Sediment and Stream Water Quality in Changing Elevation Environments: Trends and Explanation

LONG-TERM PATTERNS OF SEDIMENT TRANSPORT AFTER TIMBER HARVEST, WESTERN CASCADE MOUNTAINS, OREGON, USA

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ABSTRACT Suspended and bedload sediments were sampled from 1958-1988 on three small watersheds in the western Cascade Range in Oregon. Annual sediment yields varied greatly among watersheds, and the pattern of long-term sediment production reflects their timber harvest and mass movement histories. Total yields from 1958-1988 were 5100 t km⁻² in the clearcut watershed (WS 1), 21000 t km⁻² in the patchcut watershed with roads (WS 3), and 800 t km⁻² in the forested control (WS 2). More than 85% of the total sediment yield in WS 3 occurred during a storm in 1964 when a series of debris flows occurred in the channel to bedrock. Excluding that event, post-logging annual export from WS 3 has been more than twice that from WS 3. The importance of episodic mass motion events in this landscape limits the effectiveness of small-watershed studies for analyzing long-term sediment yields.

INTRODUCTION
Some of the world's largest and most productive temperate forests grow in the steep mountains of the US Pacific Northwest. Timber harvest has been the primary land use in this area for 100 years. Of major concern is the potential for harvest activities to increase sediment erosion, with consequent effects on water quality, channel stability, and riparian ecosystems. These concerns are compounded by prospects of interactions between changing land use and changing climate in the next several decades. A series of small-watershed experiments was initiated on the H.J. Andrews Experimental Forest in western Oregon in the 1950s to examine the hydrologic, geomorphic, and biologic effects of timber harvest. With both land use and climate may be changing rapidly and interactively, these long-term sites represent important repositories of information on natural and human-induced variation in watershed behavior. This paper describes a 30-year history of sediment production, both bedload and suspended load, from three small watersheds with different road and forest cutting treatments. Although the sedimentation history for the first few years after treatments has been reported for these watersheds (Fredriksen, 1970) along with bedload production through 1978 (Swanson & Fredriksen, 1982), this is the first comprehensive summary of the 30-year history of sediment production from this watershed experiment. The results of this 30-year investigation demonstrate both the strengths and limitations of long-term field experiments.
STUDY SITE

The H.J. Andrews Experimental Forest is located in the western Cascade Range of Oregon, a deeply dissected volcanic plateau of Tertiary age. Bedrock is a mixture of volcaniclastic rocks and debris flows cut by scattered dikes (Bowen & Smith, 1989). Landscape has been sculpted by fluvial and various soil-mass-wasting processes (Swanson & James, 1975). Major movements include shallow, rapid movements of soil or hilltops (debris slides); rapid movements of alluvium, colluvium, and organic masses down stream channels (debris flows); and large, slow-moving landslides (slump and earthflows). Annual precipitation averages 2300 mm, much of it between October and March. Rain-on-snow events within the glaciogenic snow zone (<60 to 1380 m elevation) are a major factor in generating most floods. Comfort streams dominated by 500- to 5000-year-old Douglas fir (Pseudotsuga menziesii) blanket hilltops and undisturbed valley floors.

Table 1 Characteristics of the three experimental watersheds.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Area (ha)</th>
<th>Average Elevation (m)</th>
<th>Average hill slope grade (%)</th>
<th>Aver-age minimum-channel gradient (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.96</td>
<td>440</td>
<td>1011</td>
<td>52.2</td>
</tr>
<tr>
<td>2</td>
<td>0.66</td>
<td>523</td>
<td>1065</td>
<td>61.1</td>
</tr>
<tr>
<td>3</td>
<td>1.01</td>
<td>480</td>
<td>1080</td>
<td>52.6</td>
</tr>
</tbody>
</table>

Three small adjoining watersheds (WS 1, 2, & 3) were selected based on similar sizes, aspects, and topography (Table 1), described in detail by Redeker et al. (1967). Harvest, which began in WS 1 in fall 1962 and ended in summer 1966, used a skycrane suspension system to minimize surface soil disturbance. Residual logging debris was burned in October 1966. On WS 3, a road covering 2.64 km (60% of the drainage) was completed in 1959. Three discontinuous clearcuts of 0.05, 0.18, and 0.14 km² (25% of watershed area) were logged in winter, 1962-63, by a high-speed cable logging system. This method resulted in twice the area of deep soil disturbance (10%) and nearly three times the area of compacted soil (9%) compared to WS 1 (Dymond, 1967). Logging debris was burned in September 1963. WS 2 served as a forested control. Replanted clearcuts in WS 1 and 3 now support >25-year-old stands of Douglas fir and other species.

