Streamside Management:
Forestry and Fishery Interactions

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CHAPTER TWO

Mass Failures and Other Processes of Sediment Production in Pacific Northwest Forest Landscapes

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ABSTRACT Accelerated sediment production by mass failures and other erosion processes is an important link between management of forest resources and fish resources. Dominant processes and the rates of sediment production vary greatly throughout the Pacific Northwest in response to geologic and climatic factors. The complex sediment routing systems characteristic of the area involve numerous processes that move soil down hillslopes and sediment through channels. Sediment routing models and sediment budgets offer conceptual and quantitative descriptions of movement and storage of soil and sediment in drainage basins. Temporal and spatial patterns of sediment production and routing through basins have many direct and indirect effects on fish.

In addition to their role as dominant mechanisms of sediment production in many parts of the region, mass failures also affect the geometry and disturbance regimes of channels and streamside areas. Earth flows locally control the vegetation structure and composition of riparian zones through influences on valley floor width, gradient of side slopes and channels, and frequency of streamside debris slides. Debris flows can have long-term effects on channels and streamside landforms and vegetation. It is important to consider sediment production and the effects of mass failures on channels and riparian zones in the context of an entire drainage basin, because effects vary with location in a basin.

Forestry practices can increase production of sediment. Results of experimental manipulations of vegetation on small drainage basins and studies of individual erosion processes indicate that debris slides and road surfaces are commonly dominant sources of accelerated sediment production. Some techniques are available for locating sites susceptible to accelerated erosion, for predicting change in sediment production, for evaluating the biological consequences of accelerated erosion, and for designing mitigation measures, but clearly more work is needed in each of these areas.

Two major links between forestry and fisheries management are sediment delivery to streams by a variety of erosion processes and the dramatic effects of debris slides and flows on valley floor geomorphology and stream ecosystems. Recognition of these links over the past two decades is embodied in legislation, litigation, and promulgation of forest practice rules.

Clearly, the subject of this paper--mass failures and other processes of sediment production--has strong links with all other variables affecting fish habitat and all other topics in this symposium. The abundance, timing, and size distribution of sediment delivered to streams and the flow regime determine the frequency, persistence, and mechanisms of sediment transport. Rate of sediment transport and direct impact by mass movement events strongly influence riparian vegetation, which, in turn, regulates the food base of the aquatic system by litter input and by the effects of shade on water temperature and primary production. Riparian vegetation is also the source of large woody debris for stream ecosystems. The effects of mass movement processes on delivery, redistribution, and removal of large woody debris in streams have important consequences for habitat structure. We do not discuss these interactions, but rather lay a foundation for subsequent papers dealing with these topics.

The literature on sediment production from hillslopes in various natural and managed conditions and effects of sediment on fish is extensive; a thorough review is beyond the scope of this paper. Research on effects of forest practices on sediment production and landslides has increased greatly over the past few decades, but the overall appraisal of erosional consequences of timber harvest has changed little since the review by Rice et al. (1971) . In the past fifteen years, some important new concepts have been developed and applied, notably sediment budgets and routing (Dietrich and Dunne 1978, Dietrich et al. 1982, Lehre 1982) . Most of the ingredients in fish-forestry interactions were recognized fifteen years ago (Krygier and Hall 1971) , but several aspects of the problem have gained increased prominence, especially the roles of large woody debris, reviewed by Bisson et al. in this volume, and efforts at more holistic thinking about forest-stream interactions (Swanson et al. 1982b).

Our objective is to paint a broad picture of sediment production in natural and managed drainage basins and to discuss some of the different, direct effects of slope movements on valley floors, channels, and riparian zones. Specifically, we mainly discuss three subjects: (1) the geomorphic setting of fishery-forestry interactions in the Pacific Northwest, (2) sediment sources under natural conditions and in response to forestry practices, and (3) approaches to minimizing effects of forestry practices on sediment production.

THE GEOMORPHIC SETTING. OF FISHERY-FORESTRY INTERACTIONS IN THE PACIFIC NORTHWEST

A discussion of fishery-forestry interactions and sediment production should be in the context of the general geomorphic setting of the Pacific Northwest, here defined as northern California, Oregon, Washington, Idaho, and southeastern Alaska. We emphasize areas west of the crest of the Cascade Range where timber and fisheries values are highest and the bulk of research on fishery-forestry interactions has been conducted. The area comprises geologic terranes with a remarkable variety of landforms, dominant geomorphic processes, and rates of sediment production. This diversity of landforms and processes is controlled strongly by rate and recency of uplift, by hydrologic and geotechnical properties of soils and rocks, and by precipitation. Fishery-forestry interactions should also be examined in relation to regional gradients in climate, stream hydrology, vegetation type and history, management history of channel morphology, and other factors beyond the scope of this paper.

The efficiency of sediment delivery from hillslopes to channels and from tributary streams to main-stem rivers also varies across the region. Sediment delivery is efficient, for example, in areas of short, steep slopes and narrow valley floors, such as in low coastal basins from the Willapa Hills south through the Oregon Coast Range. Where glaciation and fluvio-glacial outwash have formed valleys with steep sides and broad, flat floors, debris slides from valley walls and debris flows in tributary channels commonly do not reach the main channel. Sediment delivery efficiency can vary greatly even within a single basin.

Rates of suspended sediment yield from drainage basins of 100 km^2 and larger vary by more than two orders of magnitude and range from less than 200 t/km^2 per year on some Idaho rivers and coastal rivers of western Oregon and Washington to 2,000 to 3,000 t/km^2 per year on Mad River, Eel River, and Redwood Creek in northern California (summarized in Karlin 1980 from USGS Water Data Reports for Oregon, Washington, and California, 1962-75; Brown 1973; and Janda 1978) . The highest reported value for suspended sediment yield for the region is 35,600 t/km^2 per year on the North Fork Toutle River in the first three years after the 1980 eruption of Mount St. Helens (Janda et al. 1984) . Although no systematic comparison of these very different river systems has been undertaken, there are dramatic contrasts in channel structure, water quality, and streambed conditions that affect fish.

Sediment sources in the Pacific Northwest also exhibit great variability from year to year, because large, infrequent storms trigger mass failures delivering major pulses of sediment to channels and increase the ability of streams to mobilize and transport stored sediment. Furthermore, infrequent changes in the sensitivity of landscapes to accelerated erosion result from periodic wildfire and logging. These broad-scale disturbances of forest vegetation can lead to brief periods of dramatically increased sediment production.

SEDIMENT SOURCES IN PACIFIC NORTHWEST FOREST LAND

Sediment Routing and Budget Perspective

Sediment sources should be considered from a systems perspective that recognizes detachment, transport, and storage of material. (Sediment in the context of routing and budget studies refers to both soil and sediment.) Sediment within a drainage basin is in temporary storage in a variety of storage sites. Soil is transported periodically down hillslopes until it enters channels where it becomes sediment that can be transported by fluvial processes. Mobilized material is either transported to another storage site in the basin or it is exported out of the system. In steep landscapes, commonly four to six hillslope proc esses and three to four channel processes are significant mechanisms of sediment transport. Processes may interact in series or in parallel. Such a geomorphic system of storage sites and transfer processes may be referred to as a sediment routing system and can be depicted as a flow chart (for example, see Dietrich and Dunne 1978, Reid 1982) and described quantitatively in a sediment budget.

Descriptions of sediment routing systems and budgets are useful concepts for discussing sediment sources and production. The ingre- dients in the analysis of a sediment routing system are (1) identification of transfer processes, storage sites, and links among them and (2) quantification of the rates of transfer of soil, the volumes of material in storage, and modification of sediment size distribution while the sed iment is in transit or in storage (Dietrich et al. 1982) . Process- and basin-level scales of evaluating sediment production can be joined in studies of sediment budgets. Such a systems approach encourages recognition of all significant elements of the system.

