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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 scoured the channel to bedrock. Excluding that event, post-logging annual export from WS 1 has been more than twice that from WS 3. The importance of episodic mass erosion 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. When 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 platform of Tertiary age. Bedrock is a mixture of volcaniclastic rocks and lava flows cut by scattered dikes (Sherrod & Smith, 1989). Landforms have been sculpted by fluvial and various soil mass-wasting processes (Swanson & James, 1975). Mass movements include shallow, rapid movements of soil on hillslopes (debris slides); rapid movements of alluvium, colluvium, and organic matter down stream channels (debris flows); and large, slow-moving landslides (slumps and earthflows). Annual precipitation averages 2300 mm, much of it between October and March. Rain-on-snow events within the transient snow zone (400 to 1200 m elevation) are a major factor in generating most floods. Conifer forests dominated by 400- to 500-year-old Douglas-fir (Pseudotsuga menziesii) blanket hillslopes and undisturbed valley floors.

TABLE 1 Characteristics of the three experimental watersheds.

Watershed	Area (km^2)	Elevation (m) Min	Elevation (m) Max	Average hillslope gradient (%)	Average mainstem channel gradient (%)
1	0.96	440	1010	63.2	27.8
2	0.60	525	1065	61.1	36.4
3	1.01	480	1080	52.6	27.2

Three small adjoining watersheds (WS 1, 2, & 3) were selected based on similar sizes, aspects, and topography (Table 1), described in detail by Rothacher *et al.* (1967). Harvest, which began in WS 1 in fall 1962 and ended in summer 1966, used a skyline suspension system to minimize surface soil disturbance. Residual logging debris was burned in October 1966. On WS 3, roads covering 2.64 km (6% of the drainage) were completed in 1959. Three discontiguous clearcuts of 0.05, 0.08, and 0.11 km^2 (25% of watershed area) were logged in winter, 1962-63, by a high-lead cable logging system. This method resulted in twice the area of deep soil disturbance (10%) and nearly 3 times the area of compacted soil (9%) compared to WS 1 (Dyrness, 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 roadfill failure in WS 3 in December 1961. A very large storm in December 1964 with about a 100-year return period (Waananen *et al.*, 1971) initiated seven debris slides and several debris flows in WS 3; a somewhat smaller storm in January 1965 initated 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 sediment at the flumes, initiated in Water Year (WY) 1958, is reported here through WY 1988. Vertically integrated, suspended sediment grab samples were taken in pint bottles from the head end of each flume during and between storms. Samples were taken at as near the same time as possible at each watershed, with samples taken on rising hydrograph leg, peak, and falling leg, when possible. All samples were screened before filtering to remove sediment >2 mm. Bedload was measured annually during summer low flow by survey of the bottom elevation of sediment basins below the gauging station. Sediment yield (t $year^{-1}$) was calculated using a bulk density of 1.0 g cm^{-3} (Fredriksen, 1970; Swanson *et al.*, 1982). Total volumes of material collected were reduced by 33% to account for the proportion of organic material in the bedload traps, as measured by Swanson et al. (1982) in a neighboring 10-ha forested watershed. The proportion of organics was treated as constant in 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 photos and field reconnaissance. Volumes include organic material as well as sediment.

Time of occurrence (water year)		Volume (m^3)	Site condition
Watershed 1			
1965		90	Clearcut; earthflow-related
1965		110	Clearcut
1965		110	Clearcut
1965		190	Clearcut
1968-1972		2700	Clearcut; earthflow-related
1968-1972		1200	Clearcut; earthflow-related
1972		150	Clearcut
1972		840	Clearcut
	Total	5390	
Watershed 3			
1962		20	Road; generated debris flow
1963		1200	Road
1965		190	Road
1965		1200	Road; generated debris flow, earthflow-related
1965		7600	Road; generated debris flow
1965		460	Clearcut
1965		110	Clearcut
1968		6000	Road
1968		310	Road; earthflow-related
	Total	17090	

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. For storm periods, separate multiple regression models were developed for rising and falling hydrograph segments from all suspended sediment and corresponding

TABLE 3 Model parameters and coefficients.

