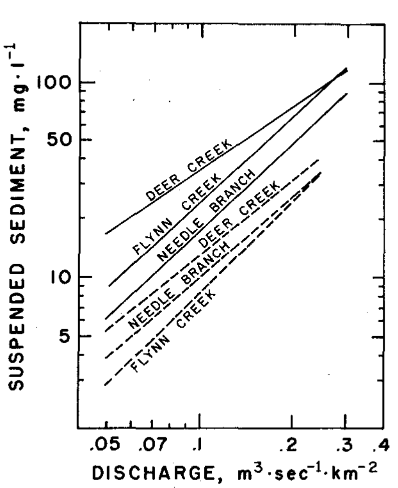

Fig. 7. Monthly suspended sediment concentrations and monthly stream discharge (1959–1965 WY). Solid lines show fall and winter months before and including the seasonal peak discharge. Dashed lines show winter and spring months after the seasonal peak discharge.

from land use was further evaluated by using discharge-weighted monthly sediment concentrations. Only those months having a stream discharge of 0.05 m^3 s^{-1} km^{-2} or greater were selected for analysis. This criterion eliminated months during which sediment concentrations were relatively low (usually ≤ 5 mg l^{-1}).

Sediment concentration data from the pretreatment period showed that early fall storms usually had a higher average suspended sediment concentration than similar storms occurring later in the winter. The critical point for a shift in the sediment rating curves was after the occurrence of the yearly peak flow. Thus monthly flows and suspended sediment concentrations before and including the yearly peak flow (prepeak data) were separated from those occurring after the yearly peak (postpeak data). Regression equations were developed from these monthly data during the pretreatment period of record (1959–1965 WY). The resultant equations (Figure 7) were compared ($P = 0.95$) to test the hypothesis that prepeak (subscript 1) and postpeak (subscript 2) equations were not significantly different for a given watershed: $\alpha_1 = \alpha_2$, and $\beta_1 = \beta_2$, where α is the intercept of the regression line and β is the slope. For each watershed the prepeak and postpeak equations were significantly different, a finding which confirms the seasonal shift in sediment rating curves after the yearly peak flow.

Because of the differences in monthly sediment concentrations, regression equations between Flynn Creek and the treated watersheds were determined for both prepeak and postpeak monthly data. After treatment, 25% of the prepeak monthly suspended sediment concentrations from Deer Creek were significantly increased (95% CL). In contrast, only 6% of the postpeak concentrations showed an increase. These results indicate that increases in sediment production associated with land use occurred primarily in the early fall and winter months on the Deer Creek watershed.

The temporal pattern of monthly suspended sediment concentration increases was different for Needle Branch. After forest-harvesting operations, 41% of the prepeak concentrations were increased (95% CL). Furthermore, 63% of the postpeak concentrations were increased, so that increased concentrations on Needle Branch occurred throughout the winter runoff period. These findings show that substantial differences in the timing of both annual and seasonal sediment yields can result from land use on watersheds that are physiographically similar.

DISCUSSION OF FINDINGS

The 15 years of streamflow and suspended sediment concentration data from the Alsea study have provided valuable insights into and documentation on the effects of land use. Several important principles concerning erosion and sediment transport from small mountain watersheds are illustrated. Both the timing and the magnitude of sediment production were altered by forest-harvesting operations.

The debris avalanches on the Deer Creek watershed in 1966 and 1972 moved considerable volumes of sediment and inorganic debris downslope. In several instances the paths of these mass failures scoured down to bedrock, and much of the material was deposited in low-gradient stream channels. Not only did the channels change, but the suspended sediment yields of Deer Creek were also significantly increased. Note that most mass failures on the Deer Creek watershed were associated with roads but did not occur until almost 7 years after their construction. Several mechanisms could account for this delayed response. Where side cast road fills had buried or incorporated organic matter during construction, decay of the organic material over time could have reduced the shear strength of the fill to the point of failure. An undercutting of fill material by the concentrated water from culverts could also have caused mass soil failures [*Burroughs et al.*, 1976]. Furthermore, a lack of road maintenance after logging may have contributed.

