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Material Transfer in a Western Oregon Forested Watershed

F. J. Swanson, R. L. Fredriksen, and *F. M. McCorison*

INTRODUCTION

Abiotic transfer of organic and inorganic materials by a diverse family of processes is an essential part of all natural, large-scale ecosystems. Physical processes of material transfer are particularly important in the coniferous forest biome, which contains many geologically youthful and geomorphically active landscapes. High-relief, steep hillslope and channel gradients, dense vegetation, massive trees, and heavy precipitation result in a complex relationship among material transfer processes and vegetation.

In a strict sense, material transfer involves erosion, transport, and deposition. This is equivalent to current usage of the term "sedimentation," which geologists and engineers use to describe transfer of predominantly inorganic material. In a system with significant depositional sites, material transfer includes routing of material through a variety of storage compartments. In this study, which deals mainly with a small, steep watershed where storage opportunities are limited, we emphasize annual material transfer rates and roles of vegetation but do not attempt to quantify deposition and storage.

Material transfer has several important roles in the functioning of forest-stream ecosystems. It is an important mechanism for nutrient redistribution and particularly nutrient export from ecosystems. Erosion and deposition create landforms that offer contrasting habitat opportunities for terrestrial and aquatic organisms on a variety of temporal and spatial scales. Erosion may also determine rates and patterns of succession following or during either erosion disturbances (for example, landslide) or disturbance of vegetation alone (for example, wildfire or insect infestation). These effects may be localized to the scales of root-throw mounds and landslide scars (generally < 2000 m^2) or they may extend over broad areas covering many hectares.

There is also a variety of ways in which vegetation regulates rates of erosion processes. These influences of vegetation may result in reduced erosion by the effects of ground cover and rooting strength, or in increased erosion, as in the case of trees serving as a medium for transfer of wind stress to the soil mantle

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The great temporal and spatial variability of erosion processes operating on a single landscape and their complex relationships with vegetation have discouraged attempts to quantify erosion on a process-by-process basis in temperate forest ecosystems. Most comprehensive erosion research has been restricted to semiarid lands (Leopold et al. 1966) and alpine and subalpine environments (Jäckli 1957; Rapp 1960; Benedict 1970; Marchand 1971, 1974; Caine 1976). Temperate forest geomorphology was studied on a broad scale in the central Appalachians (Hack and Goodlett 1960), in the Redwood Creek basin, northern California (Janda et al. 1975), and in a drainage basin on the Oregon coast (Dietrich and Dunne 1978). Numerous studies have dealt with material transfer at the scales of individual processes and small watersheds. Recent work on material transfer in forest ecosystems has centered on elemental and particulate matter input/output budgets for small watersheds (Bormann et al. 1969, 1974; Cleaves et al. 1970; Fredriksen 1970, 1971, 1972, 1975; Likens et al. 1977). In none of these small watershed studies was material transfer examined at the process level over an entire watershed.

The purpose of this chapter is to describe the nature of material transfer in a coniferous forest stream ecosystem in terms of: (1) characteristics of the important transfer processes; (2) relations among them; (3) transfer process/vegetation relations; (4) the relative importance of individual processes and process groupings; and (5) the effects of vegetation disturbance on material transfer in a historical context

DEFINITION OF PROCESSES

Material transfer processes operating in a watershed are broadly grouped into those affecting hillslopes and those operating in stream channels (Figure 8.1). The hillslope processes supply dissolved and particulate organic and inorganic material to the channel, where channel processes take over to break down the material and transport it downstream and out of the watershed. Significant transfer processes both on hillslopes and in channels include infrequent, localized, high-magnitude events and continuous, widely distributed, low-magnitude processes (Table 8.1).

Hillslope Processes

Solution transport results from leaching from vegetation, soil, and weathering bedrock or input from atmospheric sources and occurs in the dissolved state in subsurface water or, rarely, as overland flow. *Litterfall* is the transfer of organic matter as the final step in the sequence of events: nutrient uptake by roots, translocation to and incorporation in aboveground biomass, abscission
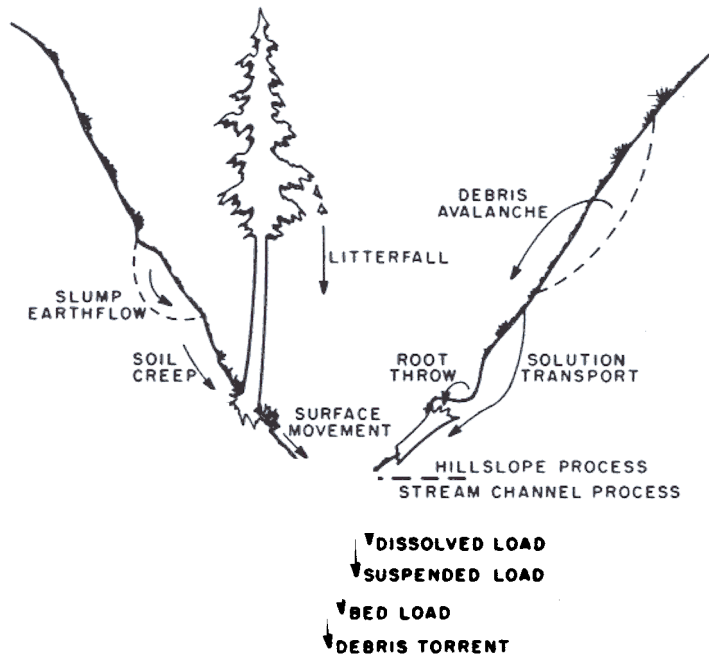
FIGURE 8.1   *Processes that transfer organic and inorganic material in a steep forest watershed ecosystem.*

or breakage, litterfall fo the forest floor or stream. In steep terrain, downhill lean of large trees and canopy closure over small streams result in a net downslope displacement of organic matter.

Surface erosion is the particle-by-particle transfer of material over the ground surface by overland flow, raindrop impact, and ice- and snow-induced particle movement and dry ravel, which occurs during dry periods (Anderson et al. 1959). *Creep* is here considered "continuous" creep (Terzaghi 1950); that is, slow, downslope deformation of soil and weathered bedrock. This is a more restrictive definition than that applied by Leopold et al. (1964) and others who include root throw, needle ice, and other processes as part of creep. *Root throw* occurs as movement of organic and inorganic matter by the uprooting and downhill sliding of trees. *Debris avalanches* are rapid, shallow (generally one- to two-meter soil depth) soil mass movements. *Slump and earthflow* are slow, deep-seated (generally five- to ten-meter depth to failure plane) rotational (slump) and translational (earthflow) displacements of soil, rock, and covering vegetation.

TABLE 8.1   *Material transfer process characteristics for watershed 10 in old-growth forest condition.*

Process	Downslope movement rate*	Frequency	Watershed area influenced	Landforms
Hillslope processes				
Solution		continuous	total	
Litterfall		continuous, seasonal	total	
Surface erosion	1	continuous	total	small terracettes
Creep	2	seasonal	total	
Root throw	3	~1/yr	0.10%*	pit & mound topography
Debris avalanche	4	~1/370 yr	1 to 2%*	shallow, linear down-slope depressions
Slump/earthflow	5'	seasonal'	5 to 8%	scraps, benches
Channel processes				
Solution	3	continuous	1%	
Suspension	3	continuous, storm	~1%	
Bedload	3	storm	~1%	channel bedforms
Debris torrent	4	~1/580 yr	~1%	incised, U-shaped channel cross section

*1 = cm to m/yr, 2 = mm/yr, 3 = m/s, 4 = 10 m/s, 5 = mm to cm/yr.
*Area influenced by one event.
'Inactive in past century in watershed 10.

Channel Processes

Solution transport is movement of material dissolved in stream water. *Suspended sediment transport* is movement of material in colloidal to sand size carried in suspension in flowing water. *Bedload transport* is movement of material approximately coarse sand size and larger by tractive forces imparted by streamflow. *Debris torrent* is the rapid, turbulent movement down stream channels of masses that may exceed 10,000 m³ of soil, alluvium, and living and dead organic matter. Whole trees may be included. *Streambank erosion* occurs as lateral cutting by a stream as it entrains material such as older alluvium or colluvium moved to the streamside area by creep, surface erosion, or other processes.
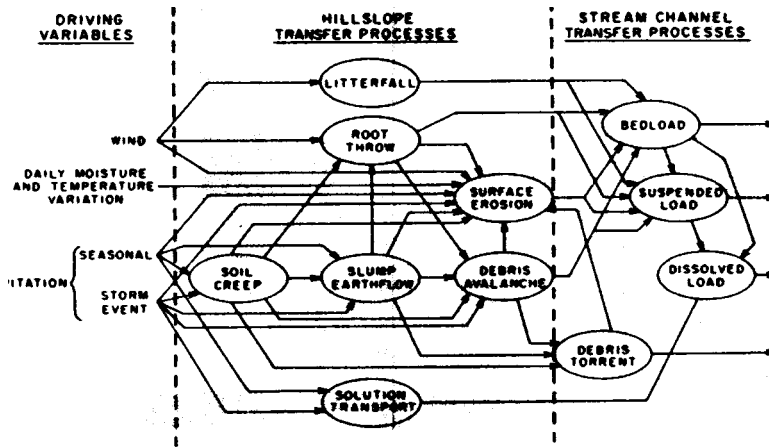
Relations Among Processes

The movement of a single particle of material through a watershed is accomplished by a series of steps involving numerous material transfer process-

es. There are in-series, or chain-reaction, relations among processes and there may be superposition of processes operating simultaneously on a particular piece of material. Principal driving variables and sequential relations among erosion processes are shown in Figure 8.2.

Possible types of sequential interactions are varied. Surface erosion rate may be increased by other processes such as root throw and debris avalanche, which expose bare mineral soil and/or locally increase slope steepness. Debris avalanches may be triggered by root throw, and debris avalanche probability is increased by local slope steepening in response to creep, slump, and earthflow activity (Figure 8.2). Probability of root throw is increased by the tipping of trees by creep, slump, and earthflow activity. Creep may be a precursor of debris avalanche, slump, and earthflow movement (Terzaghi 1950), because when strain by creep deformation exceeds a threshold value, discrete, macroscopic failure occurs and translocational or rotational displacement begins.