Review of the few sediment budget studies for forested areas in the Pacific Northwest reveals both striking differences and similarities among studies to date (Table 1) . The major common theme of these studies is the importance of localized sediment sources such as mass failures of various types and gullies; however, the types of processes and their relative importance vary greatly from one area to another. Strikingly different in the budgets are the definitions of processes contributing sediment to channels. These differences arise both from the nature of the geomorphic systems and the scale of area considered. Gully erosion on hillslopes, for example, is important in Redwood Creek, California, but not at Clearwater River, Washington, or Watershed 10, Oregon (Table 1) . Surface erosion, root throw, and animal burrowing are significant in smaller basins with slopes leading directly into channels, but may be less important in large basins, like the Van Duzen River, California, where other processes contribute to extremely high sediment yields. Suspended sediment yield from Redwood Creek, the Van Duzen River, and other basins in northwestern California are naturally very high as a result of sediment production from gullies and large earth flows. Sediment yield from these basins has been increased by management activities, principally by altering the natural drainage network through construction of roads and skid trails (Nolan and Janda 1981) .

Sediment budgets, however, are. only as good as the observational data and as the knowledge of links among processes used in budget development. Unfortunately, process-level data necessary for budgets are meager, especially for the episodic mass failure processes that can dominate sediment production in steep, unstable basins. Furthermore, models of sediment routing are frequently wrong, because appropriate models of runoff processes or erosion and transport mechanisms are missing or misapplied (Dunne 1982) . Data on sediment yield from gauged basins are an important source of information for constraining budgets.

Table 1. Summary of site descriptions and estimates of sediment production for four drainage basins where sediment budgets have been compiled.

	Clearwater River, Western Washington (Reid 1981)	Watershed 10 Cascade Range, Oregon (Swanson et al. 1982a)	Redwood Creek, California Above Highway 299 (Kelsey et al. 1981)	Van Duzen River Above USGS Gauge 11-4785 (Kelsey 1980)
Drainage area (km 2)	10	0.1	175	5TS
Period of record	*	*	1956-80	1941-75
Forest type	Western hemlock and silver fir	Old-growth Douglas-fir	Douglas-fir	Douglas-fir
Forest condition	Old-growth	Old-growth	Grassland logged 1940-70	Grassland logging, grazing
Geology	Miocene sedimentary	Tertiary volcanic sediments	Mesozoic deformed sedimentary and metamorphic rocks	Mesozoic deformed sandstone and melange
Sediment Delivery to Channel (t/km^2 per year)				
Mass Failure Processes:				
Rapid/debris slides, avalanches, flows	38	60	1, 240	522
Earth flows	0	0		146
Soil creep	29	11		
Other Processes:				
Tree throw	9	1		
Animal burrows	4			
Other surface erosion		5		
Fluvial erosion for hillslopes (mainly gullies)			2,590	2,270

* These are synthetic budgets incorporating measurements of sediment movement over different periods for different processes.

Individual Erosion Processes

Interest in sediment sources typically focuses on individual erosion processes; and in steep landscapes, mass failures usually draw the most attention. Here, we distinguish several types of mass failures and surface erosion processes and consider their rates of sediment production under natural and managed conditions.

Debris Slides: Rapid Mass Failures on Hillslopes. Debris slides and other small, rapid mass failures are processes of particular importance in fishery-forestry interactions. These processes are studied on three scales: (1) individual slide-prone sites, 10 to 1,000 m^2; (2) soil and landform units by hectare; and (3) geologic terranes covering many square kilometers. At the finest of these scales, interest of West Coast geomorphologists centers on steep, concave, slide-prone portions of the landscape, variously termed bedrock hollows, swales, and headwalls. These hollows are perceived as concave depressions on bedrock with axes that extend downslope and commonly merge with the headward tip of a first-order channel. Steep hollows are envisioned as filling slowly with soil delivered predominantly by surface erosion, root throw, and soil creep and as emptying periodically by debris slides (Dietrich et al. 1982).

The frequency and average volume of slides from hollows and other topographic settings vary dramatically both within and between geologic terranes in this region. The recurrence interval of sliding from individual hollows may vary from a few centuries to more than 10, 000 years (Reneau and Dietrich 1985, Swanson and Roach 1985). Inventories of slides in areas larger than individual hollows stratified by geologic type or soil and landform type, such as the USDA Forest Service's Soil Resource Inventory, show distinct, quantitative differences in frequency of sliding among landform units mappable in units of 1 to 100 ha (Swanson and Grant 1982, Furbish and Rice 1983, Amaranthus et al. 1985).

Slide inventories conducted over areas of 10 to 100 km^2 reveal important differences in characteristics of slides from one geologic terrane to another (Amaranthus et al. 1985, Swanson and Lienkaemper 1985). Steep, intricately dissected areas, such as the Tertiary sedimentary rocks in the vicinity of Mapleton in the Coast Range of Oregon, have a high density of small, slide-prone hollows. Consequently, this area has a high frequency of slides with low average volume, compared with slides inventoried in a variety of sites in the Cascade Range (Swanson and Lienkaemper 1985). In these two cases the average soil transfer rates by sliding in forested areas are similar: 16 to 32 m^3/km^2 per year in the Coast Range ($n = 3$) and 36 to 45 m^3/km^2 per year in the Cascade Range ($n = 3$). In some areas, sliding is much less common; Schulz (1980), for example, measured a soil transfer rate by slides in forested areas of the Bull Run basin east of Portland, Oregon, of only 4 m^3/km^2 per year.

Measurement of the effects of forestry practices on occurrence of debris slides has also been based on inventory techniques. Ice (1985) catalogued forty-three sites or administrative units in the Pacific

Northwest where one or more inventories of debris slides and, in some cases, other mass wasting features have been conducted. In general, these studies conclude that clearcutting and broadcast burning increase soil movement by debris slides by two to four times the rate in forested areas for the ten to thirty year periods of the inventories. Slide erosion from roads can be several hundred times higher than in forested areas. The increased frequency of sliding in clearcuts is believed to result from reduced contribution of tree roots to soil strength (Gray and Megahan 1981, Ziemer 1981b) .

The relative importance of roads and clearcuts in accelerating sediment production by slides can vary significantly from one area to another and through time in a single area. In a summary of slide inventories for thirteen areas in the Pacific Northwest, Ice (1985) found that the ratio of in-unit to road-related "management erosion" ranged from 5:95 to 89:11. In eleven of the thirteen cases, roads contributed more than half of the accelerated erosion. It is important to make this comparison in light of the large differences in the area of the landscape affected by each management practice. The large impact from a small area of roads can equal or exceed the smaller impact of clearcutting over a larger area (Swanson and Dyrness 1975, McCashion and Rice 1983) . Roads remain a predominant source of accelerated sliding in many areas. The impact of roads on sliding is greatest where slopes are stable enough that slides in clearcuts are unusual, but where low investment in road construction and maintenance results in a high frequency of road-related slides. In at least one area, slide frequency appears to have decreased in relation to the frequency in clearcuts as a result of improvements in road location, construction methods, and maintenance procedures (Swanson et al. 1981) .

Debris Flows. The distinction between debris slides and debris flows, based o n whether the mass movement occurs on a hillslope or in a channel, is important for land management. This distinction, however, has not been made consistently in past inventories of mass movement events (Ice 1985). Only when consistent methods are used can results of inventories address such questions as: Did a debris flow originate on the hillslope or in the channel? What was the influence of management activities on the start or maximum volume of debris flows? How can that influence be mitigated? How much material moved by a debris flow represented soil erosion and how much was remobilized colluvium and alluvium that had been stored along the channel?

