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Upland Sediment Yield and Shoreline Sediment Delivery in Coastal Southern California

Brent D. Taylor

EXTENDED ABSTRACT

In coastal southern California (fig. 1), the natural sediment system involves the continual relocation of surface geologic materials. Surface materials are eroded hydraulically from inland areas with sufficient relief and precipitation and then deposited on low-gradient coastal plains and at the shoreline where the velocity of surface runoff decreases. Generally, coarse sand, gravel, and larger particles are deposited near the base of the mountains and hills on alluvial fans, and finer sediments are deposited further downstream on floodplains, in bays or lagoons, and along the shoreline. Very fine silt and clay particles, which make up a significant part of the eroded material, are carried offshore where they eventually accumulate in deeper areas. Finally, sand delivered to the shoreline is moved along the coast by waves and currents until it is lost to offshore areas through submarine canyons and other paths.

Human developments in this region have substantially altered the natural sediment-transport system—through timber harvest, grazing, and sand and gravel mining; the construction and operation of water conservation facilities and flood-control structures; and shoreline developments.

Almost always, these developments have grown out of recognized needs and have served their primary purposes well. Possible deleterious effects on the local or regional sediment balance were initially unforeseen or felt to be of secondary importance.

Since 1975, the Environmental Quality Laboratory (EQL) at the California Institute of Technology and the Shore Processes Laboratory at Scripps Institute of Oceanography have conducted a joint study to define quantitatively:

• The natural system of inland and coastal transport of sediment in southern California.

• The extent to which human activities have altered this natural system.

A comprehensive EQL report, currently being prepared, is scheduled for publication during 1981 and will be available for general distribution.[1]

Inland areas can be identified as either erosional or depositional according to recent geological activity. Erosional areas have been subdivided into drainage basins, and estimates of average annual sediment yield have been computed based on

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[1]Sediment Management for Southern California Mountains, Coastal Plains and Shoreline, Environ. Qual. Lab. Rep. No. 17, Calif. Inst. Technol. 1981, 100 p. 17-A: Regional geological history, Edward W. Fall, 1981, 30 p., 4 maps; 17-B: Inland sediment movements by natural processes, Brent D. Taylor, 1981, 100 p., 2 maps; 17-C: Coastal sediment delivery by major rivers in southern California, William R. Brownlie and Brent D. Taylor, 1981, 292 p.; 17-D: Special inland studies, William W. Brown III, Oded C. Kolker, Nancy Palmer, Wade Wells, 1981, 150 p., 4 maps; 17-E: Shoreline sedimentation processes, Douglas L. Inman, Abraham Golick, and Martha Shaw, Scripps Inst. Ocenogr., 1981, 250 p.; 17-F: Special coastal studies, Martha Shaw, Scripps Inst. Oceanogr., 1981, 150 p., 2 maps.

debris-accumulation data from 36 entrapment structures located in the study area and a simple regression model relating sediment yield to dominant land type and drainage-basin areas.

Measured denudation rates vary from about 0.01 mm/year on plains areas to 3 to 5 mm/year in small, mountainout drainage basins. Denudation rates for each land type are remarkably uniform throughout the study area despite significant variations in rock types, geological history, and the size distribution of eroded materials.

Study results indicate that in these coastal drainage basins, an average of more than 12 million m^3 of sediment leave upland drainage basins each year. This material (6 million m^3 fines, 5 million m^3 sand, and 1 million m^3 of coarser material) is first delivered to inland valleys, coastal plains, or directly to the shoreline—depending on drainage-basin location.

Estimates have also been obtained for average annual sediment delivery to coastal areas from each of the larger hydrographic drainage units (fig. 1, table 1). Specific effects on upland erosion and shoreline sediment delivery of human developments and artificial control structures are also determined. Available data indicate that while upland erosion on 10 major rivers that drain 64 percent of the 31 000-km^2 coastal area has been altered very little, shoreline sediment delivery of beach-sized sand from these rivers has been reduced some 50 percent over the past 50 years.

Comparisons of sediment yield from upland drainage basins with coastal delivery by major rivers suggest that, under natural conditions, alluvial rivers in the southern part of the study area are depositional along their floodplains, with only a fraction of upland sediment production being delivered to the shoreline. The three northern rivers, on the other hand, are erosional on their floodplains and deliver more sediment to the shoreline than is yielded from their respective upland basins.

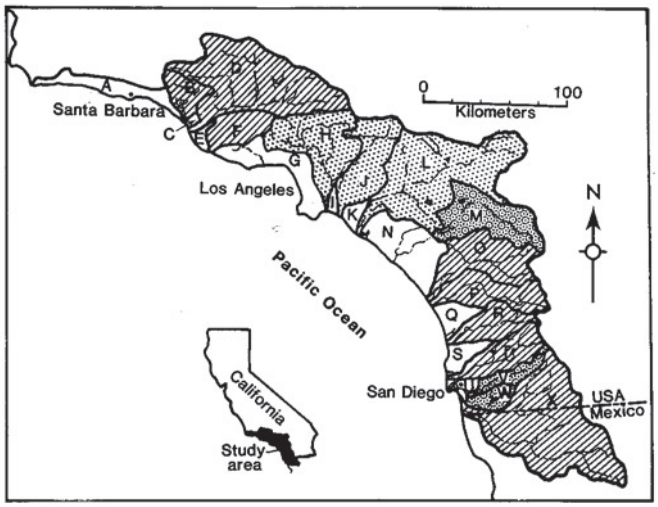


Figure 1—Coastal southern California hydrographic drainage units identified in table 1.

Table 1--Major drainage units in the sediment-management study area

Map symbol	Principal basin or group of small basins	Basin type	Controlled drainage area	Total drainage area	Percent of drainage area controlled
			- - - Square kilometers - - -		
A	Santa Ynez Mountains Group	G	--	901	--
B	Ventura River Basin	SMD	243	585	42
C	Ventura Group	G	--	52	--
D	Santa Clara River Basin	SMD	1 527	4 219	37
E	Oxnard Group	G	--	159	--
F	Calleguas Creek Basin	SMD	--	837	--
G	Santa Monica Mountains Group	G	166	1 493	11
H	Los Angeles River Basin	SED	3/866	2 155	40
I	Long Beach Group	G	--	120	--
J	San Gabriel River Basin	SED	1 400	1 663	84
K	Huntington Beach Group	G	--	234	--
L	Santa Ana River Basin	SED	3 950	4 406	90
M	Lake Elsinore Basin	SC	1 989	1 989	100
N	Laguna Hills Group	G	--	1 737	--
O	Santa Margarita River Basin	SMD	958	1 927	50
P	San Luis Rey River Basin	SMD	531	1 450	37
Q	Escondido Creek Group	G	--	568	--
R	San Dieguito River Basin	SMD	785	896	88
S	San Clemente Canyon Group	G	--	437	--
T	San Diego River Basin	SMD	686	1 119	61
U	San Diego Group	G	--	157	--
V	Sweetwater River Basin	SC	471	567	83
W	Otay River Basin	SC	255	370	69
X	Tijuana River Basin	SMD	3 175	4 483	72
Total			17 002	32 524	53

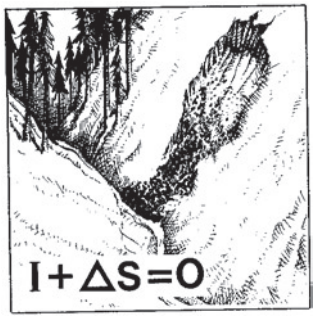
1/ G, drainage basin group; SED, single, extensively developed basin; SC, single confined basin; SMD, single, moderately developed basin.

2/ Calculated by adding the drainage areas controlled by the major water-retention structures that are farthest downstream in each basin.

3/ Whittier Narrows Flood Control Basin controls both Los Angeles and San Gabriel Rivers. This estimate assumes that 35 km^2 of the drainage area controlled by the Whittier Narrows structure lies within the Los Angeles River drainage basin.

4/ Excludes Lake Elsinor Basin (M).

5/ Closed interior basin. Overflow into Santa Ana River basin has not occurred since 1916.



Ashland Creek Drainage Basin Sediment Budgets and Routing Studies

Richard D. Smith and Bill G. Hicks

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EXTENDED ABSTRACT

The Ashland Creek drainage basin which supplies water to the city of Ashland, Oregon, has experienced major problems with erosion and landslides. Debris avalanches, originating in weathered granitic rock, have moved down the major drainages, damaging the water-supply system and partially filling the water-supply reservoir.

Two studies to develop partial sediment budgets have been conducted to assess the relative effects of natural and management-related sediment production. The first was completed by the Rogue River National Forest[1] in 1975 and specifically dealt with the material deposited in Reeder Reservoir at the base of the 5020-ha drainage basin by a major storm in January 1974. The second study was completed in 1977 by J. M. Montgomery Consulting Engineers,[2] Boise, Idaho. This study, prepared for the City of Ashland, was initiated because of the 1974 storm, but included an analysis of sediment production in the Ashland Creek drainage for the period 1955-76.

At the time of the January 1974 storm, 85 km of road had been constructed in the basin, covering about 90 ha or 2 percent of the area including cut and fill slopes. Clearcutting and partial cutting had occurred in 7 percent of the basin and another 1 percent had been thinned.

The USDA Forest Service study included mapping of all failures in the basin, subdividing them into management-related and natural events. Rough estimates were made of failure volumes released into the system. These volumes were then compared with the volume deposited in the reservoir during the storm event. The difference between the landslide failure volume and volume collected in the reservoir was then subdivided into streamchannel erosion of natural and management-related, pre-1974 material in channels. Estimates of surface erosion from roads were about equal to the estimated natural surface erosion for the 1974 storm. Additional assumptions and interpretations were made to arrive at comparative estimates of management-related and natural sources of material deposited in the reservoir (table 1). About 60 percent of the material in the reservoir was attributed to management-related activities and 40 percent to natural events.

The Montgomery study covered the full range of erosional factors in the basin. It developed a simulated history of sediment production for the entire Ashland Creek drainage. To approximate erosion rates related to roads and timber harvest, data from granitic terrane of the Idaho batholith were used. Significant volumes were attributed to road-related erosion, including effects of annual road maintenance. The study stressed that the technique used analyzes only surface and mass erosion for the entire drainage basin. The data and conclusions do not deal with routing through the drainage system to the reservoir. The approach was designed to approximate sediment supply to channels in response to various management activities within the drainage basin. This portion of the Montgomery study highlights the various factors affecting the total erosion rate and thus forms a basis for making decisions on where to intensify field investigations. The study identifies the sources of an estimated 270 000 m^3 of soil erosion from 1955 to 1977: natural (3 percent), surface erosion from 1- to 2-year-old road surfaces (6 percent), surface erosion from older road surfaces (58 percent), surface erosion from cut and fill slopes of roads (1 percent), mass movement from roads and timber harvest sites (20 percent), surface erosion from timber-harvest units (3 percent), and surface erosion from ski areas (9 percent).

Contrasts between the two studies result from the use of different data bases, recognition of channel-sediment sources in the Forest Service study and not in the Montgomery study, and differences in the time period analyzed.

Table 1--Estimates of sediment derived from various sources in Ashland Creek drainage basin[1/]

Source	Volume
	Cubic meters
Management-related:	
Mass failure of road fills	21 700
Other mass failures from roads	6 200
Mass failures from clearcuttings	150
Stream-channel erosion (debris-slide effect)	15 300
Management-related, pre-1974 material in channels	15 300
Management-related subtotal	58 650
Natural:	
Stream-channel erosion (major storm-flow effect)	35 600
Stream-channel erosion (debris-slide effect)	1 700
Debris slides	3 600
Natural subtotal	40 900
Total sediment delivery to reservoir	99 550

1/See text footnote 1.

[1] Wilson, S., and B. G. Hicks. 1975. Slope stability and mass wasting in the Ashland Creek watershed. Unpubl. rep., on file Rogue River Natl. For., Medford, Oreg.

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Channel Sediment Storage Behind Obstructions in Forested Drainage Basins Draining the Granitic Bedrock of the Idaho Batholith

Walter F. Megahan

ABSTRACT

Data on sediment storage behind obstructions were collected on seven forested, mountain drainage basins in the Idaho Batholith for a 6-year period from 1973-78. Four of the drainage basins were undisturbed throughout the study period, one contained an old road, and two were logged during the course of the study. The total volume of sediment stored behind obstructions varied between drainage basins and years in response to changes in bankfull channel width and annual peak-flow rates, respectively. Logs were the most important type of obstruction because they had the greatest longevity and stored the greatest amount of sediment. An average of 15 times more sediment was stored behind obstructions than was delivered to the mouths of the drainages as annual average sediment yield. Logging reduced total channel-sediment storage behind obstructions because many natural obstructions were destroyed by felling and subsequent clearing operations to remove logging debris from channels. Storage behind obstructions is an important component of the overall sediment routing through forested drainage basins. Accordingly, erosion and sedimentation monitoring must be carefully designed to avoid misinterpretation. Also, some guidelines are presented to help minimize the change in channel-sediment storage caused by timber harvest.

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INTRODUCTION

Development of a sediment budget for a drainage basin requires an accounting of: (1) onsite erosion; (2) the amount and rate of transport of eroded material between source and stream channels; (3) channel-sediment storage; and (4) sediment outflow from the basin. Channel-sediment storage is especially important on forested drainage basins because of additional storage potential provided by obstructions. Obstructions from logs and other debris occur naturally on forested areas, but their size and abundance may be strongly influenced by stand conditions and by disturbances such as logging (Froehlich 1973, Swanson et al. 1976, Swanson and Lienkaemper 1978).

Information on the volume of sediment storage and the type, size, number, and longevity of the obstructions causing the storage is needed to provide better understanding of channel-storage processes in forested drainage basins. Megahan and Nowlin (1976) reported on a study of sediment storage in channels draining seven small forested drainage basins in the mountains of central Idaho. Part of that study included an inventory of sediment trapped behind obstructions in 1973-74. This paper summarizes the progress made through 1978 in the channel obstruction portions of the study.

DESCRIPTION OF THE STUDY AREA

The seven drainage basins are in the Silver Creek study area in the Middle Fork of the Payette River drainage near Crouch, Idaho.

Descriptive data for the study drainage basins are presented in table 1. Four of the seven study drainage basins are undisturbed; the Ditch Creek drainage contains a low-standard road constructed during the 1930's and Control and K-1 Creeks were logged by helicopter in November 1976. The forest cover is dominated by Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and ponderosa pine (*Pinus ponderosa* Laws.) on the slopes and grades into grand fir (*Abies grandis* [Dougl.] Forbes) and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) near drainage bottoms. Timber volumes average about 117 m^3/ha in the vicinity of drainage bottoms.

The area is representative of conditions in the Idaho Batholith, a 41 400-km^2 expanse of granitic bedrock in central Idaho (fig. 1). This mountainous area is characterized by steep slopes; shallow, extremely erodible, coarse-textured soils; and large climatic events resulting from rainfall, snowmelt, or both. Erosion hazards are high and soil disturbances, both natural and caused by human activities, can greatly accelerate erosion and consequent sedimentation (Megahan 1975). Much of the total sediment discharge occurs as bedload, because of the coarse texture of the granitic parent materials. Streamflow and sediment yield exhibit marked seasonal variation in response to large winter storms, spring snowmelt, and long, dry periods in summer.

METHODS

Data on sediment storage behind obstructions were collected at sample reaches in each study drainage basin. Each sample reach is 43 m long. The first sample reach is located 30 m above a sediment basin at the mouth of each drainage. Additional sample reaches are located at 152-m intervals along the dominant channel until no indicators of perennial streamflow are obvious (such as a well-defined channel cross section or aquatic vegetation). The dominant channel was defined by following the mainstream up from the drainage-basin outlet during the period of baseflow in August and selecting the tributary with the greatest flow at each confluence.

Table 1--Descriptive data for seven drainage basins on the Silver Creek study area

Drainage	Area	Mid-elevation 1/	Dominant aspect	Mean channel gradient 2/	Total channel length 3/	Stream order 3/	Average bankfull width
	Sq. kilometers	Meters		Percent	Kilometers		Meters
C	1.94	1779	SE	21.5	9.5	3	1.5
D	1.22	1765	SE	24.2	5.5	2	1.1
Eggers	1.29	1733	SE	22.0	5.8	3	1.1
Ditch	1.06	1631	SE	20.8	2.9	2	0.8
Cabin	1.04	1533	SE	14.9	5.1	3	1.0
Control	2.02	1597	SE	15.2	6.8	3	1.1
K-1	0.26	1623	NW	31.5	1.0	1	1.0
Average	1.27	1666	--	21.4	5.1	--	1.1

1/ (Maximum elevation + minimum elevation)/2.

2/ (Total relief/length main channel to the upper ridge) x 100.

3/ Taken from a 1:31,680 planimetric map.

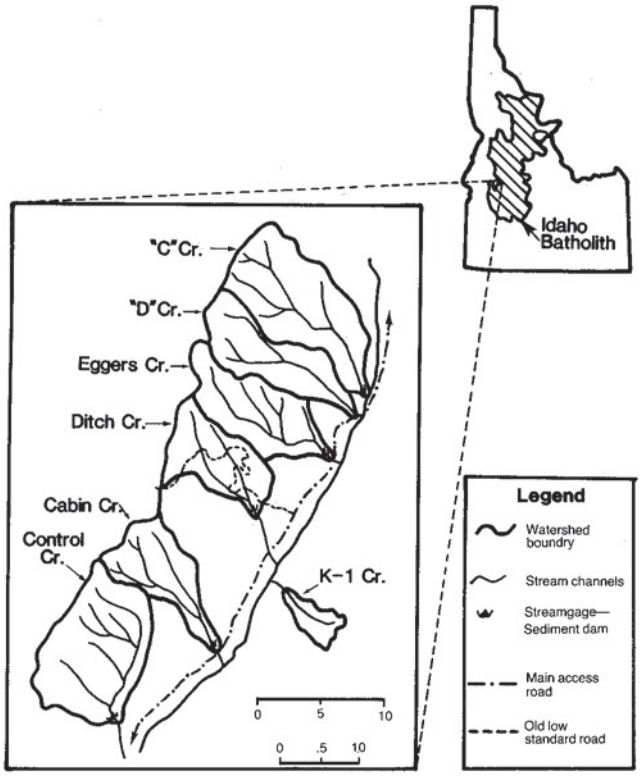

Figure 1—Study area in the Idaho Batholith.

An average of 10 reaches was sampled on each study channel for an average of 27 percent of the study channel sampled. Because sample reaches are located only on the dominant channel in each drainage basin, only about 8.7 percent of the total channel length in each drainage basin is sampled (table 2). Data are collected annually during low flow in late July and August. All reaches on all streams were sampled only during 1973, 1974, and 1978. In 1975, all samples were taken except the upper four reaches on C Creek. C, D, Eggers, Ditch, and Cabin Creeks were not sampled in 1976; C and D were omitted again in 1977.

Data for sediment deposited behind obstructions are available for 1973-78. Obstructions are defined as any material in the channel causing sediment accumulations because of discontinuities in channel gradient. In 1973, all discernible obstructions and associated sediment accumulations were measured, a procedure that proved to be too time consuming. Sampling during the following years was restricted-to obstructions with the following minimum dimensions: height, 0.2 m; average width, 0.3 m; and length, 0.6 m. The effect of the more restrictive sampling is minimal; 31 percent of the total number of obstructions fell below the allowable limit in 1973 but accounted for only 11 percent of the total volume of stored sediment. Height is defined as the difference between a level rod reading taken on the bed at the downstream side of the obstruction (the rod is raised if necessary to correct for any scouring at this point) and a rod reading taken on the sediment deposit immediately upstream from the obstruction. Rod readings are taken to the nearest 0.4 cm using an abney level. Length is the distance from the upstream end of the obstruction to the upstream end of the accumulated sediment. Width of the sediment accumulation is the average of 3 widths taken normal to the length at distances of 0.17, 0.5, and 0.83 of the length from the obstruction. The upstream end and edges of sediment accumulations are defined by breaks in channel gradient, differences in the particle-size distribution of bottom sediments, and differences in composition of bottom materials. A third rod reading is taken at the upstream end of the accumulated sediment to allow calculation of the slope of the deposited sediments. The most apparent cause of the obstruction is defined by type, as log (woody material over 10 cm in diameter), rock, root, stump, or debris, which includes branches, twigs, and leaves. Finally, the location of the obstruction is mapped.

A continuously recording streamgage and a sediment basin for determining annual sediment yields are operated at the mouth of each drainage basin. Sediment basins are surveyed twice a year in June and October using a network of closely

Table 2--Sampling intensity on study drainage basins

Drainage	Number of sample reaches	Length of study channel	Percent of study channel sampled for obstructions	Percent of total channel length sampled for obstructions
		Meters		
C	14	2198	27.2	6.3
D	8	1210	28.2	6.2
Eggers	12	1868	27.4	8.8
Ditch	11	1704	27.5	16.1
Cabin	9	1539	25.0	7.4
Control	11	1704	27.5	6.9
K-1	4	552	30.9	17.7
Average	9.9	1539	27.3	8.7

Table 3--Average number of obstructions and volume of sediment stored behind obstructions in study streams per 30 m of channel sampled

Year	C	D	Eggers	Ditch	Cabin	Control[1/]	K-1[1/]	Mean
	Number/volume cubic meters							
1973	4.5/2.3	6.2/2.3	3.2/0.6	3.9/0.7	3.9/0.7	2.8/0.4	3.6/0.7	4.0/1.1
1974	3.1/1.9	3.6/1.6	2.4/0.5	3.1/0.8	2.8/0.7	2.8/0.6	4.3/1.2	3.0/1.0
1975	2.2/1.4	3.4/1.1	2.6/0.4	3.7/0.4	3.4/0.5	2.7/0.6	4.5/0.5	3.1/0.7
1976	--/--	--/--	--/--	--/--	--/--	4.2/1.0	7.5/0.9	4.9/0.9
1977	--/--	--/--	3.9/0.4	4.4/0.5	4.9/0.7	2.4/0.3	4.6/0.6	3.9/0.5
1978	3.6/1.4	4.4/0.6	3.5/0.2	3.4/0.4	5.8/0.4	3.8/0.6	5.9/0.7	4.1/0.6
Mean	3.1/1.8	4.4/1.4	2.9/0.4	3.5/0.6	4.0/0.6	3.0/0.5	5.0/0.8	3.6/0.8

[1/] Drainage basins logged in November 1976.

spaced cross sections. Generally, more than 95 percent of the total sediment yield for the year is measured during the June survey. Trap efficiencies of the basins are estimated to average more than 75 percent because of the coarse texture of the soils on the study drainage basins (Megahan 1975). Two weather stations and a raingage network are also operated on the study area.

RESULTS AND DISCUSSION

A total of 1,715 obstructions were sampled during the 6 years of data collection. Averaging all years and streams, 3.6 obstructions were found per 30 m of channel with 0.8 m^3 of sediment storage per obstruction. This amounts to 2.9 m^3 of sediment storage per 30 m of channel or 493 m^3 for the average total channel length on the study drainage basins.

Number of Obstructions and Sediment Storage

As might be expected, the number of obstructions and stored sediment volumes vary between streams and between years (table 3). Analysis of variance tests show significant ($\alpha = 0.01$) differences between streams for both number of obstructions and volume of stored sediment.

