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TIMBER HARVESTING, MASS EROSION, AND STEEPLAND FOREST GEOMORPHOLOGY IN THE PACIFIC NORTHWEST

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INTRODUCTION

Forest operations in mountainous regions of the Pacific Northwest have a major impact on soil-erosion processes. The mountains of the region are youthful, the area has undergone recent tectonic activity, and west of the crest of the Cascades annual precipitation may exceed 375 cm. Consequently, natural erosion rates are high. Heavy forest vegetation and the high infiltration capacity of many of the forest soils protect slopes from surface erosion. The combination of these factors results in mass erosion processes generally being the dominant mechanisms of sediment transport from hillslopes to stream channels. The principal mass erosion processes are slow, downslope movement involving subtle deformation of the soil mantle (creep) and discrete failures, including slow-moving, deep-seated slump–earthflows; rapid, shallow soil and organic debris movement from hillslopes (debris avalanches); and rapid debris movement along downstream channels (debris torrents) (Fig. 1A, B). In many areas, forest vegetation plays an important role in stabilizing slopes and reducing the movement rate and occurrence of these mass erosion processes. When timber is removed from marginally stable slopes, whether by natural processes such as wildfire and wind or by the activities of man, a temporary acceleration of erosion activity is likely.

Accelerated erosion due to forest land management activities may result in reduced productivity of forest soils over sizable portions of affected watersheds, damage to roads, bridges, and other structures, and adverse impacts on the stream environment downstream.

FACTORS CONTROLING MASS EROSION PROCESSES

Geologic, hydrologic, and vegetative factors control the occurrence and relative importance of mass erosion processes. In the Pacific Northwest, areas of clay-rich bedrock and deep, cohesive soils are characterized by dominance of the slow mass movement processes of creep and slump–earthflow; notably in the extensive areas of soft sedimentary rocks of the Klamath Mountains, Oregon, and northern California Coast Range and the volcaniclastic rocks in the Cascade Range. Debris avalanches dominate mass erosion processes in terrain typified by steep slopes, cohesionless soils, and relatively competent bedrock, such as large areas of the coast ranges of Oregon, Washington, British Columbia, and Alaska.

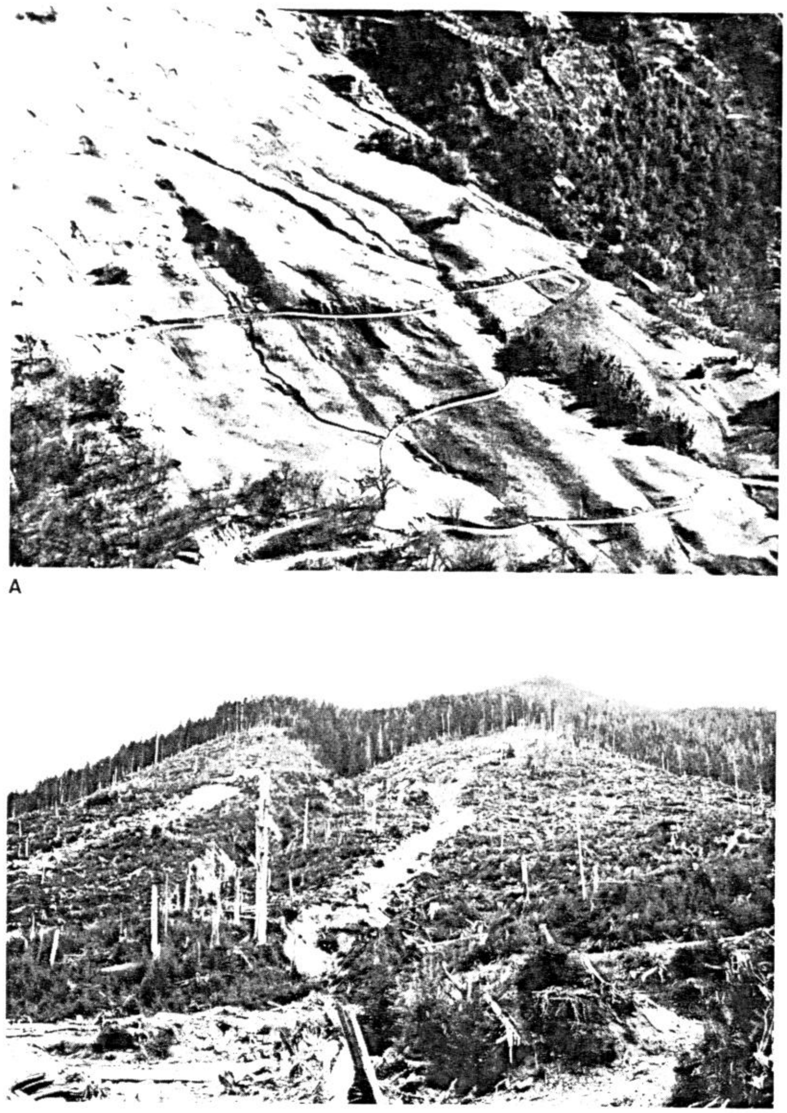


FIGURE 1 *Examples of principal mass erosion processes operating on steep forested slopes in the Pacific Northwest. (A)* creep *and* slump–earthflow *terrain on Franciscan sediments in the upper headwaters of the North Fork, Eel River, northern California. The entire slope is undergoing creep deformation but note the discrete failure (slump–earthflow) marked by the steep headwall scarp at top center and the many small slumps and debris avalanches triggered by surface springs and road construction. (B) debris avalanches developed in shallow soils overlying compact till in southeast Alaska.* Debris torrent *developed below debris avalanche at center of photo due to channeling of debris, undercutting of sideslopes, and addition of material by secondary avalanching into channel.*

Periods of high-intensity precipitation, storm events, and condensation snowmelt commonly trigger or accelerate mass wasting events on steep forest slopes (Bishop and Stevens, 1964; Fredriksen, 1965; Dyrness, 1967; Swanston, 1969). These factors directly influence the moisture content of the soil and determine the presence or absence of active piezometric levels in the subsurface. Moisture content and piezometric level affect the weight of the soil mass and control the development of positive pore pressures. These factors act to reduce the resistance of the soil mass to sliding by either mobilization of clay structures, primarily through adsorption of water into the clay mineral structure, or by reducing the frictional resistance of the soil mass along the failure surface.