Hillslope processes supply material to the channel, making it available for transport by channel processes. In the case of debris torrents the debris avalanche, a hillslope process, is a principal triggering mechanism of the channel process. Within the stream environment, chemical and physical processes break down larger particles to smaller ones, and thereby change the relative importance of bed, suspended, and dissolved modes of transport.

In addition to sequential relations, processes work together. A typical column of soil on a steep, forested slope is likely to experience surface erosion, creep, solution transport, and nutrient uptake/litterfall processes simultaneously. The same block of soil may also be subject to slump or earthflow movement.

FIGURE 8.2 *Relations among mass transfer processes and principal driving variables. Arrows indicate that one process influences another by supplying material for transfer or creating instability that culminates in the occurrence of the second process.*

Veg. Recovery 80-100 yrs = 1 Root Harvest cycle

Logging Control = Catastrophic Removal = Disturbance = Clear cut

Influences of Vegetation on Material Transfer

Vegetation factors regulate rates of transfer processes in a variety of ways (Table 8.2). These factors may either increase or decrease the rate of continuous processes or the probability of episodic events. Knowledge of vegetation-transfer process relations ranges from the obvious (for example, aboveground biomass is the source of litterfall) to the speculative (for example, the effect of windshaking of trees on creep rate). Relations in Table 8.2 are a summary based on inference, direct field observation, modeling studies, and experimentation by many workers.

The mass of living and dead vegetation on hillslopes affects the probability of or rate of hillslope mass erosion by increasing the downslope component of mass, thereby increasing the tendency for movement, and increasing the effective force perpendicular to the slope, which increases friction within the soil mass and decreases movement potential. Although these forces affect slope stability in opposite senses, their net effect is generally believed to increase

TABLE 8.2 *Roles of vegetation in regulating hillslope transfer process rates.*

Vegetation component and fraction	Solution	Litter-fall	Surface erosion	Creep	Root throw	Debris avalanche	Slump/ earthflow
Total biomass							
Loading of slope	0	0	0	+	0	+	-,0,+
Living vegetation							
Water uptake	+	0	0	--	0	0	--
Nutrient uptake	---	0	0	0	0	0	0
Regulation of snow- melt hydrology	0	0	0	-,0,+	0	++,0,--	+,0,-
Aboveground biomass							
Medium for transfer of wind stress	0	0	0	0,+	+++	++	0,+
Source of litterfall	0	+++	0	0	0	0	0
Roots							
Vertical anchoring	0	0	0				0
Lateral anchoring	0	0	0				
Living & dead groundcover							
Surface obstruction	0	0		0	0	0	0

Note: Vegetation function: increases (+) or decreases (-) transfer process rate.
Significance of vegetation function: questionable or slight (+,-), significant (++,--), substantial (+++,---).

mass movement potential on slopes steeper than 30° (Bishop and Stevens 1964; Swanston 1970; D. H. Gray, pers. comm.). The magnitude of this effect differs as a function of many variables, the principal one being soil depth.

Living vegetation takes up water and nutrients and regulates snow accumulation and melt. Evapotranspiration by plants decreases annual water yield from a watershed (for example, Harr 1976) and shortens the annual period of high soil moisture conditions (Gray 1970). Reduced water yield may decrease solution export from a watershed, and decreased quantities of subsurface water may reduce creep, slump, and earthflow activity. Nutrient uptake by vegetation reduces export of material in solution (for example, Bormann et al. 1969). Regulation of snow hydrology by vegetation may result in either increased or decreased soil moisture peaks during snowmelt events (for example, Anderson 1969; Rothacher and Glazebrook 1968; Harr and McCorison 1979). In the Pacific Northwest rain-on-snow events result in very high soil moisture conditions that trigger debris avalanches (Rothacher and Glazebrook 1968; Day and Megahan 1975) and may cause periods of accelerated creep, slump, and earthflow movement.

Aboveground biomass serves as a medium for transfer of wind stress to the soil mantle. This effect is most conspicuous in the case of blowdown, where uprooted trees may transport both organic and inorganic matter downslope. Blowdown may contribute to the initiation of debris avalanches (Swanston 1969), and Brown and Sheu (1975) have hypothesized that wind stress on the soil mantle may accelerate creep, slump, and earthflow activity. Living and dead organic matter on the ground surface may intercept and temporarily store material moved downslope by surface erosion processes (Mersereau and Dyrness 1972).

Roots may play an important role in stabilizing the soil mantle by vertical and lateral anchoring across potential failure surfaces (for example, Swanston 1970; Nakano 1971). The effectiveness of roots in stabilizing slopes depends on position of the root network relative to potential zones of movement. Roots are most important in stabilizing potential mass failures where failure surfaces are within the rooting zone.

Large organic debris derived from vegetation on adjacent hillslopes controls channel morphology and routing of sediment and water through the stream (Bormann et al. 1969; Swanson et al. 1976; Keller and Swanson 1979). The principal effects of vegetation on channel processes are to physically retard the downchannel transfer of particulate matter, to buttress streambanks, to cause channel deflection, which can increase bank cutting, and to serve as a substrate for biological activity that involves the interchange of dissolved nutrients with stream water (see Chapter 9). Although total sediment yield is largely controlled by input of hillslope processes, the timing of export from a stream may be regulated by large debris in the channel. The presence of debris and temporarily stored sediment may also reduce the rate of channel downcutting, which may, in turn, slow the rate of sediment input by hillslope processes.

Decomposing organic matter and living vegetation may remove certain nutrients from solution in stream water by plant and decomposer organism uptake. There may also be a net input of certain other dissolved nutrients by leaching and decomposition of particulate organic matter. All of this material is eventually exported from a watershed, but whether it is delivered to the gauging site as dissolved or particulate matter may depend on the uptake and dissolution processes.

MATERIAL TRANSFER IN AN OLD-GROWTH FOREST

In order to compare individual and groups of transfer processes, data on transfer rate by each process have been compiled from research results of the coniferous forest biome program, and the Pacific Northwest Forest and Range Experiment Station, USDA Forest Service. This collaborative research has centered on watershed 10 and in the adjacent H. J. Andrews Experimental Forest (see Figure 1.4). This area is located in deeply dissected Tertiary lava flows, dikes, and volcaniclastic rocks in the central western Cascade Mountains (Peck et al. 1964; Swanson and James 1975).

The area of watershed 10 above the sediment basin and gauging flume is 10.2 ha, of which 767 m^2 or about one percent is considered to be stream channel subject to perennial or intermittent surface flow. Gradients of the hillslopes and lower channel average 65 percent and 18 percent, respectively (Figure 8.3). Soils are shallow, only slightly cohesive, and highly permeable,
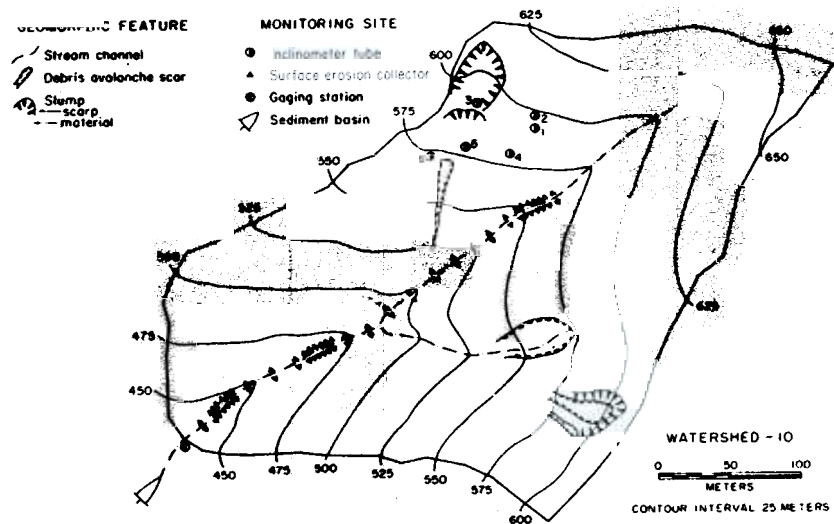

FIGURE 8.3   Geomorphic features and monitoring sites on watershed 10.

and they exhibit weakly developed profiles (Harr 1977). Before clearcutting in the summer of 1975, vegetation in the watershed was predominantly *Pseudotsuga menziesii* ranging in age from 400 to 500 years, with younger understory tree canopy composed of *Tsuga heterophylla* on moist sites and *Castanopsis chrysophylla* on dry sites as well as young *Pseudotsuga menziesii*. The dominant old-growth age class appeared to have developed after a disturbance, probably wildfire, about 1475. Portions of the area were again disturbed in about 1800 by a fire that had minor impact on the canopy, but did result in extensive regeneration of *Pseudotsuga menziesii*, *Tsuga heterophylla*, and *Castanopsis chrysophylla* in the understory. Characteristics of vegetation in the watershed are discussed in detail by Grier and Logan (1977).

The climate of the area is characterized by mild, wet winters and warm dry summers (Rothacher et al. 1967). Annual precipitation averages between 230 and 250 cm, depending on elevation. At the base of watershed 10 at 440 m elevation more than 90 percent of the annual precipitation falls as rain; snow seldom persists for more than several weeks. Rain-induced snowmelt has resulted in many of the major runoff and hillslope erosion events in the history of the area (Fredriksen 1965).

Many transfer processes are appropriately studied on the spatial scale of watershed 10. These include frequent or continuous processes such as litterfall and surface erosion, as well as less frequent, episodic processes that leave a record of numerous, datable events such as root throw. Processes such as debris avalanches and torrents, which are scattered in time and space, can be viewed better from a wider geographic perspective.

With these constraints in mind, we summarize below available data on transfer of organic and inorganic material by processes operating in a 10-ha, old-growth *Pseudotsuga menziesii* forest. Organic matter is here considered to include all particulate matter made up of carbon (C) compounds plus dissolved organic nitrogen (N) and C. Organic particulate matter includes approximately 1 to 2 percent cations, predominately calcium (Ca), potassium (K), and magnesium (Mg), derived from bedrock and atmospheric inputs. Inorganic matter includes all other material derived from bedrock, volcanic ash fall, and atmospheric sources.