Heede (1972) reported an increase in number of obstructions with increasing channel gradient on two study streams in Colorado. A similar analysis proved unsuccessful for the streams in this study. Reasons for the lack of agreement are not clear, although the fact that the Idaho streams are smaller and steeper is probably a contributing factor. As with number of obstructions, volume of sediment stored behind obstructions was not related to channel gradient. Average volume of sediment (m^3) behind obstructions showed a weak, positive relationship to average bankfull channel width (m), however. A linear regression analysis had a coefficient of determination of 0.62 and a standard error of 0.3 m^3/30 m. The regression coefficient was 0.526 (significant at the 0.05 level) and the y intercept was -0.54 m. Other, presently unexplored, factors—such as quality, type, and condition of streamside vegetation—would likely provide better predictors of number of obstructions and sediment storage behind obstructions.

Assuming no major changes in the factors introducing obstructions to the channel (such as windstorms), variations in streamflow probably account for some of the annual changes in number of obstructions and sediment storage behind obstructions. This is illustrated by comparing the frequency distribution of sediment stored behind obstructions for years of high and low flow (fig. 2). During the high-flow year of 1974, wher peak flows averaged 0.20 m^3/sec per ha, only the large, stable obstructions remained in the channel. In contrast, more obstructions with a smaller volume were found when flow energies were low, as in 1978 when average peak flows were about half those recorded in 1974.

Type of Obstruction

Debris was the most common type of obstruction, averaging about 42 percent of the total. Logs formed 34 percent of all obstructions; rocks, roots, and stumps made up an additional 13, 10, and 1 percent, respectively.

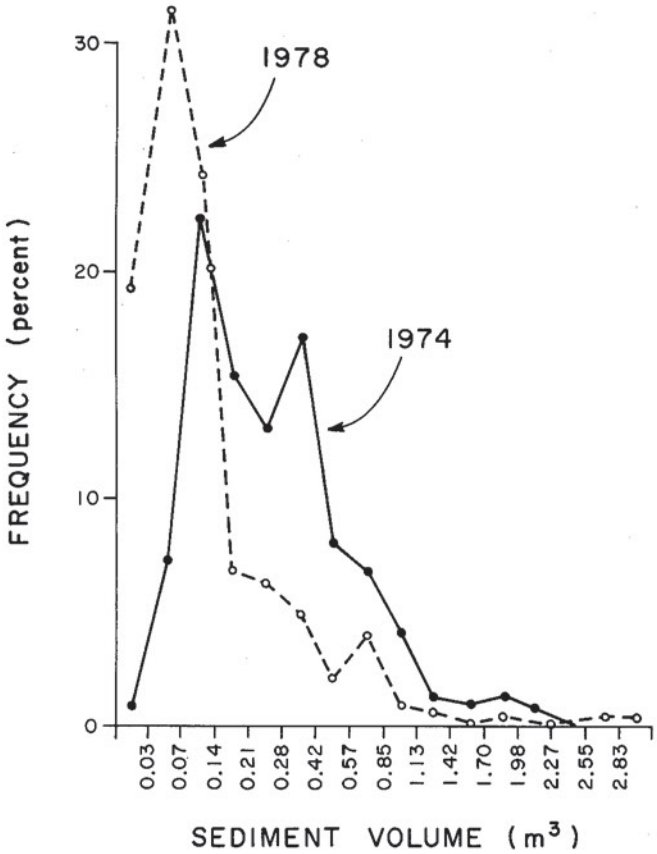

Figure 2—Frequency of occurrence of sediment volume behind obstructions by size classes.

Because of differences in amount of stored sediment, frequency of occurrence alone does not reflect the importance of obstruction type. A comparison of the frequency of occurrence of volume of sediment storage behind the two most common types of obstructions illustrates this (fig. 3). Although fewer obstructions are logs than debris, the logs store greater amounts of sediment, which greatly magnifies the importance of logs. Logs account for 49 percent of the total sediment stored, but organic debris accounts for only 29 percent. An additional 16, 6, and 0.2 percent of the sediment storage is caused by rock, roots, and stumps.

Longevity of Obstructions

The number of obstructions in a channel at any time is a function of the rate of introduction of new obstructions to the channel from adjacent slopes, the longevity of obstructions once in place, and the rate of supply of obstruction material from upstream. Introduction of new obstructions occurs as a long-term, relatively constant supply of material from normal ecological processes in the forest—such as litterfall and random mortality—plus a stochastic component caused by natural catastrophic disturbances—such as forest fire, windstorm, and logging. Once introduced, longevity of obstructions (defined as the length of time an obstruction was found at a given location) is a function of the rate of decay of organic materials and the tendency for movement

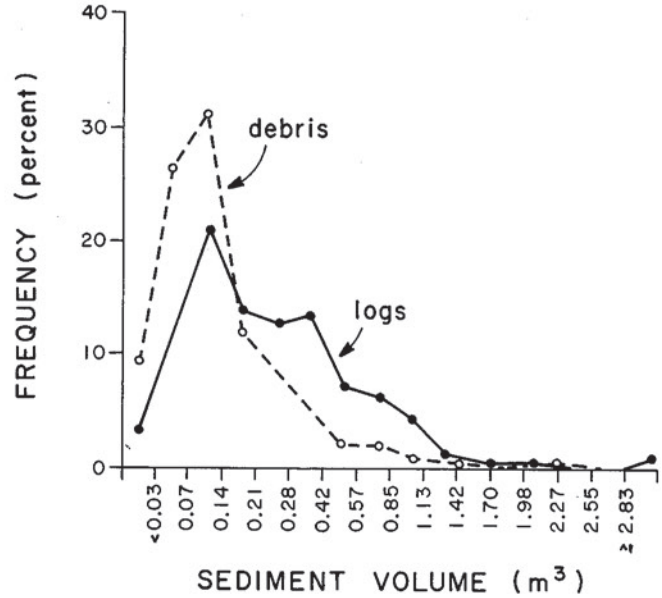

Figure 3—Frequency of occurrence of sediment volume by size classes stored behind debris and log obstructions.

of the obstruction, erosion around it, or both. If the obstruction material moves, it then has the potential for forming a new obstruction further downstream.

Development of a model for occurrence of obstructions is beyond the scope of the present data. Information is available to illustrate the longevity of obstructions once they have formed, however. During the field survey, the distance along the channel is measured from a permanent reference point. This makes it possible to define the longevity of obstructions by comparing data for successive years. Data are available for 6 years for Control and K-1 Creeks. The longevity of all types of obstructions tends to decrease rapidly with age, but the rate of decrease for logs is lower than for the other types (fig. 4). This further emphasizes the importance of logs as channel obstructions; they not only retain the most sediment but also last longest.

Decay is probably an important process influencing the rate of decline of debris obstructions. Decay rates are slow for logs in a wet environment, however, so erosion under and around the log (or both) is probably a more important cause for failure. Logs often serve as indirect causes of obstructions by acting as channel obstacles that do not in themselves restrict flow but rather form a base for the collection of debris that does. Then, the longevity of the obstruction depends on the longevity of the secondary material rather than the log itself, even though the obstruction is classified as a log.

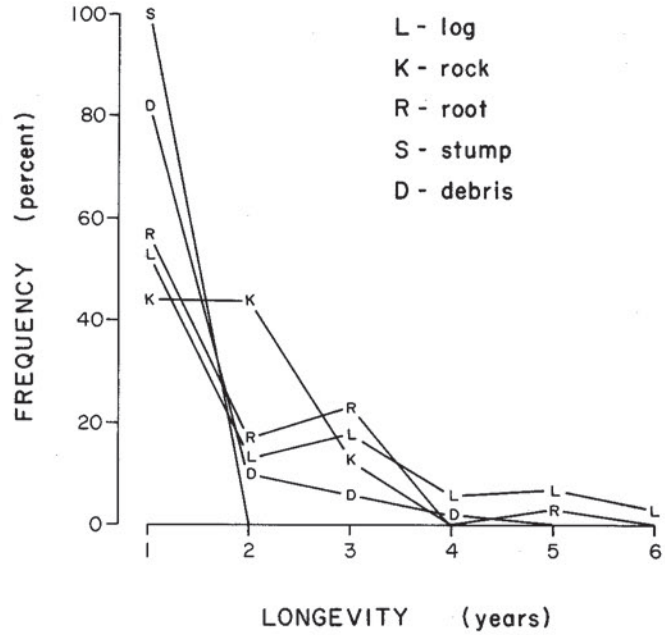

Figure 4—Frequency of occurrence of the number of years an obstruction remains in place by obstruction type.

Volume of Sediment Storage Behind Obstructions

Channel-sediment storage is an important component of the overall sediment budget for a forested drainage basin. The three types of channel storage are: (1) temporary storage in channel bedforms as a function of flow conditions and sediment-particle size; (2) longer term storage caused by obstructions; and (3) very long-term valley storage in floodplain deposits. The importance of storage behind obstructions is illustrated by comparing sediment storage with annual sediment yield. Annual sediment yield measured in debris basins at the mouth of each study drainage basin is much less than the average annual sediment storage for study reaches extrapolated to the total channel length (table 4). The ratio of storage to yield ranges from a high of 33 for the largest drainage (C Creek) to a low of 3.0 for Ditch Creek, and it averages 15. The ratio for Ditch Creek is much lower than that for any other drainage, because Ditch Creek contains an old, low-standard road that doubles sediment yield from the drainage basin (Megahan 1975).

Table 4--Average annual volume of sediment stored behind obstructions compared to average annual sediment yield in debris basins

Stream	Sediment storage behind obstructions	Sediment measured in debris basin	Obstruction storage/ debris basin
	Cubic meters		
C	534	16	33
D	282	11	26
Eggers	75	8	9
Ditch	52	17	3
Cabin	101	11	9
Control	127	11	12
K-1	24	3	8
Average	171	11	15

These observations emphasize the need to account for channel storage when working with sediment yields from small drainage basins in forested areas. On the average, about 15 years of annual sediment yields are stored behind obstructions. Given a large enough hydrologic event, much of this material could be flushed out of the system. Unless the previous channel storage were accounted for, this sudden increase in sediment yield might be attributed to recent onsite hillslope erosion when in fact it originated from channel-erosion processes.

Effects of Logging in the Study Drainage Basins

Control and K-1 Creeks were logged during this study. All trees down to 25 cm diameter breast high were clearcut in Control Creek on three major cutting units totaling 35 ha. The entire area of K-1 Creek was selection logged. Logs were removed from both drainage basins by helicopter. Only trees that were likely to die before the next timber harvest were marked for cutting within 15 m of active stream channels on both drainage basins. The logging contract stipulated that logging debris entering stream channels was to be removed.

The logging was done in November 1976. Channel surveys the following summer showed that logging debris had encroached on stream channels during timber harvest; in extreme cases, entire trees had rolled lengthwise into the channel. All logging slash was removed from the channel in accordance with the timber sale contract, however. Contrary to results at other locations, this logging temporarily decreased sediment storage behind obstructions, chiefly because some of the natural obstructions were destroyed by the tree felling and channel cleaning operations. This is illustrated by comparing double mass curves for the logged drainage basins to adjacent unlogged drainages (figs. 5 and 6). Although the trends shown are not statistically significant, numbers of obstructions and stored volumes tended to decrease in 1977 after logging. These results are reinforced by comparing the change in volume of sediment stored behind obstructions in a stream from one year to the next (table 5). Sediment storage decreased from 1976 to 1977 for both Control and K-1 Creeks, followed by a net increase from 1977 to 1978.

Table 5 also illustrates the need to consider all components of the sediment budget when developing drainage-basin sediment budgets. Positive and negative values in the table indicate annual increases or decreases in the total volume of sediment storage behind obstructions. A constant outflow of sediment occurs from the drainage basins each year into the sediment basins. Assuming that the figures in the table are correct, other forms of channel sediment storage and erosion processes both in the channel and on the slopes obviously must be evaluated to balance the Annual sediment budget.

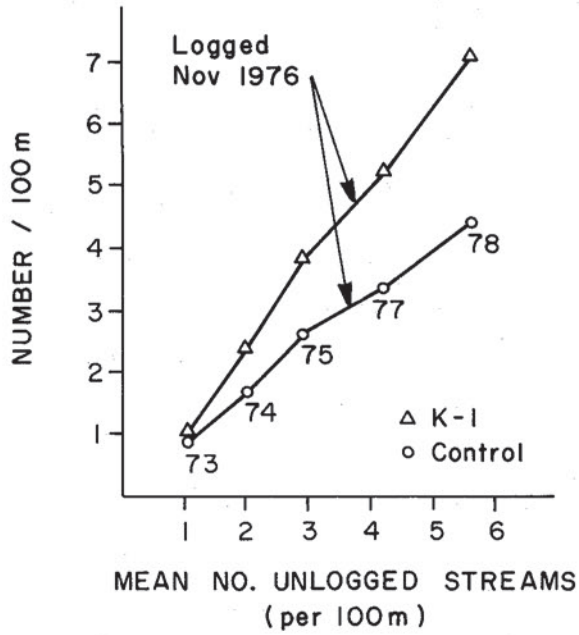

Figure 5—Double mass analysis showing number of obstructions before and after logging.

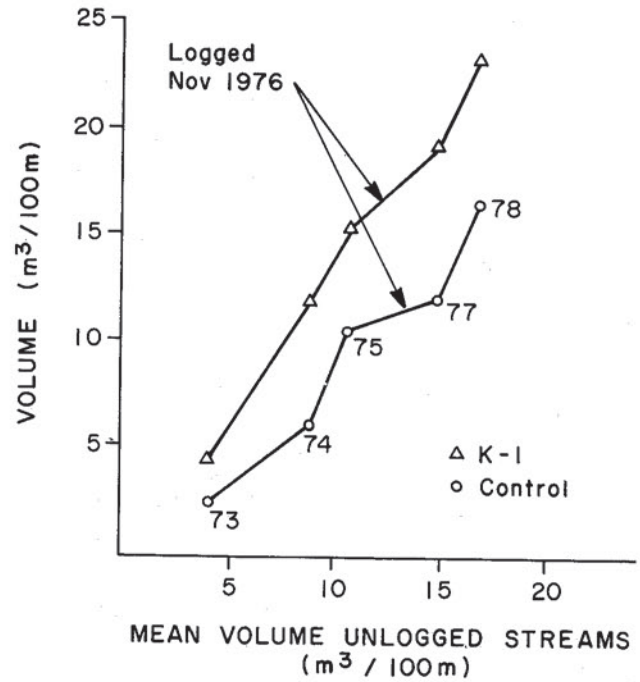

Figure 6—Double mass analysis showing volume of sediment storage behind obstructions before and after.logging.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Both numbers of obstructions and volume of sediment stored behind obstructions varied by drainage basins and by years. Differences between drainage basins were partly accounted for by a direct relationship to bankfull channel width, and differences between years were inversely related to annual instantaneous peak flow rates. Obstructions caused by organic debris were most numerous. Log obstructions were by far the most important, however, because logs store more sediment per obstruction and last longer. Longevity of obstructions is influenced by the decay rate of the material forming the obstruction and by movement of and erosion around obstructions. Most obstructions in the study area lasted less than 2 years. Even the most permanent type of obstruction, logs, lost 97 percent of their effectiveness for storing sediment within 6 years after emplacement.

Extrapolation of storage data to entire channels shows that, on the average, about 15 times more sediment is stored behind obstructions than is yielded annually at the drainage-basin mouth. This illustrates the importance of sediment storage to overall erosion-sediment budgeting for forested drainage basins.

Clearcutting and selection logging by helicopter had little effect on channel obstructions in the study area because of minimal streamside cutting and postlogging channel clearing. The net effect of logging was to cause a small decrease in the number of obstructions and in sediment stored behind obstructions for 1 year afterward.

The total amount of sediment stored behind obstructions fluctuated between years; however, sediment outflow was measured from all basins for all years. These data further emphasize the need to consider other types of channel storage, including bedforms and flood-plain storage, in addition to streambank erosion and erosion on slopes for a complete understanding of sediment budgets for forested drainage basins.

Some important land-management implications can be derived from this study for timber harvesting and methods to monitor erosion and sedimentation responses to land-management activities.

Table 5--Change in sediment stored behind obstructions in study streams

Year	C	D	Eggers	Ditch	Cabin	Control	K-1
	Cubic meters						
1973-74	-129.2	-123.9	-14.2	+ 7.4	+ 2.4	+ 46.5	+17.8
1974-75	-350.9	- 88.7	-34.2	-38.5	-25.5	+ 13.1	-21.9
1975-76	--	--	--	--	--	+ 74.0	+12.1
1976-77	--	--	--	--	--	-150.0	-10.9
1977-78	--	--	-41.2	-13.0	-49.5	+ 76.7	+ 1.9

Timber Harvest

Timber-harvest activities should be designed to minimize changes in channel-sediment storage during and after disturbance by:

Wherever possible, logging debris should be kept out of stream channels.

If logging debris does get into stream channels during logging, it should be carefully removed to avoid disturbance of natural obstructions.

An additional point to consider when evaluating the desirability of buffer strips is that they provide a source of natural channel debris that helps to stabilize channel-sediment storage over time after timber harvest.

Monitoring Erosion and Sedimentation Effects

Monitoring erosion and sedimentation from land uses is often necessary to help minimize impacts on fish, assure compliance with water-quality standards, or because of legislation calling for monitoring of the environmental effects of land-management activities. The objectives of the monitoring effort must be carefully defined and the monitoring designed accordingly. If onslope erosion is the concern on a particular area, then erosion should be measured at that point. Similarly, downstream sediment yield should be measured at a relevant downstream point if water-quality standards or fishery impacts are important. Inferences about erosion from sediment data or about sediment from data on erosion should be made with extreme caution, unless the data are collected to evaluate the third component of the erosion-sedimentation continuity equation--sediment storage. This is particularly important in areas where a large proportion of the sediment moves as bedload.

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Development, Maintenance, and Role of Organic-Debris Dams in New England Streams

Gene E. Likens and Robert E. Bilby

ABSTRACT

We propose that the formation of organic-debris dams on streams depends primarily on the size of tree (log) available. After disturbance, organic-debris dams are at first diminished and then form on larger and larger stream channels as the terrestrial ecosystem develops, and as a result, the regulation of erosion and transport of dissolved and particulate material from the landscape is enhanced. The species composition and phase of development of hardwood forests also may affect the occurrence and longevity of organic-debris dams. Steady-state amounts of organic matter in stream channels may reflect the stream order, as well as the developmental phase of the terrestrial ecosystem.

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INTRODUCTION

An organic-debris dam is an accumulation of organic matter that obstructs water flow in a stream. In general, these structures form when a piece of large woody debris falls into the stream. Unless the woody piece is extremely large, such as a tree bole, the wood will be carried downstream until it reaches a point in the channel where rocks and boulders, protruding from the streambed, catch and hold it against the current. Gradually, smaller sticks begin to collect against the larger piece, providing a framework on which leaves can accumulate. Ultimately, the structure becomes almost watertight, creating an upstream pool.

Only recently has the role of organic-debris dams in stream ecosystems been recognized (Zimmerman et al. 1967, Heede 1972, Swanson et al. 1976, Swanson and Lienkaemper 1978, Bilby 1979, Keller and Swanson 1979, Keller and Tally 1979). Debris dams are important in the development and maintenance of stream-channel morphology, and they also help to regulate the transport of particulate—and to a lesser extent, dissolved—materials through a stream system.

In the White Mountain region of New England, first-order (Strahler 1957) streams generally are 1.6 to 2.4 m wide and contain from 20 to 40 organic-debris dams per 100 m of stream channel. The frequency decreases to between 10 and 15 dams in second-order (2.5- to 2.8-m-wide) streams and from 1 to 6 in third-order (3.7- to 6.6-m-wide) streams (Bilby 1979). Organic debris dams are rare in streams larger than third-order. Debris dams contain 75, 58, and 20 percent of the total standing stock of organic matter in first-, second-, and third-order streams, respectively. Therefore, these structures are currently important in regulating sediment routing only in headwater streams. The questions we wish to address in this paper are: What factors are responsible for creating the relationship between stream size and frequency of organic-debris dams in streams in mountainous areas of New England? How variable is this pattern over time?

DEVELOPMENT OF ORGANIC-DEBRIS DAMS

The effect of precipitation and vegetative cover on erosion are well known (e.g., Ursic and Dendy 1965; Ralston and Hatchell 1971; Bormann et al. 1974; Patric 1976, 1977), but the role of organic-debris dams in regulating erosion and transport of particulate material over a long period (for example, as the terrestrial ecosystem recovers after major disturbance) is not known. In the absence of many data, we suggest that organic-debris dams may be just as important, if not more so at certain developmental periods, in controlling sediment transport from a mountainous landscape than are other environmental factors such as amount of precipitation and vegetative cover. We believe this because, in the absence of appreciable amounts of overland runoff, most of the eroded material originates from the stream channel. The roles and relative dominance of amount of precipitation, vegetative cover, and organic debris dams may be separated in time, however. For example, after some major disturbance which results in the removal of most organic matter (as would occur during catastrophic events such as glaciation or a very hot fire), amount and intensity of precipitation would be the most important factors until vegetation becomes well established. With the development of vegetation and the formation of root systems, a canopy cover, and a litter layer over the surface of the ground, erosion and transport of particulate matter would be reduced. The amount of liquid water available for runoff obviously is a critical factor affecting erosion and transport of particulate matter. The amount of water is reduced by evapotranspiration (mostly transpiration in northern hardwood forests), and the amount available for overland runoff is regulated by infiltration rate and storage capacity of the soil. Studies at the Hubbard Brook Experimental Forest in the White Mountains of New Hampshire (e.g., Bormann et al. 1974) and elsewhere, however, have shown that even in forested areas where biotic factors may function at a maximum, transport of particulate matter from drainage basins is exponentially and directly related to streamflow. Initially, then, after a major disturbance, biotic factors would tend to diminish erosion by absorbing the erosive power of raindrops and by reducing the amount of liquid water available for runoff, and this regulation could occur BEFORE trees became very large. For example, Marks (1974) has shown that the leaf area of early successional species in the White Mountains may be nearly equivalent to that of later, shade-tolerant dominants in only 4-6 years after clearcutting.

The size of woody debris produced by these early successional forests, however, is quite small. The average diameter of the major log found in organic debris dams in the White Mountains increases as stream width increases (fig. 1). As a result, debris dams would form in only the smallest channels during early developmental phases of the terrestrial ecosystems, because the trees would be too small to block larger channels. Although a young tree may be tall (long) enough to span a stream channel, its diameter (i.e., mass) appears to be the critical factor in determining whether it can maintain stability of the debris dam during extreme discharge events. As the trees become larger, dams would form in larger chan-

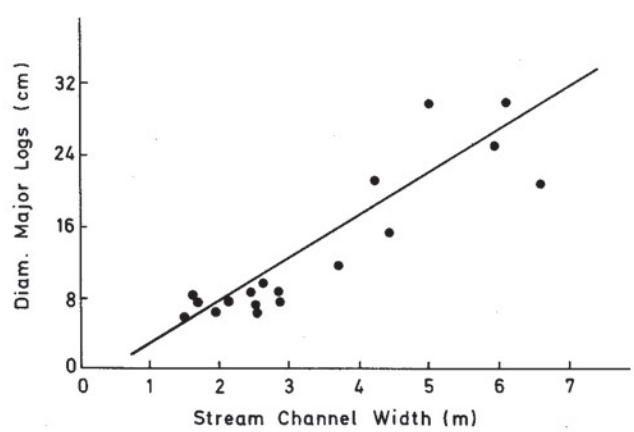

Figure 1—Relation of stream-channel width to the average diameter of the largest member of an organic debris dam sampled in the White Mountains of New Hampshire ($Y = 4.50X - 1.73$; $r^2 = 0.79$).