The soil mass-movement history of these three watersheds during the study period included a moderately large debris flow from a small postfire failure in WS 3 in December 1961. A very large burn in December 1964 with about a 100-year return period (Wiman et al., 1971) initiated several debris slides and several debris flows in WS 3. A somewhat smaller burn in January 1965 initiated four debris slides in WS 1 (Table 2). Subsequent smaller episodes of debris sliding occurred between 1968 and 1972 in both WS 1 and 3 (Table 2).

FIELD AND LABORATORY METHODS

Discharge was monitored continuously with Leopold-Stevens A-35 recorders since 1953 at calibrated flumes at the downstream end of each watershed. Sampling of suspended and bedload sediments at the flumes, initiated in Water Year (WY) 1958, is repeated here through WY 1968. Vertically integrated, suspended sediment grab samples were taken in
Sediment Transport After Timber Harvest, Oregon, USA

Print bottles from the head end of each flume during and between storms. Samples were taken at least once a week, as possible at each watershed, with samples taken on rising hydrotehgraphs, peak, and falling leg, when possible. All samples were screened before filtering to remove sediment >2 mm. Redload was measured annually during summer low flow by survey of the bottom elevation of sediment basins below the gauging station. Sediment yield (year⁻¹) was calculated using a bulk density of 1.0 g cm⁻³ (Fredriksen, 1970; Swanson et al., 1983). Total volumes of material collected were reduced by 15% to account for the proportion of organic material in the bedload trap, as measured by Swanson et al. (1972) in a neighboring 18-ha forested watershed. The proportion of organic material was treated as constant at all three watersheds, even though organic export is likely to vary with both land-use and annual discharge.

**TABLE 2: Landslide chronology and volumes for Watersheds 1 and 3 as determined by aerial photo and field reconnaissance. Volumes include organic material as well as sediment.**

<table>
<thead>
<tr>
<th>Time of occurrence</th>
<th>Volume (m³)</th>
<th>Site condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(water year)</td>
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</tr>
</tbody>
</table>

**Watershed 1**

- 1965: 90 Cleared; earthflow-related
- 1965: 120 Cleared
- 1965: 110 Cleared
- 1965: 190 Cleared
- 1968-1972: 2700 Cleared; earthflow-related
- 1968-1972: 1200 Cleared; earthflow-related
- 1972: 150 Cleared
- 1972: 840 Cleared
- Total: 5700

**Watershed 3**

- 1962: 90 Road; generated debris flow
- 1965: 190 Road
- 1955: 1200 Road; generated debris flow, earthflow-related
- 1965: 9800 Road; generated debris flow
- 1965: 460 Cleared
- 1965: 110 Cleared
- 1968: 6000 Road
- 1968: 310 Road; earthflow-related
- Total: 17900

**MODEL DEVELOPMENT**

Because suspended sediment discharge was not continuously measured, annual sediment yield was calculated using empirical models that related sediment flux to hydrograph characteristics. Annual hydrographs for all three watersheds were divided into storm and non-storm periods. Five storm periods, separate multiple regression models were developed for rising and falling hydrograph segments from all suspended sediment and corresponding
<table>
<thead>
<tr>
<th>Years</th>
<th>Treated</th>
<th>Storms</th>
<th>LOGQ</th>
<th>LQDT</th>
<th>SEQQR</th>
<th>PEAKR</th>
<th>TSPR</th>
<th>PROP</th>
<th>LOG</th>
<th>MEAN</th>
<th>r</th>
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<td>Pre</td>
<td>NS</td>
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<tr>
<td>1967-1968</td>
<td>Post</td>
<td>NS</td>
<td>1.542</td>
<td>-3.700</td>
<td>0.79</td>
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<td>Pre</td>
<td>R</td>
<td>1.417</td>
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<td>-0.18</td>
<td>0.020</td>
<td>-3.777</td>
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<tr>
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<td>Post</td>
<td>R</td>
<td>1.623</td>
<td>0.000</td>
<td>0.016</td>
<td>-0.687</td>
<td>-0.909</td>
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<td>0.016</td>
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<tr>
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<td>NS</td>
<td>1.114</td>
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<tr>
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<td>0.574</td>
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<td>R</td>
<td>1.256</td>
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<tr>
<td>1964-1966</td>
<td>Post</td>
<td>NS</td>
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<tr>
<td>1965-1966</td>
<td>Post</td>
<td>R</td>
<td>1.576</td>
<td>0.016</td>
<td>0.020</td>
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<tr>
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<td>0.020</td>
<td>-0.687</td>
<td>-0.909</td>
<td>0.67</td>
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a NS = non-treatment, R = resting, F = felling
b LOGQ = logarithm of discharge
c LQDT = rate of sediment discharge in feet per minute of stream volume per day