Years	Treat-ment	Storm leg[a]	LOGQ[b]	DQDT[c]	SEQR[d]	PEAKR[e]	FSHP[f]	PROP-STORM[g]	LOG-TIME[h]	Inter-cept	r^2
<u>Watershed 1</u>											
1958-1962	Pre	NS	1.002							-3.486	0.61
1967-1988	Post	NS	1.542							-2.700	0.79
1958-1965	Pre	R	1.417	0.331	-0.038	0.020				-3.177	0.86
" "	"	F	1.623	0.016			0.677	-0.900		3.217	0.84
1967-1988	Post	R	1.954	0.262	-0.010	-0.016			-1.075	-1.904	0.87
" "	"	F	2.088	0.023			0.608	-1.151	-0.959	-1.749	0.86
<u>Watershed 2</u>											
1958-1988	Pre	NS	1.110							-3.298	0.58
" "	"	R	1.371	0.991	-0.043	0.030				-2.686	0.74
" "	"	F	1.082	0.574			2.621	-1.112		-2.257	0.83
<u>Watershed 3</u>											
1958-1962	Pre[i]	NS	1.256							-3.107	0.56
1964-1988	Post	NS	1.544							-2.410	0.67
1958-1962	Pre[i]	R	1.928	0.406	0.029	0.048				-3.626	0.71
" "	"	F	0.899	0.176			2.017	-0.680		-2.168	0.71
1964-1988	Post	R	1.776	0.355	-0.016	-0.024			-0.620	-2.096	0.67
" "	"	F	2.140	0.031			0.664	-0.661	-0.537	-2.592	0.73

[a] NS = non-storm; R = rising; F = falling

[b] LOGQ = logarithm of discharge

[c] DQDT = rate of hydrograph rise or fall in the preceding 4-hour period

[d] SEQR = sequential number of storm within a water year

[e] PEAKR = relative rank of peak flow of storm within a water year

[f] FSHP = $\frac{Q_{peak} - Q_{end}}{T_{peak} - T_{end}}$ where Q_{peak} and Q_{end} are discharges at the peak and end of the storm, respectively and T_{peak} and T_{end} are times of the peak and end of the storm, respectively.

[g] PROPSTORM = proportion of the cumulative discharge at a point relative to the total cumulative discharge of the storm

[h] LOGTIME = number of years since logging

[i] Includes effects of roads but no logging

discharge measurements for WS 2 over the sampling period (Table 3). Sediment discharge is strongly limited by supply rather than transport energy in these steep mountain streams, so the models explicitly incorporated two variables (PEAKR and SEQR) to account for the sequence of storm events of different magnitudes which access different supply compartments in the channel. Parameters for the two treated watersheds were then fitted using this basic model structure with an additional time-since-treatment variable; separate models 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 roads 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 smearing 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 (Duan, 1983; Ferguson, 1986). The r^2 value for all models ranged from 0.56 to 0.87 (Table 3). Lowest r^2 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 analysis showed that sediment discharges during harvest were better represented by the pre- 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 & Dynress, 1972), but may underestimate the effects 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).

