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METHODS FOR TESTING EFFECTIVENESS OF WASHINGTON FOREST PRACTICES RULES AND REGULATIONS WITH REGARD TO SEDIMENT PRODUCTION AND TRANSPORT TO STREAMS

By

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JUNE 28, 1991

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THE RECOMMENDATIONS OF THIS REPORT REFLECT
THE VIEWS OF THE AUTHORS AND NOT NECESSARILY
THOSE OF THE T/F/W COOPERATIVE MONITORING,
EVALUATION AND RESEARCH (CMER) WATER
QUALITY STEERING COMMITTEE.

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1.0 INTRODUCTION

1.1 STATEMENT OF OBJECTIVES

The purpose of this project is to develop a methodology to test how effectively the Washington Forest Practice Rules and Regulations (Washington State Forest Practice Board, 1988) minimize sediment production and delivery of sediment to streams. Washington statute 173-202 WAC identifies specific forest practice regulations as Best Management Practices (BMPs), which are required to protect water quality from impacts caused by forest management activities. The Washington Department of Ecology (WDOE) is required by State and federal statute to assess how effectively the BMPs maintain water quality.

The methodology for testing the forest practice rules' effectiveness developed in this report is based on a multidisciplinary approach ranging from geomorphology to forestry. The method is based on several supporting tasks including a literature review of the sources and severity of sediment production in managed forests, the geographical variation of erosion processes and magnitudes across Washington State, and an analysis of the conceptual or theoretical effectiveness of the forest practice rules at preventing erosion.

1.2 CONCEPTUAL APPROACH

The approach taken in this report is to design a method to evaluate the effectiveness of forest practice rules (Best Management Practices) in minimizing specific erosion processes. Therefore, the emphasis is on detecting individual erosion processes in managed forested landscapes; describing their general nature, rate, timing, and persistence; and assessing the BMP measures used to mitigate them. Placing the emphasis on individual erosion processes in this way makes possible the design of a flexible field method to evaluate the effectiveness of specific forest practice rules or sets of rules that influence each process.

Measurement methods differ according to erosion process, as do the appropriate time and space scales over which measurements must be conducted. For example, numerous studies have documented that landslides related to timber harvest typically occur several years following cutting. Thus, a method designed to detect this sediment source would involve a combination of field and ground surveys conducted several years after forest practice. On the other hand, surface erosion from roads is most intense during the time in which a road is used most intensively, and so a field-based method would be most appropriate during the time of intensive use.

The proposed methodology emphasizes the production of sediment from individual erosion processes and the routing of that sediment to stream channels. General statements can be made about the amount, timing, grain size, downstream transport, and persistence of sediment in channels, but sediment transport and storage in channels is not addressed directly within this report. The method makes use of the general framework and specific tools of the sediment budget, or a quantitative statement of the production, storage, and transport of sediment in a drainage basin (for general review, see Dietrich et al., 1982), but the method is restricted to a partial sediment budget emphasizing production only, such as that used by Reid et al. (1981).

1.3 OUTLINE OF THE REPORT

This document reports on four different tasks requested by the TFW Water Quality Steering Committee and the Washington State Department of Ecology. The first task is a review of the literature on effects of forest practices on erosion and measures to mitigate erosion. It also includes a review of previous methods used to assess the effectiveness of BMPs at protecting water quality.

The second task is an assessment of the relative severity of erosion and sedimentation impacts in different regions of Washington State.

The third task is an assessment of the theoretical or conceptual effectiveness of forest practice rules in minimizing sediment production caused by forestry activities. The focus is on the expected effectiveness of the rules rather than their actual effectiveness as determined by field evaluation. The task also includes recommendations for improving rule effectiveness.

The fourth and final task is the development of a method to be applied by the State Department of Ecology for an assessment of the effectiveness of existing BMPs in minimizing sediment production and delivery of sediment to streams.

1.4 EROSION PROCESS DEFINITIONS AND TERMINOLOGY

The published and unpublished literature uses many different types of terminologies to describe erosion processes. The processes discussed in this report are defined below to aid the reader in recognizing and differentiating between sediment sources in forested landscapes. Other terminologies that are often used in the literature to describe the same processes will be noted.