d SEQQR = sequential number of storms within a year

e PEAKR = relative ratio of peak flow of stream within a year
f TSPR = rate of 3-year peak rate

g PROP = proportion of the cumulative discharges at the peak of the storm, or the midpoint of the storm, or the middle point of the storm
h LOGMEAN = number of years since logging
i Includes effects of rainfall and snow melting

Discharge measurements for WS 2 over the sampling period (Table 3). Sediment discharge is strongly limited by supply rather than transport capacity in these steep mountain streams. This is due to the strong influence of snowmelt on the discharge regime. The snowmelt regime is characterized by a sequence of warm events of different magnitudes, which control the stream flow. The models used in this study were developed for the pre- and post-treatment periods (Table 3). Pre-treatment models excluded the actual years of harvest and burning but included the effects of rainfall in WS 3, because of the short record before road construction. A simple linear regression of water discharge and sediment flux was used to calculate sediment yield during non-storm periods for all three watersheds. A smoothing correction factor was used on the log-transformed discharge measurements in all models to compensate for the underestimation that results from fitting a linear regression on a log-transformed scale (Dugg, 1963; Ferguson, 1960). The r² value for all models ranged from 0.6 to 0.87 (Table 3). Lowest r² values corresponded to...
the non-storm models when little sediment is transported. The model for WS 2 was further validated by comparing 3-week composited samples with calculated total suspended sediment yield using the model. Agreement was quite good ($r^2 = 0.87$, n = 100).

Annual suspended sediment yields were calculated using the annual discharge hydrograph along with the appropriate models (Table 4). The pretreatment models for WS 1 and 3 were used until the end of harvest because analyses showed that sediment discharges during harvest were better represented by the post- as opposed to post-treatment models. This is probably a good assumption for WS 1, where most of the erosion followed burning in 1966 (Mersereau & Dyness, 1972), but may underestimate the effect of roads and the 1961 debris flow in WS 3. Total annual sediment yield was calculated as the sum of annual suspended sediment yield and total bedload (Table 4).

![Diagram showing annual sediment yield for Watersheds 1, 2, and 3 for WY 1958-1988.]

FIG. 1  Annual sediment yields for Watersheds 1, 2, and 3 for WY 1958-1988.
### ANNUAL TRENDS IN SEDIMENT YIELD

Sediment yields from undisturbed forest watersheds

Annual rates of sediment transport in undisturbed forest watersheds can be compared using the 5 years of pre-treatment sediment yield data from WS 1 and the full 30-year history from WS 2; the 2-year record from WS 3 before road construction is too short to be useful. Average annual yields for forested watersheds was 18 t/km²-year⁻¹ in WS 1 and 25 t/km²-year⁻¹ in WS 2 (Table 4). Suspended sediment transport accounted for 98% of the total sediment exported from WS 1 before harvest and 95% of the total exported from WS 2 (Fig. 1b).

#### Effects of forest management on sediment yield

**WS 1**

Average annual production of sediment from WS 1 after clearcutting was 230 t/km²-year⁻¹, about 12 times the pre-treatment rate (Table 4). Total sediment production rates increased very rapidly and remained elevated over the first 10 years after harvest. The increment in production was 430, 198, and 198 t/km²-year⁻¹ for the first, second, and third years, respectively, and 430 t/km²-year⁻¹ for the 10th year. The post-treatment sediment yield data suggest that, if current trends continue, sediment production should decline to average pre-harvest rates by the year 1996, 10 years after harvest. Most of the post-harvest increase in total yield is in the bedload fraction (Table 4). Since WS 1972 bedload exceeded suspended load in 5 of 16 years, it is likely that sediment production is apparently recovering to pre-harvest yields more rapidly than bedload (Fig. 1a).