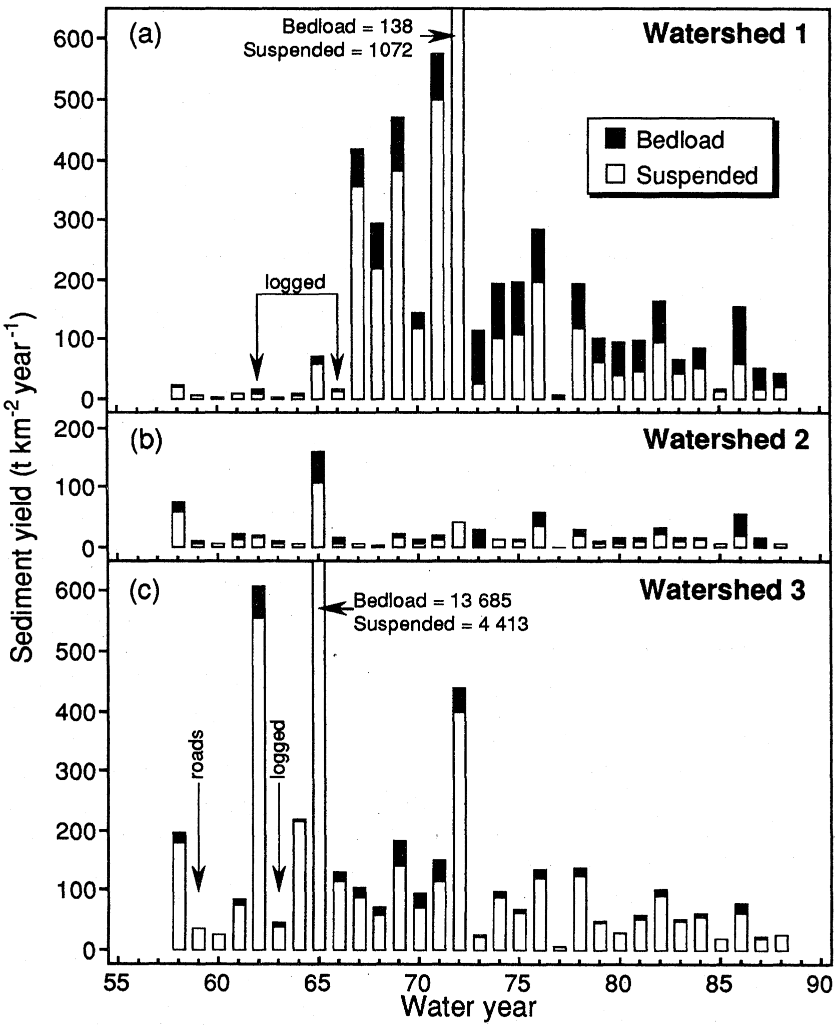

FIG. 1 Annual sediment yields for Watersheds 1, 2, and 3 for WY 1958-1988.

TABLE 4 Summary of pre- and post-treatment sediment yields for Watersheds 1, 2, and 3.

	Suspended (t km^{-2})	Bedload (t km^{-2})	Total (t km^{-2})	Bedload proportion (%)
Watershed 1				
Total pre-treatment (1958-1966)	130	29	160	
Annual average pre-treatment	14	3	18	15
Total post-treatment (1967-1988)	3600	1 300	5 000	
Annual average post-treatment	170	60	230	38
Total (1958-1988)	3800	1 400	5 100	
Watershed 2				
Total pre-treatment	490	270	760	
Annual average pre-treatment	16	9	25	30
Total (1958-1988)	490	270	760	
Watershed 3[a]				
Total pre-treatment (1958-1963)	910	85	1 000	
Annual average pre-treatment	150	14	170	8
Total post-treatment (1964-1988)	6500	14 000	20 000	
Annual average post-treatment	260	560	820	14
Total (1958-1988)	7400	14 000	21 000	