Logging roads entered the Deer Creek watershed from the

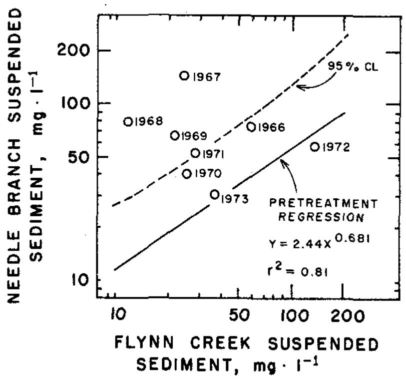

Fig. 6. Annual discharge-weighted suspended sediment concentrations after 82% clear-cut logging on Needle Branch watershed.

back of ridges to minimize mileage within the watershed. Though carefully located, constructed, and used [*Brown and Krygier,* 1971], the roads nonetheless caused most of the sediment production from the watershed. The findings show that midslope roads in steep terrain can substantially increase sediment production. Continued improvements in road location, design, construction, and maintenance are needed if increases in sediment production are to be minimized.

During the 1972 WY, several mass failures also occurred in one of the patch-cut units of Deer Creek. Although these failures were smaller than those associated with roads, they show that clear-cutting can affect mass soil erosion rates. Root decay begins as soon as a tree is felled and causes a rapid decline in numbers of fine roots and a sharp decrease in the tensile strength of remaining roots. As a result, the shear strength of the soil mantle may be reduced to the point of failure [*Burroughs and Thomas,* 1977]. Such effects would be most pronounced on steep slopes with shallow soils, such as those found on Deer Creek, and may explain the occurrence of small failures approximately 6 years after harvest. The decline in rooting strength and the subsequent occurrence of mass failures several years after logging have similarly been identified as important contributors to slope instability in shallow till and colluvial soils of southeastern Alaska [*Swanston,* 1974].

Heavy rainfall was necessary to trigger the several mass failures that occurred in Deer Creek in 1972. Thus a watershed must have not only the potential for failure but also a hydrologic event of sufficient magnitude before an increase in sediment production occurs. More information concerning subsurface flow during storms and the effect of roads and tree removal is needed if the hydrologic linkages between land use and mass failures are to be understood fully. In any event, the pattern of annual increases in sediment yields from Deer Creek amply illustrates the periodic and probabilistic nature of mass soil erosion in steep terrain of the Pacific Northwest.

Though a considerable volume of soil remains along several sections of the Deer Creek channel as a potential source of sediment, the material is apparently not being actively eroded by the stream and transported out of the watershed. Sediment yields returned to pretreatment levels within 1 or 2 years after the mass failures, so that the failures have not caused any long-term shifts in the suspended sediment rating curves for Deer Creek. That sediment increases lasted only 1 or 2 years (Figure 3) may account for the lack of significant decreases in resident trout populations of Deer Creek after treatment, as occurred in Needle Branch [*Moring and Lantz,* 1975].

High-lead cable yarding of timber on all units and the light slash burn on the lower patch-cut unit appear to have had little effect on Deer Creek sedimentation. This observation is in general agreement with others elsewhere [*Fredriksen,* 1970; *Rice et al.,* 1972]. Buffer strips of forest vegetation on the two lower patch-cut units of Deer Creek were primarily for stream temperature control, but they also prevented physical disturbance of stream beds and channel banks during yarding activities.