Hillslope Processes

Solution transport of material from hillslopes occurs as water carries dissolved constituents leached from vegetation, soil, and weathering bedrock. There are also atmospheric sources of dissolved mineral material that must be omitted from the total solution export to determine the amount derived from a watershed. Movement of dissolved materials is a pervasive process, operating over the entire watershed and through all strata of the vegetation and soil. Solution transport operates continuously as long as water movement occurs,

but variations exist in response to seasonal and storm event fluctuations in moisture availability, flow-through rate, biological activity, and availability of exchangeable cations and anions. Long-term trends in solution export are controlled by the efficiency of nutrient cycling within an ecosystem and by weathering rate, which is determined by bedrock characteristics, climate, and biological processes.

Input and output of dissolved material have been measured for watershed 10 during water year (WY) 1969 (1 October 1968–30 September 1969) through WY 1973 (Table 8.3). Methods of sample collection and analysis are described by Fredriksen (1972, 1975). Samples were collected at a stream gauging station at the base of the watershed. Since we are attempting to calculate only solution export from hillslopes, it is necessary to assume that the total quantity of dissolved material does not change while water flows from the base of the hillslope through the stream to the flume. Comparison of analyses of

TABLE 8.3 *Input and output of water and dissolved inorganic material (kg/ha) for watershed 10, water years 1969–1973.*

Year	H₂O (cm)	Ortho-P	Na	K	Ca	Mg	SiO₂	Total
1969								
In	253.0	0.01	1.54	0.25	8.77	0.73	—	
Out	169.0	0.42	33.74	1.36	53.62	12.67	—	
Net		-0.41	-32.30	-1.11	-44.85	-11.94	-199.91*	
1970								
In	215.9	0.02	2.62	0.16	2.36	1.53	0.28	
Out	134.6	0.44	25.85	2.26	50.60	12.51	213.57	
Net		-0.42	-23.23	-2.10	-48.24	-10.98	-213.29	
1971								
In	272.1	0.28	6.64	0.32	3.21	2.78	11.45	
Out	172.3	0.71	37.64	0.98	60.91	17.96	211.43	
Net		-0.43	-31.00	-0.66	-57.70	-15.18	-199.98	
1972								
In	286.3	0.02	3.98	0.33	4.92	0.82	9.87	
Out	228.52	0.85	43.48	3.25	70.20	16.76	303.75	
Net		-0.83	-39.50	-2.92	-65.28	-15.94	-293.88	
1973								
In	167.8	0.08	2.59	0.59	0.13	1.07	6.12	
Out	80.16	0.31	13.94	1.46	23.24	6.64	80.01	
Net		-0.23	-11.35	-0.87	-23.11	-5.57	-73.89	
Average net export		0.46	27.46	1.53	47.84	11.92	196.19	285.40

*Not measured. Values assigned from 1971 observations; runoff for 1969 and 1971 were approximately equal.

water samples collected at seeps and at the flume indicates that the concentrations of mineral elements do not change significantly between seep and flume sample sites. Similar analyses for N, however, suggest that there may be 10 to 20 percent uptake because of primary production and decomposition processes in the stream (S. V. Gregory, pers. comm.). Other components of the dissolved organic load do not appear to be significantly altered in the stream environment. Because this is a relatively small change based on preliminary data, we will assume that dissolved organic export measured at the gauging station equals the input to the stream from hillslope areas.

Estimation of dissolved inorganic export is based on analyses for Na (sodium), K, Ca, Mg, and orthophosphate (ortho-P) over the entire five-year period. Analyses for silica (SiO$_2$) were conducted in WY 1970 through WY 1973 only. Based on these data, annual net transfer is 2.9 t/yr of dissolved inorganic material from hillslope areas.

Dissolved organic matter export was estimated using the following algorithm: based on ten measurements of dissolved organic carbon in water samples collected at the gauging station (S. V. Gregory, pers. comm.), a concentration of 2.0 mg C/liter was applied to total discharge during the initial twenty-four-hour period of fall storms (1 October through 31 December) when flow exceeded 1 cfs (28.3 liters/s). For the remainder of the year a concentration of 0.9 mg C/liter was used. This method was applied to WY 1969 through WY 1973 and the annual estimates were multiplied by two to convert from dissolved carbon to dissolved organic matter. The average of these annual estimates of dissolved organic matter export is 0.3 t/yr, which we assume equals the input to the stream.

Litterfall is the final transfer in a chain of processes involving nutrient uptake by roots, translocation to biomass in the aboveground portion of vegetation, and the fall of litter to the forest floor. Even in predominantly evergreen coniferous forests, litterfall is strongly seasonal, coming mainly in the autumn and early winter months with storm winds, needle and leaf abscission, and snow breakage.

Fall of fine litter into the channel area was directly measured at 0.18 t/yr based on three years of collections in standard 1-m^2 traps along the watershed 10 stream (F. J. Triska, pers. comm.). An estimated 0.15 t/yr of log material is input to the stream, assuming that the standing crop (Froehlich et al. 1972) represents 150 years of input. Total organic matter input to the stream by litterfall is 0.33 t/yr.

Surface erosion of organic and inorganic particulate matter occurs throughout the year in response to wind; diel, storm event, and seasonal variations in moisture and temperature; snow creep, needle ice, and other snow- and ice-driven processes; impact of large pieces of falling litter; and movement of scientists and animals, principally deer, elk, and rodents. Much erosion from steep, bare, mineral soil surfaces results from particle-by-particle movement during dry periods (dry ravel) and by needle ice and the impact of rain and

throughfall drops during wet periods. Mersereau and Dyrness (1972) report that the highest surface erosion rate at a study site in the Oregon Cascades occurred during periods of dry ravel. Areas covered with forest litter often experience movement of surface particles when drying takes place in the spring and early summer. At this time leaves and other litter dry, curl up, and become more susceptible to downslope movement. Overland flow is observed only rarely and very locally in the study area. No evidence of rill formation exists in most forested watersheds in western Oregon except on some debris avalanche scars, road cuts, and other disturbed sites.

Organic and inorganic material moved by surface processes was collected in sixty-four fifty-cm-long erosion boxes along the perimeter of the watershed 10 stream. The rate of surface movement into the total length of boxes may be extrapolated to the entire perimeter of the stream to estimate total annual surface movement transfer from hillslopes to the stream. Based on two years of observations, 0.30 t of organic material and 0.53 t of inorganic matter were transferred annually into the stream channel.

Soil creep is the slow deformation within and between individual soil particles in response to gravitational stress but without the development of discrete failure planes. Creep grades into more rapid mass movement processes that do have well-developed failure planes, however, and distinction among these processes is somewhat arbitrary (Terzaghi 1950).

Soil creep is difficult to monitor, because it affects virtually all sloping soil masses and movement is slow, generally less than 1 cm/yr. Although precise measurements are required, it is difficult to establish stable reference points Creep measurement in watershed 10 and at nearby sites have been made with a set of inclinometer installations (D. H. Gray, pers. comm.)

Annual measurement with an inclinometer revealed downslope deflection occurring at soil depths (measured vertically) of up to 4 m. The net downslope deflection was used to calculate an average creep rate for each inclinometer tube (Table 8.4). Displacement ranged from 0.25 to 0.46 mm for four of the tubes, but the other two tubes, which were located on a bench, experienced no significant movement. Because this landform is of limited areal extent (Figure 8.3), creep rates observed for tubes on steeper sites are considered more typical of the watershed. The variability and maximum values of creep rates observed in watershed 10 are comparable to creep rates measured in similar topographic and geologic settings (D. H. Gray, pers. comm.; D. N. Swanston, pers. comm.).

There are certain limitations on the usefulness of the data in Table 8.4. Using a cumulative five-year record of creep observations to calculate annual movement minimizes the analytical problem that at certain depths and in certain tubes annual movement is less than the resolution of the instrument, approximately 0.6 mm (D. N. Swanston, pers. comm.). An additional consideration in evaluating these data is that the bases of the inclinometer tubes may not be fixed to stable bedrock. Therefore additional movement may be taking place

TABLE 8.4 *Creep measurements with inclinometer installation.*

Tube number	Hillslope angle (degrees)	Depth (m)	Annual surface displacement (mm/yr)	Average displacement over entire depth of tube (mm/yr)	Period of record
1	32	3.96	0.60	0.25	1969–1974
2	35	2.44	0.93	0.46	1969–1974
3	27	4.27	0.17	<0.01	1969–1974
4	34	3.96	1.57	0.32	1969–1974
5	27	3.66	0.34	0.04	1969–1973
6	41	3.96	0.73	0.40	1969–1974

*D.H. Gray, personal communication.

that is not recorded by these installations. Despite these limitations, we make a minimum estimate of creep transfer of material to the channel by assuming that a block of soil 2.65 m thick, the average thickness for the watershed (R. D. Harr, pers. comm.), crosses the 1150 m of channel perimeter at a rate of 0.35 mm/yr, the depth-integrated average creep rate of tubes 1, 2, 4, and 6. Based on these assumptions and an average bulk density of 1.0 t/m^3 (R. L. Fredriksen, pers. comm.), creep supplies 1.1 t/yr of inorganic material to the channel.

Organic matter transfer by creep may be estimated by creep rate (0.35 mm/yr) X channel perimeter (1150 m) X cosine of slope angle (33°) X biomass per m^2 of watershed (0.125 t/m^2; Grier and Logan 1977). Estimated organic matter transfer to the channel by creep is 0.04 t/yr.

Root throw by living and recently dead trees downed by strong winds generally move organic and inorganic material downslope. When root systems undergo extensive decay before a tree falls, binding between soil and roots is lost and little soil is moved. Pit and mound microrelief due to root throw has been well described in the gentle topography of the eastern United States, where root throw is an important soil disturbance factor (for example, Denny and Goodlett 1956; Stone 1975). In stands of large, old-growth forests on steep slopes erosion by root throw is accentuated by massive root wads and their tendency to slide downslope. Such events are episodic, occurring in windstorms that have a return period of several years to decades. Deep-seated earth movement by slump, earthflow, and creep processes can lead to tipping and even splitting of trees, thereby increasing their susceptibility to blowdown.