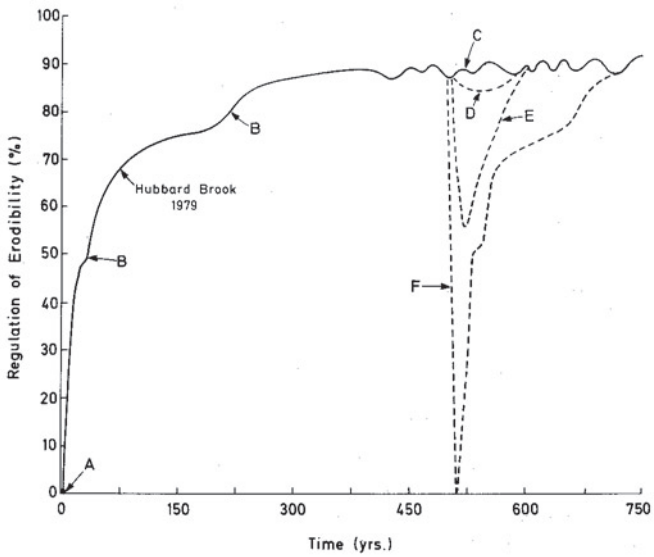

Figure 2—Change in the regulation of erodibility with time:

A. Development of a young forest (small trees, low density).
B. Successional events when organic-debris dam formation is common.
C. Vegetative cover and organic-debris dam development complete, regulation of erodibility in steady state (characteristic of climate, vegetation type, and topography).
D. Short-term disturbance to vegetative cover only.
E. Sustained disturbance to vegetative cover and loss of organic-debris dams.
F. Sustained disturbance to vegetative cover with loss of surface humic layers (litter) and organic-debris dams.

nels farther downstream and further reduce the transport of particulate matter (fig. 2).

At Hubbard Brook, a 15.6-ha drainage basin (Watershed 2 (W2)) was experimentally deforested in the autumn of 1965 and treated with herbicide for 3 years afterward to prevent any vegetative regrowth (Likens et al. 1970). Vegetation was allowed to regrow after 1969. Although no physical damage was done to the streambed during this operation, the greatly diminished input of terrestrial organic matter to the stream and increased discharge of water resulting from greatly reduced transpirational losses (cf. Hornbeck and Gee 1974) must have led to the destruction of many of the organic-debris dams on this stream. Increases in sediment yields from this drainage basin were relatively small during 1965-66 and 1966-67, but in 1967-68, they were more than 6-fold greater than on nearby uncut drainage basins and rose to 11-fold greater in 1968-69 (Bormann et al. 1974). Because essentially no overland flow occurred in the deforested drainage basin, much of this increased sediment yield must have originated from erosion of the stream channel and adjacent forest floor.

In the summer of 1976, the frequency of debris dams on W2 was still about 50 percent less than would be expected for a stream of this size in the White Mountains. The larger pieces of woody debris forming the framework of the dams, which were present in 1976, appeared old and weathered. These logs also were commonly larger than any of the trees now growing on the drainage basin. These dams thus originated before the clearcut. New dams now have formed on the first-order tributaries, but not in the second-order stream, because the woody debris produced by the forest is not yet of sufficient size to block the secondorder streams. Erosion and transport of particulate matter, however, have now been reduced almost to uncut levels, primarily because of reestablishment of biotic regulation in the terrestrial ecosystem by the regrowing vegetation. In contrast, the experimental removal of all organic-debris dams from a 175-m stretch of a second-order stream in forested Watershed 5 (W5) of the Hubbard Brook Experimental Forest led to a 6-fold increase in the export of organic and inorganic particulate matter and a 6-percent increase in the export of total dissolved substances during a 12-month period (Bilby 1979). Thus, the increase in sediment yield observed from W5 after removal of dams was about the same as that observed on W2 during 1967-68. These results support our hypothesis that organic-debris dams are a major factor in regulating the loss of particulate matter from forested ecosystems.

These patterns suggest that the amount of organic matter stored in the streambed may change appreciably after disturbance and during the subsequent developmental sequence of the terrestrial ecosystem and that this organic matter in the stream channel plays a critical role in regulating erosion and transport of materials from the landscape.

A STEADY-STATE CONDITION?

We currently believe that, within the Hubbard Brook Experimental Forest, the amount of organic debris in the first- and second-order stream channels is near steady state on an annual basis (Fisher and Likens 1973, Bormann et al. 1974), but how did this come about? According to our hypothesis, streams have not always been in steady state relative to the accumulation of organic matter. That is, after glaciation, organic matter accumulated in stream channels as debris dams formed or possibly developed downstream when larger and larger structural components became available; after major disturbance (e. g., deforestation), initial losses of organic matter and debris dams are followed by accumulation as the terrestrial ecosystem recovers. Currently, no trees are large enough to span and maintain position during flood conditions in the main Hubbard Brook channel (a fifth-order stream).

Bormann and Likens (1979) have proposed a model for biomass accumulation in northern hardwood forested ecosystems after exogenous disturbance such as clearcutting (fig. 3). According to this model, living biomass accumulates for about 170 years, during which time the trees increase greatly in size. After about 170 years or so, these trees begin to die and fall over in increasing numbers. Eventually a condition called the shifting-mosaic steady state is reached, where patches of young, intermediate, and some old trees are interspersed on the landscape. These small, even-Aged patches are caused by the endogenous disturbance as trees fall over.

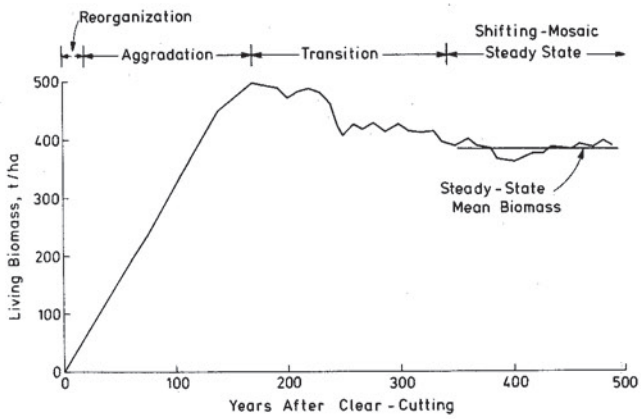

Figure 3—Changes in living biomass during ecosystem development after clearcutting of northern hardwood forests. Phases of ecosystem development are: Reorganization (I), Aggradation (II), Transition (III), and Steady State (IV) (modified from Bormann and Likens 1979).

An important question relative to the role of organic-debris dams in streams is whether they respond to these changes by "moving" up and down the stream depending upon the.size, shape, and species of tree available to produce the principal member in the organic-debris dams. Presently at Hubbard Brook, organic-debris dams are rare in streams with a mean channel width greater than 7 m. The last major cutting of the Hubbard Brook forest was in 1900-17 (Bormann et al. 1970), however, and most of the trees have not yet reached full size. The diameter and height expected of mature individuals of the dominant tree species at Hubbard Brook are listed in table 1. Assuming the relationship between diameter of the major member of an organic-debris dam and stream-channel width (fig. 1) holds true for larger logs, and that when one of these boles falls into a stream the diameter of the section crossing the channel is about equal to the diameter of the bole at half the height of the tree, we can estimate the width of channel that could be blocked by mature trees at Hubbard Brook (table 1).

Thus, before extensive logging took place in the Hubbard Brook Valley, a significant number of organic-debris dams may have occurred in stream channels up to almost 10 m in width (fifth-order). At the present time, stream channels of this size are completely devoid of debris dams. Therefore, even 60 years after a logging operation, which presumably resulted in the loss of many of the organic-debris dams from the stream systems, the drainage basin-ecosystem still has not regained its full potential to regulate sediment routing.

Obviously critical to our hypothesis are conditions that result in the falling over or blowing down of large trees. Bormann and Likens (1979) suggested that this is an important type of endogenous disturbance in the natural development of northern hardwood ecosystems. Is the falldown or blowdown of trees a random event on an areal basis? Obviously, if a large tree falls across the stream channel, the potential to form an organic-debris dam is much greater than if the tree falls in some other direction. We do not yet know whether more trees fall along a stream channel and toward a stream channel than elsewhere in a forest. If the stream channel is more than a few meters wide, this treeless zone could act somewhat like the edge of a forest where trees are more vulnerable to blowdown. Increased treefall along a stream channel might also result from increased erosion of the banks. If so, then this would be a type of positive feedback with the terrestrial system in the development and maintenance of organic-debris dams. In fact, the very presence of organic-debris dams may put more erosive pressure on the streambank (Zimmerman et al. 1967) and, thereby, enhance treefall at that spot.

Table 1--Diameter at breast height (d.b.h.) and maximum height commonly reached by the most important tree species at Hubbard Brook, and the steam channel width that could be blocked by a piece of debris equal to the diameter at half the tree height

Species	D.b.h. commonly[1/] reached by mature trees	Height commonly[1/] reached by mature trees	Diameter at half[2/] the height	Stream channel width that can be blocked
	Centimeters	Meters	Centimeters	Meters
Fagus grandifolia Ehrh.	90	24	48	9.5
Fraxinus americana L.	90	24	48	9.5
Tsuga canadensis (L.) Carr.	90	21	48	9.5
Pinus strobus L.	90	27	47	9.3
Betula allegheniensis Britton	75	21	40	8.1
Acer saccharum Marsh.	60	24	32	6.7
Picea rubens Sarg.	60	21	32	6.7
P. glauca (Moench) Voss	50	20	27	5.8
Abies balsamea (L.) Mill.	45	18	24	5.2

ROLE OF BOULDERS

Another factor rarely considered is the role of boulders in the formation of organic-debris dams. We have found that boulders are critical to the formation of organic-debris dams in stream channels in the Hubbard Brook Valley. We measured the volume of rocks protruding 10 cm or more above the streambed at randomly chosen cross sections of the stream channel and at cross sections on the downstream side of organic-debris dams. The average volume of rocks was significantly greater (students t-test at 0.05 level) behind dams than at randomly located cross sections. In streams containing large boulders, smaller logs may be able to form organic-debris dams than in streams without large boulders, everything else being equal. Very large boulders essentially divide a stream into smaller channels. We suggest that the role of boulders, so common in New England streams, should be examined before the development and role of organic-debris dams in streams can be fully evaluated.

HISTORICAL EVIDENCE

The sediment profile in Mirror Lake provides a long-term record of erosion and transport of particulate matter in the Hubbard Brook Valley (Likens and Davis 1975). This record suggests that about 4,800 years ago major mortality occurred in the extant hemlock (*Tsuga canadensis* (L.) Carr.) forests surrounding Mirror Lake. Normally, after such a major disturbance to the vegetation in a drainage area, erosion and transport of particulate matter from the landscape would be expected to increase. We suggest, however, that the hemlock decline may have been a factor in ultimately reducing transport of particulate matter by providing a source of large, dead tree trunks to form the structure for organic-debris dams. As large trees, they could have blocked much larger streams in the Hubbard Brook Valley than are presently dammed (table 1), and at the same time successional vegetation could have provided appreciable biotic regulation of erosion on the landscape. In fact, Likens and Davis (1975) found that the input of material to Mirror Lake did decrease after the hemlock decline, but they attributed the decrease to focusing of the sediments on the lake bottom. At present, we cannot resolve this problem. The blight of American chestnut (*Castanea dentata* (Marsh.) Borkh.) in New England and the current widespread death of American beech (*Fagus grandifolia* Ehrh.) also may represent periods when formation of organic-debris dams are enhanced.

The sediment record in more recent times (last 200 years) suggests a more uniform or increased transport of particulate matter to Mirror Lake (Likens and Davis 1975, Moeller and Likens 1978, Von Damm et al. 1979). This might be the result of the ultimate decay of old logs that were formed in the Hubbard Brook area before extensive cutting in 1900-17 (Bormann et al. 1970). Only now are the living trees becoming large enough to again form "stable" organic-debris dams on the larger stream channels in the Hubbard Brook Valley.

How long do organic-debris dams last in -New England streams once formed? A cesium-137 profile to a depth of 55 cm in an accumulation of sediment behind a large organic-debris dam on Bear Brook in the Hubbard Brook Experimental Forest indicated no difference in age from top to bottom, implying that the sediment has been either homogenized frequently by biological or physical activity, or that it was formed within the last 25 years and all at once. How long might a log be expected to last under such conditions in an organic-debris dam? In streams in Oregon with coniferous vegetation, organic-debris dams may last for a hundred years or so (Swanson and Lienkaemper 1978).

TEMPORAL PATTERNS OF ORGANIC-DEBRIS DAMS

What role does the type and form of vegetation play in forming organic-debris dams? How does the density of wood affect the formation and maintenance of organic-debris dams as terrestrial ecosystems develop with time? How does the growth form (height and diameter of bole) of trees affect the development and maintenance of organic-debris dams?. How does susceptibility to blowdown (e.g., life history and type of root system) of trees change with ecosystem development and affect the formation of organic-debris dams? How does variable resistance to decay affect organic-debris dams? Normally, such factors are not considered when questions about the history of erosion or land use are raised, but we suggest that these factors are of utmost importance in evaluating long-term landscape interactions. Indeed, the vegetation of the White Mountains has changed rather dramatically since glacial retreat some 10,000 to 15,000 years ago (Likens and Davis 1975). Is there a characteristic steady-state condition for amount of organic debris stored in the stream channels of the ecosystem for each dominant type of vegetation?

We suggest that the type of tree can be very important in the formation of organic-debris dams. In some western U.S. forests dominated by large, Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) trees, organic-debris dams are found on larger streams than in hardwood forests on the east coast merely because the Douglas-firs are larger in diameter and taller (Swanson et al. 1976, Bilby 1979). Thus, with ecosystem development whereby trees increase in size and species composition changes, we would expect organic-debris dam formation and longevity to change accordingly.

Hypothetical patterns for the formation of debris dams over time in three different. sizes of stream channels after logging of a previously undisturbed forested ecosystem in the White Mountains of New Hampshire are shown in figure 4. In small streams (fig. 4A), the slash produced during the cutting is large enough to block the channel; hence, the frequency of relatively small dams would increase immediately after logging. The slash decomposes and dam frequency drops until pin cherry (*Prunus pensylvanica* L.f.) trees, which are an extremely common and short-lived (-30 years),

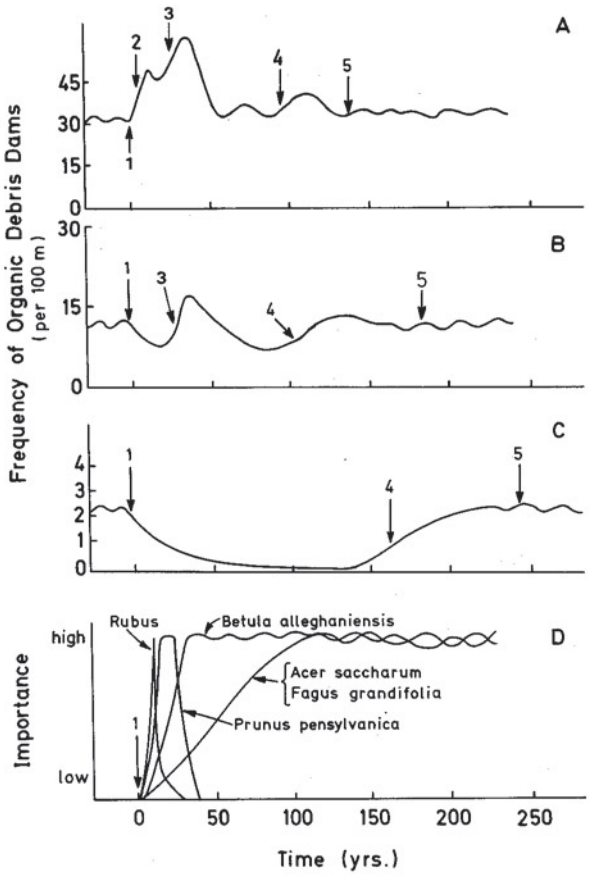

Figure 4—Hypothetical changes in the frequency of organic-debris dams over time in first-order (A), second-order (B), and third-order (C) streams in the White Mountains of New Hampshire and in the relative importance of major plant species over a successional sequence (D) (from Marks 1974):

1. Clearcut logging of the drainage basin-ecosystem.
2. Slash enters channel and causes increase in organic-debris dam formation.
3. Falling pin cherry trees enter stream channel and form debris dams.
4. Mature, late-successional tree species begin to fall and enter stream channel, forming debris dams.
5. Return to precutting, steady-state condition.

early successional species in the White Mountains (fig. 4D) begin to die and fall over. This input of organic matter produces-a second peak in dam frequency. The dams formed from pin cherry and remaining slash then decompose as the forest grows. Eventually most of the early successional dams disappear and conditions previous to cutting are reestablished.

In slightly larger streams (fig. 4B), slash is not of sufficient size to block the channel. As a result, frequency of organic-debris dams decreases after clearcutting because of the reduction of organic matter. When pin cherry trees are dying, an increase in dam frequency occurs. The pin cherry dams decompose and dam frequency drops until the forest around the stream begins to produce woody debris large enough to block the stream.

In still larger channels (fig. 4C), neither slash nor pin cherry trees are large enough to span the stream channel. As a result, frequency of dams decreases for a long period after logging. Trees must reach large size before dam formation can be initiated in these larger streams. Over 100 years may be required to return to precutting conditions in these systems. Thus, even though the upper tributaries of Hubbard Brook are now in steady state relative to organic matter, the larger tributaries are likely to be accumulating (or will be in the next few decades if the forest is not cut again) organic matter in debris dams.

We have raised more questions than answers in this short discussion, but we think these questions are provocative and important in terms of evaluating the role of organic-debris dams as regulators of erosion and transport of materials from mountainous landscapes. Clearly organic-debris dams are a common and important feature of headwater streams in forested areas. The occurrence and changing role with time of organic-debris dams in larger tributaries are less well known, but would appear to be of potentially great importance in regulating erosion and sediment transport.

ACKNOWLEDGMENTS

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Sediment Routing and Budgets: Implications for Judging Impacts of Forestry Practices

Frederick J. Swanson and Richard L. Fredriksen

ABSTRACT

Sediment budget and routing studies offer some improvements over traditional studies of small drainagebasin manipulations and individual erosion processes for analysis of impacts of forestry practices on soil erosion from hillslopes and sedimentation in streams. Quantification of long-term (century) and shortterm (decadal) impacts awaits more detailed analysis of the dynamics of sediment storage in stream channels and at hillslope sites prone to failure by debris avalanches.

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INTRODUCTION

Sediment routing can be considered the conceptual or quantitative description of the movement of soil and sediment down hillslopes and through the fluvial system from one temporary storage site to another. A sediment budget quantifies the input, change in storage, modification, and output of sediment for a landscape unit. Analysis of sediment routing and budgets has been used in a variety of ways ranging from basic geomorphology research (Rapp 1960, Leopold et al. 1966, Dietrich and Dunne 1978) to analysis of land-management impacts on sedimentation (Janda 1978, Pearce and O'Loughlin 1978). Application of sediment routing and budget studies in basic research has been rare, and their use in applied geomorphology has been even more limited.

With further development, these approaches to understanding geomorphic systems will greatly aid in analyzing and mitigating effects of forest practices on soil erosion and sedimentation in streams. A sediment budget provides measures of the relative importance of both natural sediment sources and sources induced by human activities. The persistence of sediment sources is dependent on the volume of sediment stored at a site and the rate of sediment resupply, which can be described by sediment budgets. Efficient, economic solution of erosion problems begins with identifying the major sediment sources so corrective actions can be applied at the most beneficial points in the system.

Current land-management issues on a broad scale concern identification of cumulative sedimentation impacts of progressive development of forest drainage basins and use of timber-harvest scheduling to minimize these impacts. Some understanding of sediment movement through a whole drainage basin is an essential starting point in evaluating cumulative, long-term impacts of forest practices. This whole-basin perspective should also be an important part of planning future research on effects of forest management on sedimentation.

Traditional assessments of erosional impacts of forest practices have taken a more narrow approach, emphasizing studies of individual erosion processes and small drainage basins. A process, such as surface erosion or shallow, rapid, soil mass movement,[1] may be considered in isolation. The rate of a particular process may be measured in forested and disturbed areas and compared. Small drainage basins are treated as "black boxes" and their water and sediment yields are compared before and after treatment and with a control basin. Linking studies of processes and small drainage basins for better interpretation of sediment sources is a first step toward understanding sediment routing in a landscape.

[1]Here we use the term "debris avalanche" to refer to all such mass movements, recognizing that sensu strictu debris flows, avalanches, and slides (Varnes 1978) are involved.

In this paper, we discuss examples of results and limitations of studies of certain individual processes and of small drainage basins for quantifying impacts of forest practices on sediment routing. Reexamination of these studies leads to suggestions for improved design of future investigations of management effects on sediment routing. These suggestions are generally summarized in the basic rules for developing a sediment budget.

Dietrich et al. (this volume) outline requirements for quantifying sediment routing: identify and quantify storage sites in the landscape; identify and quantify processes that transport material between storage sites; and determine linkages among transfer processes and storage sites. These are the necessary and sufficient steps for quantifying sediment budget, assuming the system is in steady state. In studies of long-term sediment budgets for natural forest and landscape conditions, this assumption may be reasonable. In assessing effects of management activities on sediment routing, however, it is commonly necessary to account for large, relatively short-term changes in sediment storage, which preclude the steady-state assumption (Pearce and O'Loughlin 1978). Management-induced changes in sediment storage may occur in more than one type of storage area, and the changes may not all have the same sign.

Here we argue that analysis of changes in sediment storage provides useful understanding of some short-term and many long-term impacts of management practices on sediment routing. To make this argument, we first offer an overview of the sediment-routing system for small, steep, western Cascade drainage basins and then discuss analysis of management impacts on crucial, but poorly understood, parts of this system.

SEDIMENT ROUTING REGIME IN STEEP, WESTERN OREGON FOREST LAND

The sediment-routing system of a drainage basin may be viewed as a variety of transport processes moving soil and sediment through a series of temporary storage sites. An example of linkages among storage sites by transport processes are shown in simplified conceptual form in figure 1 for steep, forested landscapes in western Oregon. This routing scheme is based on work at intensive study sites in the western Cascades of Oregon. The area is underlain by lava flow and clastic volcanic bedrock and forested with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and other coniferous and a few deciduous species. Most of the more than 230 cm of average annual precipitation falls as rain during long, low-intensity frontal storms between November and April.