An analysis of posttreatment sediment data from the Alsea watersheds by *Harris* [1977] shows no significant increase (95% CL) in either mean sediment yields or mean sediment concentrations from Deer Creek after treatment. The apparent conflict between his conclusions and those presented here results from the statistical analysis of posttreatment data. In this study, significant increases (also 95% CL) in annual sediment yields and concentrations were found for 3 of 8 posttreatment years. If these values are averaged with the remaining 5 years of posttreatment data, watershed response to treatment is statistically nonsignificant. *Harris* [1977, p. 8] states that the use of mean values over the entire posttreatment period . . . provides the only valid comparison . . .' for evaluating the statistical significance of any change against pretreatment regression confidence limits. This would be true, perhaps, if the time series of posttreatment responses showed stationarity and if long-term averages were useful for assessing impacts. However, Figures 3 and 4 show varying trends in the timing of response to treatment of these watersheds. These temporal patterns are also shown in double-mass plots of cumulative sediment yields illustrated by *Harris* [1977, p. 26]. Thus, to determine measurable changes, individual monthly and annual posttreatment values should be compared with pretreatment relationships. Variability in both time and space is a definite characteristic of small-watershed hydrology. Comparison of long-term averages often does not reveal the importance of annual, seasonal, or individual storm events.

The findings from Needle Branch provide an important contrast to those of Deer Creek in that debris avalanches from roads, landings, and cutover areas did not occur. The roads in Needle Branch were constructed along ridges and relatively gentle slopes, but the exposed soils along roads and landings in the watershed were undoubtedly a source of surface erosion. In addition, the broadcast burn which removed logging slash was extremely hot and left extensive areas of bare mineral soils. Without buffer strips of overstory vegetation along streams, channel beds and banks were not protected from yarding disturbances. The significance of stream bed and bank disturbances in relation to increased sediment production from Needle Branch is not known.

Because measurements at the mouth of a watershed integrate the effects of all upstream activities, precise separation of cause and effect is not always possible. Such is the case with Needle Branch. However, the increase in sedimentation has been attributed chiefly to the hot slash burn [*Brown and Krygier,* 1971]. The bare mineral soils after burning, the steep slopes, and the high rainfall are ample conditions for accelerated surface erosion. Findings in other areas of the Pacific Northwest show that the amount of soil erosion reaching streams is generally proportional to the amount of bare soil exposed on a watershed [*Rice et al.,* 1972].

Increased sediment yields from Needle Branch had returned to pretreatment levels by the 1972 WY, or approximately 6 years after road construction. The data illustrate that where surface erosion is the primary process contributing to in-stream sediment production, maximum sediment will usually follow immediately after treatment and will gradually decline over a period of years. Undoubtedly, the recovery of shrubs and herbaceous vegetation after slash burning has been a primary cause of the declining yields.

SUMMARY

In recent years, in-stream monitoring of small watersheds by land management agencies has increased as a means of assessing nonpoint sources of pollution. The Alsea watershed study sampled intensively for 15 years to identify and evaluate treatment effects. The financial investment required for paired watershed studies prohibits this type of monitoring for most nonpoint pollution problems. The natural variability in sediment-discharge relations often makes small changes in sediment yields or concentrations impossible to detect, even with intensive sampling. However, the increases demonstrated on Needle Branch and Deer Creek were not small. Land use on these drainages increased annual values as much as 5 times and monthly values as much as 10 times. These results illustrate the need to sample during periods of high streamflow and sediment loads. In Oregon's Coast Range, rainfall from frontal storms moving inland off the Pacific Ocean causes a series of freshets, or periods of high flow, throughout the late fall, winter, and early spring months. Thus monitoring year round or during low flow may be of little benefit in assessing the effects of land use upon sediment yields.

The variability in sediment-discharge relations for undisturbed streams makes changes in sediment production resulting from land use difficult to detect statistically. For Oregon Coast Range streams, sediment concentrations may vary over an order of magnitude at any given discharge. Some variability can be associated with hydrograph characteristics. *Brown and Krygier* [1971] found that sediment concentrations during the rising stage of a storm hydrograph are typically greater than those during the falling stage. Another source of variability, i.e., a seasonal shift in the sediment-discharge relation after the annual peak flow (Figure 7), has been identified in this study. The findings imply that sample collection must be timed in relation to hydrograph characteristics and annual peak flow to evaluate changes in sediment-discharge relations following land use. Correlations between sediment concentration and discharge may be affected as much by the timing of sampling and the sequence of flow events as by the conditions of the watershed and channel system. Determining the relative importance of these factors is one of the principal tasks facing wild-land hydrologists.

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