Vegetation cover in general helps control the amount of water reaching the soil and the amount held as stored water, largely through a combination of interception and evapotranspiration. In high-rainfall areas of the Pacific Northwest, interception is negligible during large storm events important to mass soil movement (Rothacher, 1963). Evapotranspiration (ET) has its principal effect on soil strength by reducing the length of time that soils remain saturated. ET reduces soil moisture during dry months, reduces the degree of saturation that can result from the first storms of the fall recharge period, and accelerates the rate of soil moisture removal at the end of the wet season. Once the soil is recharged as the wet season begins, the effect of ET loss becomes negligible. Also of importance is the depth of withdrawals by ET. Deep withdrawals may require substantial recharge to satisfy the soil-water deficit, delaying the attainment of saturated soil conditions several months or through a number of major slide-producing events. Shallow soils, on the other hand, will recharge rapidly, possibly attaining saturated conditions and maximum instability during the first major storm. ET has also been linked with at least a temporary increase of shear strength and stability during dry summer months through soil moisture depletion and buildup of soil moisture stress (Gray and Brenner, 1970; Manbeian, 1973; Gray, 1973).

Forests may also moderate the rate at which moisture enters the soil. This is particularly important in the case of warm-rain-on-snow events in which forest vegetation may influence the amount of snow collected on the land surface and the rate of melting, where advection and condensation melting are important (Anderson, 1969).

A crucial factor in the stability of active slopes is the role of plant roots in maintaining the shear strength of soil mantles. Roots add strength to the soil by vertical anchoring through the soil mass into fractures in the bedrock, and by laterally tying the slope together across zones of weakness or instability. In shallow soils, both effects may be important. In deep soils the vertical rooting factor will become negligible, but lateral anchoring may remain important. In some steep areas in the western United States, rooting strength may be the dominant factor in maintaining the slope equilibrium of an otherwise unstable area (Bishop and Stevens, 1964; Croft and Adams, 1950). Zaruba and Mencl (1969) have reported the stabilizing effect of tree roots in landslide areas in Czechoslovakia, and Nakano (1971) reports similar effects from unstable areas in Japan.

IMPACTS OF FOREST-MANAGEMENT ACTIVITIES ON MASS EROSION PROCESSES

Timber-harvesting activities, including clearcutting and road construction, modify factors influencing mass erosion in a variety of ways. Some of the most important impacts of these activities are summarized in Table 1.

TABLE 1 *Impacts of Engineering Activities on Factors That Influence Slope Stability in Steep Forest Lands of the Pacific Northwest*

	Engineering activities[a]		
Factors	Deforestation	Roading	References
I. Hydrologic influences			
A. Water movement by vegetation	Reduce evapotranspiration (–)	Eliminate evapotranspiration (–)	Gray (1970) Brown and Sheu (1975)
B. Surface and subsurface water movement	Alter snowmelt hydrology (– or +)	Alter snowmelt hydrology (– or +) Alter surface drainage network (–) Intercept subsurface water at roadcuts (–)	Anderson (1969) Harr et al. (1975) Megahan (1972)
	Alter concentrations of unstable debris in channels (–)	Alter concentrations of unstable debris in channels (–)	Rothacher (1959) Froehlich (1973)
	Reduce infiltration by ground surface disturbance (–)	Reduce infiltration by roadbed (–)	
II. Physical influences			
A. Vegetation			Swanston (1970)
1. Roots	Reduce rooting strength (–)	Eliminate rooting strength (–)	Nakano (1971)
2. Bole and crown	Reduce medium for transfer of wind stress to soil mantle (+)	Eliminate medium for transfer of wind stress to soil mantle (+)	Swanston (1969)
B. Slope			
1. Slope angle		Increase slope angle at cut and fill slopes (–)	Parizek (1971), O'Loughlin (1972)
2. Mass on slope	Reduce mass of vegetation on slope (+)	Eliminate mass of vegetation on slope (+)	Bishop and Stevens (1964)
		Cut and fill construction redistributes mass of soil and rock on slope (– or +)	O'Loughlin (1972)
C. Soil properties		Reduce compaction and apparent cohesion of soil used as road fill (–)	

[a]Influence that usually increases slope stability denoted by (+); influence that usually decreases stability denoted by (–).

The principal impacts of forest removal by clearcutting are to reduce rooting strength and to alter the hydrologic regime at the site. In Japan, Kitamura and Namba (1966, 1968) have described a period of greatly reduced soil strength attributable to rooting beginning about 3 yr following cutting, when there has been significant decay of root systems, and attaining a minimum strength 15 yr after cutting. Similar loss of roting strength on unstable sites has been reported from coastal Alaska[1] and British Columbia (O'Loughlin, 1974), with minimum rooting strength attained 3 to 5 yr after cutting.

The hydrologic impacts of clearcutting include modification of annual soil-water status and changes in peaks of soil water held in detention storage during periods of storm runoff. Increased peak flows can generate active pore-water pressures, triggering shallow debris avalanches and debris torrents. Reduced ET due to clearcutting results in the soil-water status remaining at higher levels for several months longer than it would under forested conditions (Gray, 1970; Rothacher, 1971). This modification in the soil-water regime may result in prolonged periods of active creep and slump–earthflow movement during a single season or reactivation of dormant terrain. Water-yield studies in experimental watersheds in Oregon (Rothacher, 1971; Harr, 1975) suggest that this effect may continue for more than a decade after cutting.

Timber removal may also increase peaks of soil water by accelerated snowmelt during warm-rain-on-snow conditions (Anderson, 1969). This phenomenon may also increase total surface runoff if rain and snowmelt are synchronized (Rothacher and Glazebrook, 1968).

The principal impacts of road construction are to interrupt the natural balance between the resistance of the soil to failure and the downslope stress of gravity by disturbance of marginally stable slopes and alteration of subsurface and surface-water movement. Disturbance results from careless or improper cutting of marginally stable slopes, poor construction and placement of fills on steep slopes, and improper drainage design. Roads alter the routing of water by interception of surface water at cut slopes and surface drainage from roads and by carrying this excess water through ditches (Megahan, 1972; Harr et al., 1975). Mass erosion commonly occurs where natural and artificial drainage systems are inadequate to handle this excess water.

CREEP

Characteristics

Creep is the slow, downslope movement of the soil mantle in response to gravitational stress. The mechanics of creep have been investigated experimentally and theoretically by a number of workers (Terzaghi, 1953; Goldstein and Ter-Stepanian, 1957; Saito and Uezawa, 1961; Culling, 1963; Haefeli, 1965; Bjerrum, 1967; Carson and Kirkby, 1972; and others). Movement is by quasi-viscous flow, occurring under shear stresses sufficient to produce permanent deformation, but too small to result in discrete failure. Mobilization of the soil mass is primarily by deformation at grain boundaries and within clay mineral structures. Both interstitial and absorbed water appear to contribute to creep movement by opening the structure within and between mineral grains, thereby reducing

[1] Douglas N. Swanston and W. J. Walkotten, tree rooting and soil stability in coastal forests of southeastern Alaska. Study No. FS-NOR-1604:26 on file at PNW Forestry Sciences Laboratory, Juneau, Alaska.

friction within the soil mass. This permits a "remolding" of the clay fraction, transforming it into a slurry, which then lubricates the remaining soil mass. In local areas where shear stresses are great enough, discrete failure may occur, resulting in development of slump–earthflow due to progressive failure of the mantle materials.