**WS 2**

Total sediment yield during the post-treatment period from WS 3 was over 20000 t/km², 4 times the post-treatment yield from WS 1 and 27 times the amount from WS 2 over the same time period. However, 88% of this delivery occurred in 1965, probably within a single burn. The yield of December 1960 triggered a series of debris slides and associated debris flows that transported more than 20000 t of organic and inor...
ganic material out of the watershed (Fredrickson, 1970). This rough estimate is probably conservative, much of the exported material was rapidly removed by fluvial erosion. About 50% of the material originating from-roadills with the run-off coming from channel sources (Statham & Fredrickson, 1982). Excluding WY 1965, post-logging sediment yield from WS 3 has been substantially lower than WS 1, averaging 100 t km$^{-2}$ year$^{-1}$. Sediment yield has been dominated by suspended sediment discharge, which has exceeded bedload discharge in every year since WY 1965 (Fig. 1c).

![Graph showing cumulative sediment yields for Watersheds 1, 2, and 3 for WY 1958-1988.](image)

**Watershed comparisons.** Contrasting patterns of sediment production in WS 1, 2, & 3 can be summarized in their cumulative sediment yield curves (Fig. 2). Sediment yield from WS 2 has been more erratic compared to WS 1, with a sharp peak only in WY 1965, followed by lower than average production in the next 3 years. WS 1 was highly affected by the December 1964 storm, but has diminished dramatically when clearcutting and burning stopped; these increases have diminished with time, but are still substantially higher than pre-1964 yields more than 20 years later. Virtually all of the sediment yield from WS 3 occurred during a single event; yields were uniformly low thereafter.

**DISCUSSION**

The three watersheds differ dramatically in both the magnitude and timing of sediment yield over the 30-year period. These differences cannot simply be attributed to the specific watershed treatments, but reflect a complex interplay between treatments, the timing of major storm events, and inherent geological and geomorphic properties of the watershed. The widely different responses of these seemingly similar watersheds underscore the difficulty in making categorical statements about the effects of land use on sediment production, despite a large amount of recent research, especially for small watershed studies in more mesic, forested terrain.

**Effects of the 1964 storm.**

Arguably, the most significant factor contributing to the contrasting behavior of the
three watersheds was the 1964 storm. Its consequences included both direct effects on erosional processes and the geomorphic legacy of modified landforms and sediment transport and storage processes within the watersheds after the storm.

Direct effects included both the largest peak flows in the 30-year study and initiation of debris slides and flows in both WS 1 and 3 (Table 2). Sediment transport during the storm delivered more than twice as much sediment per unit area to the mouth of WS 3 than did the remaining 30-year production from all watersheds combined. This result, in line with many other studies, demonstrates that in steep landscapes dominated by mass movement, infrequent events overshadow all others in terms of transporting sediment (Nielson et al., 1987).

Absolute effects of the 1964 storm, however, were strongly influenced by watershed condition at the time of the storm. In WS 1, logging was about half completed: absence of roads and slopes mantled by either standing vegetation or cut and downslopes resulted in only minor debris sliding and surface erosion. Total sediment yield for WS 1 was 70 t km⁻², roughly a third of the average annual post-treatment yield from WS 1 and less than half the 160 t km⁻² produced from completely forested WS 2 in WS 1965. Judging from the location of debris slide initiation sites in WS 3, channels intersecting to appear to have played only a minor role in increasing sediment delivery; instead, poorly designed and maintained mid-slope roads located in unstable slump-prone terrain were the dominant factor for the large differences in sediment yield between watersheds. Debris slides in WS 1 after harvest, however, (Table 2) were largely due to loss of residual root strength.

Differences in drainage network morphology also contributed to the contrasts in their sediments yield histories. Debris slides in WS 3, initiated from road fills at the heads of long, straight channels, triggered debris flows that flushed the channel system. Tributary channels in WS 1 generally join at high junction angles, and the smaller debris slides there did not have the volumes, velocities, or straight-down-channel trajectories to trigger debris flows.

The 1964 storm also altered channel landforms which, in turn, influenced subsequent sediment delivery. Debris flows in WS 3 scoured virtually all sediment and large organic debris from the upper channel, leaving a bedrock chute in many places. Although much of the eroded material was transported out of the basin, the debris flows left a large dense deposit of cobbles in the low-gradient reach extending about 50 m directly above the gauge. This deposit has grown by deposition of material derived from additional small debris slides between 1965 and 1972 (Table 2), and the several new sources of sediment created by the 1964 debris slides and debris flows; bare streamside areas scoured by debris flow passage, in-channel debris flow deposits, and exposed soil on debris slide scars. The deposit now extends about 300 m upstream from the gauge. Restoration of vegetation and scars, low volume sediment stored in the upper scoured channel, and high-trapping efficiency of logs and boulders in this lower reach have resulted in the very low bedload yields observed from WS 3 since 1972 (Fig. 1c). These yields do not differ statistically from pretreatment yields.