Debris flows, also termed channelized debris flows (Van Dine 1985) and debris torrents, recently have been the subject of much discussion and litigation. These events may begin as slope failures or as the result of mobilization of material in channels. Once started, debris flows can involve more than 10,000 m3 of soil, alluvium, and organic debris moving at a velocity in excess of 10 m/sec and can rearrange channel structure and riparian vegetation along their course. Debris flows may stop abruptly and leave deposits at channel junctions or on alluvial fans. Debris flows may also enter streams large enough that fluvial processes completely rework the debris flow material. In this case, no distinctive debris-flow deposit is left at the end of the tracks, but debris-laden surge of floodwaters may move downstream, batter streamside vegetation, and leave a series of discontinuous deposits (Benda 1985a, Grant 1986) .

A variety of mechanisms of debris flow initiation have been observed or hypothesized: (1) rapid slope movement (debris slide, snow avalanche, rockfall) that continues to move down an established channel (Swanson and Lienkaemper 1978, Van Dine 1985), (2) rapid slope movement that temporarily dams a stream before it fails and moves rapidly downstream, (3) mobilization of sediment at critical stream discharge or shear stress (Takahashi 1978) or by undrained loading (Sassa et al. 1985), and (4) mobilization of large woody debris in channels.

Small slides often form debris flows that ultimately entrain large volumes of material along first- and second-order channels. Benda (unpublished data) calculated a soil transfer rate of 31 m^3/km^2 per year for slides that triggered debris flows during a thirty-year period for a site in the Oregon Coast Range. (Soil transfer rate is based on the volume of soil removed from slide scars; it does not equate with sediment delivery to streams.) With the addition of material eroded from the channel bed and banks by the debris flows, the transfer rate increased to 135 m^3/km^2 per year.

The relative importance of different initiating sites and mechanisms undoubtedly varies from one geologic-climatic setting to another, and few studies provide any systematic basis for comparison. In a review of thirty-four studies in the southern Canadian Cordillera, Van Dine (1985) found thirteen cases where debris, avalanches and slides were identified as causes of debris flows. The triggering of debris flows by fluvial erosion of channel bed and bank deposits, the second most common cause, was identified specifically in only four cases. Similarly, studies along the west side of the Cascade Range in Oregon found that forty-four of fifty-three inventoried debris flows were triggered by slope failures (Morrison 1975, Swanson and Lienkaemper 1978). The other nine were apparently begun by mobilization of debris in channels. The slope failures that triggered these debris flows originated in a variety of hillslope locations, including toes of earth flows and slumps, road-fill failures, and bedrock hollows (see Dietrich and Dunne 1978, Dietrich et al. 1982) . In a sample of thrity-six debris flows in Tertiary sedimentary rocks of the Oregon Coast Range, Benda (unpublished data) found that 50% originated at roads, 45% in clearcuts, and 5% in forested areas, with 78% of all the failures occurring in hollows.

The run-out distance and stopping location of a debris flow are determined by properties of the moving material (flow volumes, size distribution of particles, water content, volume of logs at the flow front) and the geometry, roughness, and permeability of the surface it flows over. Debris flows lose velocity where a channel widens; decrease in gradient; abruptly change direction; increase in roughness as a result of containing relatively immobile objects such as very large boulders, woody debris, standing trees, and fabricated structures; or flow onto an alluvial fan where water can infiltrate the bed (Benda 1985a, b; Van Dine 1985).

The relative importance of these factors in controlling where debris flows stop varies from one landscape to another. Benda (1985a, b) examined debris flow paths in sedimentary and basaltic terranes in the central Coast Range of Oregon and found that channel junctions were predominant sites of deposition. Junctions have the combined effects of decreased gradient, increased width, and the potential for abrupt change in channel direction. Benda (unpublished data) observed that 75% of forty-seven debris flows stopped in channels where gradients were less than or equal to 6.3%. Confluences of streams where junction angles approached 90 degrees were common stopping points for debris flows. Alluvial fans are a minor part of the Oregon Coast Range landscape, although some occur where first- to second-order channels enter third- to fourth-order channels. Consequently, alluvial fans were more important stopping sites for debris flows in Benda's study area than in other environments, such as the Rocky Mountains in Canada (Van Dine 1985), where alluvial fans are more widespread landforms and important sites of debris flow deposition. Debris flow deposition on fans results from decreased gradient, increased width, and porous beds of fan surfaces.

Debris flows alter channel structure, streamside landforms, riparian vegetation, and the size distribution of sediment in the streambed within and downstream of the zone of direct debris flow impact. Grant (1986) examined the distribution of channel units (e.g., pools, rapids, boulder cascades) in fourth- and fifth-order channels along the western Cascade Range, Oregon. The distribution of channel units was similar in stream reaches with and without debris flows in the floods of December 1964 and January 1965. This could have resulted from recovery of channel morphology in the twenty years since debris flow occurrence, or, less likely, the debris flows had no effect on channel morphology. Grant (1986) observed that streamside deposits, such as boulder berms, were formed by debris flows and associated debris-laden flood surges. These events reset streamside vegetation and moved large woody debris from the channel to floodplain areas. These observations suggest that the effects of debris flows on fish habitat in fourth- and fifth-order channels may reflect primarily changes in streamside vegetation and large woody debris rather than changes in channel structure.

Everest and Meehan (1981) arrive at a contrary conclusion based on studies along Knowles Creek, an Oregon Coast Range stream flowing over sandstone bedrock. In that system, where fishery productivity is limited by pool habitat, boulders and woody debris delivered from tributary channels by debris flows can enhance fish habitat by creating pools in the main stem. Effects of debris flows on the size distribution of sediment and on aquatic organisms are discussed by Everest and Meehan (1981) and Everest et al. (this volume).

Recovery of vegetation in debris flow-affected channels is conspicuously different from revegetation along second-order channels in clearcuts without debris flows, but this is not documented quantitatively in the literature. S. Cline (unpublished data) sampled above-ground biomass along a chronosequence of streamside areas eight to thirty-five years after clearcutting which in several cases had experienced debris flows. The rate of accumulation of aboveground biomass was substantially greater along channels affected by both clearcutting and debris flows than where vegetation was clearcut only. The abundance of bare mineral soil left along a debris flow track favored establishment of fast-growing red alder (Alnus rubra).

The few available inventories of debris flows provide an indication of the effect of forestry practices on debris flow occurrence. Using inventory data from the Cascade Range and Coast Range in Oregon, Swanson and Lienkaemper (1978) argue that forest management had substantially increased the incidence of debris flows, primarily by increasing the frequency of debris slides from hillslopes. In addition, how often debris flows begin as a result of debris movement in channels can be increased as a result of decreasing the size of distribution of large woody debris in channels by bucking and removing large pieces and by allowing slash to enter channels. Large pieces of woody debris in very steep firstand second-order channels may act as natural check dams that prevent fine slash from being mobilized and triggering a debris flow in downstream reaches. Ketcheson and Froehlich (1978) observed that debris flows from clearcuts traveled farther ($\bar{x}$ = 100 m, n = 33 for flows ≥ 10 yd^3 at the initiation site) than debris flows from forested areas ($\bar{x}$ = 65 m, n = 35).