Movement Rate and Occurrence

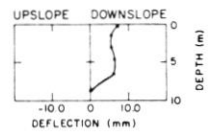
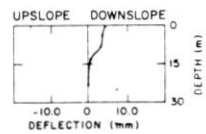
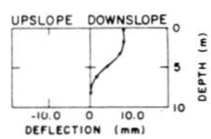
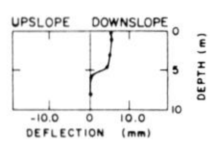
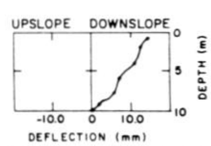
Creep movement generally occurs at rates of a few millimeters to a few centimeters per year. Therefore, long periods of observation and moderately sophisticated instruments are necessary to characterize creep. For these reasons, creep research has been focused on applied engineering problems in major construction activities (e.g., Wilson, 1970), and there have been few studies in the forest environment (Kojan, 1968; Barr and Swanston, 1970; Swanston, unpublished data). Recent measurements of creep rate using an inclinometer in flexible plastic pipe are summarized in Table 2. Also shown are examples of creep velocity profiles through soil masses.

The data shown in Table 2 are preliminary values based on 2 to 3 yr of monitoring and may not adequately represent long-term creep rates for these sites. Significant creep has been observed, however, and some interesting indications of the character of natural creep activity are apparent. Natural creep rates monitored in different geological materials in the western Cascade Range and coast ranges of Oregon and northern California indicate rates of movement between 7.1 and 15.2 mm/yr. The zone of most rapid movement usually occurs at or near the surface, although a zone of maximum displacement is usually present at depths associated either with incipient failure planes or zones of groundwater movement. The depth over which creep is active is quite variable and is largely dependent on parent material origin, degree and depth of weathering, subsurface structure, and soil-water content.

Movement rates are variable, as would be expected under natural conditions, but as a general rule lie within the range of 0 to 15 mm/yr. The maximum measured creep rates in Table 2 average 10.1 mm/yr. At many of the sites, movement takes place primarily during the rainy season when maximum soil-water levels occur (Fig. 2A), although creep may remain constant throughout the year in areas where the water table does not undergo significant seasonal fluctuation (Fig. 2B). This is consistent with Ter-Stepanian's (1963) theoretical analysis, which showed that the downslope creep rate of an inclined soil layer was exponentially related to the piezometric level in the slope.

Creep is generally the most persistent of all mass erosion processes. It operates at varying rates in clayey soils at slope angles of even just a few degrees. Therefore, in small watersheds developed in cohesive materials, creep may be operating over more than 90% of the landscape. The result of this creep activity is a continuing supply of soil material to the stream in the form of encroaching banks and small-scale bank failures. The quantity of soil delivered is quite large, and the supply is continuous from year to year. For example, assuming a creep rate of 10 mm/yr moving mantle material with a dry unit weight of 1,600 kg/m^3 to a stream with a bank approximately 2 m high (conservative estimates for watersheds in pyroclastic materials within the western Cascades Range, Oregon), approximately 64 metric tons/lineal km/yr will be supplied to the channel annually. During high-flow events, this material is carried into the stream by direct water erosion and by undercutting and local bank slumping. Such processes have been demonstrated to be a major contributor to sediment loads of the Eel and Mad rivers in northern

TABLE 2 *Examples of Measured Rates of Natural Creep on Forested Slopes in the Pacific Northwest*

Location	Data source	Parent material	Depth of significant movement (m)	Maximum downslope creep rate: Surface (mm/yr)	Maximum downslope creep rate: Zone of accelerated movement (mm/yr)	Representative creep profile
Coyote Creek South Umpqua River drainage, Cascade Range of Oregon, site C-1	Swanston[a]	Little Butte Volcanic Series: deeply weathered clay-rich andesitic dacitic volcaniclastic rocks	7.3	13.97	10.9	
Blue River drainage—Lookout Creek H. J. Andrews Exp. Forest, Central Cascades of Oregon, site A-1	Swanston[a]	Little Butte Series: (same as above)	5.6	7.9	7.1	
Blue River drainage IBP Experimental Watershed 10, site No. 4	McCorison[b] and Glenn	Little Butte Volcanic Series	0.5	9.0	—	
Baker Creek, Coquille River, Coast Range, Ore., Site B-3	Swanston[a]	Otter Point Formation: highly sheared and altered clay-rich argillite and mudstone	7.3	10.4	10.7	
Bear Creek, Nestucca River, Coast Range, Ore., site N-1	Swanston[a]	Nestucca Formation: deeply weathered pyroclastic rocks and interbedded, shaly siltstones and claystones	15.2	14.9	11.7	
Redwood Creek, Coast Range, northern Calif., site 3-B	Swanston[a]	Kerr Ranch Schist: sheared, deeply weathered clayey schist	2.6	15.2	10.4	

[a]Douglas N. Swanston, unpublished data on file at Forestry Sciences Laboratory, U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Ore.

[b]F. Michael McCorison and J. F. Glenn, data on file at Forestry Sciences Laboratory, U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Ore.

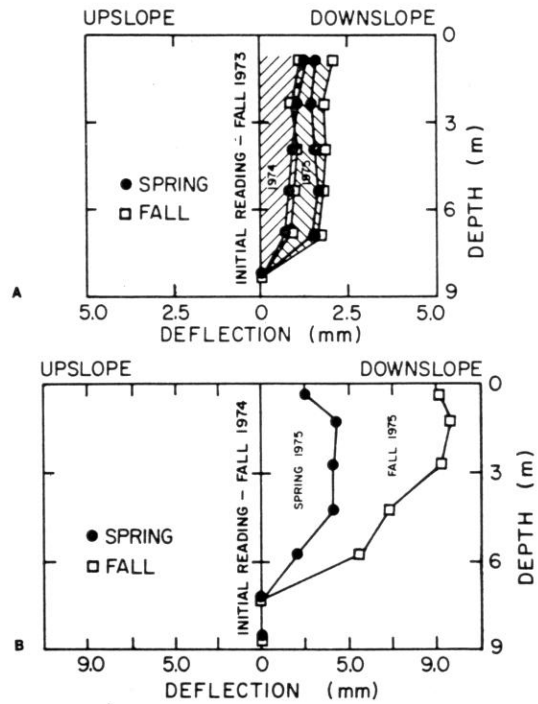


FIGURE 2 *Deformation of inclinometer tubes at two sites in the southern Cascade Range and Coast Range of Oregon. (A) Coyote Creek in the southern Cascade Range showing seasonal variation in movement rate as the result of changing soil-water levels. Note that the difference in readings between spring and fall of each year (dry months) is very small. (B) Baker Creek, Coquille River, Oregon Coast Range, showing constant rate of creep as a result of continual high-water levels.*