Root throw is such a sporadic phenomenon that a long-term historical record is necessary to validly estimate its occurrence. Fortunately, root wads, soil mounds, and pits from which roots and soil were removed are clearly recognizable and their features are datable for more than a century following the event. Events are dated by counting rings of trees growing on the pit, soil

mound, or the downed tree. The persistence of pits and mounds attests to slow rates of surface erosion and creep.

In watershed 10, 112 mapped root-throw sites have abundant root and bole material still present. Dendrochronologic observations and the stage of decay of residual organic matter (P. Sollins, pers. comm.) suggest that the inventoried root-throw occurred to large, old-growth trees in the past 150 years. Root-throw sites are distributed rather uniformly over most of the watershed with some concentration along the lower slopes, particularly along the north side of the stream. Direction of fall was predominantly downslope.

The annual quantity of sediment supplied to the stream is difficult to determine, because most root wads in the stream slid >10 m down to the channel, loosening soil along the way. Eight of the inventoried root wads reached the stream. If we assume that these events occurred over the past 150 years, that each one transported or pushed 2 m^3 of soil to the stream, and that soil bulk density was 1.0 t/m^3, annual transfer to the channel would be 0.1 t of inorganic material. The organic matter in roots of <5 cm diameter in the root wad of a 120-cm-dbh old-growth Douglas-fir is estimated to be about 2 t (Santantonio et al. 1977; D. Santantonio pers. comm.), which would result in 0.1 t/yr of annual organic matter transfer to the channel.

Debris avalanche is used here as a general term for rapid, shallow soil mass movements, including events that have been classed by other workers as debris flows, slides, and rapid earthflows (Varnes 1958). These mass movements commonly occur as a result of periods of intense rain or rain plus snowmelt while the soil is already very moist (Fredriksen 1965; Dyrness 1967). Occurrence of debris avalanches are scattered in both time and space. In the H. J. Andrews Experimental Forest, for example, it has taken storms of about a seven-year return period to trigger debris avalanches in forested areas (F. J. Swanson, pers. comm.).

Debris avalanches are commonly believed to be a dominant erosion process in landscapes such as watershed 10 and similar terrains in the H. J. Andrews Experimental Forest (Fredriksen et al. 1975; Swanson and Dyrness 1975); however no debris avalanches of larger than 75 m^3 occurred in the watershed during at least the past century. Their earlier occurrence is suggested by landforms interpretable as avalanche scars (Figure 8.3). The oldest trees growing on these features range in age from 200 to more than 400 years.

Because a 10-ha watershed offers a limited record of its debris avalanche history, examination of a larger area of similar terrain that would contain more recent, datable events for study is useful. A record of all debris avalanches greater than 75 m^3 has been compiled for the period from 1950 to 1975 in the H. J. Andrews Experimental Forest (Dyrness 1967; Swanson and Dyrness 1975). In this twenty-six-year period fourteen debris avalanches occurred in the 20-km^2 portion of the forest that is similar to watershed 10 in terms of soil, topography, and forest cover. The annual frequency of debris avalanches was 0.27 event$\cdot km^{-2} \cdot yr^{-1}$, or 0.0027 event/yr in 10 ha, the area of watershed 10.

The return period for a single event, the inverse of event frequency, is 370 years in a 10-ha area, assuming equal probability of occurrence over the inventoried area.

The fourteen debris avalanches in the terrain similar to watershed 10 transported a total of 30,870 m^3 of soil, an average of 2205 m^3 per event (for a description of field methods see Swanson and Dyrness 1975). The dimensions of mapped debris avalanche scars in watershed 10 indicate that this is a reasonable estimate of the volume of recent, significant (greater than 75 m^3) debris avalanches in the watershed.

Twelve inventoried events entered streams and 99 percent of the volume of material transported was readily available to perennial or intermittent streams. The straight, steep slopes of watershed 10 present no impediments to debris avalanches on their way to the stream. Assuming that all of the debris avalanches move soil from hillslopes to stream channels, and that soil bulk density is 1.0 t/m^3 (R. L. Fredriksen, pers. comm.), transfer of inorganic particulate matter occurs at a rate of 6.0 t/yr.

Debris avalanches also transport organic matter to the stream. The average plan view area of the fourteen inventoried debris avalanches is about 1200 m^2, calculated from average volume, assuming average soil depth of 1.5 m and a slope of 36°. Assuming 0.125 t/m^2 of terrestrial biomass (Grier and Logan 1977), such a debris avalanche would transport 150 t of biomass. If one average-sized event occurred in the watershed in 370 years annual biomass transfer would be 0.41 t/yr.

Slump and earthflow landforms are developed where masses of earth undergo rotational or translational movement along discrete failure planes or zones of failure (Varnes 1958). In the western Cascades these features range in size from less than 1 ha to hundreds of hectares (Swanson and James 1975). Increased rates of slump and earthflow may occur in response to periods of heavy precipitation (R. D. Harr, pers. comm.; F. J. Swanson pers. comm.). In other instances, slump and earthflow features appear to have been inactive for hundreds or thousands of years. Where slumps and earthflows encroach on streams, the channel cross-section is progressively constricted and banks are oversteepened (Swanson and Swanston 1977).

Rotational and translational slump and earthflow movement has produced landforms covering approximately 6 percent of the area of watershed 10 (Figure 8.3). Field observations suggest that the slumps have been dormant for decades or perhaps centuries. Trees growing on the slump benches and deposits exhibit no signs of having experienced splitting, tilting, or periods of eccentric growth typical of vegetation growing on moving ground (Swanson and Swanston 1977). In areas of the Andrews Experimental Forest where differential movement is occurring at rates greater than 1 cm/yr, open tension and shear cracks are formed. Since none of these features has been observed in the slump areas of watershed 10, we conclude that during the past century slump movement in watershed 10 has been negligible.

Stream Channel Processes

Solution transport is a persistent process, operating under all streamflow conditions. Dissolved material in stream water is derived from the dissolved load of groundwater, direct atmospheric inputs, throughfall, and leaching of particulate matter weathering or decomposing in the channel. Values of dissolved inorganic and organic material determined for watershed 10, were 2.9 and 0.3 t/hr, respectively.

Suspended sediment is made available to the stream by all hillslope processes that transport particulate matter and by lateral and vertical cutting of the streambanks and bed. Small amounts of suspended sediment are carried by streams throughout the year, but most of the total annual load is transported during a few large storms. During stormflow fine particulate matter is scoured from streambed and bank deposits of alluvium and colluvium; it is produced by the breakdown of larger particles, and released from temporary storage in coarse alluvium when bedload movement commences.

The input and output of fine particulate matter at watershed 10 have been measured over a five-year period by Fredriksen (1975). Inputs come primarily as atmospheric fallout of particles greater than 0.05 mm in size. Particulate matter was filtered from precipitation collected in birdproof precipitation collectors. The relative contributions of natural and man-influenced and distant and local sources of atmospheric particulate matter are not known (Fredriksen 1975). Aeolian entrainment of organic particulates has not been quantified in ecosystem studies, although several mechanisms for entrainment have been suggested (Fish 1972).

Suspended sediment export was sampled at the flume with a pumping proportional water sampler (Fredriksen 1969, 1975). Both the suspended sediment and atmospheric input samples for WY 1972 and WY 1973 were analyzed for carbon (Fredriksen 1975) and the total organic component was calculated assuming that it is twice the amount of carbon.

Because of the ambiguous status of fine particulate inputs to the watershed, we report export of suspended sediment both with and without subtracting apparent atmospheric inputs. Suspended organic matter export from the watershed was 0.12 t/yr, or 0.07 t/yr when apparent atmospheric input is subtracted. Suspended inorganic matter export amounted to a gross value of 0.78 t/yr, and 0.56 t/yr when atmospheric dust input is subtracted.

For purposes of comparison, we have also examined data for gross organic plus inorganic suspended sediment export from four nearby experimental watersheds with soil, forest cover, and geomorphic conditions similar to watershed 10. The average annual fine particulate export for these watersheds (98 $kg \cdot ha^{-1} \cdot yr^{-1}$) is in close agreement with the five-year average for watershed 10 (90 $kg \cdot ha^{-1} \cdot yr^{-1}$).

Bedload transport commonly occurs during only a few major runoff events each year. Material available for bedload transport is temporarily stored in the

stream channel, commonly behind large pieces of organic debris, boulders, or outcrops of resistant bedrock. Concentrations of large organic debris in a channel greatly influence its sediment storage capacity. Therefore, on a time scale of years or decades, bedload transport is regulated by changes in channel storage capacity, rates of sediment supply from hillslopes, and hydraulic forces tending to move sediment out of the channel.

Bedload export from watershed 10 was monitored for only two years before logging. The record is inadequate to characterize this erosion process for the basin, so we use the longer record available for experimental watersheds with generally similar forest cover, topography, soil, and geomorphic conditions.

A total of twenty-nine watershed years of bedload data is available for watersheds 1, 2, 3, 9, and 10 in and adjacent to the H. J. Andrews Experimental Forest (Table 8.5; Fredriksen 1970, pers. comm.).

Bedload from watershed 10 was collected in large nets placed at the downstream end of the flume. Sampling was done on a continuous basis during low flow using a 80 μm net and periodically during high flow using a 1 mm net. Bedload export from other watersheds was measured by annual surveys of settling basins at the bottom of each watershed. In all cases reported values are minimum estimates of the true value, because trapping efficiencies of the basins are probably less than 100 percent particularly during peak periods of bedload transport.