Continued production above pretreatment yields of both suspended and bedload from WS 1 reflects several sources: (a) release from storage in the channel system in the pre-logging period and during the 1964 and subsequent storms; (b) surface erosion after burning; and (c) active earthflow complex in the upper part of the watershed. Sediment is primarily stored in the channel behind large organic debris, and pulses of sediment are exported to wood shifts during storms.
Effects of mass movements

The sediment yield histories from the three watersheds underscore the importance of episodic mass movements as controls on timing and magnitude of sediment yield from these small, steep watersheds. Mass movements dominated sediment production during the 1964 storm. Throughout the study, highest annual sediment production corresponded with mass movements within the watersheds. (Fig. 1, Table 2). Sediments and organic matter were delivered to the channel system by debris slides over the 30-year period approximated total organic sediment export in WS 1 and were 81% of total export in WS 3 (Table 2, 4). More generally, results from this study demonstrate that mass movements can radically alter the volumes and patterns of sediment delivery, depending on whether they transform into debris flows that reach the watershed mouth, and whether they occur at the beginning, middle, or end of a measurement period, or not at all.

The importance of episodic processes has significant implications for interpreting long-term erosion studies in small watersheds. The pattern of sediment production observed during multiple decades of monitoring is strongly affected by whether or not a major, infrequent event is captured during the study period. Episodic processes are not well sampled or represented in long-term, small-watershed studies, however. In forested watersheds in the western Cascades, debris slide frequency is estimated at 0.077 events km\(^{-2}\) year\(^{-1}\), based on extensive debris slide inventories (Swanson et al., 1982; Swanson & Grant, 1983). On average, forested watersheds of the area of WS 2 might be expected to experience 0.5 debris slides during a 30-year period; none were observed in WS 2 during the study. The frequency of slides increases markedly to 0.086 and 2.12 events year\(^{-1}\) of clearcut or roaded area, respectively (Swanson & Grant, 1983). Even in these more landslide-prone watersheds, a 1 km\(^2\) watershed without roads, such as WS 1, is predicted to experience only 2.6 debris slides during a 30-year period.

Even slide frequencies based on extensive aerial photo inventories may not adequately represent long-term sliding rates. Slide frequencies cited above for the western Cascades may be overestimates because they are dominated by the effects of the 1964 storm, an event whose 100-year return period exceeds the period of record by at least three times. A more rigorous analysis requires defining slide frequencies in units of cumulative area per unit time, such as foccare-years, for characterizations and readings of different age classes and relating these frequencies to storms of different return periods (Swanson et al., 1981). Stratigraphic and dendrochronologic techniques may also be used to extend the length of record to more closely approximate the return period of major storms.

CONCLUSIONS

Long-term records of sediment production and export in small, mountain watersheds, like WS 1, 2, and 3, reveal that sediment yields are highly contingent on an interplay of factors. Many of these factors relate to differences in the proportion of unstable watershed area, drainage network morphology, and antecedent conditions, such as volume of sediment stored in channels. Difficulty in quantifying most of these factors means that they are not usually considered when siting paired watershed experiments. The location of land-use activities in mass movement-prone parts of the landscape clearly affects the degree to which land use affects sediment production. This study suggests that the timing of land-use activities with respect to large storms is equally important. Radically different trajectories of sediment yield result depending on whether infrequent storms initiate mass movements.
Even well-designed, long-term studies using paired watersheds and controls have limited applicability in a landscape dominated by episodic processes. Predictive models based on multiple decade studies must explicitly consider the effects of extreme events and episodic processes on sediment yield. This requires incorporating rates of mass erosion determined by extensive mass movement inventories over many decades. Even these inventories must be interpreted cautiously, because they too can be dominated by presence or absence of storms whose return periods exceed the length of record.

ACKNOWLEDGEMENTS This work was supported by the National Science Foundation under the Long-Term Ecological Research Grant BSRRX-14325. We gratefully acknowledge the early work on these watersheds by R.I. Fredriksen and the field assistance of A. LeVine, G. Lieskaemper, and the rest of the field crew. We thank P. Swanson and F. Nakamura for their reviews of this manuscript and R. Thomas and D. Hendrow for assistance with the statistical analysis.

REFERENCES

PAST

INTRO

Historic and modern research to come in the future.

In the past, we have recorded very little about the edge of the forest.

By far, the most useful lands are the areas that have been altered by human activity.