California, which have the largest sediment discharges in the world. Anderson (1971) cites estimates that 80 to 85% of the total volume of sediment produced by these two rivers is the result of landslide and streambank erosion. In areas characterized by low-flow conditions supplemented only occasionally by storm flows, creep may fill the channel with soil and debris, and the stream water may be carried by subsurface flow and piping within the channel filling. Only during storm periods is flow great enough to open the channel and remove the debris stored there, resulting in the periodic discharge of excessive sediment loads from affected streams, and occasional torrent flow occurrence where local damming by debris occurs. Such a mechanism dominates in the great majority of smaller watersheds in the creep-dominated areas of the Pacific Northwest.

Impact of Forest Operations

There have been no direct measurements of the impact of harvesting activities on creep rates in the forest environment, mainly because of the long periods of record needed both before and after a disturbance. However, there are a number of indications that creep rates are accelerated by clearcutting and road construction.

Wilson (1970) and others have used inclinometers to verify accelerated creep following modification of slope angle, compaction of fill materials, and redistribution of soil mass at construction sites. The common occurrence of shallow-soil mass movements in these disturbed areas and open tension cracks along roadways at cut and fill slopes suggest that similar features along forest roads are indicators of significantly accelerated creep movement.

On slopes where clearcutting is the principal influence, impact on creep rates may be more subtle, involving modifications of hydrology and root strength. Where creep is a shallow phenomenon (less than 2 to 3 m), the loss of root strength due to clearcutting is likely to be significant. Reduced evapotranspiration following clearcutting (Gray, 1970; Rothacher, 1971) may result in greater duration of the annual period of creep activity and, thereby, increase the annual creep rate.

Brown and Sheu (1975) have developed a mathematical model of creep that accounts for root strength, wind stress on the soil mantle, weight of vegetation, and soil moisture. The model predicts a brief period of increased slope stability following clearcutting due to removal of the weight of vegetation and elimination of wind stress. Thereafter, creep rates are accelerated as soil strength is attenuated by progressive root decay. The net result of the short-term increase and longer-term decrease in slope stability is expected to be an overall increase in creep activity.

SLUMP–EARTHFLOW

Characteristics

In local areas where shear stresses are great enough, discrete failure occurs and slump–earthflow features (Varnes, 1958) are formed. Simple slumping takes place as a rotational movement of a block of earth over a broadly concave slip surface and involves very little breakup of the moving material. Where the moving material slips downslope and is broken up and transported either by a flowage mechanism or by gliding displacement of a series of blocks, the movement is termed slow earthflow (Varnes, 1958). The combined term slump–earthflow is used because many deep-seated mass movements in the Pacific Northwest have slump characteristics in the headwall area and develop earthflow features downslope.

Slump–earthflows have been described by Varnes (1958), Wilson (1970), Colman (1973), Swanson and James (1975), and others. In the Pacific Northwest, these features may range in area from less than 1 hectare to more than several square kilometers. The zone of failure occurs at depths of a few meters up to several tens of meters below the surface. Commonly, there is a slump basin with a headwall scarp at the top of the failure area. Lower ends of earthflows typically run into stream channels. Transfer of earthflow debris to stream channels may take place by shallow, small-scale debris avalanching or by gullying and surface erosion, depending on soil and vegetation conditions. Therefore, the general instability set up by an active slump–earthflow initiates erosion activity by a variety of other processes.

Geologic, vegetative, and hydrologic factors have primary control over slump–earthflow occurrence. Deep, cohesive soils and clay-rich bedrock are especially prone to slump–earthflow failure, particularly where these materials are overlain by hard, competent rock (Wilson, 1970; Swanson and James, 1975). Earthflow movement also appears to be most sensitive to long-term fluctuations in the amount of available soil water (weeks, months, annually) (Wilson, 1970; and others).

Because earthflows are slow moving, deep-seated, poorly drained features, individual storm events probably have much less influence on their movement than on the occurrence of debris avalanches and torrents. Where planes of slump–earthflow failure are more than several meters deep, weight of vegetation and vertical root-anchoring effects are negligible (O'Loughlin, 1974).

Movement Rate and Occurrence

Movement rates of earthflows vary from imperceptibly slow to more than 1 m/day in extreme cases. In parts of the Pacific Northwest, many slump–earthflow areas appear to be presently inactive (Colman, 1973; Swanson and James, 1975). Areas of active movement may be recognized by fresh ground breaks at shear and tension cracks and by tipped and bowed trees. Rates of movement may be monitored directly by repeated surveying of marked points, by inclinometers, and by measuring deflection of roadways and other reference systems. These methods have been used to estimate the rates of earthflow movement shown in Table 3. However, these average rates, stated so simply, are somewhat misleading, because of the great variability of movement rate over both time and space, even for a single slump–earthflow (Colman, 1973; Swanson and James, 1975). Open tension cracks and degree of disturbance of vegetation on slump–earthflows indicate that some part of an earthflow terrane may move rather rapidly, while other areas appear to be temporarily stabilized.

The history of individual slump–earthflows may extend over thousands of years. This is indicated by age estimates based on radiometric dating of included wood, calculation of volume of eroded material, estimated long-term rate of earthflow erosion from site, presence of 7,000-yr-old Mazama ash on preexisting earthflow terrain, and characteristics of drainage development over earthflow surfaces. During this long history, periods of relatively high precipitation or forest removal may increase water content of an earthflow and accelerate movement rate. This downslope movement will decrease the relief at the site until the stability of the mass is increased to a point where the velocity decreases markedly. A period of temporary inactivity will take place until there is reactiviation during a period of high moisture availability, or when the area had been destabilized by stream erosion at the toe of the earthflow.