The proportion of area affected by mass failures differs dramatically between hillslope and channel environments. Even after major storms in steep lands trigger numerous slides, commonly less than 1% of the landscape is in slide scars, but debris flows can scour well over 10% of the channel network (Swanson and Lienkaemper 1978). In study basins in the Oregon Coast Range and the Cascade Range the greatest extent of stream length directly affected by debris flows over twenty to thirty year periods was in second- and third-order channels. Debris flows are routed down a few of the numerous and relatively short first-order channels before passing into the less numerous second- and third-order streams. Channel gradients in lower thirdorder and upper fourth-order streams are low enough that debris flows stop moving. This is a result of the effect of topography channeling mass movement down the drainage network.

Slump, Earth Flow, Soil Creep. Slumps, earth flows, and soil creep are widespread, locally important sources of sediment. Earth flows are large, periodically active, generally slow-moving, translational mass failures that occupy 10 to 20% of some mountain landscapes in the Pacific Northwest. Large earth flows may have lifetimes of 10, 000 years or more, made up of periods of dormancy interspersed with periods of movement. Slumps are generally smaller, periodically active, commonly slow-moving, rotational mass failures. The effect of management activities on slumps and earth flows is conspicuous where excavation or alteration of drainage has destabilized dormant slumps and earth flows.

Recently, progress has been made in the development of a theoretical framework for creep and earth flow mechanics, using sites in the Redwood Creek basin, California (Iverson 1985, in press). In another study in the same area, various combinations of creep and earth flow movement varied from 0.5 to 104 mm/yr over an eight year period based on measurements made with inclinometer tubes (Swanston et al. 1983) . Movement rate correlated well with an index of accumulated daily antecedent precipitation for the periods between measurements of tube deformation (Ziemer 1984).

The effect of removing trees on slumps and earth flows is open to debate. It is generally believed that weight of trees and strength of tree roots have only a trivial effect on stability of mass failure features with depths greater than a few meters. The strong response of movement rate to water input (Ziemer 1984, and others) suggests, however, that reduced evapotranspiration following timber harvest or other events, such as wildfire or defoliation by insects, could lead to periods of accelerated movement.

Soil creep operates at a very slow rate, but it is considered to be widespread and therefore potentially important in yielding sediment where the toes of hillslopes creep into small channels (Swanston 1981). Finlayson (1985), in a paper provocatively titled "Soil Creep: A Formidable Fossil of Misconception," argues that we know little of the mechanisms and rates of soil creep in any environment. Long-term studies of soil creep rates and the distribution of creep rate with depth are rare in the Pacific Northwest, and it is commonly difficult in the available records to distinguish widespread soil creep from more localized plastic creep associated with earth flows.

Surface Erosion. Surface erosion on steep, forested slopes in the region is another family of processes that is poorly understood. The Universal Soil Loss Equation (USLE) has been used with success by land managers wishing to estimate surface erosion by overland flow. However, overland flow on natural forest floors is exceedingly rare in most of the Pacific Northwest, because of low precipitation intensities and high infiltration capacities. Overland flow is common locally on severely disturbed sites. A variety of other surface processes, such as dry ravel, rain and throughfall drop splash, animal activity, and freeze-thaw phenomena, appear to operate on steep, forest soils in the region.

Several studies document surface movement of soil and organic material on steep (>50% slope gradient), forested hillslopes. Measurements of soil erosion during and after slash burns and wildfires indicate that dry ravel and, to a lesser extent, overland flow on hydrophobic soil surfaces can result in substantial soil movement (Megahan and Molitor 1975, Bennett 1982) . Dry ravel is a widespread phenomenon particularly in dryer parts of the region such as Idaho (Megahan and Molitor 1975,), southwestern Oregon (McNabb 1985), and parts of the Oregon Cascades (Mersereau and Dyrness 1972). Ravel occurs primarily on steep (>60% slope gradient) areas, even under natural forest cover. Burning greatly accelerates the rate of ravel by removing live and dead organic matter that binds soil particles together.

Effects of forestry practices on surface erosion have been investigated with plot studies before and after logging and slash burning.

The rate of increase in surface erosion varied with treatment. McCorison (data) observed a fourfold increase in the transport of surface material to the stream draining a 10 ha basin (HJA10, Table 2) over a 3.75 year period after clearcutting an old-growth forest without broadcast burning on slopes with average gradients of 60%. Clearcutting and hot broadcast burning on slopes steeper than 60% in the Oregon Coast Range resulted in 224 m^3/ha of surface erosion from sample plots over the first posttreatment year (Bennett 1982) . This was ten times greater erosion than that observed on gentler slopes. Remarkably, two-thirds of the first-year erosion on these steeper slopes occurred in the twenty-four hours beginning with the burn. These surface erosion rates measured on small plots in Bennett's study do not constitute sediment delivery to channels. Bennett (1982) measured no surface erosion on plots in forested areas.

Roads as Sediment Sources. Roads are important management-induced sources o se iment. The importance of debris slides resulting from road-fill failures was recognized in the earliest inventories of slides (Dyrness 1967) . In the redwood region of northern coastal California, haul roads and tractor skid roads caused extension and diversion of the drainage network. This altered both basin hydrology and sediment yield (Nolan and Janda 1981). Cederholm et al. (1981) drew attention to the importance of roads as sources of fine (<0.85 mm) sediment by reporting a significant ($r^2 = 0.62$, n = 45), positive correlation between the percentage of basin area in roads and the percentage of fine sediment in spawning gravels as sampled on the Olympic Peninsula, Washington. Working in the same area, Reid (1981) and Reid and Dunne (1984) identified both road-related landslides and surfaces of heavily used logging roads as major sources of fine sediment. Duncan and Ward (1985) pointed out that geologic and soil conditions in a basin may strongly control the abundance and size distribution of fine sediment in spawning gravel. Bilby (1985) examined the size distribution of sediment contributed to streams from road surfaces and argued that most of the sediment was so fine (80% <0.004 mm) that it did not enter the streambed riffles. Despite the numerous studies of production and fate of fine sediment from roads, the overall question of effects of roads on fine sediment, and ultimately fish, is far from answered.

Rills, Gullies, and Other Sediment Sources. Erosion plots averaging 4.5 ha were use to assess the importance of rills, gullies, slides, and slumps in producing logging-related erosion in northern coastal California (Rice and Datzman 1981) . Gullies associated with roads and tractor skid trails, and slides in clearcuts, were dominant causes of accelerated erosion. This observation points up major differences in dominant erosion processes in various parts of the region; in many other areas, gullies are of negligible significance. These differences are the result of both natural variability and contrasting logging practices.

Sediment Delivery

Results of studies of the rate of soil movement by individual processes do not necessarily represent sediment production, because material observed in movements down hillslopes may not enter the fluvial system. Sediment delivery of material mobilized by debris slides, for example, can vary greatly, depending on size distribution and water content of the mobilized material (Megahan et al. 1978) and the topography it moves over. In the Mapleton, Oregon, area, characterized by short, steep slopes and narrow valley floors, Swanson (data) observed a 70% delivery rate. This contrasts with the 10% delivery rate estimated by Megahan (1981) for slides in granular, granitic soils during dry years in the Idaho batholith.

Sediment delivery from roads to streams has recently been a subject of keen interest but of few published papers. Megahan et al. (in press) measured the delivery of sediment from roads to stream channels and storage sites on slopes in three steep, granitic basins in Idaho. This study employed a sediment budget approach for the four-month period of road construction for three intensities of erosion control practices. Of the sediment produced from roads in these 104 to 130 ha basins, 15% entered stream channels and 7% was delivered to the watershed outlet. The remainder was stored temporarily on hillslopes.