Bedload export for all watersheds has been 93 kg·ha⁻¹·yr⁻¹. For the four watershed years at watersheds 9 and 10, 65 percent of total bedload was com-

TABLE 8.5 *Average annual bedload and suspended load export from forested watersheds in the H. J. Andrews Experimental Forest.*[a]

Watershed	Period of record (water year)	(yr)	Bedload (kg·ha⁻¹·yr⁻¹)	Suspended load (kg·ha⁻¹·yr⁻¹)
	1957–1962	6	61	78[b]
2	1957–1972	16	122	—
	1957–1967	11	—	134[b,c]
3	1957–1959	3	95	130[b]
9	1974–1975	2	21	—
	1969–1973	5	—	31[d]
10	1973–1974	2	32	—
	1969–1973	5	—	90[d]

[a] Bedload average for 29 watershed years = 93 kg·ha⁻¹·yr⁻¹. Suspended sediment average for 30 watershed years = 98 kg·ha⁻¹·yr⁻¹.
[b] Based on depth integrated hand sample at flume.
[c] Includes two highest floods on record in December 1964 and January 1965.
[d] Based on integrated samples collected with a pumping proportional sampler.

posed of inorganic material. Therefore the estimated inorganic matter export from watershed 10 is 0.60 t/yr, and coarse particulate organic matter export is 0.33 t/yr.

Debris torrents are commonly triggered by debris avalanches entering the channel from adjacent hillslopes (Swanson et al. 1976). A debris avalanche may maintain its momentum, becoming a debris torrent as it moves directly down the channel, scouring the streambanks and bed. Debris torrents are also initiated by mobilization of debris that had previously entered the channel by a variety of processes such as debris avalanches, windthrow, and bank cutting. Debris torrents are infrequent events, occurring in response to major storms. Most torrents in small streams are in part regulated by the debris avalanche potential of hillslopes in the basin. Most small basins experience a torrent less frequently than once in a century.

As in the case of debris avalanches, debris torrent history is not adequately represented in a small area the size of watershed 10. This analysis is based on debris torrent activity in the H. J. Andrews Experimental Forest from 1950 through 1975. Nine debris torrents occurred in 20 km^2 of terrain with geomorphic and forest conditions similar to those of watershed 10. It follows that there were 0.017 debris torrents $\cdot$ km$^{-2} \cdot$ yr^{-1}, which is an annual probability of 0.0017 that an event will occur in an area the size of watershed 10, or an estimated average return period of one event in 580 years.

Eight of the nine inventoried events were triggered by debris avalanches. Debris avalanches also appear to be the dominant triggering mechanism of debris torrents in watershed 10 where steep, smooth slopes lead directly from debris avalanche-prone areas to the stream channel (Figure 8.3). The average length of inventoried events was 370 m. In watershed 10 the two most prominent debris avalanche sites would initiate torrents at points about 260 m upstream from the flume.

If the entire mass of an average debris avalanche (2205 t inorganic matter and 150 t organic) were to move through the channel and past the flume as a debris torrent, it would involve 5.3 t/yr export of inorganic matter and 0.26 t/yr export of organic material, based on the occurrence of a single event during the estimated 580-year return period. This hypothetical debris torrent would also entrain alluvium, organic debris, and soil from the channel and adjacent banks. Of course the volume of material in a channel varies greatly with recent history of storms, vegetation, and geomorphic processes. The prelogging concentrations of organic and inorganic material in the channel of watershed 10 represented a moderate level of channel loading relative to observations made in other streams (Froehlich et al. 1972; Froehlich 1973). Before logging, approximately 40 t of organic matter was in a four-meter-wide strip along the 260 m of the channel between the most likely point of introduction and the flume (Froehlich et al. 1972). Inorganic matter in this strip along the channel is estimated to be 470 t, assuming a 0.3 m average depth of alluvium and soil with bulk density of 1.0 t/m^3 and a six-meter-wide torrent track. If all of this

material were entrained by a debris torrent, total debris torrent export from the watershed (entrained material plus debris avalanche material) would be 4.6 t/yr of inorganic matter and 0.33 t/yr organic matter.

Accuracy and Limitations of Estimates

The usefulness of erosion process rate estimates summarized in Table 8.6 is directly related to their accuracy. Unfortunately, in most cases it is impossible to calculate an estimate of accuracy objectively owing to lack of data to quantify some of the key assumptions used to make the erosion rate estimate. Accuracy of estimates is a particular problem in the cases of debris avalanches, torrents, and bedload transport, which occur mainly during infrequent, large storms. A few storms can dominate even a record of more than 25 years such as that available for mass movement processes. This period of record contained only three of the top ten annual peak flows recorded in the fifty-nine-year record for the McKenzie River at McKenzie Bridge, the nearest long-term gauging site (Dalrymple 1965). The highest peak flow of the entire fifty-nine-year record, however, occurred in December 1964, and on Lookout Creek in the H. J. Andrews Forest it was 27 percent higher than the estimated fifty-year recurrence interval event (Waananen et al. 1971). Because the return period of this event was much greater than the length of record, these rates of debris avalanches, torrents, and bedload transport may be overestimated. The available record is too brief to characterize these episodic processes accurately. Furthermore, transfer rates for the mass-movement processes are based on small sample sizes. Therefore we estimate that the measures of debris avalanche and debris torrent rates have an accuracy of no better than +60 percent to −100 percent. As a result of more frequent occurrence of bedload transport and sampling inefficiencies, we estimate accuracy of bedload transfer rate to be ±60 percent.

The more frequent or continuous processes are better characterized by the available data. Rates of solution transport and to some extent creep and suspended sediment are related to total annual water yield. Analysis of long-term streamflow records suggests that the transfer estimates for solution transport, creep, and suspended sediment are good representations of the past twenty-five years, but may overestimate rates for the past sixty-five years, which includes some drier periods earlier this century. Estimated accuracy of transfer rates for these processes is about ±30 percent. For all other process rates, we estimate an accuracy of approximately ±50 percent.

It is important to note that these estimates of transfer rates apply to old-growth forest conditions; some process rates vary significantly for different stand conditions on the same landscape. This is particularly true immediately following ecosystem disturbances such as wildfire or clearcutting. These factors are considered further in a later section.

EROSION UNDER FORESTED CONDITIONS

Material transfer data may be examined in terms of total watershed-ecosystem export, contrast of total hillslope and channel transfer, and comparisons among processes. In each case we compare the roles of episodic and the more frequent or continuous processes, the relative importance of organic versus inorganic transfer, and dissolved versus particulate material export.

Watershed-Ecosystem Export

Total watershed-ecosystem export by channel processes is $0.99 \, t \cdot ha^{-1} \cdot yr^{-1}$ (Table 8.6). This figure includes debris torrents, which account for an estimated 50 percent of the total, even though it is assumed that only one event occurs in 580 years. Total export by the commonly measured processes of dissolved, suspended, and bedload sediment transport is $0.5 \, t \cdot ha^{-1} \cdot yr^{-1}$. Par-

TABLE 8.6 *Transfer of organic and inorganic material to the channel by hillslope processes (t/yr) and export from the channel by channel processes (t/yr) for watershed 10.*

Process	Inorganic matter	Organic matter
Hillslope processes		
Solution transfer	3	0.3
Litterfall	0	0.3
Surface erosion	0.5	0.3
Creep	1.1	0.04
Root throw	0.1	0.1
Debris avalanche	6	0.4
Slump/earthflow	0	0
Total	10.7	1.4
Total particulate		
Including debris avalanche	7.7	1.1
Excluding debris avalanche	1.7	0.7
Channel processes		
Solution transfer	3.0	0.3
Gross suspended sediment	0.8	0.1
Net suspended sediment	0.6	0.1
Bedload	0.6	0.3
Debris torrent	4.6	0.3
Total	8.9	1.0
Total particulate		
Including debris torrent	5.9	0.7
Excluding debris torrent	1.3	0.4

12.1

9.9

ticulate matter composes 34 percent of this total. Organic matter makes up 24 percent of the particulate matter export (excluding debris torrents) and 9 percent of total dissolved export.

Values for organic and inorganic, particulate and dissolved materials are summarized in Table 8.7 along with similar data from Hubbard Brook, New Hampshire, the only site for which complete comparable data exist. Characteristics of these two watershed ecosystems (Table 8.8), are the basis for contrasting the two systems.

In the cases of all four constituents, export values for watershed 10 (even excluding debris torrents) exceed those for watershed 6, Hubbard Brook, by a factor of at least 2. Some of the apparent contrasts may arise from differences in methods and efficiencies of sample collection and analysis, from possible differences in the relative magnitude of major storms (in terms of return period) that occurred within the respective sampling periods, and possibly from differences in magnitudes of storms of comparable return period. Contrasts in estimated export from the two watersheds is so great for each of the variety of forms of export, however, that much of the difference may be due to real differences in system behavior.

Systems may differ in terms of the availability of material to be transported and the energy available to transport material. Export of dissolved constituents

TABLE 8.7 *Export of dissolved and particulate organic and inorganic material (kg·ha^{-1}·yr^{-1}) from watershed 10, H. J. Andrews Experimental Forest, Oregon, and watershed 6, Hubbard Brook, New Hampshire.*[a]

	Watershed 10 H. J. Andrews Experimental Forest		Watershed 6 Hubbard Brook
	Excluding debris torrents	Including debris torrents	
Dissolved			
Organic	30	30	15
Inorganic	300	300	58
Total	330	330	73
Particulate			
Organic	40	70	10
Inorganic	130	590	15
Total	170	660	25
Total			
Organic	70	100	25
Inorganic	430	890	73
Total	500	990	98

[a]Bormann et al. 1974.

tends to be directly related to total annual discharge, while particulate matter export is controlled by high discharge events (Bormann et al. 1974). Availability of particulate material for transport from a channel depends on the input rate of material from adjacent hillslopes and stream power, a function of discharge and channel gradient. Availability of material for transport in solution is determined in part by the ability of the biota to immobilize nutrients in living vegetation and detritus. In the case of inorganic material, rates of weathering and decomposition also determine availability of dissolved material.

Dissolved organic matter export from watershed 10 is twice that of watershed 6, which may largely reflect the higher annual runoff from the Oregon site (Table 8.8). The five times greater standing crop of organic matter in watershed 10 also results in more material available for leaching from the ecosystem. The contrast is especially striking considering that dead biomass in watershed 10 equals total biomass reported for the Hubbard Brook site.