The areal occurrence of slump–earthflows is mainly determined by bedrock geology. In the Redwood Creek Basin, northern California, Colman (1973) observed that, of the 27.4% of the drainage which is in slumps, earthflows, and older or questionable landslides, a very high percentage of the unstable areas are located in the clay-rich and

TABLE 3 *Observations of Movement Rates of Four Active Earthflows in the Western Cascade Range, Oregon*

Location	Period of record (yr)	Movement rate (cm/yr)	Method of observation
Landes Creek (Sec. 21 T22S R4E)	15	12	Deflection of road
Boone Creek (Sec. 17 T17S R5E)	2	25	Deflection of road
S.W. Cougar Reservoir (Sec. 29 T17S R5E)	2	2.5	Deflection of road
Lookout Creek (Sec. 30 T15S R6E)	1	7	Strain rhombus measurements across active ground breaks

pervasively sheared portions of the Franciscan assemblage of rocks. Areas underlain by schists and other more highly metamorphosed rock are much less prone to deep-seated mass erosion. The areal occurrence of slump–earthflows in volcanic terranes of the Pacific Northwest is also closely linked to bedrock type. In the H. J. Andrews Experimental Forest, western Cascade Range, Oregon, for example, approximately 25.6% of areas underlain by volcaniclastic rocks are included in active and presently inactive slump–earthflows. Less than 1% of areas of basalt and andesite flow rock have undergone slump–earthflow failure.

Impact of Forest Operations

Engineering activities that involve excavation and fills frequently have dramatic impact on slump–earthflow activity (Wilson, 1970). In the forest environment, there are numerous unpublished examples of accelerated or reactivated slump–earthflow movement after forest road construction. Undercutting of toe slopes of earthflows and piling of rock and soil debris on slump blocks are common practices that increase slump–earthflow movement. Stability of such areas is also affected by modification of drainage systems, particularly where road drainage systems route additional water into the slump–earthflow areas. These disturbances may increase movement rates from a few millimeters per year to several tens of centimeters per year or more. Once such areas have been destabilized, they may continue to move at accelerated rates for several years.

Although the impact of clearcutting alone on slump–earthflow movement has not been demonstrated quantitatively, several pieces of evidence suggest that it may be significant. In massive, deep-seated failures, lateral and vertical anchoring of tree-root systems is negligible. However, hydrologic impacts appear to be important. Increased moisture availability due to reduced evapotranspiration will increase the volume of water not utilized by the vegetation. This water is therefore free to pass through the rooting zone to deeper levels of the earthflow. Although the hydrology of slump–earthflows has not yet been investigated, hydrology research on small watersheds suggests that this effect may be substantial. For example, even 9 yr after clearcutting of a small watershed in the H. J. Andrews Experimental Forest, runoff may still exceed by 50 cm the estimated yield for the watershed in a forested condition (Rothacher, 1971; Harr, 1975, pers. comm.). In watersheds with steep slopes and relatively permeable soils, this increased water yield comes as higher base flow during dry months and higher peak and base flow during early and late stages of the wet season (Rothacher, 1971). On poorly drained earthflows, the increased available moisture is likely to be stored in the subsoil for longer periods of time, possibly contributing to increased rate and duration of the wet season earthflow movement. It is not known whether possible clearcutting-related increases in peak discharge of surface and subsurface water influences earthflow movement.

DEBRIS AVALANCHES

Characteristics

Debris avalanches are rapid, shallow-soil mass movements from hillslope areas. Here we use the term "debris avalanche" in a general sense encompassing debris slides, avalanches, and flows, which have been distinguished by Varnes (1958) and others on the basis of increasing water content. From a land-management standpoint, there is little purpose in differentiating failures among these types of shallow hillslope, since the mechanics and controlling and contributing factors are the same, and one frequently leads to another.

Debris avalanches have rather consistent characteristics in the variety of geologic and geomorphic settings extending from northern California to southeast Alaska (Colman, 1973; Morrison, 1975; Dyrness, 1967; Gonsior and Gardner, 1971; Fiksdal, 1974; O'Loughlin, 1972; Bishop and Stevens, 1964; Swanston, 1970). In all these areas, debris avalanches are usually triggered by infrequent, intense storms. For example, in the H. J. Andrews Experimental Forest, Oregon, it has taken storms of a 7-yr return period or greater to initiate debris avalanching in forested areas. Swanston (1969) has correlated storms with a 5-yr return interval with accelerated debris avalanching in coastal Alaska.

Debris avalanches leave scars in the form of spoon-shaped depressions from which less than 10 to more than 10,000 m^3 of soil and organic debris have moved downslope. Average volumes of individual debris avalanches in forested areas in the Pacific Northwest range from about 1,540 to 4,600 m^3.

Several of the factors discussed previously control the occurrence of debris avalanches. Debris-avalanche-prone areas are typified by shallow, noncohesive soils on steep slopes where subsurface water may be concentrated by subtle topography on bedrock or glacial till surfaces. Because debris avalanches are shallow failures, factors such as root strength, anchoring effects, and the transfer of wind stress to the soil mantle, are potentially important influences. Factors that influence antecedent soil moisture conditions and the rate of water supply to the soil by snowmelt and rainfall also have significant control over when and where debris avalanches occur.

Movement Rate and Occurrence

Movement rates of debris avalanches have seldom been measured because of the extreme storm conditions under which they occur. However, based on the few available accounts and the steep slope conditions where debris avalanches occur, their rates of movement probably range as high as 20 m/s.

The rate of occurrence of debris avalanches is controlled by the stability of the landscape and the frequency of storm events severe enough to trigger them. Therefore, the rates of erosion by debris avalanching will vary from one geomorphic–climatic setting to another. Table 4 shows that annual rates of debris-avalanche erosion from forested areas of study sites in Oregon, Washington, and British Columbia range from 11 to 72 $m^3/km^2/yr$. These estimates are based on surveys and measurements of erosion by each debris avalanche occurring in a particular time period (25 yr or longer) over a large area (12 km^2 or larger).

Impact of Forest Operations

The net impact of engineering activities can be estimated by determining the rate of debris-avalanche erosion in clearcut areas and road rights-of-way and comparing these levels of erosion with the erosion rate for forested areas during the same time period. Such an analysis (Table 4) reveals that clearcutting commonly results in acceleration by a factor of 2 to 4 of debris-avalanche erosion. Roads appear to have a much more profound impact on erosion activity. In the four study areas listed in Table 4, road-related debris-avalanche erosion was increased by factors ranging from 25 to 340 times the rate of debris-avalanche erosion in forested areas.