1.4.1 Shallow-rapid Landslide

A landslide characterized by thin soils (or colluvium) generally less than 2 meters in thickness and typically overlying steep bedrock or compacted glacial deposits. Soil thickness is shallow compared to slope length or length of the landslide. *Rapid* refers to the speed at which the landslide debris moves downslope, often breaking apart and developing into a debris flow. Shallow-rapid landslides are often localized in converging bedrock topography (known as bedrock hollows, swales, or zero-order basins), which is characterized by thicker saturated layers and hence greater instability.

Other names given to shallow-rapid landslides: landslides, debris avalanches, planar failures.

1.4.2 Debris Flow

A highly mobile slurry of soil, rock, vegetation, and water that can travel many kilometers from its point of initiation and usually occurring in steep (more than 5 degrees gradient), confined mountain channels. Debris flows are initiated by liquefaction of landslide material concurrently with failure or immediately thereafter as the soil mass and reinforcing roots break up. Debris flows contain 70 to 80 percent solids and only 20 to 30 percent water. Entrainment of additional sediment and organic debris in first- and second-order channels (Type 4 and 5 Waters) can increase the volume of the original landslide by 1,000 percent or more, enabling debris flows to become more destructive as their volume increases with distance travelled.

A debris flow can have an impact on channel structure and fish habitat considerable distances from its point of initiation and therefore is one of the most destructive forms of soil-mass movement in forested watersheds.

Other names given to debris flows: debris torrents, sluice outs, mud flows.

1.4.3 Dam-break Flood

Erosion from flooding caused by the failure of a temporary sediment and organic-debris dam within a narrow valley floor or canyon. These dams are formed from deposits of landslides and debris flows, and when the dams break, the flooding destroys riparian vegetation and causes significant erosion and sedimentation along entire lengths of stream-order segments (Benda and Zhang, 1989). In the Pacific Northwest, debris flows and dam-break floods have often been referred to as debris torrents.

In this report, dam-break floods will be included under the general erosion category of debris flows, particularly in Task 4, Section 5.0, the methodology for evaluating the effectiveness of the forest practice rules.

Other names given to dam-break floods: debris torrents, sluice outs.

1.4.4 Slump-earthflow

Slumps are deep rotational failures, typically triggered by the build up of pore water pressure in mechanically weak, and often clay-rich, rocks (Swanston, 1974). The plane of failure is generally at least several meters below the ground surface. Slumping is the downward and backward rotation of a soil block or group of blocks. The main head scarp is often steep and generally bare of vegetation, and the toe is hummocky or broken by individual slump blocks.

Earthflows move through a combination of slumping and slow flow; they can remain active for thousands of years with periods of activity and dormancy (Swanson et al., 1987). Earthflows typically occupy a much larger portion of the landscape and move larger amounts of soil than do slumps. The toe of an earthflow is typically lobate and hummocky.

Slump-earthflows can initiate on slopes as gentle as 4 to 20 degrees (Sidle, 1980), and in Washington they occur in altered sedimentary and volcaniclastic rocks and glacial sediments of the western Cascades, Olympics, and coastal ranges. Sites have also been identified and studied in the drier eastern Cascades (Swanston, 1981; Fiksdal and Brunengo in NCASI, 1985).

Studies in the Pacific Northwest indicate that deep-seated failures move most rapidly during the wet season, and unlike shallow failures, which are influenced by individual storms, deep-seated failures are controlled by the seasonal buildup of groundwater at the base of the failure (Iverson and Major, 1986). Movement thus can accelerate as the wet season progresses (Swanston and Swanson, 1977).

1.4.5 Surface Erosion

Erosion by rainsplash, sheetwash, rilling, gullying, and dry ravel of exposed mineral soil. Erosion in managed forests is located on roads and road margins, recent landslide and debris-flow scars, and soils disturbed by timber harvest.

1.4.6 Channel-bank Erosion

Acceleration of stream-bank erosion leading to channel widening. Forestry practices can accelerate bank erosion by (1) logging in and adjacent to streams, thereby decreasing stream-bank stability; (2) increasing bedload, thereby raising the streambed elevation and causing bank instability; (3) increasing the incidence of debris flow; (4) causing dam-break floods; and (5) increasing flood runoff and thereby causing channel scour.

1.5 SEDIMENT BUDGET APPROACH

A sediment budget is a quantitative statement of the rates of production, transport, and storage of sediment throughout a watershed. Construction of a sediment budget for a drainage basin requires identification of individual erosion processes, storage elements on hillslopes and in streams, and the links between storage and transport mechanisms.