In this area, creep, surface erosion, root throw, debris avalanches, slump, and earthflow are all potentially significant processes of particulate matter transport down slopes and into channels. Once in the channel, this material either enters temporary storage sites or moves as suspended sediment and bedload and in debris torrents.

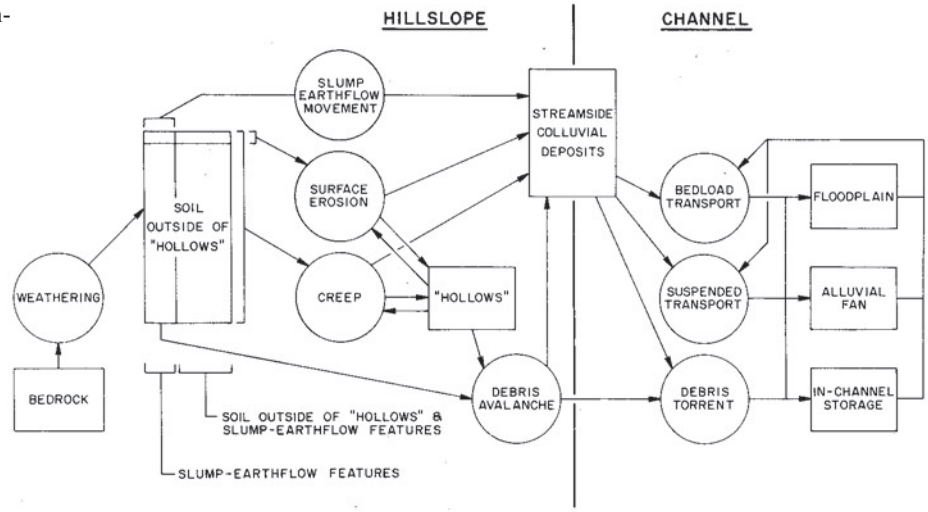

Figure 1—Simplified flow chart of relationships among storage sites (boxes) and transport processes in steep, volcanic terrane in the western Cascades, Oregon.

Hillslope and channel processes have a variety of serial interactions in which one process may (1) directly trigger another, (2) supply sediment for transfer by another process, and (3) increase the potential for occurrence of another process. These interactions complicate sediment budgets by making it difficult to attribute sediment delivery to a point in a drainage basin to one transport process. Creep, for example, carries soil to locations adjacent to channels, but delivery to the channel occurs by surface erosion, bank erosion by debris torrents, or small mass failures of streambanks. Debris avalanches deliver sediment to channels from steep microdrainages or "hollows" (Dietrich and Dunn 1978). Debris avalanches also initiate at the oversteepened headwall and toe areas of recently active slumps and earthflows and on some planar slopes, particularly where root throw triggers events. The hollows are slowly refilled by surface erosion, root throw, and creep before being catastrophically evacuated again by debris avalanching. Sometimes, streambank cutting contributes to stream side failures, especially from toes of earthflows. Other interactions among transport processes in this landscape are discussed in Swanson et al. (1982).

Temporary storage of material occurs in a great variety of sites in drainage basins (fig. 1). The soil mantle can be considered an area of storage and divided into subunits on the basis of types of transport processes involved. Surface erosion by dry ravel, rain splash, and freeze-thaw processes, for example, affect the upper centimeter or so of the soil surface. Surface movement is faster than soil creep, which affects the entire soil column. Creep, surface processes, and rotational translational failure are superimposed in slumpearthflow terrain (fig. 1).

Storage sites for alluvial material vary in relative importance along a river system. Large organic debris commonly forms dominant storage sites in first-, second-, and third-order channels in old-growth forests. Deposits in channels not related to organic debris and flood plain deposits are the principal storage sites for alluvium in larger streams. Alluvial fans are potentially important long-term storage sites located at junctions of low-order (generally first- or second-order) channels and higher order rivers. Fans accumulate where flood plains are broad enough to provide sites for storage (Swanson and James 1975).

The sediment-routing system described above and in figure 1 is simplified and ignores important aspects of system behavior. Much of the soil movement by hillslope processes, for example, involves redistribution on slopes rather than delivery to a channel. Transfer of sediment between slope and channel areas is also far more complex than described here. Furthermore, important feedback mechanisms, such as acceleration of slope-transport processes by bank cutting and streamside mass failures, are not treated explicitly.

DIFFICULTIES IN INTERPRETING MANAGEMENT IMPACTS ON SEDIMENT ROUTING

Studies of individual erosion processes and manipulations of small drainage basins in areas with this general type of sediment-routing system have revealed many-fold increases in soil and sediment movement after logging and road construction (Fredriksen 1970, Fredriksen and Harr-1979). Several problems arise in isolating effects of different management practices and distinguishing between short-term (decadal) and possible longterm (several cutting rotations) management effects on erosion. Crucial problems are understanding and quantifying the dynamics of two important storage sites in the system: (1) sites on hillslopes from which debris avalanches orginate and (2) channel storage sites, particularly those related to large organic debris.

Debris-Avalanche Sites

Impacts of forest practices on soil erosion by debris avalanches are commonly measured with inventories of soil movement by debris avalanches in forest, clearcut, and road right-of-way areas (Dyrness 1967, Swanson and Dyrness 1975, and others). Dietrich and Dunne (1978) and Dietrich et al. (this volume) have critically reviewed some aspects of this procedure. Analyses of debrisavalanche inventories in steep, unstable land generally have documented increased

soil erosion by debris avalanches in the first few decades after clearcutting and road construction (Swanston and Swanson 1976). The increase in failure frequency in clearcut areas has been attributed mainly to reduced root strength when root systems of killed vegetation have decayed significantly, but before roots of incoming vegetation are well established (Swanston 1970, O'Loughlin 1974, and others). Road failures generally result from altered distribution of soil, rock, and water on a slope.

The effects of cutting on debris-avalanche erosion over an entire rotation (80 to 100 years in much Federal land in the Pacific Northwest) and over several rotations are unknown. H. A. Froehlich (School of Forestry, Oregon State University, Corvallis, personal communication) and others have argued informally that the 10- to 15-year period of increased debris-avalanche erosion is followed by an extended period of debris-avalanche occurrence significantly below the rate observed in the areas of older, established vegetation usually sampled to determine a reference "natural" rate. If this is true, clearcutting may alter the timing of debris-avalanche erosion, but may not necessarily increase the overall rate on the time scale of one or more timber rotations. This hypothesis cannot be tested with existing inventories of debris-avalanche occurrence because of complexities of land use and storm histories and shortness of record.

Interpreting the effects of management on debrisavalanche erosion on the time scale of a century or more depends on understanding the recharge and storage dynamics of sites that fail by debris avalanching. Disregarding roads, debris avalanches in many areas of western Oregon originate predominantly from (1) hollow sites defined and described by Dietrich and Dunne (1978) and Dietrich et al. (this volume), and (2) sites locally oversteepened by slump-earthflow movement. Hollows are recharged by surface erosion, root throw, creep, and weathering of bedrock. Debris avalanches associated with slump-earthflow features occur on headwall scarps, at breaks in slope in midslope positions, and at toes of earthflows. Continued slump-earthf low movement creates opportunities for repeated failure at these sites.

The relative importance of debris-avalanche initiation at hollow and slump-earthflow sites varies greatly from one landscape to another. Debris avalanches from hollows predominate in many steep, highly dissected areas, but earthflow activity determines the incidence of debris avalanches in terrain of lower relief sculpted by slow, deep-seated, mass movements. Both types of sites are important in the volcanic terrane of the western Cascade Range. About 30 percent of soil moved by debris avalanches in the 62 km2 of forested and clearcut areas in the H. J. Andrews Experimental Forest (1950-1979) originated from slump-earthflow features.

Effects of clearcutting on the rate of debrisavalanche erosion in a landscape containing numerous sites that repeatedly fail by debris avalanching is related to the rate of recharge of those sites and effects of management practices on processes that recharge the sites. If recharge time is much shorter

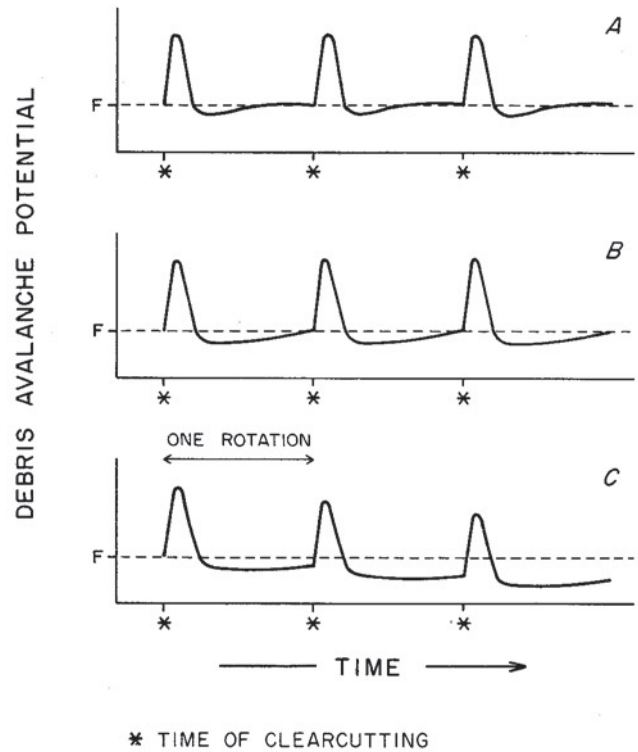

Figure 2—Hypothetical variation in debris-avalanche potential in a landscape with many sites for debris-avalanche failure, only a few of which fail in the first 10 to 15 years after clearcutting.
A. Refilling of failed sites is fast relative to cutting frequency.
B. Refilling occurs in about one rotation.
C. Refilling takes much longer than cutting frequency.
Debris-avalanche potential rather than erosion rate is shown because actual erosion occurs in brief, infrequent periods.

than the period between cuttings, the rate of debris-avalanche erosion between the period of accelerated erosion and the next clearcutting is similar to the background forest rate (fig. 2A). Under these conditions, successive cuts will have an impact on debrisavalanche erosion similar to the first cut because sites of recent failures will be recharged at the time of subsequent cuts. Where recharge typically occurs in the period of one rotation, subsequent cuts may have the same impact as earlier cuts, but the rate of debris-avalanche erosion after the period of accelerated erosion may drop significantly below the background forest rate during each rotation (fig. 2B). If recharge occurs over periods much longer than the cutting rotation, several successive cuts may progressively have reduced impact on debris-avalanche erosion because some sites that failed after earlier cuts are not ready to fail again when subsequent cuts occur (fig. 2C). This effect may also result in debris-avalanche erosion below the background forest rate between the period of accelerated erosion and the next cut.

Filling rates of debris-avalanche scars are poorly known. Dietrich et al. (this volume) estimate that refilling of hollows occurs on the time scale of 1,000 years, based on estimates

of creep rate for forested areas. The rate may be appreciably faster if root throw, animal activity, and various surface-erosion processes are also taken into account. Furthermore, the rate of each of these processes—except root throw—may be accelerated by removal of vegetation. Wildfire, logging, and slash burning trigger periods of accelerated soil movement (summarized in Swanson 1981) which presumably causes accelerated hollow filling. How important are such periods of accelerated erosion in filling a hollow? Swanson (1981) attempted such an analysis for sediment yield in the central western Cascades of Oregon and estimated that about 25 percent of long-term sediment yield occurred in periods of accelerated erosion after wildfire. Although this estimate contains great uncertainties, it suggests that hollow filling during periods that include severe disturbances of vegetation may be significantly faster than the rate estimated for forested conditions only.

Current knowledge of the recurrence of debris avalanches from sites related to slump-earthf low features is beset with similar uncertainties. Many slump-earthflow features in this area move at rates of centimeters to meters per year (Swanston and Swanson 1976), so sites of debris-avalanche failures in slump-earthflow deposits may be recharged as quickly as in a few years to decades. Other slump-earthflows move more slowly or infrequently, so recharge of associated debris-avalanche sites is slower. Effects of clearcutting on slow, deep-seated, mass movement features have not been documented quantitatively. Gray (1970) and others hypothesize that the major effect is that reduced evapotranspiration results in increased availability of soil moisture, which may prolong seasonal periods of movement.

In summary, short-term (decadal) increases in debris-avalanche erosion after clearcutting have been documented, but effects over a whole rotation or multiple rotations (centuries) are unknown. These longer term effects are determined by rates of processes that prepare sites to fail again. All of these processes are ultimately limited by the rate of rock weathering and soil formation. Before we can assess long-term management impacts on debris-avalanche erosion, we need more information on (1) rates and mechanisms of refilling of hollows, (2) rates and mechanisms by which slumpearthflows prepare associated debris-avalanche sites for repeated failure, and (3) effects of management practices on these mechanisms and rates. Field measurements of recharge processes should be made in appropriate geomorphic contexts. It is essential to analyze debris avalanches in their overall sediment-routing context, including the storage dynamics of sites of debris-avalanche initiation.

Small Drainage Basin Studies—Channel Storage

Manipulation of small drainage basins has been used to measure erosional consequences of forest practices. USDA Forest Service researchers have conducted this type of research on 10- to 100-ha drainages in the H. J. Andrews Experimental Forest in the western Cascade Range, Oregon. In a series of paired-basin experiments, sediment yields from control and manipulated basins are monitored and compared for periods before and after logging and road construction. Originally these studies were designed to measure impacts of forest practices on sediment yield and nutrient loss in different terrains (Fredriksen 1970, 1972; Swanson et al., 1982). As these studies have progressed, we increasingly recognized the need to understand sediment routing through each basin.

Channel-storage dynamics are a particularly important, but commonly neglected, element in the response of basins to forest cutting (Pearce and O'Loughlin 1978). The potential significance of sediment stored in channels is revealed by estimates that average annual export of coarse particulate material from small basins is less than 5 or 10 percent of sediment stored in the few channel systems analyzed (Megahan and Nowlin 1976; Megahan, this volume; Swanson and Lienkaemper 1978). Consequently, moderate changes in volume of stored sediment can account for large year-to-year changes in sediment yield, even if sediment supply from hillslopes is constant. Accelerated erosion from hillslopes may not show up as increased sediment yield if sediment is stored in channels (Pearce and O'Loughlin 1978).

Management practices can alter channel storage by (1) altering rates of sediment input and output by changing peak flows, availability of erodible sediment, and rates of hillslope erosion, (2) altering storage capacity by changing quantity and distribution of large organic debris, and (3) increasing potential for debris torrents, which can flush stored sediment and large organic debris from steep channels. Studies of experimental basins in the Andrews Forest provide examples of a broad range of changes in channel storage in response to management activities.

Unfortunately, we have insufficient data at this time to compute complete sediment budgets. Only fragmentary data exist for change in channel storage and sediment input to channels by processes other than debris avalanches. The variety of channel-storage changes, however, emphasizes the importance of quantifying channel storage in future studies of management impacts. The history of debris torrents over the past 40 years has strongly influenced patterns of sediment yield from Watersheds 1, 2, and 3, while analysis of Watershed 10 over a shorter period when torrents occurred reveals other effects of channel storage.

Studies on Watersheds 1, 2, and 3

Measurement of suspended sediment and sediment trapped in ponding basins (here termed bedload[2]) began in 1957 at the 96-ha Watershed 1 (WS1), 60-ha WS2, and 101-ha WS3 (Fredriksen 1970). WS1 was completely clearcut without

[2] Some of the material caught in sediment basins includes suspended sediment. About 25 percent of material collected in the sediment basin at WS10 after logging has been less than 2 mm.in diameter.

roads between 1962 and 1966, and the slash was burned in a hot fire in the fall of 1966. WS2 has been maintained as a control; it is forested with 400- to 500-year-old Douglas-fir and western hemlock, and a mix of younger trees established after a light wildfire about 135 years ago. Roads covering 6 percent of WS3 were constructed in 1959, and three areas totalling 25 percent of the drainage basin were clearcut and broadcast-burned in 1963.

WS1 and WS3 have responded very differently to their respective treatments (fig. 3) because of contrasts in types of treatments, timing of treatments with respect to major storms, and roles of the two channel systems as sediment sources and sinks. WS3 was freshly logged and burned when the two extreme storms of Water Year 1965 (WY1965) occurred. The storm of late December 1964 triggered a series of debris torrents, most of them initiated from roadfill failures, that sluiced out much of the drainage network of WS3 (Fredriksen 1970). These torrents carried about 20 000 t of organic and inorganic material out of the drainage basin. Over 90 percent originated from the roadfills, and most of the remainder was material stored in the channel before logging. During the following 13 years (WY1966 through WY1978), about 900 t of bedload material were exported from WS3 (annual bedload yield from WS2 has been 9.9 t/km^2 for WY1957-WY1976). Thus a few momentary events of WY1965 transported more than 22 times as much sediment as the entire next 13 years. The torrents greatly reduced both the volume of material in storage and the storage capacity of WS3 channel system by removing large organic debris.

The history of WS1 has been very different. The basin was only partially cut--and burning had not yet occurred--when the WY1965 storms struck, so the absence of roads and earlier stage of cutting made WS1 less sensitive to these storms than WS3. No debris torrents occurred in WS1, and most of the 800 m3 of soil moved to channels by debris avalanches in WY1965 collected temporarily behind the abundant, large organic debris in the channel. Broadcast burning and some clearing of debris from the channel in 1966 initiated a period of accelerated export of bedload that totalled about 2900 t in WY1966 through WY1978. Thus bedload yield for this period from WS1 is over 3 times the yield from WS3. From measurements of channel cross sections, we estimate that about 4300 t of the material that entered the WS1 channel after logging remains in temporary storage in the channel system. The channel is now undergoing net decrease in storage. The large volume of sediment stored in the WS1 channel and unstable channel conditions suggest that bedload yield derived from these readily available sources can remain high for another decade or so.

Presence or absence of debris torrents has been an important factor in the contrasting sediment export between WS1 and WS3. Roadfills that were poorly constructed and poorly located by today's standards failed in the heads of long, straight, steep channels of WS3. These are ideal conditions for initiating debris torrents that move long distances down channels (Swanson and Lienkaemper 1978).

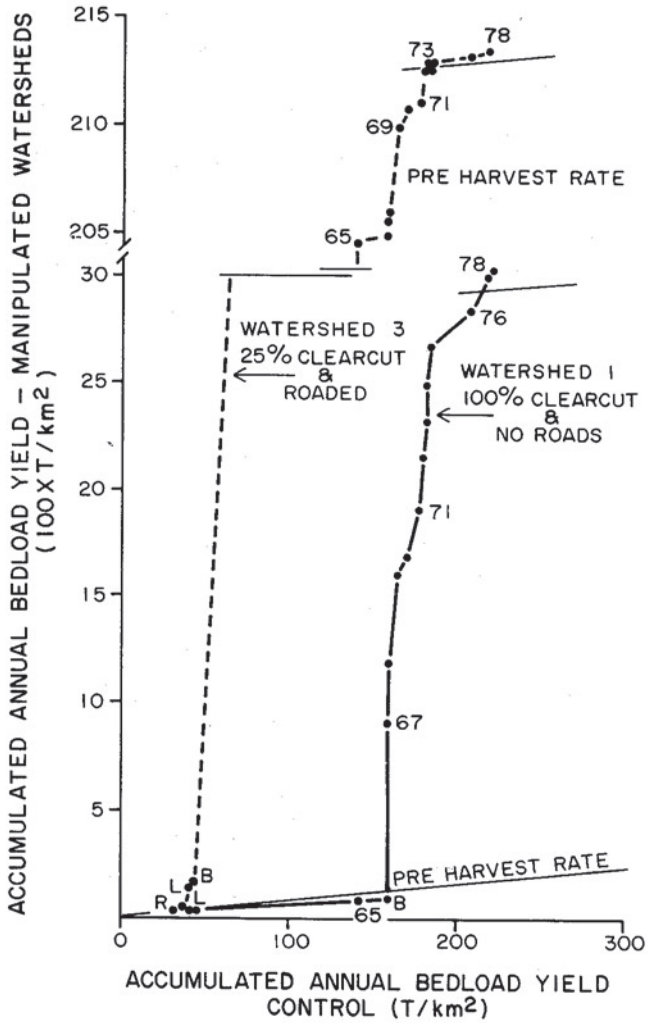

Figure 3—Double mass plot of sediment collected in ponding basins at Watersheds l and 3, H. J. Andrews Experimental Forest. Preharvest rates are based on relationships between manipulated drainage basins and the control established in the predisturbance period. L = year of logging, R = road construction, B = broadcast burning.

Eight debris avalanches, each of which transported more than 75 m^3 of soil, have occurred in WS1 since clearcutting, but none triggered a debris torrent because they did not enter the main channel with sufficient mass and velocity and sufficiently straight trajectory to maintain momentum down the main channel.

Much of the contrast in sediment yield between WS1 and WS3 over the period of several decades after logging and road construction results from differences of channel-storage factors. WS3 was flushed and now has relatively low volume of stored material and low capacity for additional storage because of low quantities of large organic debris. Bedload export from WS3 is now limited by sediment supply from hillslopes rather than from release from channel storage. On the other hand, the timing of sediment release from channel storage is a dominant factor controlling persistent, high bedload yield from WS1, although continued sediment supply from hillslope sources is also important.

These observations point up the need in future drainage-basin studies to quantify changes in channel storage and, if possible, to distinguish material that entered the channel before and after disturbance. The mass budget equation for the channel should be: output = input + change in volume of material that entered the channel before disturbance + change in volume of material entering the channel after disturbance. Surveyed and monumented cross sections combined with stratigraphic analysis of deposits encountered on cross-section lines can be used to measure these aspects of channel-storage dynamics.

Studies on Watershed 10

Studies at WS10 in the H. J. Andrews Experimental Forest reveal the need to account for changes in channel storage when evaluating management impacts on sediment yield in basins where torrents have not dominated the recent history of sediment export. This steep, 10-ha drainage basin was studied intensively under forested conditions from 1970 to 1975 and since clearcutting and skyline yarding in summer 1975 (Fredriksen 1972; Swanson et al., 1982). Large slash was yarded to the ridge-top landing; the basin was not broadcast burned. About half of the 50 logs that had been in the main channel of WS10 before logging were removed, and slash larger than about 5 cm diameter and 50 cm length was hand-cleaned from the channel.

Measurement of effects of logging on sediment yield is based on samples of successive storms at manipulated WS10 and 9-ha control WS9. Unfortunately, sediment-basin collections before logging were of short duration and marginal quality because of intense research activity in lower WS10, so bedload yields are compared for the postcutting period only.

Four storms during WY1976 transported 18.9 t of particulate material into the sediment pond (here termed bedload) at the outlet of WS10.2 The first two storms produced peak flows that typically occur several times a year, yet combined they exported about 6.8 t of bedload—about 7 times the average annual bedload yield for small, oldgrowth forest basins (Swanson et al., 1982). The third and fourth storm events produced successively higher peak flows and exported 8.4 and 3.7 t of bedload, respectively.

WY1977 was the driest in the 86-year history of precipitation records in central western Oregon; no significant bedload transport occurred in WS10. Several major events during WY1978 exported a total of 8.8 t of bedload, although this period included two peak flows that exceeded those of WY1976. Over this 3-year period after cutting, WS10 exported 27.6 t of bedload, while WS9 yielded only 0.8 t.