The condition of greater biomass available for export from watershed 10 doubtless contributes to its fourfold higher particulate organic matter export. Availability of material for export from watershed 10 is also affected by the much steeper hillslopes, which result in greater rate of particulate matter transfer to the channel. The much higher litterfall rate in watershed 10 also contributes to greater particulate organic matter export. These factors must more than compensate for slightly higher gradient in the lower 100 m of channel and

TABLE 8.8   *Characteristics of watershed 10, H. J. Andrews Experimental Forest, Oregon, and watershed 6, Hubbard Brook, N.H.*

Water-shed no.	Area (ha)	Slope Total water-shed (%)	Slope Channel lower 100 m (%)	Runoff Av (1/sec⁻¹/ ha⁻¹)	Runoff Peak (1/sec⁻¹/ ha⁻¹)	Runoff Av annual peak (1/sec⁻¹/ ha⁻¹)	Av annual (cm)	Av annual air temp (°C)	Dominant t species
10	10.2	60	18	0.5	19	12	156	9.5[a]	*Pseudotsuga menziesii, Tsuga heterophylla*
6	13.2[d]	26[c]	21[c]	0.3[c]	25[c]	15[c]	80[c]	4.3[d]	*Acer saccarum, Fagus grandifolia, Betula alleghaniensis*[d]

[a]Waring et al. 1978.
[c]Grier and Logan 1977.
[r]P. Sollins, personal communication.
[d]Bormann et al. 1970.

higher average annual peak discharge for the five-year periods of record at the Hubbard Brook site.

Particulate organic matter export from small watersheds may also be regulated by retentiveness or roughness of the channel system. Boulders and living and dead vegetation in and adjacent to the channel slow downstream routing of particulate matter, providing more opportunity for biological processing and export from the system by respiration and leaching. In streams at Hubbard Brook boulders are the dominant elements of bed roughness, whereas large woody debris is the major controller of particulate matter routing through a small Oregon stream. Both systems appear to have high roughness and therefore a tendency to retain organic detritus until it is processed by aquatic organisms (Bormann et al. 1969; Sedell and Triska 1977).

The export of dissolved inorganic matter from watershed 10 exceeds that of watershed 6 by about sixfold (Table 8.7). Part of this difference is accounted for by higher total runoff from watershed 10, but a more important factor is the greater weathering rate of soils and bedrock at the Oregon site. The higher weathering rate at the Oregon site is due to higher temperatures and precipitation and the mineralogy of altered volcanic rocks. Hydrothermal alteration of these volcanic breccias resulted in formation of readily weathered secondary minerals and amorphous materials even before the rocks were subjected to the modern weathering environment. Weathering of bedrock and the compact till that blankets the Hubbard Brook watershed proceeds at a slower pace in response to mineralogic properties and the weathering environment of the soil.

Age (yr)	Biomass (watershed) (kg/m³)		Litterfall incl. stems (kg/m³)	Bedrock	Soil
	Live	Dead			
100 to 150 and 400 to 500	86[b]	38[b]	1.1[b,c]	volcanic breccias, tuffaceous sediments propylitically altered	Dystrochrept, poor horizon development
55[f]	16[f]	22[f]	0.57[f]	Quartz-biotite gneiss, sillimanite-zone metamorphism[f]	Spodosols (Haplorthods), moderate profile development[f]

[b] Bormann et al. 1974.
[f] Federer 1973.
[c] Gosz et al. 1976.

Differences in ability of the biota to immobilize cations and thereby regulate dissolved inorganic matter export from the two watersheds are probably minor, because 70 to 80 percent of this export component is made up of SiO_2 and Na, which are not significantly accumulated in the plant or microbial biomass of these ecosystems.

Estimated particulate inorganic matter export from watershed 10, excluding debris torrents, is about nine times greater than that of watershed 6 (Table 8.7). As described in the case of particulate organic matter, in their lower reaches the two channel systems appear to have similar transport capability, except in the case of debris torrents. Therefore, marked differences in particulate inorganic matter export probably arise from a more rapid rate of sediment input to the channel from steeper hillslopes of watershed 10.

Comparison of Hillslope and Channel Material Transfer

Estimated total particulate organic and inorganic inputs to the watershed 10 channel are greater than comparable output values. Much of the input/output difference for particulate organic matter is due to biological utilization (see Tables 10.3 and 10.4), whereas the difference for particulate inorganic matter is within the error of input and output estimations. If input generally exceeds output, the streambed should experience net aggradation. Actually the watershed 10 stream is at the bottom of a steep-sided, V-notch valley, indicating a long history of downcutting. Short-term watershed budget studies and examination of sediment routing function and history of large woody debris in streams (Swanson et al. 1976) suggest, however, that channel systems may be sites of net increase in storage for long periods of time interrupted by infrequent, major flushing events. Consequently, such forested streams may be aggrading on the time scale of years and decades, while experiencing degradation on a broader time scale.

Comparison of Processes

The material transfer data may also be evaluated in terms of relative roles of various processes. Rates of processes accounting for inorganic matter transfer vary over a broad range (Table 8.6). The most infrequently occurring processes, debris avalanches and torrents, appear to be dominant, although only one event occurs every few centuries on the average. Solution transfer, one of the most continuous processes, is the second most important mechanism of inorganic matter transport. Processes of secondary importance include creep, surface erosion, and root throw on hillslopes and suspended sediment and bedload transport in the channel. Litterfall, slump, and earthflow processes are presently insignificant in terms of transporting inorganic matter.

In the case of organic matter transport there is much less variation in the relative importance of most processes (Table 8.7). Among hillslope processes debris avalanche, surface erosion, litterfall, solution, and root throw each supplies material to the channel at rates of about 0.1 to 0.4 t/yr. Particulate organic matter transfer by creep is about an order of magnitude lower, and slump and earthflow processes are presently negligible. Estimated organic matter export rate for each channel process is in the range of 0.1 to 0.3 t/hr. Episodic processes are relatively less important than more continuous ones in transporting organic matter.

EFFECTS OF ECOSYSTEM DISTURBANCE

As a result of numerous interactions between vegetation and material transfer processes in forests, severe disturbances of vegetation affect transfer processes throughout forested watershed ecosystems. This fact has been amply demonstrated in terms of sediment yield from paired forested and manipulated watersheds in areas of diverse climate, vegetation, and geomorphic setting (for example, Fredriksen 1970; Brown and Krygier 1971; Bormann et al. 1974; Fredriksen et al. 1975). Results of watershed manipulation experiments in the Pacific Northwest have been highly varied, depending on treatment, terrain, and history of past disturbances. Effects of timber harvest on sediment yield range from negligible in the case of two watersheds of low slope (7 to 12 percent) that were 25 percent clearcut (Fredriksen et al. 1975) to a twenty-three-fold increase in suspended sediment export over a fourteen-year period from watershed 3 in the H. J. Andrews Experimental Forest, which was 25 percent clearcut and 6 percent roaded (Fredriksen 1970; pers. comm.). Watershed 10 was clearcut and cable yarded in summer 1975 and early stages of postlogging erosion are being examined.

Initial observations in watershed 10 and other experimental watersheds suggest that postclearcut watershed export comes from three sources, each associated with a specific time frame: (1) material input to the channel during falling and yarding operations, consisting of mainly fine, green organic matter and some mineral soil; (2) material that had entered the channel by natural processes and was in temporary storage behind debris obstructions before logging, but is released from storage when large pieces of organic debris are removed from the channel during logging; and (3) material input to the channel by hillslope erosion processes following logging. A general phasing of watershed export of materials from these three sources may occur with material from source 1 mainly leaving the watershed in the first one to three years following cutting, source 2 gaining importance in the latter part of this period, and the postlogging hillslope erosion (source 3) becoming a dominant source several years after cutting. This phasing or routing of material through a watershed is an important element of ecosystem response to disturbance and it is relevant to

interpretation of sediment yield data. Sediment yield from manipulated water-sheds is commonly interpreted in terms of hillslope transfer processes, where in some cases it may result from changes in channel storage.

Ultimately, postcutting studies in watershed 10 will test hypotheses concerning the role of revegetation in returning individual process rates to levels characteristic of forested conditions. Each process has a different magnitude and timing of response to deforestation due to differences in interactions between transfer processes and vegetation. Hypothetical trajectories of several hillslope process rates following cutting are shown in Figure 8.4. The timing of change in debris avalanche potential is partly a response to the timing of decay of root systems from the precutting vegetation and the buildup of root systems in the postcutting stand. The net effect of this and possibly other factors in areas of the H. J. Andrews Experimental Forest similar to watershed 10 has been a 2.8 times increase in debris avalanche erosion over about a twelve-year period following clearcutting (Swanson and Dyrness 1975). Surface erosion involves a pulse of material transfer during and soon after the logging operation followed by a period of recovery. Timing of recovery is controlled by the rate of re-establishment of ground cover or development of a residual armor layer of coarse soil particles. Soil solution transport is regulated by nutrient and water uptake by vegetation. With recovery of leaf area and rates of primary production, a proportion of available nutrients is incorporated into biomass and a smaller amount is flushed from the system. Additionally, recovery of vegeta-
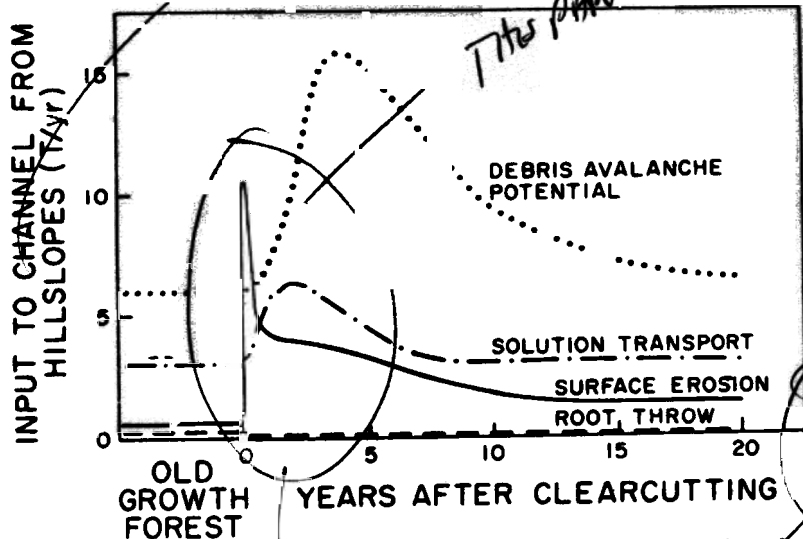

FIGURE 8.4   *Hypothetical trajectories of potential rates of selected hillslope transfer processes after clearcutting of watershed 10.*

tion reduces annual water yield to predeforestation levels over a period of a decade or more. Root throw within the deforested watershed is eliminated as a significant process for several decades until regeneration trees are large enough to be subject to blowdown. Rates of other hillslope and channel processes and channel storage conditions may all vary somewhat out of phase with one another, although there is some degree of interdependence since hillslope processes supply material for transport by channel processes.