[a] Includes debris flows

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 9 years of pretreatment 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 km^{-2} year^{-1} in WS 1 and 25 t km^{-2} year^{-1} in WS 2 (Table 4). Suspended sediment transport accounted for over 80% of the total sediment exported from WS 1 before harvest and 55% 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 km^{-2} year^{-1}, about 12 times the pretreatment rate (Table 4). Total sediment production rates increased very rapidly and remained elevated over the first 10 years after harvest. The largest increase was in WY 1972, when over 1200 t km^{-2} year^{-1} were produced, more than 67 times the pretreatment average (Fig. 1a). Sediment production has since declined but remains above pre-harvest rates; from WY 1984-88, average sediment production was 70 t km^{-2} year^{-1}, more than 4 times the pre-harvest rate. An exponential curve fit to the post--treatment sediment yield data predicts that, if current trends continue, sediment production should decline to average pre-harvest rates by the year 1996, 30 years after harvest. Most of the post-logging increase in total yield is in the bedload fraction (Table 4). Since WY 1972, bedload exceeded suspended load in 5 of 16 years; in the pre-harvest period, suspended load exceeded bedload in all years. Suspended sediment is apparently recovering to pre--harvest yields more rapidly than bedload (Fig. 1a).

WS 3 Total sediment yield during the post-treatment period from WS 3 was over 20000 t km^{-2}, 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 WY 1965, probably within several hours. The storm of December 1964 triggered a series of debris slides and associated debris flows that transported more than 20000 t of organic and inorganic material out of the watershed (Fredriksen, 1970). This rough estimate is probably conservative; much of the exported material was rapidly removed by fluvial erosion. About 90% of the material originated from roadfills with the rest coming from channel storage (Swanson & Fredriksen, 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).

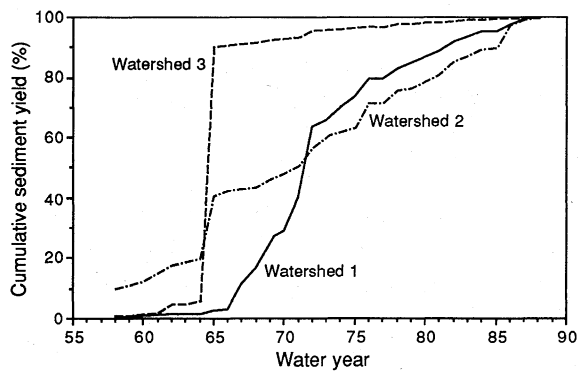

FIG. 2 Cummulative sediment yields for Watersheds 1, 2, and 3 for WY 1958-1988.

Watershed comparison 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 or less constant over time, with a sharp rise only in WY 1965, followed by lower than average production in the next 3 years. WS 1 was little affected by the December 1964 storm, but rose dramatically when clearcutting and burning stopped; these increases have diminished with time, but are still substantially higher than pretreatment 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 watersheds. The widely different responses of these seemingly similar watersheds underscores the difficulty in making categorical statements about the effects of land use on sediment production, despite a long-term empirical record, especially for small-watershed studies in mass movement-prone terrane.

Effects of the 1964 storm

Arguably, the most significant factor contributing to the contrasting behaviors 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 during the 30-year study and initiation of debris slides and flows in both WS 1 and 3 (Table 2). Sediment transport during this storm delivered more than twice as much sediment per unit area to the mouth of WS 3 than did the remaining 30-years production from all watersheds combined. This result, in line with many other studies, demonstrates that in steep landscapes dominated by mass movements, infrequent events overshadow all others in terms of transporting sediment (Nolan *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 downed trees resulted in only minor debris sliding and surface erosion. Total sediment yield for WY 1965 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 WY 1965. Judging from the location of debris slide initiation sites in WS 3, clearcutting per se appears 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 sediment 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 this eroded material was transported out of the basin, the debris flows left a large 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. Revegetation of cutbanks and scars, low volume of 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 WY 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 of material deposited in the channel system in the pre-logging period and during the 1964 and subsequent storms; (b) surface erosion after burning--local surface erosion rates exceeding 450 $t\ km^{-2}$ were measured by Mersereau & Dyrness (1972); and (c) continued production from the 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 as 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 organics delivered to the channel system by debris slides over the 30-year period approximated total inorganic 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 sediment 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 0.027 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 $year^{-1}$ km^{-2} of clearcut or roaded area, respectively (Swanson & Grant, 1983). Even in these more slide-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 hectare-years, for clearcuttings and roads 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.

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