A sediment budget approach is useful for testing forest practice rules because it requires that the investigator search for specific erosion processes in the appropriate places in a drainage basin at the appropriate times. When erosion processes and rates are overlayed with forest management activities in a watershed, the relationship between forestry and sediment production becomes more apparent, and the effectiveness of the forest practice rules becomes more evident.

1.6 EROSION PROCESSES AND FORESTRY ACTIVITIES

Forestry practices are viewed in the context of individual erosion processes during the course of this report. In the context of the forest practice rules (BMPs), forest practices are grouped under three general categories: logging roads (includes landings, gravel pits, borrow pits, and spoil disposal areas); timber harvest (includes clearcuts and partial cuts); and reforestation (includes slash burning and mechanical site preparation).

Individual erosion processes affected by each general category of forestry activity are listed in Table 1.1. This table is also a cross-reference guide to the report, showing the portions of the literature review, conceptual efficacy, and methods sections that apply to each of the combinations of forest practices and erosion processes.

Table 1.1

Report reference guide for literature review, BMP conceptual effectiveness, and test method by erosion process and forest activity.

Forestry Activity	**Erosion Process**			
	Landslide/ Debris Flow	**Slump-earthflow**	**Surface Erosion**	**Channel-bank Erosion**
Roads	Literature Review: p. 27 Conceptual Efficacy p. 60 Method: p. 75	Literature Review: p. 24 Conceptual Efficacy p. 64 Method: p. 91	Literature Review: p. 27 Conceptual Efficacy p. 69 Method: p. 97	Literature Review: p. 25 Conceptual Efficacy: p. 67 Method: p. 102
Timber Harvest	Literature Review: p. 20 Conceptual Efficacy p. 63 Method: p. 84	Literature Review: p. 23 Conceptual Efficacy p. 66 Method: p. 94	Literature Review: p. 30 Conceptual Efficacy p. — Method: p. 100	Literature Review: p. 25 Conceptual Efficacy p. 68 Method: p. 103
Reforestation	Literature Review: p. — Conceptual Efficacy p. 64 Method: p. 88	Not Applicable	Literature Review: p. 31 Conceptual Efficacy p. — Method: p. 102	Not Applicable

2.0 LITERATURE REVIEW
TASK 1

2.1 EROSION IN MANAGED PACIFIC NORTHWEST FORESTS

The literature on erosion in forested watersheds of the Pacific Northwest and its association with forest practices is extensive and has been the subject of several recent reviews, each having a different emphasis. These reviews include Geppert et al. (1984; cumulative effects), Sidle et al. (1985; landsliding and land use), NCASI (1985; landslide inventories), Swanson et al. (1987; overview of erosion processes), and MacDonald and Ritland (1989; dynamics of Type 4 and 5 Waters).

Because the goal of this project is to design a method to evaluate the effectiveness of BMPs in minimizing individual erosion processes, the following review focuses on forestry-induced erosion, methods to measure it, and its mitigation. The literature on stream-sediment monitoring, channel dynamics, or cumulative effects is not reviewed.

This summary groups erosion processes as follows: (1) shallow-rapid landslides and debris flows; (2) deep-seated slumps and earthflows; (3) channel-bank erosion; and (4) surface erosion by water and dry ravel.

2.1.1 Shallow-rapid Landslides and Debris Flows

Shallow-rapid landslides are a common landscape process from northern California to Alaska and involve the rapid failure of soil and weathered bedrock, typically to a depth of about 1 to 2 meters. They are generally triggered by the build up of soil water in response to storms or rain-and-snowmelt events. For the purpose of this literature review, shallow-rapid landslides will be referred to as landslides.

Debris flows, which in the Northwest are also termed "debris torrents," are rapidly moving slurries of sediment, water, air, and vegetative debris. They form as landslide material liquefies concurrently with failure or immediately thereafter as the soil mass breaks up. Debris flows are generally confined to steep, first- and second-order channels (Type 4 and 5 Waters in the Washington State stream typing system). Debris flows incorporate additional sediments, water, and organic debris as they move downchannel, dramatically increasing in volume, typically by more than 1,000 percent. Debris flows deposit in low-gradient channels and valley floors (Type 1 through 3 Streams).

Debris flows can deposit sediment in streams and affect fish habitat several kilometers from the initiating landslide (Swanson et al., 1987) and therefore are one of the most destructive forms of mass movement in forested watersheds (Eisbacher and Clague, 1984).