Sediment Production from Drainage Basins

Natural rates of sediment production and the effect of forestry practices on those rates have been examined based on analysis of sediment yield from large and small drainage basins. Anderson's studies (1954, 1972, 1981), in which he observed substantial effects from forest land use on suspended sediment discharge, remain virtually the only efforts at the scale of large (>100 km^2) drainage basins in the Pacific Northwest. Studies of this type are hindered by a lack of sediment discharge records for the rivers of this region.

Experimentally manipulating vegetation and constructing roads in small drainage basins have been widely used in the Pacific Northwest to examine effects of forest practices on hydrology, sediment, nutrients, and fish. Changes in mean annual suspended sediment yields provide one measure of effects of forestry practices on fish habitat. We make this evaluation by comparing data from twenty basins in seven sets of experimental basins (Table 2 and Figure 1) (based on data from Beschta 1978, Rice et al. 1979, and Larson and Sidle 1980). Although suspended sediment records exist for other sites in the region, the basins in western Oregon are emphasized because they represent a relatively narrow range of annual precipitation (1,200 to 2,600 mm), basin area (9 to 303 ha), period of observation (four to twelve years), and dominant land use (forestry only, no grazing). The background average suspended sediment yield from these terranes these basins are located in is generally low, probably less than 300 t/km^2 per year (Karlin 1980, Larson and Sidle 1980) .

Although interpretations of these data are limited by the diversity of treatments applied in this rather small sample of basins, several general observations can be made. Basin response reflects the interaction between intensity of disturbance and the sensitivity of a basin to accelerated erosion; we use mean basin slope as a measure of sensitivity to increased erosion. Production of suspended sediment from basins with a mean slope less than 35% is low, even after road construction,

Table 2. Site characteristics and mean annual suspended sediment yield for five sets of experimental basins in Oregon and California for which at least five years of data exist for each site condition.

Basin	Basin Are (ha)	Mean Basin Slope (%)	Suspended Sediment Site Condition*	Period of Yield (t/km².yr)	Record (water year)
Fox Creek, Bull Run, Western Cascade Range, Oregon					
Fox1	59	8	R, 25CC, BB	2.9	1972-79
Fox2	254	8	R	2.0	1970-79
Fox3	71	8	R, 25CC	2.7	1973-79
Coyote Creek, South Umpqua River, Southwestern Cascade Range, Oregon					
Coyote l	69	40	R, 50PC	22	1972-79
Coyote2	68	40	R, 30CC	16	1972-79
Coyote3	50	40	R, 90CC, BB	181	1972-79
Coyote4	50	40	F	47	1970-79
H. J. Andrews Experimental Forest, Central Western Cascade Range, Oregon					
HJA1	96	63	F	8	1957-61
HJA1	96	63	100CC, BB	183	1967-76
HJA2	60	61	F	11	1957-76
HJA3	101	53	R, 25CC, BB	456	1965-76
HJA6	13	28	R, 100CC, BB	13	1976-79
HJA7	15	31	50PC	2.5	1972-79
HJA8	21	30	F	11	1972-79
HJA9	9	60	F	3.4	1969-79
HJA10	10	60	F	9.5	1969-75
HJA10	10	60	100CC	57	1976-79
Alsea River, Coast Range, Oregon					
Deer	303	50	F	97	1959-65
Deer	303	50	R, 25CC, BB	136	1966-73
Needle	71	37	F	53	1959-65
Needle	71	37	90CC, BB	146	1966-73
Flynn	202	50	F	98	1959-73
Caspar Creek, Coast Range, California					
North Fork	508	44	F	125	1963-67
North Fork	508	44	F	124	1968-71
North Fork	508	44	F	262	1972-76
South Fork	424	41	F	103	1963-67
South Fork	424	41	R	188	1968-71
South Fork	424	41	R, 64PC	442	1972-76

Sources: Larson and Sidle 1980, Rice et al. 1979.
* F = forest. R = road. 50CC = 50% of area clearcut.
BB = broadcast burning. 50PC = 50% of stand removed in partial cut.

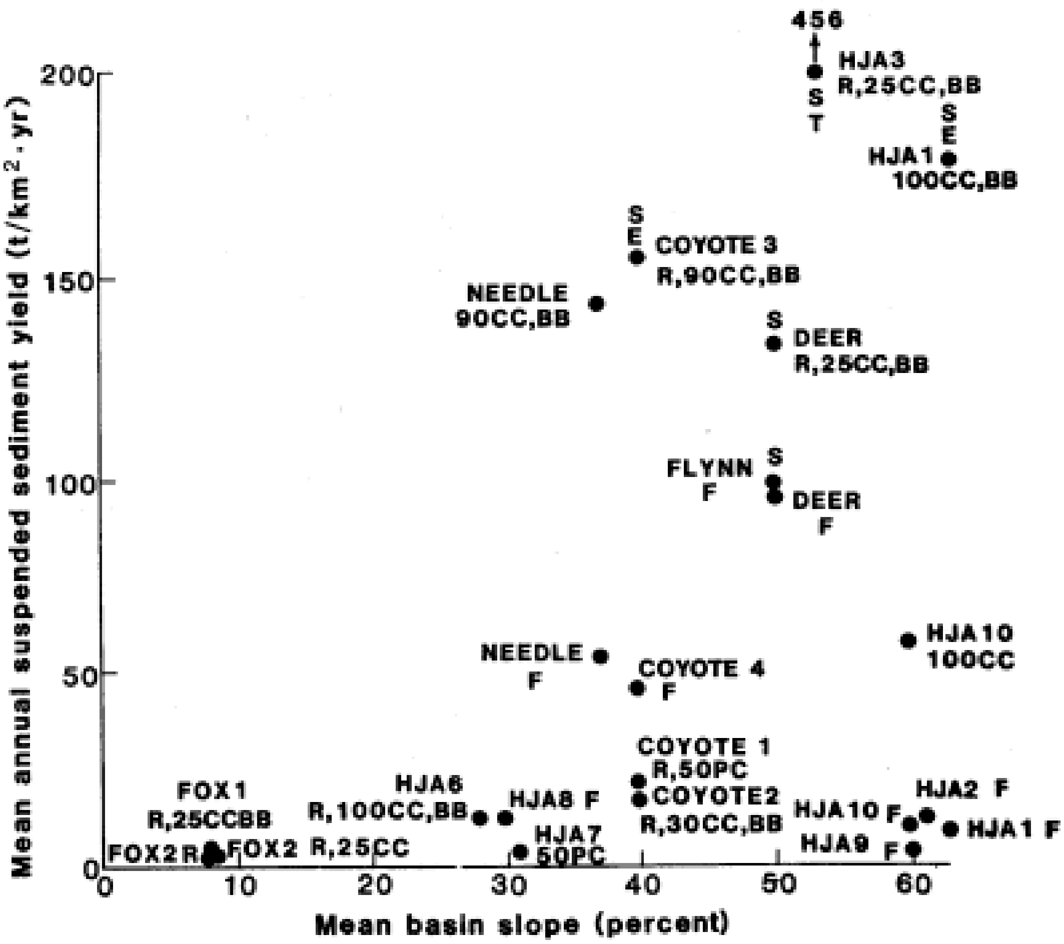

Figure 1. Suspended sediment yield for experimental basins in the Fox, Coyote, Alsea, and Andrews areas, western Oregon, with at least four years of record for forested or treated conditions. S = debris slides. T = debris flows. E = active earth flows in observation period. See Table 2 for definitions of treatment codes.

clearcutting, and broadcast burning (HJA6, Foxl) (Table 2, Figure 1). The lack of significant change in suspended sediment yield in Fox3, HJA6, and HJA7 reflects, in part, the "light" treatment each received; no roads crossed perennial streams in these basins, and the clearcut units in the Fox study did not extend to the streambank.