To fully assess effects of ecosystem disturbance on material transfer, a broad historical perspective is needed. Typically in the assessment of management impacts, manipulated systems are compared with forested reference or benchmark watersheds; however, most natural, unmanaged watersheds are subject to periodic severe disturbance. Consequently material transfer history under both managed and natural conditions is composed of periods with transfer rates characteristic of established forest conditions interspersed with periods of accelerated transfer spanning up to several decades following severe disturbance of the ecosystem.

In many Pacific Northwest *Pseudotsuga menziesii* forests, natural pre-management disturbances during the past 1000 years have been predominantly major crown fires with a return period of several centuries. Erosional consequences of this type of disturbance are doubtless great, but unknown in steep landscapes. Timber harvest in this area is expected to recur at 80 to 100-year intervals, and its consequence in terms of material transfer is understood in only a preliminary fashion. Based on these assumptions and data, we construct a hypothetical variation in sediment yield from watershed 10 relative to a 500-year history of wildfire and a projected pattern of future management activities and related accelerated material transfer (Figure 8.5). Clear understanding of timber management impact in such a long-term perspective will require knowledge of frequency and consequences of both management and natural pre-management disturbances of the ecosystem.
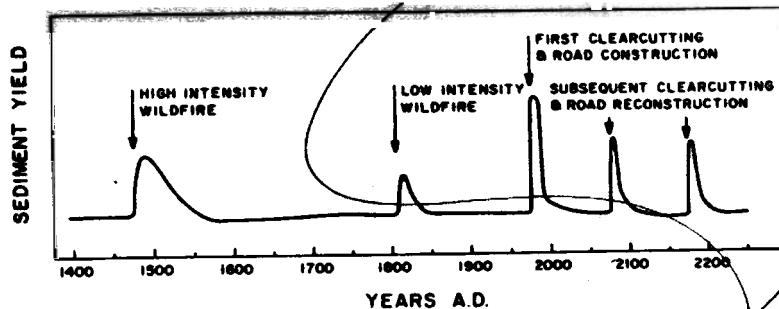
FIGURE 8.5   *Hypothetical history of sediment yield in response to vegetation disturbances on watershed 10.*

SUMMARY

Physical transfer of organic and inorganic matter is an important part of ecosystem behavior. At the system level, physical processes of material transfer account for principal nutrient cycling fluxes. From the standpoint of vegetation distribution, erosion and deposition create constrasting habitat opportunities for aquatic and terrestrial organisms. Erosion also reduces the nutrient capital of a site and affects the course of succession.

Material transfer in steep, forested watersheds of the coniferous forest biome is accomplished by processes that interact with one another and with various components of vegetation. The principal hillslope processes are solution transfer, litterfall, surface erosion, debris avalanche, creep, root throw, slump, and earthflow. These processes supply organic and inorganic material to the channel where downstream transport then occurs as dissolved and suspended material, bedloads, and debris torrents.

These processes operate on a variety of scales in time and space. At one extreme, debris avalanches and torrents may occur in a small watershed only once every few centuries under forested conditions and an event affects only a small percentage of the landscape. On the other hand, creep, litterfall, and solution transfer operate continually over the entire watershed.

These processes are highly interactive. Some events may directly trigger other processes, as in the case of root throw, which may instantaneously initiate a debris avalanche. One process may also set the stage for the occurrence or acceleration of another process, such as the baring of mineral soil by root throw and debris avalanche, which leads to a period of increased surface erosion. Processes also supply material for transport by other processes, so that transfer of a particular particle of soil through a watershed occurs as a series of steps in a variety of modes of transport.

Vegetation increases the rates of some transfer processes while decreasing others. Rooting strength, the mass of vegetation on a hillslope, and hydrologic effects of vegetation regulate rates of debris avalanche, creep, slump, and earthflow activity. Root throw occurs because standing trees serve as a medium for transfer of wind stress to the soil mantle. Nutrient uptake by plants and other processes regulate export of dissolved material. Litterfall results in a net downslope transfer of particulate organic matter as a result of nutrient uptake, incorporation into biomass, and subsequent abscission or pruning by wind or other means. Large woody debris forms retention structures in streams and regulates particulate matter transport by stream processes.

Studies in a small (10-ha) western Oregon watershed and adjacent areas have quantified transfer process rates in an example of an old-growth *Pseudotsuga menziesii/Tsuga heterophylla* ecosystem. Excluding debris torrents, total export is estimated to be 500 $kg \cdot ha^{-1} \cdot yr^{-1}$, of which 6 percent is dissolved organic matter, 60 percent dissolved inorganic matter, 8 percent particulate

organic matter, and 26 percent particulate inorganic matter. Total export including debris torrents is 990 $kg \cdot ha^{-1} \cdot yr^{-1}$.

Even excluding from consideration debris torrents, the values for each of these forms of export exceed similar estimates for watershed 6 in the fifty-five-year-old hardwood forest at Hubbard Brook, New Hampshire. Higher export values from the Oregon watershed are mainly a result of its higher annual runoff, more readily weathered bedrock and soil, warmer environments for weathering and decomposition, steeper hillslopes, higher litterfall rates, and greater standing crop of living and dead biomass.

Transfer of inorganic matter appears to be dominated by episodic processes, debris avalanches, and torrents. Solution transfer of inorganic matter is second in importance, followed by suspended sediment and bedload transport in the channel and creep, surface erosion, and root throw from hillslopes.

The relative importance of processes in organic matter transport is less varied. The magnitude of importance of episodic processes suggests that nutrient cycling studies based on short-term records may lead to misleading conclusions concerning long-term ecosystem behavior.

The rate of each process varies in response to ecosystem perturbations as a result of numerous interactions between vegetation and transfer processes. The magnitude and duration of rate increases or decreases vary widely from process to process, depending on the type of ecosystem disturbance. For example, clearcutting eliminates root throw while increasing debris avalanche occurrence by several times over a period of one to two decades. Timing of recovery of various process rates to levels typical of forested conditions is dependent on rates of recovery of key components of vegetation.

Short-term comparisons of transfer rates under clearcut conditions with forested conditions may not yield realistic estimates of management impacts on long-term soil loss. In forests of the Pacific Northwest, long-term erosion history under both natural and human-influenced conditions involves long periods with only minor year-to-year fluctuations interrupted by periods of severe ecosystem disturbance and resulting pulses of accelerated material transfer. Clearcutting and road construction have replaced wildfire as major disturbances of these forests and landscapes. Therefore assessment of management impacts requires knowledge of the frequency and consequences of both management and premanagement disturbances.

LITERATURE CITED

Anderson, H. W., 1969, Snowpack management, in *Snow*, Seminar of Oregon Water Resources Research Institute, Oregon State University, Corvallis, pp. 27–40.

Anderson, H. W., G. B. Coleman, and P. J. Zinke, 1959, Summer slides and

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winter scour—Dry-wet erosion in southern California mountains, *U.S. Department of Agriculture Forest Service Technical Paper PSW-36*, Berkeley, Calif., 12p.

Benedict, J. B., 1970, Downslope soil movement in a Colorado alpine region: Rates, processes and climatic significance, *Arct. and Alpine Res.* 2:165–226.

Bishop, D. M., and M. E. Stevens, 1964, Landslides on logged areas in southeast Alaska, *U.S. Department of Agriculture Forest Service Research Paper NOR-1*, Juneau, Alaska, 18p.

Bormann, F. H., G. E. Likens, and J. S. Eaton, 1969, Biotic regulation of particulate and solution losses from a forest ecosystem, *BioScience* 19:600–610.

Bormann, F. H., T. G. Siccama, G. E. Likens, and R. H. Whittaker, 1970, The Hubbard Brook ecosystem study: Composition and dynamics of the tree stratum, *Ecol. Monogr.* 40:373–388.

Bormann, F. H., G. E. Likens, T. G. Siccama, R. S. Pierce, and J. S. Eaton, 1974, The export of nutrients and recovery of stable conditions following deforestation at Hubbard Brook, *Ecol. Monogr.* 44:255–277.

Brown, C. B., and M. S. Sheu, 1975, Effects of deforestation on slopes, *J. Geotech. Eng. Div., Am. Soc. Eng.* 101:147–165.

Brown, G. W., and J. T. Krygier, 1971, Clear-cut logging and sediment production in the Oregon Coast Range, *Water Resour. Res.* 7:1189–1198.

Caine, N., 1976, A uniform measure of subaerial erosion, *Geol. Soc. Am. Bull.* 87:137–140.

Cleaves, E. T., A. E. Godfrey, and O. P. Bricker, 1970, Geochemical balance of a small watershed and its geochemical implications, *Geol. Soc. Am. Bull.* 81:3015–3032.

Dalrymple, T., 1965, Flood peak runoff and associated precipitation in selected drainage basins in the United States, *U.S. Geological Survey Water-Supply Paper 1813*, Washington, D.C., 406p.

Day, N. F., and W. F. Megahan, 1975, Landslide occurrence on the Clearwater National Forest, 1974, *Geol. Soc. Am. Abstr. with Prog.* 7:602–603.

Denny, C. S., and J. C. Goodlett, 1956, Microrelief resulting from fallen trees, in *Surficial Geology and Geomorphology of Potter County, Pennsylvania*, C. S. Denny, ed., U.S. Geological Survey Professional Paper 288, Washington, D.C., pp. 59–72.