These results follow two general patterns: an increase in total yield after clearcutting and a decline in total yield for a given peak-flow magnitude through the sequence of storms. Greater total export after disturbance could be attributed to increased transport capability of the system (such as increased peak flow), to increased availability of material to be transported, or both. After clearcutting of WS10, the magnitude of peak flows from snowmelt actually decreased relative to control WS9, and no detectable change occurred in peak flows for events with rainfall only (Harr and McCorison 1979). Therefore, changes in sediment export from WS10 primarily reflect changes in sediment availability and storage rather than altered basin hydrology.

Based on measurements of hillslope erosion and qualitative observations of the amount and type of material stored in the channel, export from WS10 appears to come from three sources: (1) soil and organic matter—mainly green twigs and needles-moved into the channel during felling and yarding operations, but not removed during channel cleaning, (2) material that entered the channel by natural processes before logging and had been in temporary storage behind logs in the channel, but was released from storage when logs were removed, and (3) material transported to the channel by hillslope erosion after logging. Each of these sources makes sediment available at different times. Source 1 was most significant in the first few major storms after cutting. By the fourth storm of WY1976 much of this readily transported material rich in organic matter had been flushed downstream to the basin or deposited in more stable debris accumulations within the channel. Source 2 gained importance in the first few years after logging and after material in Source 1 had been moved. Postlogging hillslope erosion (Source 3) will probably not become dominant in WS10 until several years after cutting. The timing of sediment availability from Source 3 in WS10 is a result of (1) absence of roads feeding sediment-laden water directly into the drainage system, which could supply sediment even before cutting occurs, and (2) the effect of hand-piled slash along the stream channel in retarding movement of soil to the channel. These sediment traps become less effective as they collapse from decay and snow loading. Sediment supply by debris avalanches and possibly creep is believed to increase several years after cutting in response to decay and loss of strength of roots (Swanston 1970).

This scenario could, of course, be altered in other drainage basins if, for example, accelerated surface erosion from broadcast burning or occurrence of debris avalanches soon after cutting quickly flood the channel system with material from Source 3. In WS10, though, we have measured only 1.2 t of material transported into the channel system between October 1975 and February 1976, although 19.8 t were exported. The inputs resulted from surface erosion by dry ravel, rain splash, and needle ice. Transport rates to the channel were sampled in 34 0.5-m-wide boxes located along the stream perimeter. No debris avalanches have transported soil to the channel since cutting.

The results from WS10 indicate that an understanding of channel-storage dynamics is essential to interpreting short-term (few years) data on sediment yield from disturbed drainage basins. Furthermore, changes in storage of material that entered the channel before and after logging must be distinguished. This distinction would provide better resolu-

tion of the quantity and fate of soil eroded after logging. Too often, changes in sediment yield are interpreted only in terms of altered hillslope erosion.

Channel Storage—Long-Term Considerations

Forest-management practices can have long-term effects on quantities of large organic debris in channels and associated channel-storage capacity and aquatic habitat. Although poorly quantified, the strong positive correlation between amounts of large organic debris and stored sediment in small, steep, V-notch channels is obvious in field reconnaissance. Presence of large debris in steep channels also benefits aquatic ecosystems by providing cover, a source of nutrients, diversity of aquatic habitats, and depositional sites where organic matter can accumulate and be available for consumption by aquatic organisms. The sediment storage of large debris may also benefit aquatic organisms by buffering areas downstream from sites of pulses of sediment by processes such as debris avalanches. Downstream movement and subsequent accumulation in higher order channels may cause damage to structures, blocks to fish passage, and other problems.

When a channel such as in WS3 is flushed by a debris torrent that removes large debris, the period of recovery of debris loading and associated capacity for sediment storage may span several decades to a century or more if a source of large woody debris is available. Clearcutting without leaving trees along the channel removes the future source of large debris. Unless we specifically manage streamside stands to produce large debris for streams, little significant woody material will enter streams in managed stands. Intensive silviculture and harvesting practices produce no large woody residues.

Concentrations of large debris have persisted in streams affected by natural wildfire disturbances in western Oregon forests (Swanson and Lienkaemper 1978). Large pieces carried over from the previous stand had residence time greater than the time it took the postfire stand to grow trees large enough to produce large debris. Consequently, debris loading and associated sediment storage was likely to be maintained through the period of recovery after natural forest disturbances.

Unless the ecosystem is consciously managed otherwise, the net effect of intensive forest management is likely to be a gradual, widespread decrease in large organic debris in streams. The sediment-storage capacity of high-gradient, loworder portions of channel systems would decline greatly, and travel time of coarse particulate matter through such stream reaches presumably would be reduced. Reduced diversity and area of prime aquatic habitat is also a likely result.

Further quantification of the role of large organic debris in sediment storage throughout a river network would help strengthen arguments for or against this hypothesis. Analysis of rates of input of large debris to channel sections with different histories of flushing and disturbance of adjacent stands are also essential to predicting long-term impacts of management activities on roles of channel storage in sediment-routing systems.

CONCLUSIONS

We have traditionally measured effects of forest practices on soil erosion and sedimentation with studies of individual processes and small drainage basins. Viewing the problem of impact assessment from the perspective of overall sediment routing suggests specific ways to strengthen our understanding of impacts on soil and aquatic resources. Sediment-routing concepts encourage analysis of storage sites as well as transfer processes and analysis of each in the context of the whole system. Use of this approach to reexamine studies of management effects on debris-avalanche erosion and sediment yield from small basins reveals numerous unanswered questions, particularly in terms of impacts over periods greater than a few decades.

Debris-avalanche inventories document short-term (decadal-scale) increases in debris-avalanche erosion after clearcutting. Determining longer term (century-scale) impacts is contingent on understanding the types and rates of processes that refill storage sites subject to failure by debris avalanche. Field installations to measure these recharge processes should be placed in an appropriate geomorphic setting. For example, the role of creep and other processes in filling hollows should be based on measurements in microdrainages contributing soil to hollows, as well as on smooth or hummocky slopes where convergent soil and subsurface water movement does not occur or is more unpredictable than in hollows. Measuring effects of management practices on recharge processes is essential because rate of recharge is a long-term control on both the kind and degree of management impact on debris-avalanche erosion. Soil formation is the ultimate controlling factor.

Changes in channel storage regulate sediment yield from small drainage basins affected by management practices. Altering the location, size, or replenishment of large organic debris alters the sediment storage and yield characteristics of channel systems. Where basins have been treated as "black boxes," changes in sediment yield have been mainly attributed to variation in hillslopeerosion processes. Future studies should assess dynamics of channel-storage systems by using repeated surveys of monumented cross sections and, where possible, distinguishing between stored sediment that entered the channel before and after disturbance of the adjacent stand. Assessment of long-term effects of management practices on sediment storage in low-order forested channels is keyed to understanding (1) relations between large organic debris and sediment storage and (2) management influences on the role of adjacent stands as sources of pieces of large wood in streams.

These examples of research needs emerge from using sediment routing and budgeting concepts to analyze shortcomings of earlier approaches. Ultimately, management impacts will be quantified with detailed sediment budgets. For the present, however, routing and budgeting concepts provide new perspectives for analyzing management effects on geomorphic systems and help to identify important problems for future research.

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Discussion Group Summaries

Evaluating and Mapping Sources and Temporary Storage Areas of Sediment

Leslie M. Reid

INTRODUCTION

Legislation to regulate forest practices, water quality, and management of federal lands has increased the land managers' need for efficient methods of identifying and mapping sources of sediment in forested basins. At the same time, theoretical analysis of landscape evolution has led research geomorphologists to the consideration of many of the same sedimentation problems as those confronting land managers. This discussion session demonstrated that, although many of the fundamental questions addressed by these groups are identical, the approaches taken in answering those questions differ widely.

APPROACHES AND GOALS

Land managers are interested in the effects of varying land use on sediment production. Often they are asked to map the distribution of and predict sediment production from natural as well as management-induced and management-enhanced sources. They may also wish to predict distribution of sediment sources and rates-of sediment production for different management alternatives in specific areas. They are interested in such questions as how timber harvesting or road-building affects slope stability in an area, how the amount of sediment currently in storage in flood plains will be affected by a change in land use, and what happens to sediment introduced into a stream system by a change in land use. Usually answers are desired quickly.

Research geomorphologists may try to answer these same questions from a theoretical standpoint. They are interested in the distribution of erosional processes, for example, in order both to understand the importance of various external controls on those processes and to infer the importance and specific influence of the processes on landscape form and development. The goal of a land manager's investigation is a prediction specific to a locale, but the research geomorphologist's goal is usually an understanding of a general principle. Such general principles may be useful to a land manager as tools for making predictions in a specific area, but if other methods give adequate results more quickly or more economically, there is no compelling reason to use a theoretical approach.

The difference in approach stems from a basic difference in intent. The land manager must answer site- or area-specific questions quickly, but the researcher is interested in elucidating general principles and has the luxury of working on a more relaxed time scale.

Land managers have used the landscape stratification approach--also referred to as terrain mapping or morphogenetic classification--to characterize erosion processes over wide areas quickly. Underlying this approach is the assumption that areas of similar climate, topography, bedrock, vegetation, and land use experience the same kinds of erosion processes, produce sediment at similar rates, and respond in a similar manner to a given land use. The criteria used to define stratification units are chosen not only because of their genetic importance in controlling distribution and rate of erosion processes, but also because they are visible

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on aerial photographs or, as is often the case with bedrock geology, have already been mapped. A representative area in each defined unit can then be examined in detail by using field mapping, transects, monitoring programs, or more detailed aerial-photograph interpretation, and the results of the studies may be used to determine a characteristic sediment yield, process distribution or rate, or, if a disturbed area is selected, response to land use. The values for a representative area are then used to typify that unit or to provide the basis for revised stratification criteria that are more appropriate for the area of interest. This method has been widely used to evaluate slope stability (examples from T. Chamberlin, B. Hicks, and W. Megahan) and has also proved useful in assessing and predicting effects of logging on channel stability (example from O. Williams). In this last example, topographic maps and aerial photographs were used to classify the channels into one of seven stability classes. Observations of the response of representatives of each stability class to a given logging practice were then used to predict the response of a specific channel to that practice.

The stratification approach cannot be used when site-specific answers are needed. This approach can predict the kind of landslide likely to occur and the average failure frequency in an area, but it cannot be used to determine the locations of individual failures or the conditions under which a given site will fail. Nor can the stratification approach be used reliably to predict process distribution or response beyond the range of the impacts already existing on each stratification unit. For example, a stratification-based approach may use data from a 10-year-old clearcutting to predict that clearcutting of a certain basin will result in a threefold increase in yearly sediment production from landslides. The approach can give no indication, however, of how long the effect will last unless a series of progressively older clearcuts exists in the same stratification unit. Similarly, the effect of a management plan for which no prototype exists on that stratification unit cannot be evaluated. Finally, the method is restricted to areas and processes for which controlling variables are easily mapped. In areas where debris-avalanche occurrence is controlled by the distribution of deep soil wedges or of localized bedrock joints, stratification by hillslope gradient, vegetation, and bedrock lithology, each of which may have little relation to the primary controls, would be of little value.

For such areas, an approach frequently adopted by researchers may be useful. Individual erosion processes are conceptually isolated and the controls on the rate and distribution of each process are quantified (Dietrich et al., this volume). Long-term impacts of current management activities or the effects of a proposed management activity may then be predicted by analyzing the response of the processes to the changing primary controls. Sediment production from gravel road surfaces, for example, is largely controlled by factors such as overland flow length, road gradient, and road use. These relationships have been defined in the Clearwater basin, Washington, and can be used to estimate sediment yields from new road designs and use patterns by determining the effects of the changes on the factors controlling sediment production (L. Reid). If process controls are adequately understood, site-specific process rates may be predicted using a combination of this technique and a probabilistic treatment of the driving variables.

The process approach thus can be used not only to solve the same kinds of problems that the stratification approach deals with, but also to make predictions for specific locations and for conditions without prototypes. The process approach requires an initial investment of effort that may make it impractical for short-term reconnaissance work, but if more specific questions are anticipated or if the necessary scale of stratification is expected to become more detailed, the stratification criteria will need to be more processoriented. In such a case, an initial commitment of time toward the development of a quantitative understanding of primary controls of process distribution and rate may be most economical in the long run.

METHODS: DISCRETE SOURCES

The methods used to evaluate sediment sources can be applied to both the stratification and process approaches. Methods such as field mapping and aerial photograph interpretation are standard techniques for evaluating discrete sediment sources such as landslides. If these techniques are to be used quantitatively, however, care must be taken to avoid comparing areas of different resolution without making allowances for that difference. For example, debris-avalanche frequencies cannot be compared by counting landslide scars if the scars heal more quickly in one area than in another, and a count of scars in a logged area compared to one in a forested area has little meaning unless the size of the smallest scar recognizable beneath the tree canopy is known.

Analysis of sequential aerial photographs is of particular value in determining frequencies and recovery times for different processes, but in many areas, few photograph sets are available. A source of aerial photographs frequently overlooked is county tax records in courthouse files: since the early 1940's, governments of many timberproducing western counties have been taking aerial surveys at 4- to 10-year intervals to assess timber holdings (R. Janda, D. Hardin, M. Nolan).

Ground photographs, too, may facilitate the evaluation of past geomorphic and vegetative change or even allow the reconstruction of process distribution and rate in areas before disturbance. In addition, both sequences of aerial and ground photos may be used in conjunction with climatic records to assess the impact of specific storms (S. Duncan, D. Hardin). Historical photographs of the area of interest may exist locally, and during the 1930's the Soil Conservation Service compiled a series of high-quality photographs documenting erosion problems in each State. Though the emphasis of the series was on agricultural and range lands, other land use categories were included. The photograph collection is preserved in the National Archives (S. Trimble). The U.S. Geological Survey also maintains a collection of historical photographs (R. Janda).

Other remote-sensing techniques have recently been applied to geomorphic problems. Both aerial infrared and radar imagery have been used successfully to map areas of landslide hazard. Lineations observed on infrared photographs in New Zealand were found to correspond to moisture differences between coherent bedrock and more slide-prone, crushed zones, and thus correlated well with landslide distribution (M. Harvey). In Idaho, lineations made visible by radar imagery also correlated very well with landslides (W. Megahan). Computer-rectified side-scanning radar images, because of their fine resolution and low-angle illumination, are useful in discerning subtle differences in relief such as those produced by landslides, but like visible-light photography, radar imagery cannot penetrate forest cover. These techniques can be used not only to map sediment-source distribution, but also to help map the distribution of rate-controlling variables such as vegetation, hillslope gradient, and bedrock geology. Other controls, such as soil depth and ground-water level, are less amenable to analysis by remote-sensing techniques.

Wedges—areas of deep soil on hillslopes with otherwise uniform soil depth—are very important in determining the location of debris avalanches in some areas, yet because wedges may have little or no surface expression, they are very difficult to recognize in the absence of road cuts. Portable seismic units have shown promise in measuring soil depth if the soil-bedrock interface is distinct (S. Duncan), and a portable conductivity meter is being developed for this purpose by the Bureau of Land Management. A prototype already on the market has been used successfully in southern Oregon. The conductivity meter is used to measure the depth to a subsurface contrast in conductivity, and because such a contrast may be the result of any of several factors including material, density, and moisture differences, readings must be calibrated for each area by digging test pits (B. Hicks). Eventually an understanding of how wedges form may make possible the prediction of their frequency and distribution in specific areas.

Mapping of peak or time-averaged piezometric levels is fraught with similar difficulties. Because the temporal occurrence of landslides is so closely tied to the occurrence of,major storms and thus to high piezometric levels, maps showing the probable duration of a given piezometric level may prove useful in determining landslide potential in an area (T. Chamberlin). But as yet, the use of piezometers is the only widely available method for measuring ground-water pore pressures, and the time and effort necessary to install piezometers has restricted their use to networks covering only small areas. In this case, a more process-oriented approach, where the controls on piezometric levels are determined in detail in a small area and then projected to the larger area of interest, may be most useful (S. Duncan). The technology necessary for remote sensing of soil thickness, ground-water depth, and other process controls may already exist; it may require only a closer working relationship with specialists in remote sensing to link the geomorphologist's needs with the capabilities of remote sensing.

METHODS: DISPERSED SOURCES

In many areas, dispersed sources such as surface wash, rill erosion, and small-scale bank erosion may contribute as much or even more sediment to stream channels than large, discrete sources. Even in areas where the net contribution from dispersed sources is small, they may be important as persistent sources of fine material. In addition, dispersed sources may prolong the impact of a landslide by preventing its revegetation, and in the case of bank erosion, may locally create the potential for discrete failures.

Because of the more continuous nature of their sediment production and because they are not discernible by remote sensing, dispersed sources require a more process-oriented approach to analysis even for purposes of stratification. Empirical correlations of sediment yield with different types and intensities of land use have in the past dealt implicitly with such sources, but because these studies require a large data base and do not distinguish specific source types, they are generally useful only in broad stratification schemes.

Direct monitoring of individual sources provides information that can be projected to stratification units of any size based on the distribution of rate-controlling variables. Monitoring methods depend, of course, on the types of processes in question. Surface erosion by such processes as rainsplash and rilling has been monitored using erosion pins on slide scars and gully walls (Lehre, this volume); erosion pins have also proved useful for measuring back-cut retreat on roads. With frequent observations it is possible to isolate the effects of specific storms and freeze-thaw, and careful selection of study plots allows the isolation of other variables such as aspect, lithology, slope angle, and slope length. Gerlach troughs are effective in monitoring sediment loss from the same sources (R. Janda), as are repeated measurements of surface elevation and sediment character on erosion plots (R. Rice). Erosion-plot studies using measurement of erosional landforms such as rainsplash pedestals and gullies have also been used to estimate effects of timber harvest and road construction on soil movement (Hauge 1977). Surface erosion by overland flow on gravel roads is also a significant source of fine sediment and can be monitored by measuring sediment concentrations in surface or culvert drainage. Sites must be selected carefully to isolate rate-controlling variables such as road gradient, drainage area, back-cut contribution, road use, and storm intensity. Use of a portable rainfall simulator may add flexibility in site selection (L. Reid).

In some areas, surface erosion can be measured by observing the depth of soil profile truncation. Because profile truncation is a criterion used in describing soil series, the extent of surface erosion may on occasion be mapped directly from existing soils maps (S. Trimble). Similarly, buried profiles indicate net accumulation or storage.

SEDIMENT STORAGE

Once sediment has entered the transport system, it may be stored for periods ranging from minutes to millions of years in landscape elements such as hollows, streambeds, gravel bars, and terraces. Though measurements of sediment production rates are important in determining the amount of sediment entering stream systems, an evaluation of sediment storage is necessary if the location, magnitude, and duration of the long-term impacts resulting from sediment production are to be determined. In addition, many sediment-related impacts of major concern involve a change in the location of sediment storage or in the character and amount of the material stored; such impacts include stream siltation, infiltration of fine sediment into spawning gravels, filling of pools, and channel destabilization. Finally, any accounting of sediment production that attempts to relate production rates from individual sources to a basin sediment yield must also take account of changes in volume of material in storage, because sediment may be either gained from or lost to storage during transport.

Trimble (1981) demonstrated the importance of this effect for the Coon Creek basin in Wisconsin, and further suggested that the present sediment load of many streams was determined by basin conditions over past decades or even hundreds of years. At Coon Creek, sediment originally produced by poor agricultural practices in the late 1800's was stored in the uplands for several decades. By the 1930's, it had been transported downstream as far as the main valley, resulting in massive aggradation of flood plains, even though agricultural practices had improved markedly by that time.

Similar effects are seen in the movement of sediment waves through stream systems. Coarse sediment introduced into a river at a point (as from a landslide) may travel as a slow-moving wave that may be recognizable only as an otherwise anomalous local change in channel morphology. This sediment is effectively in storage and is moving independently of any processes occurring at its source; its major impact at a downstream point will not be felt until the wave of sediment reaches that point. Such effects have been described in western Washington (Madej, this volume), northern California (Kelsey 1980), New Zealand (M. Harvey), and elsewhere. Thus, an analysis of sediment storage is necessary to answer such questions as what happens to sediment once it enters the transport system, what areas will be affected by an increase in sediment production, how long will the impact persist, and how will material already in storage respond to a change in land use.

A major problem in the evaluation of sediment storage is that the distinction between a source and a sink for sediment is not always clear. Because of the continuum between transport and storage, a meaningful assessment of either must consider residence time of material (D. Harden). Most landscape elements can act in either capacity, depending on recent climatic conditions, location in a basin, magnitude of a specific climate event, or local environmental conditions. This last point is of special interest, because it implies that a change in land use, and thus in factors such as local water balance or apparent soil cohesion from root strength, maybe large enough to convert storage elements into active sources.

Location within the drainage network is also important in determining the response of a storage element to changing conditions. In the northern California Coast Range, for example, small headwater streams tend to aggrade their beds during small storms and degrade during large, peak-flow events, but sediment aggrades in larger streams during large events and is gradually eroded during the smaller ones (Janda 1978).

A further complication to the analysis of sediment storage is the discontinuous nature of sediment transport. Transport of gravel is accomplished by the alternation of long periods of stationary storage on the streambed with brief episodes of rapid transport during storms. Similarly, flume studies in Colorado suggest that coarse material introduced into a stream is transported as a series of prograding fans in channels (Harvey, this volume). A clast is stored in any given fan for a relatively long period before it is once again eroded out and transported to the toe of the fan. In each case, the sediment in "active" transport spends a large proportion of its transport time in storage.

On a larger scale, entire landscape elements may be undergoing similar cycles. Hollows, for example, are thought to gradually fill with colluvium until the fill--or wedge--reaches a critical depth. At this point, high pore-water pressure during a large storm can cause it to fail. The colluvial fill is transported downslope, and the slightly enlarged bedrock depression is left to refill (Dietrich et al., this volume).

The importance of time scale is evident in each of these examples. Wedges and low-order stream channels, which appear to be stable sediment traps during most of their cycles, are seen to be net sources of sediment when observed over several cycles. In addition, the dependence of geomorphic response on storm magnitude adds a probabilistic variable to any long-term evaluation of a landscape element.

SUMMARY

Maps based upon quantitative, process-based studies and those based upon empirical correlations of source distribution with landform parameters both have been used to evaluate sediment production. Which of these approaches is most useful depends on the purpose of the specific study, but methods that have been developed for measuring production rates can be used in conjunction with either approach. These methods include various mapping techniques, monitoring programs, and experiments. Analysis of sediment production in a drainage basin must take into account changes in sediment storage, but this is made difficult by the sensitivity of storage elements to factors such as climatic history, magnitudes of individual storms, and local physical and

biological conditions. In addition, because the distinction between storage and transport is to some extent arbitrary, and because landscape elements may undergo natural cycles alternating between net sediment input and net output, the definition of sediment-storage elements is partially dependent on the time scale of interest.