Experimental basins with mean slopes greater than 35% had increased suspended-sediment yield after treatment; the exception was in the Coyote Creek. study where basin-to-basin differences in background rates of sediment production appeared to overshadow some of the expected treatment effects. The highest proportionate increase in sediment yield occurred in basins where debris slides from roads (HJA3, Deer) and where clearcut and burned areas (HJA1, Coyote3) were major sources of sediment. Only in the case of HJA3 did debris flows deliver sediment produced by debris slides to the gauging site (in February 1986, HJA10 had a debris flow that passed the gauging site and destroyed it). At the other sites, notably Deer, most of the slide debris was stored in the channel and was not observed in the suspended sediment yield; the fraction of slide debris that was sampled at the gauging site appeared to significantly increase posttreatment suspended-sediment yield. Earth flows were important sediment producers in HJA1 and Coyote3 during the period of observation. In other basins, accelerated surface erosion was the dominant sediment source after clearcutting and broadcast burning (HJA1, Needle) and clearcutting only (HJA10). In some basins, sediment stored in the channel before logging may have been released by removal of coarse woody debris, but this has been observed systematically in only a few studies (Bilby 1981, 1984; Megahan 1982).

We hypothesize that these general patterns of higher background suspended sediment yield and greater management-induced increase in erosion of steeper basins occur elsewhere, but absolute values of sediment yield may vary. There are insufficient data available to explore the patterns in detail for other areas, but results from the Caspar Creek basins, northern coastal California (Rice et al. 1979) , are instructive (Table 2) . These basins of moderate relief in highly erodible soil and bedrock have average suspended sediment yields under forested conditions (mature second growth after logging of old-growth redwood) nearly twice those of the Oregon basins. The basin treated with roads and partial cutting produced suspended sediment at a rate comparable to the most heavily impacted basin in the sample from western Oregon. This suggests that the general pattern in Figure 1 may hold for other areas, but may shift within the field of annual suspended sediment yield and mean basin slope.

Yield of bedload and other coarse sediment has been measured in sediment-collection basins at the Coyote, HJA1-3, HJA9-10, and Caspar Creek sites. Effects of management treatments on bedload production appear to parallel those for suspended sediment yield, but this is difficult to evaluate because there are fewer data, and the published interpretations of the data are less complete.

A drawback of the experimental basin approach is that some treatments have been experimental or are now obsolete in some ownerships (e.g., the midslope roads in HJA3, low slope roads in Caspar, and clearcutting and hot broadcast burning along the full length of Needle Branch), but many of the treatments are still widely applied. The relation between storm history and the timing of treatments also contributes to the "case history" characteristics of this study approach. Major storms have had variable effects within this population of basin studies; the floods of the 1964-65 winter occurred in the pretreatment period of the Alsea and Caspar Creek studies, in the immediate posttreatment year of HJA3, and during treatment at HJA1. In Caspar Creek, flows equaling the 1964-65 winter flows occurred in the posttreatment 1973-74 winter (Ziemer 1981a). The other studies all postdate the 1964-65 events.

Studies of management effects on sediment production are complicated by problems of storm event size and timing and the limited replication and range of treatments. Some of these problems can be overcome by compiling synthetic sediment budgets. Reid (1981) , for example, compiled budgets for natural and managed conditions for the Clearwater River basin, western Olympic Peninsula, Washington. Based on observations at the process level, Reid estimated sediment production in two 10 km2 basins. Fine sediment (<2 mm) and total sediment production was estimated for the completely forested condition and for a road density of 2.5 km/km^2 having a distribution of traffic use typical of land managed by the Washington State Department of Natural Resources. This level of road density and use led to total sediment production 3.4 and 4.9 times the natural levels. Fine sediment increased 4.5 and 7.2 times the estimated natural level. The dominant road-related source of total sediment was landslides, but road surfaces, particularly heavily used roads (more than four loaded logging trucks per day), contributed substantially to the production of fine sediment.

In summary, steeper basins tend to produce more sediment and to have a greater response to management activities, in part because of the importance of mass wasting in steep land. Overall rates of sediment production and the dominant erosion processes vary with intensity of management treatment and geographically in response to topography, climate, vegetation, and geology.

Viewing Mass Failures and Other Sediment Sources Across Drainage Basins

Forestry-fishery interactions must be examined across entire drainage basins because the movement of water, sediment, fish, energy, and nutrients extends throughout the drainage network and connects on-site forestry practices with off-site fishery resources. The timing and size of erosion and runoff events are important in sediment routing. Areas of high rates of natural sediment production from-small debris slides or by persistent earth flow movement can be identified within a drainage basin. Areas with high potential for accelerated sediment production can also be shown on maps and aerial photographs with the techniques outlined by Sidle et al. (1985) , Swanston (1985) , and Megahan and King (1985) . Planning for forestry operations and fishery enhancement projects should be done considering the distribution of sites of high natural and accelerated sediment production.

Knowledge of the movement of debris flows through drainage networks also .leads to opportunities for basinwide planning to minimize damaging effects of forestry operations on fishery resources. For example, by combining information on debris flow initiation, runout, and stopping location with effects of debris flow deposits on channel morphology and fish habitat, Benda, Everest, and Sedell (in preparation) have devised a scheme. zoning the entire 52 km^2 Knowles Creek drainage basin in the Oregon Coast Range (Figure 2). Steps in the analysis are: (1) Predict runout patterns of debris flows originating within all first-order basins in the area using criteria such as change in slope and channel direction. (2) Evaluate fish habitat and population use throughout the basin. (3) Estimate the effect of debris flow deposits on channel morphology and fish habitat over the .full array of potential deposition sites of debris flows. (4) Assess debris flow source areas (at the scale of first- or second-order basins) in terms of potential effects