TABLE 4 *Debris-Avalanche Erosion in Forest, Clearcut, and Roaded Areas*

Site	Period of record (yr)	Area (%)	Area (km²)	Number slides	Debris-aval. erosion ($m^3/km^2/yr$)	Rate of debris-avalanche erosion relative to forested areas
Stequaleho Creek, Olympic Peninsula (Fiksdal, 1974)						
Forest	84	79	19.3	25	71.8	× 1.0
Clearcut	6	18	4.4	0	0	0
Road R/W	6	3	0.7	83	11,825	×165
			24.4	108		
Alder Creek, western Cascade Range, Oregon (Morrison, 1975)						
Forest	25	70.5	12.3	7	45.3	× 1.0
Clearcut	15	26.0	4.5	18	117.1	× 2.6
Road R/W	15	3.5	0.6	75	15,565	×344
			17.4	100		
Selected Drainages, Coast Mountains, S.W. British Columbia (O'Loughlin, 1972, and pers. comm.)						
Forest	32	88.9	246.1	29	11.2	× 1.0
Clearcut	32	9.5	26.4	18	24.5	× 2.2
Road R/W	32	1.5	4.2	11	282.5[a]	× 25.2
			276.7	58		
H. J. Andrews Experimental Forest, western Cascade Range, Oregon (Swanson and Dyrness, 1975)						
Forest	25	77.5	49.8	31	35.9	× 1.0
Clearcut	25	19.3	12.4	30	132.2	× 3.7
Road R/W	25	3.2	2.0	69	1,772	× 49
			64.2	130		

[a]Calculated from O'Loughlin (1972, and pers. comm.), assuming that area involving road construction in and outside clearcuts is 16% of area clearcut.

The great variability of the impact of roads reflects not only differences in the natural stability of the landscapes, but also differences in road-location design and construction. For example, the Alder Creek and H. J. Andrews Experimental Forest study sites are in similar climatic, geologic, and geomorphic settings, both areas are managed by a single National Forest, and the level of debris-avalanche erosion in forested areas of the two drainage is similar. However, the level of road-related debris-avalanche erosion in the Alder Creek drainage has been nearly eight times greater than in the Andrews Forest. This contrast in road impact appears to result from higher proportions of midslope road mileage and large, unstable hillslopes in the Alder Creek area, which was managed in a less stringent fashion than the experimental forest (Morrison, 1975).

The duration of impacts of clearcutting and road construction on debris-avalanche erosion is not well documented. Ideally, it would be useful to know how the various factors influencing slope stability, such as rooting strength and soil-moisture storage, each vary as a function of time since disturbance. However, such information is known only in a qualitative sense.

The duration of the net effects of harvesting activities can be deduced from historical records such as those for the H. J. Andrews Experimental Forest, where the history of debris avalanches and associated clearcutting and road construction since 1950 has been documented (Swanson, unpublished data). Based on these observations, clearcut slopes appear to undergo a period of increased susceptibility to debris avalanching for about 12 yr after cutting. However, the strength of the conclusions that can be drawn from a record of only 25 yr is limited by the irregular, episodic nature of both storms and harvesting activities. The history of road-related debris avalanches with respect to road age is further complicated by the disproportionately high levels of natural instability in areas where road access has not yet been developed and by the changing standards of road construction and maintenance. These factors contribute to the very irregular patterns of road age at the time of failure shown in Table 5. It is important to note that roads in the two study areas (Table 5) continued to be very active sites of debris-avalanche erosion for more than 16 yr after initial construction of the road. Therefore, the duration of impact of road construction on erosion by debris avalanches may persist more than twice as long as clearcutting impacts.

The relative impacts of clearcutting and road construction on the total level of accelerated erosion are not clearly reflected in the data in Table 4. For example, in the H. J. Andrews Experimental Forest, roads accelerate debris-avalanche erosion to a much greater extent than clearcutting, but road rights-of-way cover much less area of the forest than do clearcut units. When road and clearcutting impacts are weighted by the area influenced by each activity, the two types of forest engineering activities contribute about equally to the total level of accelerated debris-avalanche erosion (Swanson and Dyrness, 1975).

DEBRIS TORRENTS

Characteristics

Debris torrents involve the rapid movement of water-charged soil, rock, and organic material down steep stream channels. Debris torrents are distinguished from debris

TABLE 5 *History of Debris Avalanches with Respect to Road Age*

Road age (yr)	Percent of debris avalanches	
	H. J. Andrews Exp. Forest[a]	Clearwater Natl. Forest[b]
0–5	57	5
6–10	11	50
11–15	20	34
16+	12	11

[a]Swanson, unpublished data, based on a complete 25-yr history of road construction and 73 debris avalanches.
[b]Day and Megahan, 1975, based on debris avalanches occurring in a single large storm during Jan. 1974.

avalanches because the two types of mass movement events occur over different parts of the landscape; consequently, they have differing implications for the land manager.

Debris torrents typically occur in steep intermittent first- and second-order channels. These events are triggered during extreme discharge events by slides from adjacent hillslopes, which enter a channel and move directly downstream, or by the breakup and mobilization of debris accumulations in the channel. The initial slurry of water and associated debris commonly entrains large quantities of additional inorganic and living and dead organic material from the stream bed and banks. Some torrents are triggered by debris avalanches of less than 100 m^3, but ultimately involve 10,000 m^3 of debris entrained along the track of the torrent. As the torrent moves downstream, hundreds of meters of channel may be scoured to bedrock. When a torrent loses momentum, there is deposition of a tangled mass of large organic debris in a matrix of sediment and fine organic material covering areas up to several hectares.

The main factors controlling the occurrence of debris torrents are the quantity and stability of debris in channels, steepness of channel, stability of adjacent hillslopes, and peak discharge characteristics of the channel. The concentration and stability of debris in channels reflects the history of stream flushing and the health and stage of development of the surrounding timber stand (Froehlich, 1973). The stability of adjacent slopes is dependent on a number of factors described in previous sections on other mass erosion processes. The history of storm flows has a controlling influence over the stability of both soils on hillslopes and debris in stream channels.

Movement Rate and Occurrence

Although debris torrents pose very significant environmental hazards in mountainous areas of the Pacific Northwest, they have received little study (Fredriksen, 1963, 1965; Morrison, 1975; Swanson and Lienkaemper, 1975). Velocities of debris torrents, estimated to be up to several tens of meters per second are known only from verbal and a few written accounts. The occurrence of torrents has been systematically documented in only two small areas of the Pacific Northwest, both in the western Cascade Range of Oregon (Morrison, 1975; Swanson, unpublished data). In these studies, rates of occurrence of debris torrents were observed to be 0.005 and 0.008 events/km^2/yr for forested areas (Table 6). Torrent tracks initiated in forest areas ranged in length from 100 to 2,280 m and averaged 610 m of channel length. Debris avalanches have played a dominant role in triggering 83% of all inventoried torrents. Mobilization of stream debris not immediately related to debris avalanches has been a rather minor factor in initiating debris torrents in these Cascade Range streams. Therefore, the susceptibility of an area to debris avalanching is a direct indicator of the potential for debris torrents.