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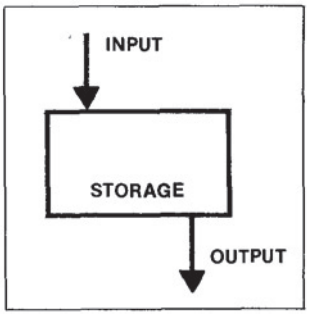

Tracing and Dating the Movement and Storage of Sediment

Randall B. Brown and Linda B. Brubaker

STATEMENT OF THE PROBLEM

Participants agreed that the most recent sediments, including those that are currently active, are of primary concern in tracing and dating the movements of sediment in forest drainage basins. Thus, the discussion revolved around techniques that might be applicable in dating and tracing sediments up to tens of thousands of years in age. Of interest are the rates of movement and the magnitude and frequency of sediment-transport processes. A particularly acute problem is the dating of recent alluvium in channels and terraces, and of colluvium on hillslopes and fans.

Participants further agreed that the technology is more advanced for DATING sediments than for TRACING the movement of sediment. Thus, for discussion, the two problems were separated.

Dating of Sediment

Dendrochronology holds great promise for application in sediment budgets and routing. The central technique of dendrochronology is counting annual growth-rings in wood to date the tree; the age of the tree may then place limits on the onset or duration of some geomorphic process—such as sheet or gully erosion, deposition, or flooding at the site. Other information extracted from patterns of tree-ring width or density provide data on environmental conditions, such as drought or cold weather, which are germane to the interpretation of sedimentary records.

The range of time over which these methods are useful extends from the present as far back as several thousand years. Living or dead trees can be used and compared with accurately dated, treering chronologies on file at research centers, to date sequences of ring widths. Recent developments in the measurement of density by X-rays aid in finding late-wood density patterns that are otherwise unrecognizable.

Sigafoos (1964), for example, has shown how the counting of tree rings outside of healed scars-and the bowing of trees and consequent adjustments in wood anatomy and sprouting—can indicate flood damage to trees at various elevations on a valley floor. Careful documentation and dating of these indicators allow the construction of a flood-frequency curve. Sigafoos also dated changes in rooting patterns after partial burial of tree trunks to document sedimentation on a floodplain. LaMarche (1968) measured the height of exposed roots on bristlecone pine (*Pinus aristata* Engelm.) trees in the White Mountains of California. The trees, which are several thousand years old, were dated by counting growth rings. Dunne et al. (1978, 1979) have used the method on much younger trees and bushes to map profiles of erosion along hillslopes in Kenya, and to indicate recent acceleration of erosion. Dietrich and Dunne (1978) used dendrochronology to define the rate of infilling of hillside hollows that had been excavated by landslides. Other studies have considered damage to live trees by fire (Heinselman 1973) and splitting by differential ground movement (Schroder 1978), which

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both produce rings that are not continuous around the trunk circumference. Alestalo (1971) used dendrochronology to study a variety of geomorphic processes.

One intriguing approach is suggested by the tendency for exposed tree roots to take on the character of tree stems for the duration of the exposure. Dating the sequence of change from root to stem character on cut faces can aid in the reconstruction of cut and fill sequences. Relative dating techniques might then be used to relate such cut faces and escarpments with associated geomorphic surfaces.

The width of lichen colonies is an index of the age of exposed raw materials under a constant climate (Benedict 1967). Before this approach can be applied in a given area, however, age-size relationships must be defined by the measurement of lichens on surfaces of known age. Because of the possibility of lichens invading a fresh deposit or exposure before trees, lichenometry can be a valuable tool in dating, especially in the range of tens to hundreds of years before the present.

Several isotopes can be used as markers/tracers in sediment movement studies. Lead-210, for example, is a natural isotope that falls from the atmosphere at a more or less constant rate at a given latitude, and is deposited in reservoirs and other depositional sites. Changes in 210Pb levels in depth profiles reveal periods of accelerated sedimentation rates that, in at least one instance, have been shown to correspond with historical records of human disturbance (Nevissi and Schell 1977). The technique is useful over the range of about 10 to 200 years before the present.

Cesium-137 is a nuclear-fission product with fallout levels that peaked in the early 1960's as a consequence of atmospheric testing of nuclear weapons (Ritchie et al. 1975). This isotope is attached readily to soil particles and serves as a tag on fine sediments. Its best use seems to be as a datable stratigraphic marker. Overthickening or thinning of 137Cs-rich surface layers likewise has utility in estimation of sedimentation/erosion rates.

Applications also may exist for some other geochemical techniques, such as the use of 12C/13C ratio changes in organic materials as a function of increased burning of fossil fuels in recent times, the worldwide increases in Pb content of organisms from accelerated gasoline use over recent decades, or changes in deuterium ratios in wood.

Classical 14C dating has severe limitations over, the range of tens to hundreds of years. Imprecision over this range, fluctuations in atmospheric 14C levels, contamination problems, and the complexity of interpreting 14C dates for decomposed organic materials combine to make 14C dating on very recent sediment a risky undertaking (Campbell et al. 1967, Rube 1975).

Historical records are a powerful tool in assessing recent geomorphic events. Stream cross sections taken in bridge design and construction work, topographic information collected in railroad construction, aerial photographs taken over the last 50 years, and other photographic records have been used with great success in assessment of modern erosion and sedimentation rates, stream-channel changes, and gullying. Historical and archeological artifacts are also of use (Leopold and Snyder 1951; Trimble 1970, 1981). Knowledge of fire and earthquake activity and major climatic events can give important clues to periods of high landscape instability in some areas.

Several other dating techniques were discussed in this session. Changes in pollen percentages in a sediment core sample, the arrival of exotic species, and other uses of time boundaries in pollen profiles can be helpful in sedimentation studies. Pedogenic processes and the degree of development of soil features can serve as indicators of age on recent geomorphic surfaces or buried surfaces. Particle-size distribution and the depth variation of grain size can help in assessing erosional/depositional history. Natural stratigraphic markers--such as volcanic ash deposits and paleosols—are useful in identifying buried, exposed, or relict geomorphic surfaces.

Tracing of Sediment

The task of tracing sediment movement is more difficult than dating, because the conceptual methods and technology for tracing sediments are not as well developed. Nevertheless, some tracing techniques do exist and several were discussed.

Rock and mineral provenance studies, including study by scanning electron microscope of quartz-grain morphology (Glasmann and Kling 1980), are useful techniques in identifying source areas of sediment. The influence of deep-seated failures or deep gullying may be detectable with provenance studies in those instances where source landscapes have depth variations in mineralogy or degree of weathering (Youngberg et al. 1971). Thompson et al. (1980) have reviewed how the analysis of various magnetic properties of sediment can be used to identify sediment sources both after deposition of the sediment and during its transport.

Application of other sedimentological techniques developed by petrologists and engineers also have use in sediment routing. Areal/depth variation in particle-size distribution, and analysis of sedimentary structures, can be useful in assessing rates and types of transport processes.

Tracing experiments that use painted, fluorescent, or exotic rocks have limitations in natural systems. Because only a small percentage of the tagged objects are usually recovered, the fate of the majority of tagged objects is uncertain and so, thus, are the major transport pathways of the system. Also, the dynamics of the mass or pulse of sediment as a whole are not well elucidated by this technique. Participants suggested that simpli-

fied versions of such experiments, as in a rock-floored channel or a controlled, areally limited environment would be easier to interpret at the current stage of knowledge. More complex experiments could be designed later.

Use of radioactive tracers presents other problems. The controversial nature of such materials and their dilution in transport and consequent low detectability make them almost prohibitive in field studies. Tracers are more useful in controlled settings such as small flumes or small drainage-basin models. Radioactive minerals such as uraninite are traceable in small-scale bedload-transport studies.

We now have a dearth of conceptual models to describe the fate of a marked particle in a sedimentary system. Until such models are developed, designing useful tracing experiments and interpreting the results of experiments already done will be difficult (e.g., Laronne and Carson 1976, p. 82; Mosley 1978; Dietrich et al., this volume).

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Weathering and Soil Profile Development as Tools in Sediment Routing and Budget Studies

Deborah R. Harden, Fiorenzo Ugolini, and Richard J. Janda

INTRODUCTION

Studies of soil morphology and genesis have, for the most part, focused on sites where profile characteristics result primarily from vertical pedogenic processes and are little influenced by repeated erosion or deposition. Soil investigations at such sites may be used to place limits on the age of some relatively stable parts of the landscape (Birkeland 1974), but they are of little value in studying processes and rates of sediment movement through drainage basins. On most sloping landscapes, periodic erosion and deposition are integral factors in soil formation. Additionally, weathering and soil formation strongly influence the hydrologic and erosional characteristics of the regolith. The interactions between geomorphic and pedogenic processes have been discussed in a variety of intriguing papers (e.g., Zinke and Colwell 1965, Conacher and Dalrymple 1977, Parsons 1978); however, workshop participants believe that these concepts will have to be developed more fully before they can be used routinely in developing sediment budgets for forested drainage basins. Nonetheless, participants did cite several ways in which soils and weathering characteristics can increase understanding of some aspects of sediment routing.

Pedological and geochemical processes concurrently operating near the earth's surface contribute to the production of material that is potentially erodible. In some instances, as in the case of areas affected by podzolization, the distinction between pedological and geochemical processes is strikingly distinct (Ugolini et al. 1977). Common to these processes is weathering which changes the strength, grain size, and mineralogical composition of geological materials.

The discussion revealed that recent attempts by soil scientists to achieve professional consensus on terminology used to classify and to describe soil profiles (U.S. Department of Agriculture, Soil Survey Staff 1960, Soil Conservation Service 1975) have resulted in a complex vocabulary that is not yet widely accepted by geologists and hydrologists. Most workers discuss concepts of soil morphology and genesis in terms that strongly reflect their professional specialization and field experience in specific types of terrain. Thus, communication between researchers with different specializations or experience in contrasting terrains is sometimes difficult. The greatest difficulty is in describing profiles that reflect episodic deposition or erosion as well as weathering; such conditions are widespread on forested hillalopes. Additional complications in terminology result when stratigraphic studies indicate that deep soil horizons reflect past climatic and vegetation conditions different from existing conditions (Janda 1979). Soil horizons, e.g., B3 horizons in ultisols, considered crucial in some soil stratigraphic studies are regarded to be below the solum and in some studies of nutrient cycling and erosion processes, considered saprolite or parent material.

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Table 1--Soil properties and diagnostic horizons useful as age indicators (adopted from Yaalon 1971)

Easily reversible, rapidly developed (10^1–10^3 years)	Less easily reversible (10^2–10^4 years)	Irreversible, slowly developed (10^3–10^5 years)
pH	Clay illuviation	Oxic horizon
Organic matter	Iron oxide accumulation	Plinthite
Base saturation	Physical properties (bulk density, engineering properties)	Fragipan
Folic horizon		Placic horizon
C:N ratios	Argillic horizon	Duripan
Cambic horizon----------	Cambic horizon	Calcrete
Gleying	Histic horizon (fire area)	Histic horizon
Spodic horizon	Clay mineralogy	Clay mineralogy
Mollic horizon	Calcic horizon	Weathering rinds
	Umbric horizon	Mineral etching

NOTE: Many of the properties may be more or less reversible in different environments.
Absolute age determination methods: ^{14}C, fission-track, thermoluminescence, ^{137}Cs, U-series, amino acid racemization.

STRATIGRAPHIC STUDIES

Soil stratigraphy (the use of surface and buried soils to subdivide and to correlate sediments primarily of Quaternary age (Birkeland 1974)) may be useful in constructing sediment budgets by identifying the relative stability of different landscape elements and by placing limits on frequency and rate of erosion. Participants in the discussion group compiled a table of soil properties that can serve as possible age indicators and their response times to environmental change (table 1).

Easily reversible properties, such as pH, organic material, carbonates, and others, are probably in equilibrium with existing climatic and vegetation conditions at a site, but irreversible properties, such as plinthite, oxic horizons, duripan, and others, may persist under conditions that are drastically different from those under which they developed (Yaalon 1971).

Soil stratigraphy may be used to identify relative contributions of different landscape units to the overall sediment yield from a drainage basin. Low erosion rates on hillslopes and ridges are indicated by soils displaying strongly developed profiles andby clay mineralogy and pollen reflecting climatic and vegetation conditions that have not existed for tens or even hundreds of thousands of years. In contrast, hillslopes bearing weakly developed soil profiles or active colluvium indicate more rapid erosion rates. Downslope movement of weathered colluvium or intact blocks of strongly developed soils complicate the use of soil-profile characteristics for estimating rates of erosion.

Application of erosion rates computed from measured stream-sediment discharges to only those parts of drainage basins where soils suggest active erosion provides more realistic estimates of rates of landscape development than traditional computations of drainage basin-wide denudation. In addition, areas of temporary sediment storage may be identified in the landscape, and rates of accumulation or residence time may be estimated by soil-profile characteristics.

Another potential use of soil stratigraphy in studying erosion processes is as an indicator of recurrence intervals of episodic erosion events. Different ages of landslide episodes can often be recognized by differences in soil depth and weathering intensity, or by buried soil horizons. Workshop participants believe that this type of investigation in terrain sculpted by frequent (that is, where frequency of failure at a site is on the order of 101-103 years), shallow debris slides would require a refinement of existing soil stratigraphic techniques and probably the use of rapidly developing, easily reversible soil properties (table 1). In constrast, age difference between larger, more infrequent slumps and translational slides can probably be established through use of existing soil stratigraphy techniques based on slowly developing, irreversible soil properties (table 1).

Several participants pointed out that such time-dependent weathering characteristics as thickness of weathering rinds of clasts, ratios of fresh to weathered clasts, and etching of heavy minerals are diagnostic and often easier to use than soil-profile development. In some settings, differences in specific surface and subsurface rock-weathering characteristics actually give a clearer separation of Quaternary sediments than differences in soil-profile development (Burke and Birkeland 1979).

PROCESS STUDIES

Map distributions and profile characteristics of soils in forested areas can help distinguish erosion and deposition processes operating on hillslopes. For example, some hillslopes in northwestern California that appear sculpted predominantly by creep and streamside translational slides show progressively less weathered colluvium and younger, shallower soils in a downslope direction. In contrast, some slopes that experience episodic debris avalanches show imbricate or interfingering arrangements of fresh colluvium over saprolite, or of strongly developed soils over weakly developed ones. Some hillslopes that appear sculpted by large-scale rotational slumping show intact blocks of deep, mature soils that moved downslope from stable interfluve positions. Detailed soil maps may help identify the prevalent erosional processes operating on individual hillslopes and the frequency with which those processes occur.

One model of the linkage between soil formation and hillslope erosion in regions sculpted primarily by shallow, episodic mass movement and creep assumes that rates of weathering determine availability of sediment (Dietrich and Dunne 1978; Dietrich et al., this volume). As the regolith becomes deeper and increasingly weathered, it becomes increasingly susceptible to catastrophic removal by debris slides. In terranes where the rate of production of saprolite is exceeded by its rate of removal, the rate of soil formation determines sediment production. However, in landscapes where rocks do not have to be weathered to be eroded or where mass-movement processes extend deeper than the regolith, erosion rates may be independent of rates of weathering. Workshop members also pointed out that the type and rate of revegetation may be a controlling factor in reconstituting eroded soils.

Workshop participants agreed that better understanding of weathering and soil-forming processes is necessary for developing a model of hillslope erosion. Much recent work has been done on chemical weathering in soil formation, but physical weathering processes in forested environments have been studied much less intensively. Production of fine-grained particles from exposed and buried rock surfaces disrupts primary rock structure (stratification, foliation, etc.). Some members believe this disruption is caused solely by physical disaggregation, but others think that volume changes associated with chemical weathering may aid in disrupting primary rock and saprolite structure. Some scientists use disruption of rock structure to define the boundary between the solum and the undisturbed saprolite or bedrock. In a landslide scar, accretion by sloughing into the bare surface followed by revegetation may be necessary before rock disaggregation and soil formation can proceed. The model of physical disruption of saprolite to produce the solum may be valid if shallow erosion processes are prevalent. Other landscapes may have different regimes of soil erosion and formation and of regolith formation, however. Workshop members agreed that a better understanding of these regimes would aid in applying soil studies to studies of sediment production and budgets.

Several participants pointed out that residence times in some temporary sediment-storage compartments in forested drainage basins are long enough to allow weathering to modify grain-size distributions and other physical properties of sediment and thereby influence subsequent erosion. In areas of relatively slow erosion and rapid weathering, weathering may also significantly reduce the total mass of sediment moving through the drainage basin. In these circumstances, landscape evolution can probably be understood best by working with mass budgets that include transport of dissolved solids as well as sediment (Cleaves et'al. 1970; Bormann et al. 1974; Swanson et al., 1982).

RESEARCH NEEDS

1. Refine techniques of using soil-profile development and rock-weathering characteristics to assign ages to deposits. Emphasis should be placed on the use of rapidly developing soil properties to provide finer resolution and greater applicability to younger deposits.

2. Expand criteria for distinguishing those soil properties that are in equilibrium with existing climatic and vegetative conditions from those properties that are a relic of former conditions.

3. Develop criteria for distinguishing between sediment weathered in place after transport and sediment that was weathered primarily before its most recent movement.

4. Integrate more observations of water chemistry and soil-profile development into sediment- (or mass-) routing studies in forested drainage basins.

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Influence of Magnitude, Frequency, and Persistence of Various Types of Disturbance on Geomorphic Form and Process

Harvey M. Kelsey

The relative importance of events of various magnitude and frequency on geomorphic form and process is one of the earliest recognized basic questions of geomorphic theory, and this workshop discussion seemed to point out that the subject is not much better developed than it was when Wolman and Miller (1960) published "Magnitude and Frequency of Forces in Geomorphic Processes." We tried to focus the discussion on defining data limitations, asking the proper questions, narrowing the scope of the problem(s) to workable limits, identifying statistical sampling problems, and suggesting investigative techniques. As one participant pointed out, we are all victims of our own experience, and though our observations and backgrounds are the foundations for moving forward, they also can cause tunnel vision. We hope the range of participants to some extent removed these limitations.

The best way to summarize the discussion is to pose a set of questions and tentative statements that reflect the major concerns of the participants. Obviously, we reached no conclusions, but we did cover a number of important questions that should be confronted. We began by asking if we are interested in the effects of magnitude and frequency of events on (1) processes that sculpt landforms (shape the landscape) or (2) processes that mobilize the greatest amount of sediment out of a basin. In other words, are we to address the landform-evolution problem or the sediment-routing problem. To this end, the group posed the question, "Should we apply the problem of the effects of magnitude and frequency of events to different drainage-basin segments or sites?" For example, the following basin segments or sites can be studied:

1. Hillslope processes (e.g., debris-slide events, surface erosion),
2. "Fingertip" tributaries,
3. Main channels (higher order channels in a basin),
4. Points of output of a basin (gaging station at end of basin—the Wolman and Miller (1960) approach).

When dealing with the problem of the effects of magnitude and frequency on geomorphic process and form, must we define first whether we assume a landscape is in dynamic equilibrium (Hack 1960), whether a landscape evolves by exceeding critical thresholds (Schumm 1973, Bull 1979), or whether another model is more appropriate? Are different landscape models mutually exclusive, or are they pertinent in different time frames?

Thinking of the geomorphic event/climatic event relationship in terms of force and response is useful: climatic event = driving force; geomorphic event = response. Perhaps we need to apply magnitude-frequency analysis separately in different climatic regimes because the relationship between driving force and response varies for different climatic areas. Therefore, climatic regime as well as basin segment must be defined. Complicating the picture, significant climatic changes on the scale of 102-104 years will alter the magnitude-frequency character of geomorphic response. Perhaps a cutoff point exists in terms of time period beyond which pursuing magnitude-frequency analysis is not useful because of climatic changes.

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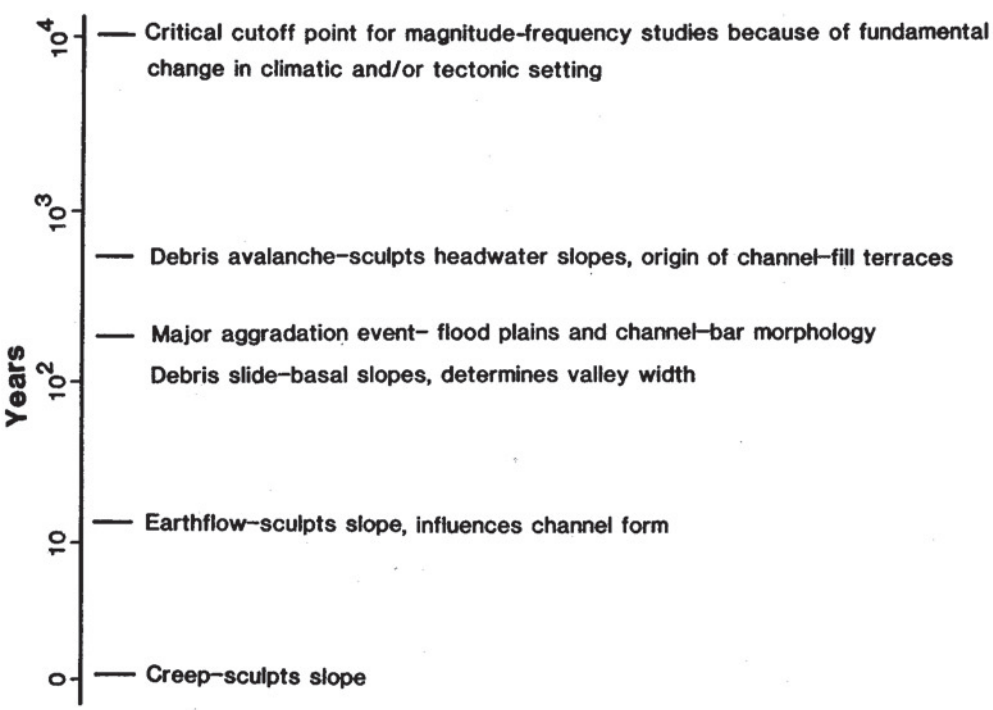
A basic problem of magnitude-frequency studies is the need to extrapolate for long time spans from a limited period of scientific observation. This problem raises the question, can space be substituted for time? Using the example of soil hollows and related debris avalanches (Dietrich and Dunne 1978; Lehre, this volume), frequency of failure and the rate of soil infilling of the hollows can be estimated by examining the depth of soil in hollows and the occurrence of debris avalanches over a broad area for a relatively short period of time. Alternatively, the estimate can be made by analyzing the filling rate and failure probability of one hollow over a long period. If space is substituted for time in studying magnitudefrequency relations of geomorphic processes and/or form, two criteria, in most cases mutually exclusive, should be met: (1) a homogeneous sample area (similar geology, tectonic setting, and climate) and (2) a large sample area. If we cannot take a look at a long record, an alternative is the deterministic approach of applying existing theory in an attempt to extrapolate from a limited sample population.

How should we deal with channel-storage compartments in space and time as compared to slope processes in space and time, and how can changes in these compartments best be monitored? Maybe we should first ask how related geomorphic features (headwater slopes, flood plains, footslopes, interfluves) form. Then the problem might be divided among different drainage-basin segments. For example, sediment is stored in major channels at sites with different residence times: active channel, channel down to depth of scour for major events, and the part of the channel that is storing alluvium for longer periods. Each channel-storage compartment is most influenced by a discharge of a different magnitude and frequency.