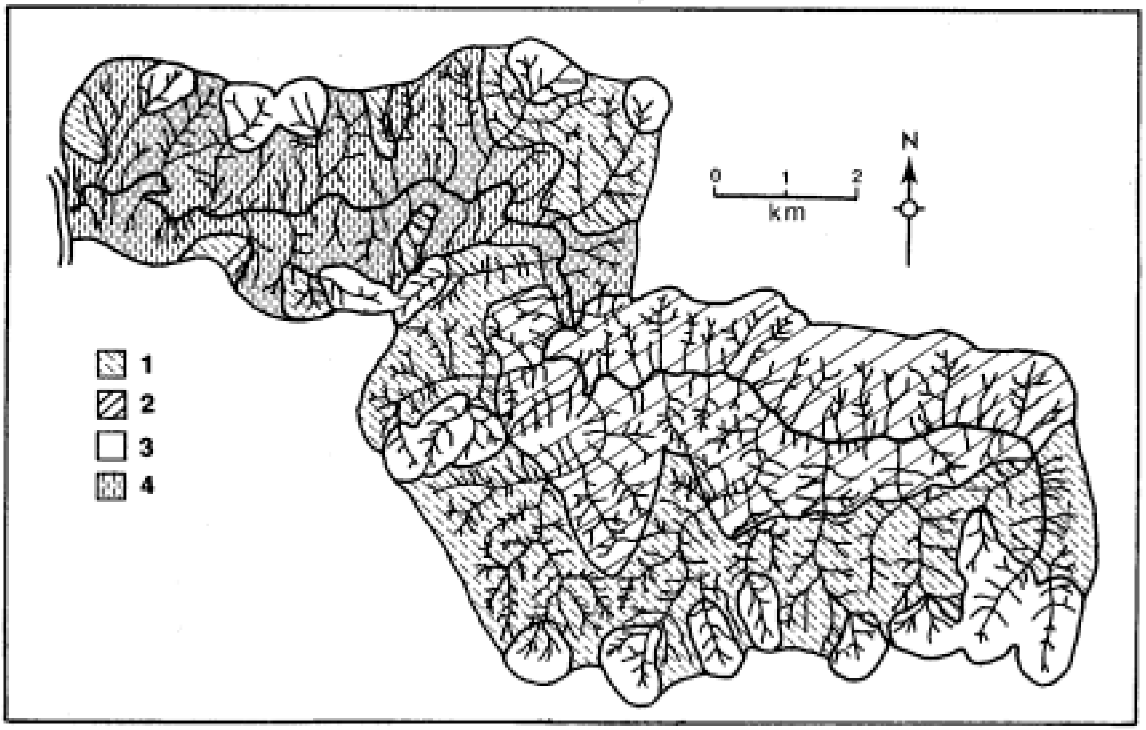

Figure 2. Map of Knowles Creek basin, Oregon Coast Range, showing zoning of potential effects of debris flows on anadromous fish habitat. Mapping units: (1) debris flow deposition outside range of fish habitat, (2) debris flow deposit may form pools that improve fish habitat, (3) debris flows likely to travel >1 km and affect third-order channels, (4) debris flows may transform into debris-laden flood flows in main stem of Knowles Creek.

on fish habitat, people, structures, or other valued resources. (5) Distribute the efforts at mitigating debris flow initiation according to this potential for damage to fish habitat and other resources.

The effect of a debris flow of a particular volume depends on the size of the receiving channel. This is particularly evident for Knowles Creek, where salmonid production is limited by availability of pool habitat, so pool development behind logand boulder-rich debris flow deposits may be locally beneficial to fish. This benefit occurs along portions of the main stem of Knowles Creek, which drains 5 to 10 km^2, where the debris flow deposit forms a pool (L. Benda, unpublished data). Debris flows entering small channels may form deposits that block fish passage, but this typically occurs at the upstream extent of fish habitat. Debris flow deposits in large channels are likely to dissipate downstream in a woody debris-laden flood wave.

Management of riparian zones along large streams and rivers should also be planned within the context of the long-term geomorphic behavior of different valley floor units. Valley floors can be zoned in terms of type and degree of external influences on the rate and frequency of change of channel position and riparian vegetation. These external influences may either cause or constrain change in valley floor landforms and ecosystems. As a first approximation we identify four valley floor units: (1) earth flow constriction zones, (2) channel junctions where alluvial fans accumulate and debris flows may deposit material, (3) bedrock outcrops acting as passive constraints, and (4) reaches free of these constraints. These valley floor units may have differing susceptibilities to change in channel habitat and riparian vegetation under either natural or managed conditions. Swanson et al. (1985) gave an example of how earth flow constrictions affect channels and valley floors.

Approaches to Mitigating Effects of Forest Practices on Sediment Production

A theme throughout this volume is that the geomorphic and biological setting in which fishery-forestry interactions take place is extremely complex. This complexity requires attention to specific characteristics of each site before predicting system response to natural or management-induced disturbance or applying prescriptions. Despite this complexity, both conceptual and practical tools are available for management of sediment sources.

A variety of methods for mitigating effects of forestry practices on sediment production have been developed and applied: Approaches to mitigation can involve several steps: (1) locate areas susceptible to accelerated erosion, (2) evaluate susceptibility of each site to accelerated erosion, (3) evaluate the direct effects of mass failures on channels and valley floors, and (4) design and implement mitigation measures.

Location of Susceptible Areas. Many aerial photographic, mapping, and field techniques are available-for identifying existing landslides and areas prone to sliding and accelerated erosion by other processes (for general discussions see Burroughs et al. 1976, Sidle et al. 1985, Swanston 1985) . Identification of areas susceptible to accelerated sediment production has been approached at several scales. At a planning level, landscape units at the scale of 1 to 100 ha can be delineated and distinguished by different susceptibilities to erosion based on slope gradient, vegetation, and other factors. This has been done by the Forest Service using groupings of Soil Resource Inventory (SRI) units, which are mapped from aerial photographs with some field checking.

Site-specific identification of areas susceptible to accelerated erosion commonly incorporate observations of topography, geology, soil, hydrology, and vegetation. For discussion of some common techniques see Burroughs et al. (1976) , Sidle et al. (1985) , and Swanston (1985).

Evaluation of Susceptibility to Accelerated Erosion. There are many ways to estimate rates o natura and accelerated erosion (Dunne 1984) . Techniques for evaluating slope stability range from quantitative engineering factor of safety analysis (Swanston 1979, Burroughs et al. 1985) to semiquantitative and qualitative systems, such as the headwall rating system of the Siuslaw National Forest (Sidle et al. 1985) and the method of Swanston et al. (1980).

Several approaches to identifying sites susceptible to mass failures also incorporate quantitative evaluation of failure potential. Prellwitz et al. (1983), for example, describe a scheme for landslide analysis using scales for resource allocation (1:24,000) , project planning (1: 6,000) , and critical sites (1:240 to 1:1,200) . Slope stability is analyzed at each level, based on factor of safety analysis that is progressively more refined at the larger scales, for which more site-specific information is available. Rice and Pillsbury (1982) applied discriminant analysis to a sampling of sites in granite bedrock, with and without recent slides, to develop a function defining site stability based on slope gradient, horizontal distance from slide scarp to stream, drainage area above the slide scarp, and crown cover of dominant trees. In a similar study restricted to the inner gorge of the Six Rivers National Forest, northern California, Furbish and Rice (1983) found slides to be most prevalent in narrow draws and at sites near stream channels or below the break in slope separating the inner gorge from the surrounding terrain. Such discriminant functions can be used to estimate the risk of failure at other sites with similar geologic conditions.

Future rates of slide erosion could also be estimated from the past rates of sliding per units of area and time for different site conditions, such as forest, young clearcut, or road right-of-way for different ages and construction standards. This sort of analysis must be carefully couched in the history of storm events and in changes in forestry and in road construction, location, and maintenance practices.

Predicting slides can also be considered in terms of the magnitude and frequency of hydrologic events leading to failure. Using a compilation of worldwide data, Caine (1980) defined a threshold of rainfall intensity and duration necessary to trigger slides. Sidle et al. (1985) discuss additional considerations that should go into an analysis of threshold conditions in a particular area. This approach for estimating precipitation conditions leading to slope failure is further complicated in parts of the Pacific Northwest where snowmelt significantly augments the delivery of water to the soil.

The Universal Soil Loss Equation (USLE) has been proposed as a method for predicting surface erosion from forest lands of the Pacific Northwest (Curtis et al. 1977) , and the method has apparently been applied with some success to forest lands where harvest methods are similar to those for agriculture (Wischmeier 1976, Dissmeyer and Foster 1984) . Attempts to apply the USLE to forested, steep lands generally have been unsuccessful--mainly because of inappropriate basic assumptions (Wischmeier 1976) . The principal weakness of the USLE is that it relates to interrill surface erosion produced by overland flow on gentle slopes. Even if the individual factors could be adjusted to account for conditions found in forested areas, interrill surface erosion is a process of negligible importance on forested lands in the Pacific Northwest. A more useful approach would be a series of equations designed to predict erosion from specific types of disturbance that are subjected to specific types of erosional stress, such as road-surface erosion (Reid and Dunne 1984) .