Dietrich, W. E., and T. Dunne, 1978, Sediment budget for a small catchment in mountainous terrain, *Zeit. Geomorph. Suppl.* 29:191–206.

Dyrness, C. T., 1967, Mass soil movements in the H. J. Andrews Experimental Forest, *U.S. Department of Agriculture Forest Service Research Paper PNW-42*, 12p.

Federer, C. A., 1973, Annual cycles of soil and water temperatures at Hubbard Brook, *U.S. Department of Agriculture Forest Service Research Note NE-167*, Portland, Oreg., 7p.

Fish, B. R., 1972, Electric generation of natural aerosols from vegetation, *Science* 175:1239–1240.

Fredriksen, R. L., 1965, Christmas storm damage on the H. J. Andrews Experimental Forest, *U.S. Department of Agriculture Forest Service Research Note PNW-29*, Portland, Oreg., 11p.

Fredriksen, R. L., 1969, A battery-powered proportional stream water sampler, *Water Resour. Res.* 5:1410–1413.

Fredriksen, R. L., 1970, Erosion and sedimentation following road construction and timber harvest on unstable soils in three small western Oregon watersheds, *U.S. Department of Agriculture Forest Service Research Paper PNW-104*, Portland, Oreg., 15p.

Fredriksen, R. L., 1971, Comparative chemical quality—Natural and disturbed streams following logging and slash burning, in *Forest Land Uses and Stream Environment*, J. T. Krygier and J. D. Hall, eds., Continuing Education, Oregon State University, Corvallis, pp. 125–137.

Fredriksen, R. L., 1972, Nutrient budget for a Douglas-fir forest on an experimental watershed in western Oregon, in *Proceedings—Research on Coniferous Forest Ecosystems—A Symposium*, J. F. Franklin, L. J. Dempster, and R. H. Waring, eds., U.S. Department of Agriculture Forest Service, Portland, Oreg., pp. 115–131.

Fredriksen, R. L., 1975, Nitrogen, phosphorous and particulate matter budgets of five coniferous forest ecosystems in the western Cascades Range, Oregon, Ph.D. dissertation, Oregon State University, Corvallis, 127p.

Fredriksen, R. L., D. G. Moore, and L. A. Norris, 1975, The impact of timber harvest, fertilization and herbicide treatment on streamwater quality in western Oregon and Washington, in *Forest Soils and Forest Land Management*, B. Bernier and C. H. Winget, eds., Les Presses de l'Université Laval, Quebec, pp. 283–313.

Froehlich, H. A., 1973, Natural and man-caused slash in headwater streams, *Loggers Handb.* 33:15–17, 66–70, 82–86.

Froehlich, H. A., D. McGreer, and J. R. Sedell, 1972, Natural debris within the stream environment, *US/IBP Coniferous Forest Biome Internal Report No. 96*, University of Washington, Seattle, 7p.

Gosz, J. R., G. E. Likens, and F. H. Bormann, 1976, Organic matter and nutrient dynamics of the forest and forest floor in the Hubbard Brook forest, *Oecologia* 22:305–320.

Gray, D. H., 1970, Effects of forest clearcutting on the stability of natural slopes, *Assoc. Eng. Geol. Bull.* 7:45–77.

Grier, C. C., and R. S. Logan, 1977, Old-growth *Pseudotsuga menziesii* communities of a western Oregon watershed: Biomass distribution and production budgets, *Ecol. Monogr.* 47:373–400.

Hack, J. T., and J. C. Goodlett, 1960, Geomorphology and forest ecology of a mountain region in the central Appalachians, *U.S. Geological Survey Professional Paper 347*, Washington, D.C., 66p.

Harr, R. D., 1976, Forest practices and stream flow in western Oregon, *U.S. Department of Agriculture Forest Service General Technical Report PNW-49*, Portland, Oreg., 18p.

Harr, R. D., 1977, Water flux in soil and subsoil on a steep forested slope, *J. Hydrol.* 33:37-58.

Harr, R. D., and F. M. McCorison, 1979, Initial effects of clearcut logging on size and timing of peak flows in a small watershed in western Oregon, *Water Resour. Res.* 15:90-94.

Jäckli, H., 1957, Gegenwartsgeologie des bundnerischen Rheingebietes-ein Beitrag sur exogenen dynamik alpiner gebirgslandschaften. *Beiträge zur geologie der Schweiz, Geotechnische serie Leiferung 36,* 126p.

Janda, R. J., K. M. Nolan, D. R. Harden, and S. M. Colman, 1975, Watershed conditions in the drainage basin of Redwood Creek, Humboldt County, California, *U.S. Geological Survey Open-File Report 75-568,* Menlo Park, Calif., 266p.

Keller, E. M., and F. J. Swanson, 1979, Effects of large organic material on channel form and fluvial processes, *Earth Surface Process.* 4:361-380.

Leopold, L. B., M. G. Wolman, and J. P. Miller, 1964, *Fluvial Processes in Geomorphology,* W. H. Freeman, San Francisco, 522p.

Leopold, L. B., W. W. Emmett, and R. M. Myrick, 1966, Channel and hillslope processes in a semiarid area, New Mexico, *U.S. Geological Survey Professional Paper 352-G,* Washington, D.C., 61p.

Likens, G. E., F. H. Bormann, R. S. Pierce, J. S. Eaton, and N. M. Johnson, 1977, *Biogeochemistry of a Forested Ecosystem,* Springer-Verlag, New York, 146p.

Marchand, D. E., 1971, Rates and modes of denudation, White Mountains, eastern California, *Am. J. Sci.* 270:109-135.

Marchand, D. E., 1974, Chemical weathering, soil development and geochemical fractionation in a part of the White Mountains, Mono and Inyo Counties, California, *U.S. Geological Survey Professional Paper 352-J,* Washington, D.C., 46p.

Mersereau, R. C., and C. T. Dyrness, 1972, Accelerated mass wasting after logging and slash burning in western Oregon, *J. Soil Water Conserv.* 27:112-114.

Nakano, H., 1971, *Soil and Water Conservation Functions of Forest on Mountainous Lands,* Report of Forest Influences Division, Government Forest Experiment Station, Japan, 66p.

Peck, D. L., A. B. Griggs, H. G. Schlicker, F. G. Wells, and H. M. Dole, 1964, Geology of the central and northern parts of the western Cascade Range in Oregon, *U.S. Geological Survey Professional Paper 449,* Washington, D.C., 56p.

Rapp, A., 1960, Recent development of mountain slopes in Karkevagge and surrounding, northern Scandinavia, *Geogr. Ann.* 42:71-200.

Rothacher, J., and T. B. Glazebrook, 1968, Flood damage in the national

forests of Region 6, *U.S. Department of Agriculture Forest Service,* Portland, Oreg. 20p.

Rothacher, J., C. T. Dyrness, and R. L. Fredriksen, 1967, Hydrologic and related characteristics of three small watersheds in the Oregon Cascades, *U.S. Department of Agriculture Forest Service Miscellaneous Publication,* U.S. Department of Agriculture Forest Service, Portland, Oreg., 54p.

Santantonio, D., R. K. Hermann, and W. S. Overton, 1977, Root biomass studies in forest ecosystems, *Pedobiologia* **17:**1–31.

Sedell, J. R., and F. J. Triska, 1977, Biological consequences of large organic debris in Northwest streams, in *Logging Debris in Streams, II: Forestry Extension Workshop,* G. D. Wingate, compiler, 21–22 March 1977, Oregon State University, Corvallis, Oreg., 10p.

Stone, E. L., 1975, Windthrow influences on spatial heterogeneity in a forest soil, *Mitt. Eidg. Anst. Forstl. Versuchswes.* **51:**77–87.

Swanson, F. J., and C. T. Dyrness, 1975, Impact of clearcutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon, *Geology* **3:**393–396.

Swanson, F. J., and M. E. James, 1975, Geology and geomorphology of the H. J. Andrews Experimental Forest, western Cascades, Oregon, *U.S. Department of Agriculture Forest Service Research Paper PNW-188,* Portland, Oreg., 14p.

Swanson, F. J., and D. N. Swanston, 1977, Complex mass-movement terrains in the western Cascade Range, Oregon, *Rev. Eng. Geol.* **3:**113–124.

Swanson, F. J., G. W. Lienkaemper, and J. R. Sedell, 1976, History, physical effects and management implications of large organic debris in western Oregon streams, *U.S. Department of Agriculture Forest Service General Technical Report PNW-56,* Portland, Oreg., 15p.

Swanston, D. N., 1969, Mass wasting in coastal Alaska, *U.S. Department of Agriculture Forest Service Research Paper PNW-83,* Portland, Oreg., 15p.

Swanston, D. N., 1970, Mechanics of debris avalanching in shallow till soils of southeast Alaska, *U.S. Department of Agriculture Forest Service Research Paper PNW-103,* Portland, Oreg., 17p.

Terzaghi, K., 1950, Mechanism of landslides, in *Application of Geology to Engineering Practice,* S. Paige, ed., Berkey Volume, Geological Society of America, Boulder, Colo., pp. 83–123.

Varnes, D. J., 1958, Landslide types and processes, in *Landslides and Engineering Practice,* E. B. Eckel, ed., Highway Research Board Special Publication 29, Washington, D.C., pp. 20–47.

Waananen, A. O., D. D. Harris, and R. C. Williams, 1971, Floods of December 1964 and January 1965 in the far western states, Part 1: Description, *U.S. Geological Survey Water-Supply Paper 1866-A,* Washington, D.C., 265p.

Waring, R. H., H. R. Holbo, R. P. Bueb, and R. L. Fredriksen, 1978, Documentation of meteorological data from the Coniferous Forest Biome primary station in Oregon, *U.S. Department of Agriculture Forest Service General Technical Report PNW-73*, Portland, Oreg., 23p.

In: Edmonds, Robert L., ed. Analysis of coniferous forest ecosystems in the western United States. US/IBP Synthesis Series 14. Stroudsburg, PA: Hutchinson Ross Publishing Company; 1982. Reproduced by USDA Forest Service, for official use.