Impact of Forest Operations

Timber-harvesting activities appear to dramatically accelerate the occurrence of debris torrents by increasing the frequency of debris avalanches. Although it has not been demonstrated, it is also possible that increased concentrations of unstable debris in channels during harvesting (Rothacher, 1959; Froehlich, 1973; Swanson and Lienkaemper, 1975) and possible increased peak discharges (Rothacher, 1973; Harr et al., 1975) may accelerate the frequency of debris torrents.

The relative impacts of these factors and of clearcutting and roads may be assessed by using the frequency of occurrence of debris torrents (events/km^2/yr) in forest areas as an estimate of the natural, background level of debris-torrent activity against which to compare the rates of occurrence attributed to roads and clearcutting (Table 6). In the H. J. Andrews Experimental Forest and the Alder Creek study sites, clearcutting appeared to increase the occurrence of debris torrents by 4.5 and 8.8 times; roads were responsible for increases of 42.5 and 133 times.

Although the quantitative reliability of these estimates of harvesting impacts is limited by the small number of events analyzed, there is clear evidence of marked increase in the frequency of debris torrents as a result of clearcutting and road building. The history of debris avalanches in the two study areas clearly indicates that increased debris torrents are primarily a result of two conditions: debris avalanches trigger most debris torrents (Table 6), and the occurrence of debris avalanches is greatly increased by clearcutting and road construction (Table 4).

The data in Table 6 suggest that clearcutting in the H. J. Andrews Experimental Forest may have had a significant impact on frequency of debris torrents. In several cases, increased concentrations of debris in streams appeared to have contributed to debris-torrent occurrence. The extent of management impact on stream debris concentrations is directly related to how carefully engineering activities are designed and carried out. Under different geomorphic conditions and management practices, logging-related increases of debris in streams may have a more dramatic impact on debris-torrent occurrence.

The close relationship between occurrence of debris avalanches and debris torrents also indicates that the duration and the relative impacts of roads and clearcutting on debris torrents and debris avalanches (discussed previously) will be very similar in timing and magnitude.

RELATIONSHIPS AMONG PROCESSES

Creep, slump–earthflows, debris avalanches, and debris torrents function as primary links in the natural transport of soil material to streams in the Pacific Northwest. The importance of the linkage among these processes and the apparent impact of timber harvesting on rate of movement and sediment yield to streams is illustrated by results from ongoing investigations at Coyote Creek in the South Umpqua Experimental Forest and in the H. J. Andrews Experimental Forest, both in Oregon.

Coyote Creek Erosion Research

The Coyote Creek research area is located approximately 65 km southeast of Roseburg, Oregon, in the western Cascade Range. Four research watersheds have been established on deeply weathered volcaniclastic materials of the Little Butte Formation. Since 1966, both streamflow and sediment discharge have been monitored in these watersheds to determine water yield and nutrient outflow under forested and clearcut conditions.[1] Two access roads were constructed across the upper half of watershed 3 in 1971, and the watershed was logged by clearcutting in 1972.

From 1966 to 1970, total bedload export, estimated from volumes of sediment removed from a weir at the mouth of the watershed, was much less than 0.01 m^3/m of

[1] Study 1602-10, A Study of the Effects of Timber Harvesting on Small Watersheds in the Sugarpine, Douglas-Fir Area of Southwestern Oregon, U.S. Department of Agriculture Forest Service, Forestry Sciences Laboratory, Corvallis, Ore.

TABLE 6 *Characteristics of Debris Torrents with Respect to Debris Avalanches and Landuse Status of Site of Initiation in the H. J. Andrews Experimental Forest (Swanson, Unpublished Data) and Alder Creek Drainage (Morrison, 1975)*

Site	Area of watershed (km^2)	Period of record (yr)	Debris torrents triggered by debris avalanches	Debris torrents with no associated debris avalanche	Total		Rate of debris torrent occurrence relative to forested areas
					No.	No./km^2/yr	
H. J. Andrews Experimental Forest, western Cascade Range, Oregon							
Forest	49.8	25	9	1	10	0.008	X 1.0
Clearcut	12.4	25	5	6	11	0.036	X 4.5
Road	2.0	25	17	—	17	0.340	X 42.0
Total	64.2		31	7	38		
Alder Creek drainage, western Cascade Range, Oregon							
Forest	12.3	90	5	1	6	0.005	X 1.0
Clearcut	4.5	15	2	1	3	0.044	X 8.8
Road	0.6	15	6	—	6	0.667	X 133.4
Total	17.4		13	2	15		

TABLE 7 *Estimated Annual Bedload Export from Clearcut Coyote Creek Watersheds 3 and 4*

Year	Precipitation (cm)	Total bedload volume $(m)^3$	Volume/unit stream length (m^3/m)	Basin condition
1966	120.5	3.9	0.0091	Forested
1967	118.5	0.5	0.0012	Forested
1968	87.6	0.6	0.0014	Forested
1969	110.9	0.2	0.0005	Forested
1970	116.3	1.3	0.0030	Forested
1971	155.7	21.9	0.051	Roads
1972	153.3	69.9[a]	0.163	Clearcut
1973	89.5	3.2	0.0074	Clearcut
1974	156.5	46.4	0.108	Clearcut
1975	122.6	7.7	0.018	Clearcut

[a]Minimum estimate; basin overflowed.

active stream channel/yr (m^3/m/yr) (Table 7; R. L. Fredriksen, pers. comm.). In 1971, sediment yield dramatically increased to approximately 0.05 m^3/m/yr as the result of unusually heavy winter precipitation and increased runoff from the construction of logging access roads. The bedload materials were derived primarily from debris avalanching and rotational slumping along the banks of the stream draining the watershed. In 1972, the first year after the entire watershed was clearcut and also a year of exceptionally heavy rainfall, bedload movement tripled over prelogging and road-building levels to an estimated volume of 0.16 m^3/m/yr. During this period, two new debris avalanches reached the channel from midslope, possibly triggered by reduction of rooting strength of vegetation following the logging process. Part of this overall bedload increase is due to surface erosion of severely scarified soil resulting from piling of slash after logging. However, the greater part can be directly linked to mass movements along the channel.