A general erosion hazard rating (EHR) system, based on regression equations, was used in the administration of California's forest practice rules (Rice and Datzman 1981) . A commonly used form of the EHR was based on slope, soil series, and mean annual precipitation. Rice and Datzman (1981) evaluated the EHR using data on rill, gully, slide, and slump erosion from harvest units in northwestern California and conclude that the EHR was a poor predictor of accelerated erosion. They developed a modified form of the rating equation that is a better predictor of observed erosion, but they caution that the performance of individual equipment operators is a crucial factor in determing the magnitude of accelerated erosion. More qualitative EHR predictors are now being used.

Many current techniques for predicting location and susceptibility of erosion are based on extrapolation of the rate and spatial pattern of past events (Dunne 1984) . These methods are most useful and accurate in the area for which they were developed. Statistical studies, particularly inventories of debris slides and flows, operate within inherent design constraints and the vagaries of storm history and edaphic factors. Major unknowns include the filling rate of hollows to depths critical for subsequent failures and the potential importance of climatic cycles in triggering widespread sliding. The uncertainty of these factors, combined with the limited knowledge of the physics of the: processes, limits the use of some existing techniques for evaluating erosion and slope stability.

Evaluation of Direct Effects of Mass Failures on Channel and Valley Floor Environments. Prediction and evaluation of the direct effects of mass failures on aquatic and riparian resources are in a very early stage of development. Potentially important factors include the, extent and magnitude of effects of debris flows and earth flows on channel morphology and riparian vegetation. The more indirect effects of accelerated sediment production and transport rate on channel morphology are addressed in other papers in this volume.

Study of the runout distance and stopping locations of debris flows in forest land of the region is limited to that of Benda (1985b) , although the Japanese and some others have done extensive work on this problem with physical and computer modeling for areas of rural development, principally on alluvial fans. Benda's work suggests that debris flow behavior and effects on fish habitat can be predicted and evaluated within a drainage basin context.

The behavior of the toes of earth flows encroaching on a channel is even more poorly understood. However, the observations of Swanson et al. (1985) on the relation between constriction rate of channels and the frequency of sliding from the earth flow toe suggest that accelerated earth flow movement will lead to more frequent and perhaps smaller streamside slides. At present, it is uncertain how earth flow velocity affects the probability of debris-laden flood surges initiated by release of material from the earth flow-constricted channel.

Grant et al. (1984) developed a general technique for assessment of the extent and causes of opening of the canopy of riparian vegetation and changes in channel width. This technique has been useful in documenting the magnitude of direct effects of mass failures on channels.

Mitigation of Accelerated Erosion. Many approaches to mitigating accelerated sediment production have been widely applied in the practice of forestry over the past several decades. Chief among these has been on-site, best management practices involving improved road location, design, and maintenance and decreased intensity of broadcast burning. Erosion from roads has been reduced by avoiding hazardous areas through mapping and risk identification and by control of sidecast, end halving, minimizing amount of organic matter in fills, design of road drainage systems, and other techniques. Careful design and designation of skid trails minimize erosion and the proportion of the landscape compacted by heavy equipment. Strips of vegetation and logging residues along streams have been left to reduce production of sediment from streambanks and toeslopes and to trap sediment transported from upslope. There is also a limited number of examples of vegetation left in upslope areas to mitigate the occurrence of slides as a result of clearcuts. These "headwall leave areas," including either all forest vegetation or just the understory, are left in areas of 1 to 2 ha at the steep, headward tip of channels on sites judged to have high ,potential for sliding if vegetation is cut. The effectiveness of headwall leave areas implemented on the Mapleton Ranger District, Siuslaw National Forest, western Oregon, is under study now. Other efforts to mitigate erosion cut areas include minimizing soil disturbance during felling (e.g., by curtailing operations during very wet periods), yarding, and residue manipulations.

These approaches are all at the on-site, project scale. The potential benefit of distributing management activities through time and over a drainage basin are currently discussed under the label "cumulative effects." From the standpoint of sediment production alone, on-site practices are of singular importance. Workable measures for mitigating accelerated sediment production are, by the nature of the problem, site specific. A possible exception is that the frequency of harvest may affect the rate of erosion by slides and surface processes on the time scale of several rotations. In the case of slides, for example, shorter rotation length may mean that a greater proportion of a drainage basin is in the sensitive condition of reduced root strength at any time.

A major problem in evaluating the effects of land use practices or effectiveness of mitigation measures is that only a small part of the landscape is subject to accelerated erosion for a small portion of a rotation. It is the large, infrequent storm occurring at a vulnerable time and place that results in extreme erosion. It may take many years before a site is adequately stressed that mitigation effectiveness can be evaluated.

LIMITATIONS OF GENERALIZATIONS FROM PUBLISHED RESEARCH

This paper summarizes effects of mass failures and other processes of sediment production on streams of the Pacific Northwest and is based primarily on published research. This body of knowledge is incomplete as a result of the uneven research on the potential topics, time scales, and locations of study. The inadequacies of our knowledge may lead to overestimation or underestimation of effects or regionwide forest management on fisheries or other resources. Here are two examples:

1. Most published studies of erosion have been done on federal land where the management objectives and practices of federal agencies are applied. For example, of the twenty-five areas in Alaska, Idaho, Washington, and Oregon for which there are quantitative inventories of slides summarized by Ice (1985) , twenty-one are on Forest Service land. The four areas with inventories of slides on state and private land are an inadequate basis for comparing slide frequency among ownerships and their contrasting approaches to road construction and other practices.

2. Most studies of erosion use sites in mature to old-growth forests as the control condition. There has been little effort to evaluate the true baseline erosion rate under natural conditions that included periods of accelerated sediment production following wildfire and wind throw.

These two examples of the limitations of present knowledge hint at two unresolved but essential questions in the issue of forestry-fishery interactions: What is the net effect of forestry activities on the fishery resource across the patchwork of landownerships, each with different management objectives and styles? And, how do forestry activities contrast with the natural disturbance regime (type, frequency, intensity, areal extent of disturbance) of fire, flood, and other processes that shaped the landscape and fish populations of the Pacific Northwest long before forestry was practiced here?

CONCLUSIONS

Sediment production varies greatly in rate and dominant processes across the steep, forest lands of the Pacific Northwest primarily because of differences in tectonic history, geology, soils, and climate. Sediment production is also temporally complex and reflects infrequent major storms and wildfire or other disturbances of vegetation that increase the sensitivity of the landscape to erosion. Sediment production within even a single small drainage basin involves the complex interactions of a variety of soil and sediment transport processes and sites of temporary storage. This system of material transport and storage, termed a "sediment routing system," can be described quantitatively in a sediment budget, which provides a useful basis for determining the relative importance of transport processes within a single basin and among basins in different geomorphic and land use settings.

Forestry practices can accelerate sediment production by a variety of processes. Mass failures, particularly small, rapid debris slides, are a dominant erosion process in many steep, forested landscapes, and their frequency of occurrence and soil movement rates are increased by logging and road construction. Mass failures have been major sediment sources in most steep experimental basins subjected to clearcutting, broadcast burning, and road construction. Road surfaces are also important sources of fine sediment, and the rate of sediment production increases with traffic load. Analysis of sediment routing at the scale of the drainage basin highlights the need for improved understanding and quantification of delivery of sediment from slide scars, road surfaces, and other sources to stream channels.

Accelerated sediment production can be somewhat mitigated by existing techniques for (1) locating erosion-prone sites, (2) predicting the erosion rate for various management treatments, (3) predicting the extent of direct effects of debris flows, earth flows, and sediment on receiving channels, and (4) designing mitigation measures. Successful application of these techniques and effective planning of the integrated management of forestry and fishery resources must consider entire drainage basins from a system perspective.

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