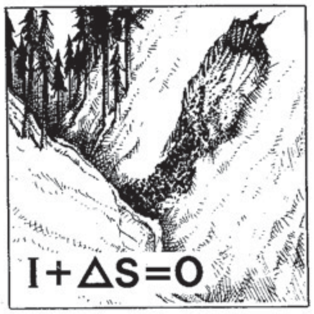

Sediment Routing and Budgets: Implications for Judging Impacts of Forestry Practices

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.

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.

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[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.

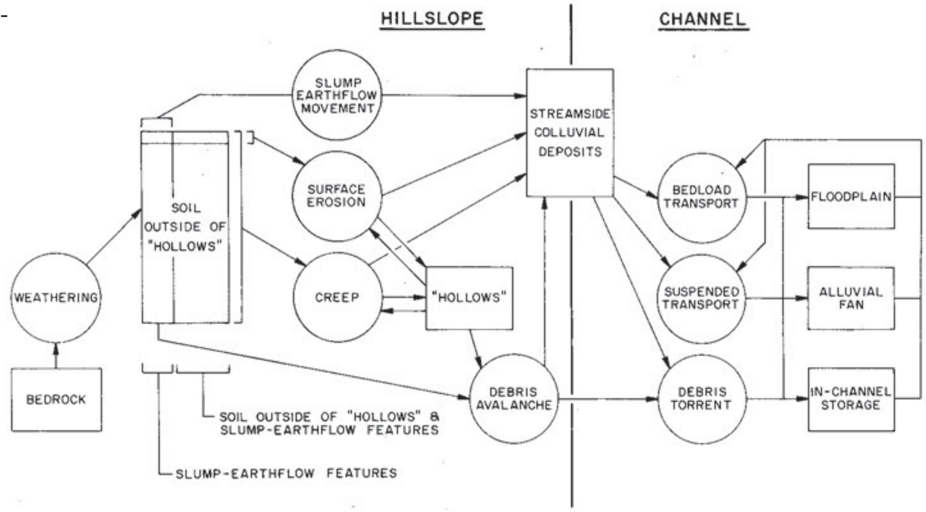

Figure 1—Simplified flow chart of relationships among storage sites (boxes) and transport processes in steep, volcanic terrane in the western Cascades, Oregon.

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 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.

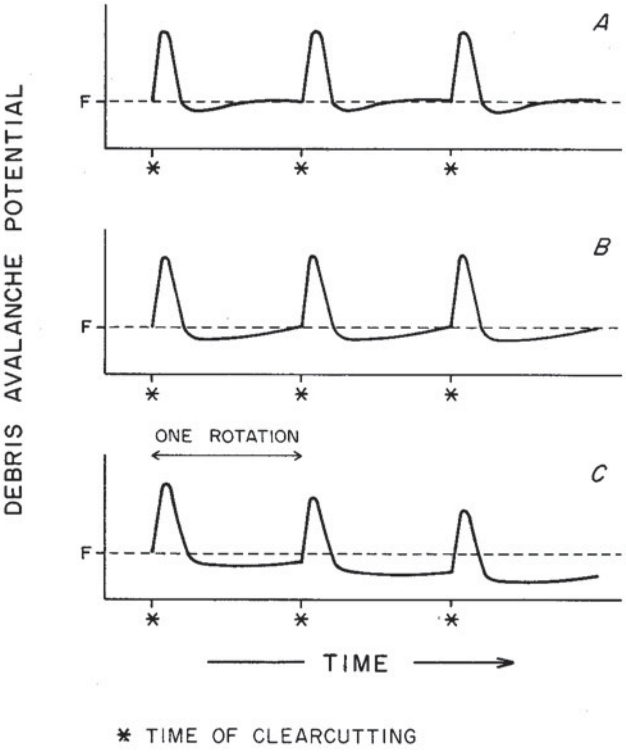

Figure 2—Hypothetical variation in debris-avalanche potential in a landscape with many sites for debris-avalanche failure, only a few of which fail in the first 10 to 15 years after clearcutting.
A. Refilling of failed sites is fast relative to cutting frequency.
B. Refilling occurs in about one rotation.
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.

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-earthflow 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

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[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).

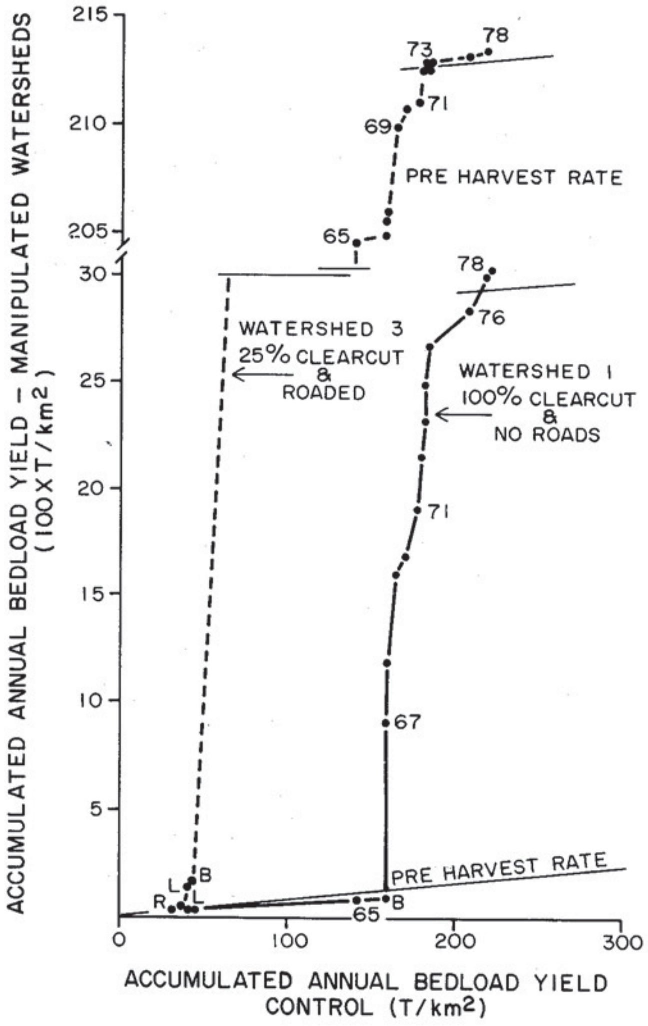

Figure 3—Double mass plot of sediment collected in ponding basins at Watersheds l and 3, H. J. Andrews Experimental Forest. Preharvest rates are based on relationships between manipulated drainage basins and the control established in the predisturbance period. L = year of logging, R = road construction,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