When dealing with the geomorphic importance of events of various magnitudes and frequencies, distinguishing whether the system (drainage basin, hillslope, higher order channel, or other geomorphic unit) is material-limited or energy-limited or transitional between the two is important. For example, debris avalanching on steep headwater slopes in resistant, competent rock types may be limited by availability of material if the rate of weathering is slow relative to the frequency of large storms that trigger debris avalanches. A contrasting example is bedload transport in a channel reach that has recently aggraded. Here, the system is limited only by transport capability because abundant sediment is available.

Is there a characteristic frequency for each process and is there a most important frequency for each type of landscape change? Perhaps attempting to characterize the most important frequency of activity for various geomorphic processes and events in a given area over a log time scale (fig. 1) would be instructive. The recovery of various components of geomorphic systems and ecosystems to severe disturbance, such as some of those depicted in figure 1, may occur on an exponential basis, so characteristic time scales might best be described in terms of half-life. Refilling of hollows after a debris slide, for example, may occur first rapidly and then progressively slower.

Figure 1—Log time scale showing characteristic frequencies for different geomorphic processes.



When investigating effects of magnitude and frequency of events on process and form, we must ask whether the events are independent of each other. Magnitude-frequency analysis is most useful when independence of successive events can be assumed. Recurrence intervals cannot be used for prediction if the recurrence of one event is dependent on the last. Where records of a sufficient number of events are available, statistical techniques can aid analysis of relationships among successive geomorphic events. As Rice (this volume) and others point out, however, geomorphic change in steep lands is typically dominated by infrequent events, so a record of even 40 to 50 years is too brief for this type of analysis.

In magnitude-frequency analysis, we must distinguish between geomorphic events and climatic events. Frequency of geomorphic events and frequency of climatic events are often confused. One problem in magnitude-frequency analysis is that successive climatic events may be considered independent of one another, but successive geomorphic events may be highly related. The second of a pair of back-to-back major floods, for example, will operate on a different set of sediment-storage and streamside-vegetation conditions and therefore have different geomorphic consequences than the first flood. Independence of successive events is a basic assumption in the magnitude-frequency analysis of Wolman and Miller (1960).

Another way of addressing the same problem is to ask what is the length of memory or recovery rate of a system relative to the frequency of climatic events that trigger the geomorphic change. Expressed graphically, changes in a system may all originate from the same base level (case I, fig. 2) when recovery is fast relative to event frequency. Where events may occur so frequently that recovery from previous events is not complete (case II), the effect of any one event is determined in part by the magnitude and timing of past events. A third alternative (case III) is a combination of independent events and events that are influenced by previous disturbance.

What is human influence on magnitude and frequency of events? Land use may well be fundamentally changing the resilience and shape of the earth's surface. As a consequence, a driving force of the same magnitude may now trigger events of greater magnitude more frequently than before widespread ground disturbance. Is land use changing the character of geomorphic response to climatic events? If so, is land use likely to trigger geomorphic change in a nonlinear fashion? What is the relative importance of land use in influencing the frequency of high-magnitude as compared to low-magnitude events?

The discussion group sketched a summary figure showing some possible relationships ofethe magnitude and frequency of driving force and geomorphic response at different locations within a fluvial system (fig. 3). The different locations are expressed by position on a simplified longitudinal stream profile. Positions on the profile are delineated as being terial-

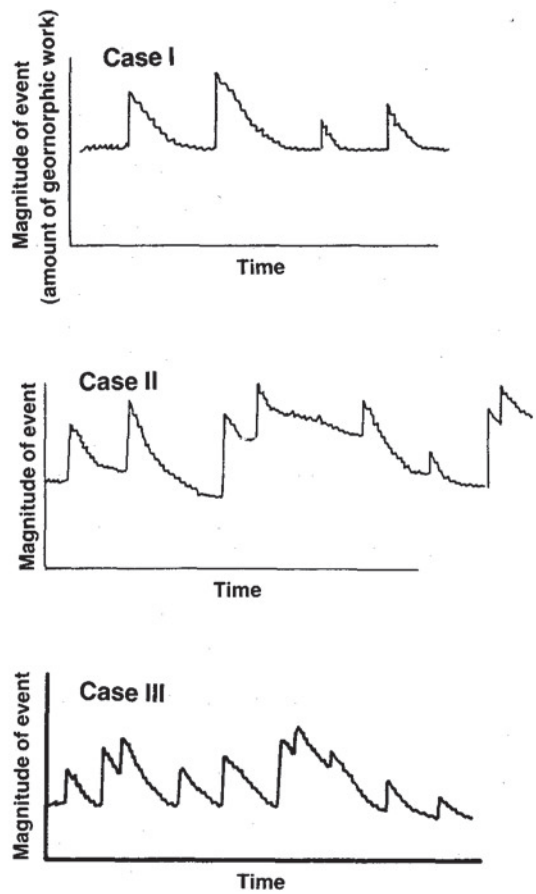


Figure 2—Different case example of the effect of recovery rate in a geomorphic system on the magnitude of individual events in a series of geomorphic events. See text for discussion.

limited, energy-limited, or transitional, in terms of geomorphic process.

Participants generally concluded that magnitudefrequency analyses hold much promise for analyzing and contrasting geomorphic systems and determining minimal sampling periods for episodic events. Magnitude-frequency analysis has not been rigorously applied and examined since Wolman and Miller's original paper. Problems may arise in using this approach in systems that have strong memory (interdependence of successive events). This may be particularly true in steep, geomorphically active, forested terrain.

To better understand the magnitude-frequency characteristics of geomorphic systems, long-term data collection systems such as the Vigil Network and water resources monitoring program of the U.S. Geological Survey should be maintained. Such efforts provide both essential records of lowmagnitude, frequent events, as well as some opportunity to document major, infrequent events. Further work using stratigraphic, dendrochronologic, and other methods should be employed to supplement efforts to monitor infrequent events directly, because records based on direct observation are far from adequate to answer important questions concerning magnitude-frequency characteristics of geomorphic change in geomorphically active areas.

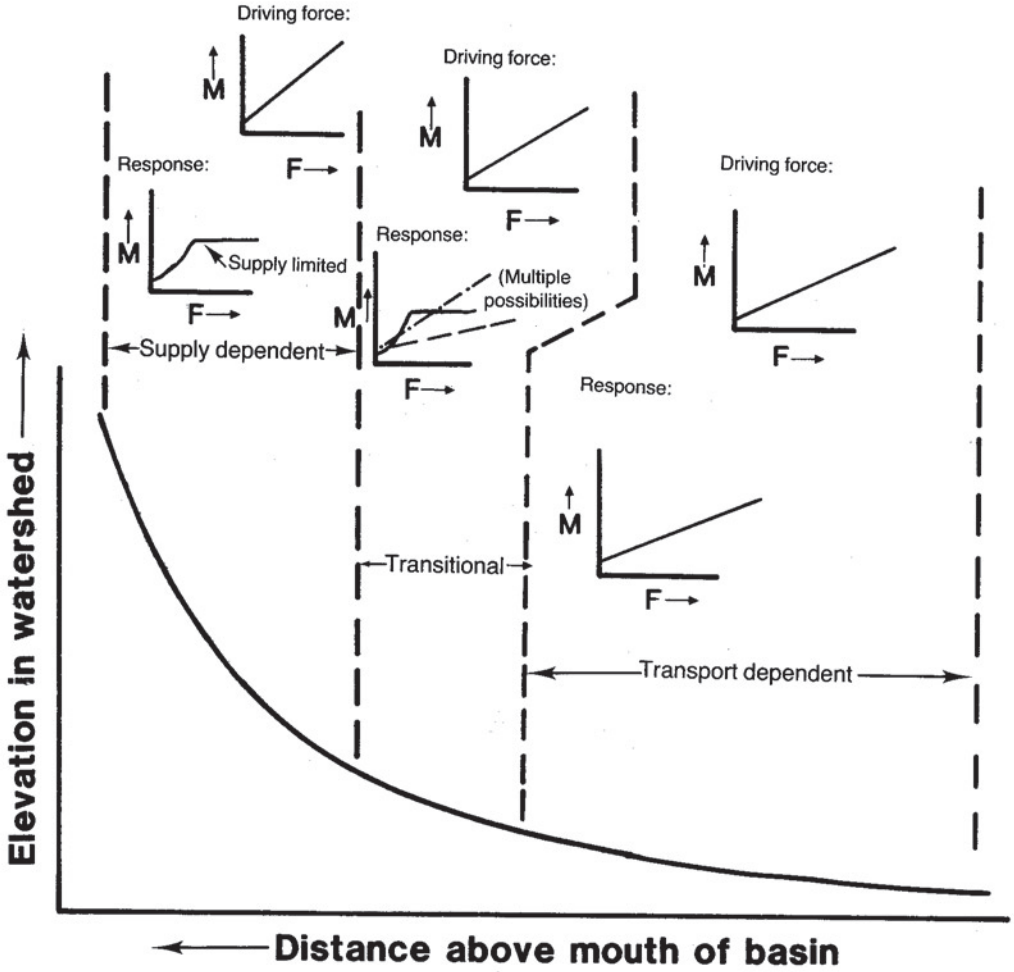


Figure 3—Summary diagram showing possible relationships of magnitude of magnitude (m) and frequency (f) of driving force and geomorphic response at different sites within a fluvial system. Sites are depicted on a schematic version of a longitudinal stream profile.

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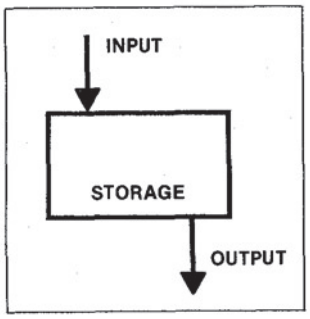

The Use of Flow Charts in Sediment Routing Analysis

Leslie M. Reid

THE USE OF FLOW CHARTS IN SEDIMENT ROUTING

Flow charts are a widely used means of diagramming relationships among transport processes and storage sites during analyses of sediment routing. Because they have taken so many different forms, however, it is very difficult to use published flow charts to compare geomorphic systems. Though they generally are constructed to achieve the same purpose, flow charts differ in the definition of the material being transported, type of transport processes involved, and the kinds of landscape elements considered to be sediment storage sites. In addition, the structure of flow charts may vary greatly. During this discussion, we attempted to probe the advantages and disadvantages of the different types of charts in hopes of arriving at a general form that would facilitate direct comparison of sediment budgets from different environments. Though a general form was not attained, many criteria necessary for a general flow chart, and for flow charts in general, were recognized.

Formally, a flow chart is a schematic representation of a series of operations. In the context of geomorphology, these operations are generally processes such as landslides, sheetwash, and solution transfer, which transport material from one storage site to another. Operations might also include processes such as chemical weathering and abrasion which change the character of the material; or information flow, which controls interactions between processes. Which operations are selected depends ultimately on the understanding of how the system operates, the amount of information available about the system being diagrammed, and the use to which the flow chart will be put.

Flow charts can be used to organize information, to describe a system, or to provide a framework for predictive calculations. At the least sophisticated level, a flow chart can be used to expose conceptual holes in our understanding of the relationships in a system. Such a chart need only be qualitative, though as the level of understanding increases and the recognized conceptual gaps occur at finer scales of resolution, the complexity of the flow chart and the need for quantification also increase. The same kinds of charts may be used to pinpoint critical, ratecontrolling steps deserving more careful evaluation.

Flow charts are also useful for describing a specific system once data have been collected. Here, too, the level of sophistication may vary from a qualitative diagram of process interactions to a quantitative sediment budget. A corollary of this function is the use of flow charts to compare systems in different environments, and it is for this use that a need for some uniformity in structure and definitions becomes apparent. The most common means of comparison has been the single number index of sediment yield per unit area, both because it is the only parameter that has been widely reported and because it is relatively easy to measure. But important differences in processes and rates in different basins cannot be described by a single number. More useful would be a comparison based directly on sediment production and transport processes. A standardized flow-chart form would provide a means of organizing data for such a comparison.

At the most sophisticated level, a flow chart may allow prediction of the response of a basin to changes in environmen-

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tal variables. The construction of such a model requires a quantitative understanding of all process rates and feedback controls operating in the system, as well as of the dependence of those rates on the driving variables.

The need for three types of flow charts can thus be recognized. Descriptive-qualitative charts organize information about relationships, and descriptive-quantitative charts attach average or instantaneous transfer rates to the qualitative framework. The third type of chart, a predictive-quantitative flow chart, includes measurements of feedback mechanisms and dependencies upon driving forces and thus allows calculation of the effects of changing conditions on the parameters of interest. Construction of such a chart, however, requires data not currently available for any natural geomorphic system.

The descriptive-qualitative flow chart has been the most widely used in geomorphology, largely because difficulties in measuring the rates of gain and loss of material to storage have prevented quantification of the charts. The traditional form of a descriptive flow chart is a series of boxes joined by arrows showing a temporal or spatial sequence. Boxes, however, can stand for many different items or concepts. Recent geomorphic flow charts have used boxes to represent (1) idealized locations as geometrically defined landscape units (e.g., units of a segmented landscape discussed by Simons et al., this volume), (2) geomorphically defined locations (swale—channel banks—channel bed of Lehre, this volume), (3) sediment deposits (soil—wedge—fan-channel bed, ,as described by Dietrich and Dunne 1978), (4) transport processes (creep—slump-debris slide—debris torrent shown by Swanson et al., 1982), and (5) material character (bedrock—saprolite—soil). The arrows then correspond to transport processes, weathering processes, or merely indicate sequential development.

Appropriate definitions of elements of a flow chart depend on the purpose of the flow chart. The limitations of each approach to flow-chart development must be recognized. Over long periods, for example, landforms and idealized locations may evolve from one kind to another (swales may fail, form channels, and gradually refill) and deposits may erode away or new kinds form. Storage elements, too, are difficult to evaluate, because storage and transport form a continuum that may be distinguished only by an arbitrary selection of a minimum residence time to define storage. Charts based on processes tend to be complex because most processes interact with others. Complexity is also introduced because a change in material character may be interpreted as an indirect expression of mass transfer; weathering may change bedrock to saprolite in situ, for example. In any case, care must be taken to avoid mixing different types of elements in one diagram, unless the elements are distinguished symbolically.

The more complete the flow chart, the more difficult it is to interpret, and the less useful it becomes as a graphical description of a system. Increasing complexity may be avoided by breaking the flow chart into several charts, each dealing with a separate subsystem. The.subsystems may then be recombined by way of a master chart that treats each subsystem as a separate compartment. Each subsystem may represent an individual process, landform, or time segment.

A similar approach may be used to handle the change of process type and rate as channel order increases. Debris torrents, for example, are an important transport process in steep, low-order basins. But as the channel gradient decreases with increasing basin order, torrents become less important and eventually disappear altogether. Such an effect cannot be shown on a simple chart, but if a separate flow chart is constructed for each order of channel, the effect becomes evident. These separate charts are then combined by way of a master chart that specifies the transfers between channels of different orders.

Several approaches have been used to show quantitative sediment budget data on flow charts. The relative importance of different elements or transport routes may be shown by the relative sizes of the element boxes or the thickness of interconnecting arrows, even if the actual values are not known.

If process rates and storage volumes have been measured, a quantitative, descriptive flow chart may be constructed. Rates of material transport can be shown by appending the actual transport rates to the flow chart. This method is useful in that it preserves the visual impact of the generalized chart and facilitates direct comparison of flow charts, but it becomes unwieldy as the complexity of the chart increases.

Highly complex systems can be quantitatively described using transitional matrices. With this method, locations (absolute or idealized), landforms, or storage elements are used as labels for columns and rows of a matrix (fig. 1). Sediment is considered to be transported from the location noted in a row to that noted in a column, and transport processes are differentiated by planes in the third dimension; mass transfers are filled in according to source, destination, and transport process. Sequence—an important aspect of flow charts and a critical factor in understanding a geomorphic system—is difficult to discern, but may be partially reconstructed by comparing inputs and outputs from different locations. Though visually obscure, the result makes the organization of information relatively easy and is useful in accounting; change in storage volume may be easily determined by comparing the totals in the rows and columns for each location. This operation also makes apparent the restrictions of this budget and any other descriptive-qualitative budget that is based on short-term measurements and does not deal explicitly with probabilistic variations in driving variables; the budget can reflect only what is happening at a specific time or the average result over a longer period. Otherwise, loss of material in transport to storage would imply infinite aggradation.

The third type of flow chart—the predictivequantitative model—requires a quantitative understanding of process rates, driving variables, and information flow; each

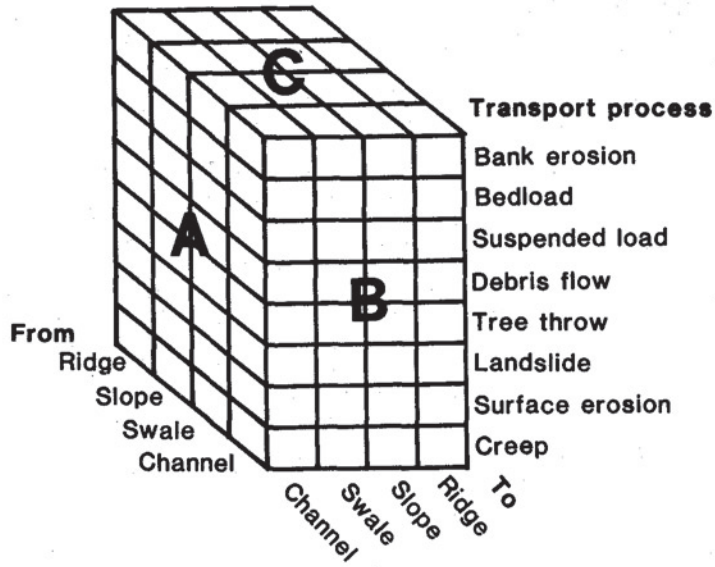

Figure 1—Hypothetical three dimensional matrix for tabulation of material transfer rates between storage locations in a forested basin. Material is moved from source A to location B by transport process C. Hypothetical tabulations, in t/km^2 per year, are shown in 1A, 1B, and 1C. Change in storage at a location can be calculated by subtracting total output from total input at that location. In the example given, the rate of change of the volume of material stored in swales would be (total (1B) - total (1A)) = -5 t/km^2 per year.

A Destination

	Channel	Swale	Slope	Ridge
Bank erosion	3	1	–	–
Bedload	17	1	–	–
Suspended load	30	.5	–	–
Debris flow	40	3	–	–
Tree throw	5	12	–	–
Landslide	12	4	–	–
Surface erosion	1	1	–	–
Creep	–	38	–	–

From swale

B Source

	Ridge	Slope	Swale	Channel
Bank erosion	–	–	1	–
Bedload	–	–	1	–
Suspended load	–	–	.5	–
Debris flow	–	2	3	–
Tree throw	–	15	12	–
Landslide	3	19	4	–
Surface erosion	–	1	1	–
Creep	–	63	38	–

To swale

C Landslides

From	Channel	Swale	Slope	Ridge
Ridge	–	3	1	–
Slope	28	19	23	–
Swale	12	4	–	–
Channel	–	–	–	–

To

is incorporated into the chart to form a model of the real system. When values for the driving variables are specified, the chart can be used to predict the response of any part of the system or of the system as a whole. The complexity of a realistic model, and the necessity to handle driving variables probabilistically, usually requires the model to be programmed onto a computer, leaving only the framework to be represented as a chart.

After discussing flow charts in general, we attempted to develop a general qualitative chart to describe sediment movement through steep, forested landscapes. We failed. After several hours, we had just begun to resolve the difficulties and confusion that arose in settling on a particular type of flow chart, definitions of storage sites and transport processes, and rules for showing linkages among them. The makeup of the flow chart was found to depend heavily on the specific objectives for its use, even though a general form was desired.

The consensus among discussion participants was that flow charts are extremely useful in organizing thoughts about a sediment-routing system and in comparing different landscape units. Such comparisons, however, require that flow charts be developed using a common set of rules and definitions, so that differences in flow charts for different geomorphic systems reflect real geomorphic differences. Guidance for developing a useful flow-chart form could come from other fields, such as hydrology, nutrient and energy cycle modelling for ecosystems, and network theory. Developing common definitions of landscape units and processes requires extensive discussion and a knowledge of what is geomorphically important in a wide variety of environments.

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Summary: Sediment Budget and Routing Studies

Frederick J. Swanson, Richard J. Janda, and Thomas Dunne

ABSTRACT

Sediment budget and routing studies have been useful in dealing with a variety of basic and applied problems over a wide range of scales in time and space. Further research and application is needed to: define and quantify sediment storage; improve knowledge of mechanisms of sediment-transport processes; quantify frequency and magnitude of episodic processes; integrate biological factors into quantitative analysis of sediment budgets and routing; improve knowledge of effects of weathering on sediment routing; and mesh better the computer simulation of sediment routing with field studies of conditions in forested mountain land.

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INTRODUCTION

Studies of sediment budgets and routing have increased understanding of a broad spectrum of geomorphic and ecological problems (Jackli 1957; Rapp 1960; Leopold et al. 1966; Caine 1976; Dietrich and Dunne 1978; Kelsey 1980; Swanson et al., 1982). By sediment budget, we mean the quantitative description of sediment movement through a single landscape unit; sediment routing, is either the computation of sediment movement through a series of units or the more qualitative concepts of sediment movement through a drainage basin. Much early work centered on computing total denudation and assessing the relative importance of individual erosion processes. Other workers have applied sediment budget studies to practical problems associated with the effects of human activities on geomorphic processes and associated landform changes (Kelsey 1980, Reid 1981). Applications of sediment budget and routing analysis in Redwood Creek basin (California) (Kelsey et al. 1981), areas near Mount St. Helens (Washington), and elsewhere deal with a variety of management-related issues, including the persistence of high rates of sediment transport.

The basic ingredients of complete budgets are: identification of storage sites, transport processes, and linkages among them, and the quantification of storage volumes and rates of transport processes. Despite these common elements, papers on sediment budgets published here and elsewhere display marked differences in the time scales considered and the relative emphasis placed on storage and transfer processes. These differences reflect contrasts in objectives and site-specific conditions such as vegetation, land-use history, and dominant erosion process. Of particular concern at this workshop were the distinctive effects of forest vegetation on sediment storage and transport.

Although the utility of sediment budgets has been amply demonstrated, they continue to be little used. Increased application of the sediment-budget studies, even where data are seriously limited, would increase understanding of geomorphic and ecological systems--this volume was compiled to encourage such increased use. Here, we summarize some advantages of the sediment-budget approach over studies focused on individual processes or on sediment-yield data alone, six major themes that recur throughout the papers and workshop discussions, and new and continuing research needs.

RATIONALE FOR MAKING SEDIMENT BUDGET AND ROUTING STUDIES

Enthusiasm and need for quantification of erosion and sediment transport have led to many field measurements and computer simulation models of sediment production on hillslopes and along streams. Monitoring of drainage-basin sediment yield provides an integrated, “black box” view of how sediment output from basins responds to average conditions, fluctuations in weather, and management and other disturbances. Monitoring of hillslope erosion can provide more detailed information on processes than can measuring basin sediment yield alone. This approach, however, has often been weakened by lack of attention to sampling problems and by uncertainties of how particular mechanisms fit into the sequence of processes that transport sediment out of a drainage basin. Measurement of both sediment yield and rates of processes offers little information on the role of temporary storage or the linkage between transport processes.