The major increases in bedload deposition in the weir basins have occurred during storm periods. Reconnaissance of the area and dissection of the weir deposits immediately after a major storm during the winter of 1972 exposed layering of heterogeneous sedimentary materials separated by zones of organic accumulations, which defined short periods or pulses of heavy sediment deposition. Such pulses result from repeated episodes of slumping and debris avalanching into the channel above the weir. A survey of the channel above the weir showed that nine new bank slumps and debris avalanches had occurred as a result of the storm, two of which were large enough to provide the volumes of material necessary to fill the weir basin (approximately 5.4 m^3 each). After 1972, bedload yields have been much lower, but still substantially above prelogging levels. This reflects accelerated bank erosion and removal of stream-stored sediment due to increased peak flows. A detailed survey of the watershed has since revealed over 50 sites of active bank slumping and debris avalanching along the active stream channel, with volumes ranging from 5.6 to 350 m^3. Much of this material moved into the channel, diverting it or causing water to flow beneath the surface. At least 12 debris dams have blocked the channel, leading to temporary storage of from 45 to 1,340 m^3 of alluvium, soil, and organic debris behind each dam. In 1974, the total volume of material available for stream transport was estimated to be 3,100 m^3. Of this, 1,090 m^3 was stored as slump blocks and 2,010 m^3 was stored behind debris dams.

In addition, quantitative creep measurements in the soil and deeply weathered volcaniclastic rocks in the lower half of the watershed indicate creep of the soil in the zone of maximum movement of approximately 10.9 mm/yr, with much of the movement taking place along a narrow zone of weakness at a depth of approximately 8.2 m (Table 2). Since the banks in the watershed average at least 1 m in height, soil material is supplied to the stream channel in the lower part of the watershed at annual rates of 0.02 m^3/m of active channel. There are approximately 430 m of active stream channel in watershed 3. Thus, approximately 8.6 m^3 of soil are made available for stream transport annually by creep movement. The average annual yield since 1972 has been 31.8 m^3/yr. This suggests that about 27% of the annual yield is being supplied by creep processes. The remainder is supplied by active slump–earthflows, surface erosion, and debris avalanching, or derived from stored channel deposits.

H. J. Andrews Experimental Forest

The H. J. Andrews Experimental Forest is located in the western Cascade Range of Oregon in an area characterized by lava flow and volcaniclastic bedrock (Swanson and James, 1975), average annual precipitation of 230 cm, and Douglas fir–western hemlock forest vegetation (Franklin and Dyrness, 1973). Erosion research in the forest has been focussed on two scales: (1) studies in small watersheds (less than 110 hectares) involving continuous monitoring of bedload and suspended sediment outflow since 1956 (Fredriksen, 1963, 1965, 1970), and (2) mapping and historical analysis of slump–earthflows, debris avalanches, and debris torrents throughout the forest (Dyrness, 1967; Swanson and James, 1975).

The history of mass erosion in the small watersheds and the entire experimental forest reveals the close interactions among the various mass erosion processes. As shown diagramatically in Figure 3, areas of creep and slump–earthflow activity may overlap, and these two processes contribute to the instability of areas that ultimately fail by debris avalanching. Debris avalanches, in turn, are dominant initiators of debris torrents.

Creep and slump–earthflow processes are interrelated in at least two senses. Creep deformation is thought to be a common precursor of slump–earthflows, occurring where strain in the form of creep has exceeded the shear strength of soil and rock material. Even where discrete failure has occurred and slump–earthflow movement has begun, superimposed creep deformation is likely to occur in the earthflow material. In one slump–earthflow terrain that is moving at the rate of about 5 cm/yr (Lookout Creek earthflow, Table 3), creep deformation within a single slump block of earthflow material has been measured at 7 mm/yr using an inclinometer tube.

Active slump–earthflow movement, which extends over only 3.3% of the entire forest, appears to have contributed to the instability leading to nearly 40% of the total volume of debris-avalanche erosion from forested areas in the past 25 yr. Slightly more than half of this earthflow generated erosion by debris avalanches occurred in streamside areas where earthflow movement constricted channels, and subsequent streambank cutting has led to rapid, shallow-soil mass movements. Much of the remaining debris-avalanche erosion in undisturbed areas has occurred in steep midslope areas where creep activity is an important destabilizing factor.

These close relationships among mass and fluvial erosion processes suggest that, if one

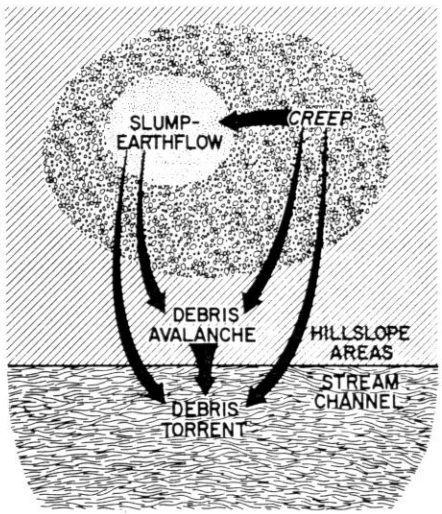


FIGURE 3 *Relationships among mass erosion processes. Arrows point from a process that sets up instability leading to failure by the process at head of the arrow. Width of arrows is a rough indication of degree of influence based on studies in the H. J. Andrews Experimental Forest.*

process is accelerated, the others may also be. Available data are insufficient to demonstrate the extent of impact of timber-harvesting activities on creep and slump–earthflow erosion in the H. J. Andrews Experimental Forest. However, in areas that have been clearcut and where roads have been built, debris-avalanche erosion has been increased by about five times (Swanson and Dyrness, 1975). This might be viewed as a reflection of accelerated creep and slump–earthflow activity in disturbed areas. Increased frequency of occurrence of debris avalanches also has resulted in a dramatic increase in debris torrents (Table 6).

CONCLUSIONS

Creep, slump–earthflows, debris avalanches, and debris torrents function as primary links in the natural transport of soil material to streams in the Pacific Northwest.

In areas characterized by deeply weathered, clay-rich mantle materials, creep movement may range as high as 15 mm/yr. Locally, where strain buildup causes discrete failure and the development of progressive slump–earthflows, transport rates of material to the stream may increase by several orders of magnitude. In areas characterized by steep slopes, shallow, coarse-grained mantle materials and steep, incised drainages, discrete failures producing debris avalanches and debris torrents transport large volumes of material to the stream at rates as high as 20 m/s.

Timber-harvesting operations, particularly clearcutting and road construction, accelerate these processes, the former by destroying the stabilizing influence of vegetation cover and altering the hydrologic regime of the site, the latter by interrupting the balanced strength–stress relationships existing under natural conditions by cut and fill activities, poor construction of fills, and alteration of surface and subsurface water movement.

ACKNOWLEDGMENTS

The work reported in this paper was supported in part by National Science Foundation Grant No. BMS74-20744 to the Coniferous Forest Biome, Ecosystem Analysis

Studies, U.S./International Biological Program. This is contribution no. 216 from the Coniferous Forest Biome.

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GPO 997-172