Some of these problems are reduced by drawing up a conceptual sediment budget or sediment-routing scheme early in the investigation of sediment movement. This requires explicit recognition of how sediment is generated, transferred, and modified during its passage through drainage basins. The initial conceptual model may be only qualitative or approximately quantitative, but it must be based on field work. Dietrich and Dunne (1978), Dietrich et al. (this volume), Lehre (this volume), and Kelsey (this volume) have all stressed the need for careful classification of transport processes and storage sites in the landscape under investigation. This preliminary analysis draws attention to the most important processes and aids the design of appropriate measurement strategies. No single approach to the definition of a sediment budget or routing scheme exists because of the variety of processes, materials, and disturbing factors even in the restricted setting of drainage basins covered by temperate forests.

Field observations of sediment transfer and storage also suggest how the accounting of sediment can be carried out. The investigator is forced to consider how sediment moves between sites and whether errors can result from adding together contributions of sediment to a channel by processes that act in series. An example occurs where soil creep merely supplies sediment to sites of landsliding which then conveys it to a channel. Dietrich and Dunne (1978) have pointed out that adding these two inputs would be double accounting and would overestimate the sediment flux to the channel.

Processes should be classified to help define the temporal and spatial requirements of a sampling scheme. Do the processes operate over extensive areas or in a limited number of restricted sites? Which processes operate persistently and which are episodic? Whether a process is viewed as persistent or episodic in part reflects the time reference of the budget. Most geomorphic measurements have been carried out over too short a time and at too few sites for adequate definition of long-term average sediment yields, their sources, controls, and response to disturbance. Field work necessary for construction of a sediment budget or routing scheme focuses attention on the need for spatial stratification of measurement sites and for lengthening the period of record by means of dendrochronological and other techniques (Brown and Brubaker, this volume).

A sediment budget or routing procedure and attendant assumptions may apply. to a particular time scale only. The procedure of Dietrich and Dunne (1978), for example, is founded in the long-term view of sedimentary petrology and steady-state geomorphology. The steady-state assump-

Table 1—Channel storage in relation to mean annual sediment discharge. Definition of channel storage varies from study to study, but generally includes readily mobilizable material. Note that (storage/annual discharge) is a measure of residence time of sediment in storage in years

Stream (author)	Drainage area	Storage	Annual sediment discharge	Storage - annual discharge
	Square kilometers			
Watershed 10, OR (Swanson et al., 1982)	0.10	510 t (subject to debris torrent)	6.6 t Total particulate transport including episodic debris torrents	77
Average of seven streams in Idaho batholith (Megahan, this volume)	1.27	171 m^3 "behind obstructions"	11 m^3 debris basin accumulation	15
Rock Creek, OR (Dietrich and Dunne 1978)	16.2			
First-order tributaries				1/19 yr
Third-order tributaries				1/231 yr
Main channel, active sediment				1/619 yr
Big Beef Creek, WA (Madej, this volume)	38	49,200 t "active, to depth of scour"	1,000 t bedload	50
Redwood Creek, CA (M. A. Madej, Redwood National Park, personal communication)	720	7,200,000 main channel only	1,860,000 total sediment load	3.9
Otamarahu River, New Zealand (Mosley 1977, cited in Pearce and O'Loughlin 1978)				35-40

1/Residence time for particle entering channel of this order at midpoint of channel segment.

tion is invalid for other time scales, however. Nonsteady-state behavior occurs where significant change in storage takes place, whether as a result of human activities or major storms (which affect geomorphic systems on the scale of years and decades), climatic change (on the 10^3 year scale), or drainage development (on the scale of 10^3 years and longer). Swanson and Fredriksen (this volume), for example, stress the value of not assuming steady-state conditions when examining sediment routing on the time scale of vegetation disturbance and recovery.

The sediment budget and routing approach led Dietrich and Dunne (1978) to consider the relation of weathering to transport of soil entering channels and to grain-size distribution of sediments transported down stream channels. The grain-size distribution of stream sediments is important because it influences channel form, fish-spawning habitat, sorption of nutrients and other chemicals, and rates at which large, short-lived influxes of sediment can be flushed from a system.

MAJOR CONCLUSIONS AND RESEARCH NEEDS

Sediment Storage

Sediment storage is an essential but poorly understood part of the geomorphic system. Geomorphologists have traditionally emphasized transport processes. Storage of sediment, however, is an equally important aspect of long-term movement of material through drainage basins. Total stored sediment, duration of storage at various sites, changes in volume of material stored, and changes in the physical properties of materials while in storage have important implications in analysis of sediment routing.

Quantitative data on sediment storage in channels is meager, but more abundant than information on storage of material on hillslopes. Available quantitative studies of sediment storage in channels in forested areas (table 1) define and measure storage in different ways. Nonetheless, these data indicate that the volume of temporarily stored alluvium is commonly more than 10 times larger than the average annual export of total particulate sediment. Mean residence times are on the order

of decades and centuries. Thus, moderate changes in storage can cause major changes in sediment yield even if sediment supply from hillslopes remains constant.

Rough estimates of mean residence time of soil on hillslopes are several orders of magnitude greater. For a soil loss rate of 100 t/km^2 per year (on the low side of typical rates for mountain land), the mean residence time of a 1-m soil profile is 10,000 years. This is somewhat less than the residence time of soil on hillslopes computed by Dietrich and Dunne (1978) and Kelsey (this volume) for very different terrains.

Changes in sediment storage can drastically affect interpretations of erosional conditions within a drainage basin based on sediment-yield data alone (Janda 1978). The timing and magnitude of erosion of soil and its ultimate delivery as sediment to a downstream point may be very different. Kelsey (1980), Trimble (1981), and others have demonstrated that storage in channels and flood plains may delay and subdue the peak of downstream delivery of sediment introduced from hillslope sources. Conversely, increased peak flows because of altered hillslope hydrology can result in increased erosion and downstream transport of stored sediment without increased hillslope erosion (Park 1977). Management impacts on hydrology or sediment availability can therefore have cumulative effects on sediment routing downstream, an issue of growing concern in many areas of forest-land management.

Residence time of sediment in storage determines the opportunity for stabilization by rooting of vegetation on the scale of years and decades and for changes in size distribution of material by weathering over centuries and millenia. Weathering of deposits in gravel bars, flood plains, and other storage sites facilitates breakdown of sediment, thus changing the relative importance of transport as dissolved, suspended, and bedload (Bradley 1970, Dietrich and Dunne 1978). Effects of weathering are particularly important in tectonically active areas, such as the Pacific Rim--much of which is underlain by mechanically weak rocks. On the time scale of significant weathering, geomorphologists can learn much through application of the techniques developed by Quaternary stratigraphers and sedimentologists (Birkeland 1974, Tonkin et al. 1981).

Erosion Processes—Mechanisms and Linkages

The mechanics of erosion processes and their controls are not well understood. These problems limit efforts to model movement of sediment through drainage basins. Several examples of these limitations sparked vigorous discussion at the workshop. One example is the widespread application of infinite slope assumptions to stability analysis of shallow debris slides, despite knowledge that many sites prone to debris sliding may not be well represented in hydrologic and other respects by infinite slope assumptions (Pierson 1980). This is true for “hollow” (Dietrich and Dunne 1978) and “swale” (Lehre, this volume) types of failure sites, which appear to be essentially the same and are hereafter referred to as hollow/swale sites.

Mechanics of surface-erosion processes in steep forest land in areas with low to moderate intensities of rainfall are also poorly understood, as evidenced by continued interest in applying to steeplands the Universal Soil Loss Equation (USLE) developed empirically by Wischmeier and Smith (1955) in lowland environments. The USLE was developed to estimate surface erosion by rainsplash and sheetwash on gradients of less than 20 percent. Overland flow is rare in forested landscapes. The surface-erosion processes that do operate, such as dry ravel and splash, may have very different relationships between transfer rate and slope length, rainfall characteristics, soil characteristics, and gradient than those described by the USLE.

Analysis of individual erosion processes in their overall geomorphic context is also critical. The rate or frequency of one process may be closely linked to the rates of other processes. Long-term erosion by debris slides, for example, may be limited by recharge of slide-prone hollow/swale sites by soil creep, root throw, and other processes. Thus measuring soil creep into hollow/swale sites would help in estimating rates of filling of slide-prone portions of the landscape. These data could then be used to judge effects of management practices on refilling rates as well as on initiation of debris slides. Similarly, progressive downslope movement of streamside earthflows may temporarily buttress the toe of the slope, impeding further movement. Subsequent stream erosion of the earthflow toe can remove support and accelerate movement, hence interpretations of earthflow movement rates should consider recent stream history.

Sediment transported as suspended load or bedload has been the subject of extensive, sophisticated analyses by hydraulic and civil engineers. Application of their equations in sediment-routing studies in steep forest lands is difficult, however, because sediment transport there is commonly limited by the rate of sediment supply from hillslopes, fans, and the streambed below an armor layer. These equations are not well suited for dealing with the coarse, poorly sorted sediment and large woody debris that forms the complex roughness elements typical of forested mountain streams. Channel form and pattern in these environments may be controlled by vegetation, bedrock, and hillslope mass movements rather than channel hydraulics and sediment properties that predominate in lowland streams.

Problems Posed by Episodic Processes

Many sediment-transport processes, such as creep and bedload transport in sand channels, are persistently active, although at widely varying rates. Debris slides and other processes are episodically active for only short periods. The distinction between persistent and episodic processes are muted in dealing with periods much longer than the time between episodes of activity. Geomorphologists have had a long-standing interest in the importance of episodic processes in longterm transfer of material and landscape sculpture (e.g., Wolman and Miller 1960). Episodic processes are generally considered to be the dominant mode of sediment

transport in steep forest land, but no concensus exists on how to deal with them quantitatively in studies of sediment budgets and routing. Estimating sediment transport by episodic processes is an essential but difficult part of computing a sediment budget. For example, alternative approaches to estimating debris-slide erosion have been proposed. Dietrich and Dunne (1978) and Dietrich et al. (this volume) attempt to quantify frequency of failure at a particular site; others (Swanson et al., in press; Lehre, this volume) apply a geographically broader inventory method of computing erosion per unit area and time.

An important difficulty in dealing with episodic events is evaluating the interaction of successive major disturbances within a drainage basin (Be van 1981; Kelsey, discussion group report, this volume). The approach to magnitude-frequency analysis proposed by Wolman and Miller (1960) assumes independence of successive events, but studies in a variety of areas indicate that major floods may change the quantity of sediment available for transport (Brown and Ritter 1971) and channel conditions (Ritter 1974, Baker 1977) encountered by subsequent events.

"Geomorphic recovery" after major disturbances is an essential part of judging effects of episodic events on sediment yield, but it is a concept interpreted in many ways. Wolman and Gerson (1980) discuss channel recovery in terms of return to predisturbance geometry, but judge recovery of landslide scars on the basis of degree of revegetation. Geomorphic recovery from a sediment-routing standpoint could be viewed as the refilling of storage sites and their readiness to fail again. The rate of such recovery for landslide scars varies greatly depending on the scale of the feature. Massive slope failures of essentially entire, first-order drainage basins (Kelsey, this volume) recover by rock weathering and soil formation. A much smaller proportion of a drainage basin fails in hollow/swale sites. Hollow/swale sites are recharged by transport of colluvium from adjacent areas, so their recovery is likely to be more rapid than that of the more massive failures where recharge is limited by weathering rate. Over several episodes of sliding, however, weathering must be the rate-limiting process in both systems.

Clearly the long-term significance of episodic events in sediment budgets and routing systems is difficult to quantify because the meager record of past events is dominated by the most recent one or two and the longer term sequence and timing of past events is important. Here again, the geomorphologist may have to rely on the tools of the dendrochronologist and Quaternary stratigrapher to place limits on the timing of past events.

Biotic Factors in Sediment Routing

Biological parts of landscape systems contribute important components of sediment, act as agents of sediment transfer, form sediment-storage structures, and record forest and geomorphic history. Biological influences on geomorphology are particularly well developed in forest vegetation--reflecting, in part, the massive size and relatively slow decomposition rate of woody material in many forest environments.

The role of organic matter as a soil component is better understood than its role as sediment. Organic matter in soil is an essential part of both nutrient cycling and mineral weathering, which strongly influences soil stability. Sediment-transport studies by hydrologists and geomorphologists typically disregard the importance of organic matter in sediment both in deposits and in transit, but ecological research on drainage basins has emphasized the importance of streams in exporting organic matter from ecosystems (Arnett 1978). Organic matter may comprise a large proportion of sediment in transport, thus potentially complicating sediment sampling and confounding interpretation of the data (Arnett 1978). Sedimentologists have long been interested in the alteration of sediment characteristics during transport through a drainage basin, but interest among geomorphologists in extending these concepts to soilsediment relations is rather new (Diet rich and Dunne 1978). Aquatic ecologists are becoming increasingly interested in the parallel issue of variation in the quantity and type of organic matter transported or temporarily stored throughout a drainage network (Naiman and Sedell 1979, 1980). Interactions between dissolved and fine particulate organic and inorganic matter (Jackson et al. 1978) present problems for sampling, distinguishing, and interpreting dissolved and suspended sediment yield from a sediment-routing standpoint. These interactions affect the fate and persistence of pollutants in ecosystems.

Plants and animals also affect soil and sediment movement and temporary storage in a variety of ways, many of which are described in papers in this volume. Effects of fauna and flora on individual erosion processes have been quantified in some detail, ranging from Darwin's (1881) work on erosion by earthworms to recent studies of tree-root effects on the potential for shallow mass movements (O'Loughlin 1974, Ziemer 1981). Where vegetation decreases the effectiveness of sediment-transport processes, it enhances sediment storage and increases the residence time of sediment by dissipating the energy of sedimenttransporting media and by holding sediment in place. Large woody debris in streams and on hillslopes and tree roots are examples of biological materials that retain sediment at temporary storage sites.

The multiple, cumulative effects of vegetation on sediment routing through small (less than 100 ha) drainage basins have been demonstrated by studies in both forested and disturbed conditions (Bormann et al. 1969, 1974; Fredriksen 1970; Swanson et al., 1982; and others).

Dendrochronology may also be an integral part of sediment-routing studies by placing limits on the date of an event, rate of a process, and residence time of material in storage (Alestalo 1971; Schroder 1978; Hupp and Sigafoos, this volume; Brown, this volume; and others). Furthermord, general aspects of vegetation history can be interpreted by dendrochronologic analysis of events, such as wind storms and wildfire, and by palynological analysis of vegetation

response to change in climate. This knowledge affects extrapolation of sediment-budget information to periods longer than those covered by direct observational data.

Interest in these long-term interactions between biotic and geomorphic systems goes beyond basic, academic concerns, and forms a foundation for interpreting and predicting impacts of management activities on forest ecosystems and landscapes. The successional development of ecosystems after disturbance determines the pace of recovery of vegetative control of sediment movement and storage. Likens and Bilby (this volume), Swanson et al. (1982), and others have argued that analysis of geomorphic systems should be placed in the context of vegetative succession and disturbance history.

Weathering

Study of weathering and its effect on availability of plant nutrients, soil development, and soil stratigraphy is advanced compared with knowledge of weathering as a regulator of sediment routing. Weathering affects the availability of material for transport and the types and rates of transport processes operating in an area (Dietrich and Dunne 1978). Geological material enters the sedimentrouting system by weathering of bedrock, which makes it available for transport.

Dietrich and Dunne (1978) suggest that weathering is a critical rate-limiting factor in the longterm movement of sediment in many mountain environments. This may be particularly true in steeplands with shallow soils over competent bedrock; examples are the Oregon Coast Ranges (Dietrich and Dunne 1978) and the mountains of Hawaii (Scott and Street 1976). Weathering is less crucial in determining the availability of erodible material where primary sediment sources are deep soils, unconsolidated sediments, or tectonically shattered rock, such as recently glaciated terrain (Madej, this volume) and the tectonically active California Coast Ranges (Kelsey, this volume).

Once material is available for transport, the types and rates of movement depend strongly on soil depth and on physical properties of the material determined by parameters such as grain-size distribution and clay mineralogy (Dietrich and Dunne 1978). Dietrich et al. (this volume) argue that change in soil depth with refilling of "hollows" results in increasing susceptibility of the site to failure by additional debris sliding. Weathering processes and their interaction with biota alter soil cohesion, bulk density, and mechanical properties, consequently controlling the rates of virtually all hillslope transport processes.

Weathering changes material while it is in temporary storage at various sites within a drainage basin. The rates and types of weathering reactions may vary from one storage site to another, depending on characteristics of the local weathering environment, such as hydrology, temperature fluctuations, pH, and oxidation-reduction conditions. Glancy (1971) and others, for example, have noted the break up of pebbles of sedimentary rock on gravel-bar surfaces over a period of months. They suggest that this is a bar-surface phenomenon only, so stones buried at shallow depths within the bar would not undergo this partial conversion from bedrock to suspended-load particle sizes.

The residence time of material in some storage sites stretches to. the time scale of significant weathering and soil-profile development. Workshop participants (Harden et al., this volume) argued that soil stratigraphic techniques could profitably be used to determine residence time of storage sites and sometimes to set limits on the time since the last mass movement at a site.

These few examples indicate that weathering studies have an important, but little used, place in sediment-routing research.

Modeling of Sediment Budgets and Routing

Computer simulation of sediment routing holds great promise for aiding compilation of sediment budgets and for simulating sediment-routing systems in ways useful for predicting system change in response to disturbances. A simulation model provides a rigorous statement of a sedimentrouting system and highlights the kind and quality of field data needed for prediction. Existing simulation models require much more development before they meet this promise, however.

Two types of models were discussed at the workshop: a model by Simons et al. based on physical processes and Rice's Monte Carlo simulation of sediment production in response to a long sequence of fires and rainstorms. Each approach has its benefits and limitations.

Limitations of the model described by Simons et al. and of similar models developed for agricultural lands include: lack of treatment of mass wasting processes that can dominate sediment transport in steep land; uncertainty about the accuracy of some components of the model, such as the use of equations developed for sediment transport in deep stream channels to estimate transport by sheetflow; and the need for calibration of the model against a set of field data to obtain several parameters of the equations. Calibrations include such physically ill-defined concepts as soil "detachment coefficients" for rainfall and overland flow. Finding a set of coefficients that produce a good fit between predicted and observed water and sediment discharge does not necessarily lead to understanding of what is actually happening in the landscape, or even of where most of the sediment originates in a heterogenous landscape. Nor do such fits promote confidence in predictions of the consequences of some disturbance by climate or land use. More field experiments need to be conducted and generalized so that model parameters can be estimated a priori and tested against a few measured outputs. Nevertheless, information organized in such models is useful for developing other models and conducting field experiments to refine them.

Rice proposes the application of Monte Carlo simulation to describe the response of an erosionsedimentation system to random meteorological events that drive the sequence of fires and rainstorms and interactions among them. He questions the utility of process-based mathematical models because of the need for calibration. Particularly in a region where the sediment budget is strongly affected by random phenomena that vary greatly from year to year, the model should be calibrated against a large number of events covering the most important combinations of parameter values. Rice also points out, however, that in addition to frequently discussed difficulties with the structure of geophysical data, empiricalstatistical models suffer the same drawback as process models; the instrumental record is unlikely to contain sufficient important events to include adequate combinations of the most effective factors.

The refinement of studies of sediment budgets requires a combination of: field monitoring of processes coupled with measurements of the controlling variables, so that physically based process models can be developed; field experiments under controlled conditions to extend the range of observations on which the process models are founded; and the development of deterministic models of processes and their linkages. These models can then be used in Monte Carlo simulations, as suggested by Rice. A precedent in hydrology is the recent work of Freeze (1980) on runoff processes.

CONCLUSIONS

In this workshop, we took an interdisciplinary look at the state of knowledge on development and use of sediment budgets and routing studies for forest drainage basins and identified important directions for future research. Most analyses have considered channels as the major storage sites and budgets have included hillslope processes, changes in channel storage, and outflow by fluvial processes. Temporal scales range from one year to millenia, spatial scales from less than a hectare to tens of thousands of square kilometers. Objectives of current studies range from purely basic questions of how geologic materials move through drainage basins to analyses of impact of management practices on sedimentation and a variety of resources.

Central points identified and further research needs are:

Sediment storage is an essential but poorly understood and poorly quantified component of sediment budgets or routing analyses.

- Our ability to conduct field studies and to develop computer simulation models of sediment transport processes is limited by our knowledge of mechanisms of transport and the geomorphic context in which they operate.
- Episodic processes dominate sediment transport in many steep terrains, but theory and quantification of these processes are not well developed, particularly the interactions between successive events.
- Biota play a variety of essential roles in the production, transport, and storage of sediment, but knowledge of biological functions is poorly integrated into quantitative analysis of sediment budgets and routing.
- Weathering affects the availability and properties of sediment, but because significant weathering commonly occurs over long periods relative to traditional studies of processes, weathering has been little studied or used in sediment budget and routing studies.
- Computer simulation modeling is useful for predicting system behavior and for integrating concepts, process mechanisms, and field data. Modeling efforts, however, have not yet dealt with the types of storage sites and erosion processes that dominate in many forested mountain lands.

Advance of knowledge in each of these areas would be facilitated by improving theoretical analyses of processes, accumulation of long-term data sets, and more standardization of procedures and terminology. Economic considerations, in part, are leading to declining support by science managers for collecting long-term data sets, although scientists at the workshop were unanimous in their support of the need for such records. Computer simulation modeling, although a useful way of maximizing the value of field data, does not by itself provide useful surrogate records in geomorphic systems where infrequent events dominate sediment transport and where knowledge of interactions between successive events is weak.

Standardization of procedures and terminology in field and modeling efforts would facilitate future efforts to compare and contrast budgets and routing in diverse geomorphic systems. Efforts to standardize, however, must be tempered by the need to express adequately the sediment routing characteristics of particular terrain, climate, and vegetation types. The inability of the discussion group on use of flow charts in sediment routing studies to develop a single flow chart common to many landscapes reflects the difficulty of balancing details of local knowledge with the general need of achieving a basis for comparing diverse systems.

Use of sediment budget and routing analysis of drainage basins is in its infancy. Continued application of these methods in a variety of environments in studies with diverse objectives attests to increasing recognition of the value of sediment budgets and routing studies.

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Sediment budgets quantify the transport and storage of soil and sediment in drainage basins or smaller landscape units. Studies of sediment routing deal with the overall movement of soil and sediment through a series of landscape units. The 14 papers and S summaries from discussion groups in this volume report results of sediment budget std routing studies conducted principally in forested drainage basins. Papers also deal with sediment routing studies using computer models, physical models, and field observations in nonforest environments.

This work emphasizes methods for judging the relative importance of sediment sources within a basin, the many roles of biological factors in sediment transport and storage, and the importance of recognizing changes of sediment storage within basins when interpreting sediment yield. Sediment budget and routing studies are important tools for both research scientists and land managers.

Keywords: Sedimentation, watershed management, sediment budget, drainage basins, geomorphology.

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