2.1.1.1 Occurrence Rate of Landslides and Debris Flows

Studies of the incidence of landsliding in managed forests typically take one of three forms. Landslide inventories tally events per unit area per unit of time; managed and unmanaged areas are usually done separately. Soil transfer rate studies convert the number of landslides to volumes of soil that move within a unit of area over a specified time. Sediment budget studies include landsliding as part of a quantitative statement of rates of production, transport, and storage of sediment in a watershed.

Landslide Inventories

Twenty-five landslide inventories have been conducted in Washington and Oregon since the early 1970s. Most of these inventories are based on aerial photo interpretation and field surveys. Typically, inventories are made on aerial photos from the earliest available date, which in Washington State is often the 1940s or 1950s, and every four to eight years thereafter. Landslides are usually classified into one of three groups depending upon their place of origin on the landscape: 1) unmanaged forests; 2) clearcut units; and 3) logging roads. The number of landslides per unit area per time (landslide rate) is computed for each group. The landslide rates for clearcuts and logging roads are then divided by the rate for unmanaged forests to estimate the factor or percent increase attributed to forest management practices. A more detailed discussion of the landslide inventory approach is found in NCASI (1985).

Landslide inventories made with aerial photo analysis only and no field component may underestimate the rate of landsliding in mature forests and thereby exaggerate the increase of landslides due to forest management. Ketcheson and Froehlich (1978) estimated that only 0.2 to 10 percent of landslides identified in ground surveys in mature forests were noticed on aerial photos, although this problem is probably most acute in the Oregon Coast Range where they worked because of the high number of small landslides there (NCASI, 1985). It has been stressed that aerial photo analysis be combined with field surveys to avoid or minimize this problem (Swanson and Lienkaemper, 1978).

Debris flows in mature forests are more readily visible on photos than are landslides, and inventories of debris flows can be reliably free of bias when made from photographs only.

Figures 2.1 and 2.2 summarize 14 landslide inventories conducted in Washington and Oregon by state and federal forestry agencies and the forest industry. Various factors complicate the precise comparison of these studies. For example, different study areas have different ratios of road length to area of timber harvest and have different spans of years since roading or harvest. Summary of the studies is useful, however, because it illustrates the general magnitude of road- and tree cutting-related landslide rates.

The figures show that between 200 and 3,300 percent more landslides occurred in clearcuts than in mature forests (Figure 2.1). On average, landslides were 900 percent more frequent than in mature forests. Most of these inventories were made between 1970 and 1990.

Even higher incidence of landsliding from logging roads have been documented. Figure 2.2 shows that landslides associated with roads ranged from 1,000 to 38,000 percent (average of 11,100 percent) more than in unroaded and unlogged forests. These inventories indicate that logging roads are the major source of landslides in managed forests in Oregon and Washington. The results of these inventories for Washington and Oregon are consistent with studies conducted in British Columbia, New Zealand, and Alaska; these studies are not discussed here but can be found in Sidle et al. (1985) and NCASI (1985).

Four of the landslide inventories in Figures 2.1 and 2.2 are from Washington State. Inventories conducted in four tributaries of the Nooksack River in the northwest Cascades of Washington found that the incidence of landslides from clearcuts and roads averaged 450 and 550 percent higher than in unmanaged forests (Peak Northwest, Inc., 1986). Using data obtained from Syverson (1984), Benda (1990) computed increased rates of landslides from clearcuts and orphaned roads of 300 percent and 800 percent respectively; these data were used in an environmental assessment of the Smith Creek basin to predict future landslides and sediment yields from proposed timber harvest in the basin. A landslide inventory in the upper Tolt River basin conducted by Weyerhaeuser Company, the Washington Department of Natural Resources, and the Tulalip Tribes showed landslide occurrence from clearcuts and logging roads was 600 and 1,500 percent the rate in mature forests (Paul Kennard, Tulalip Fisheries Agency, unpublished data). Johnson (1991) found landslide occurrence increases of nearly 40,000 percent and more than 500 percent for roads and clearcuts in the National Forest surrounding the Canyon Creek tributary of the South Fork Stillaguamish River. Not included in Figures 2.1 and 2.2 is a study by Fiksdal (1974) which showed that landslides associated with logging roads occurred at a rate 168 times or 16,800 percent greater than in unmanaged, unroaded forests of the Olympic Peninsula's Stequaleho Creek drainage.

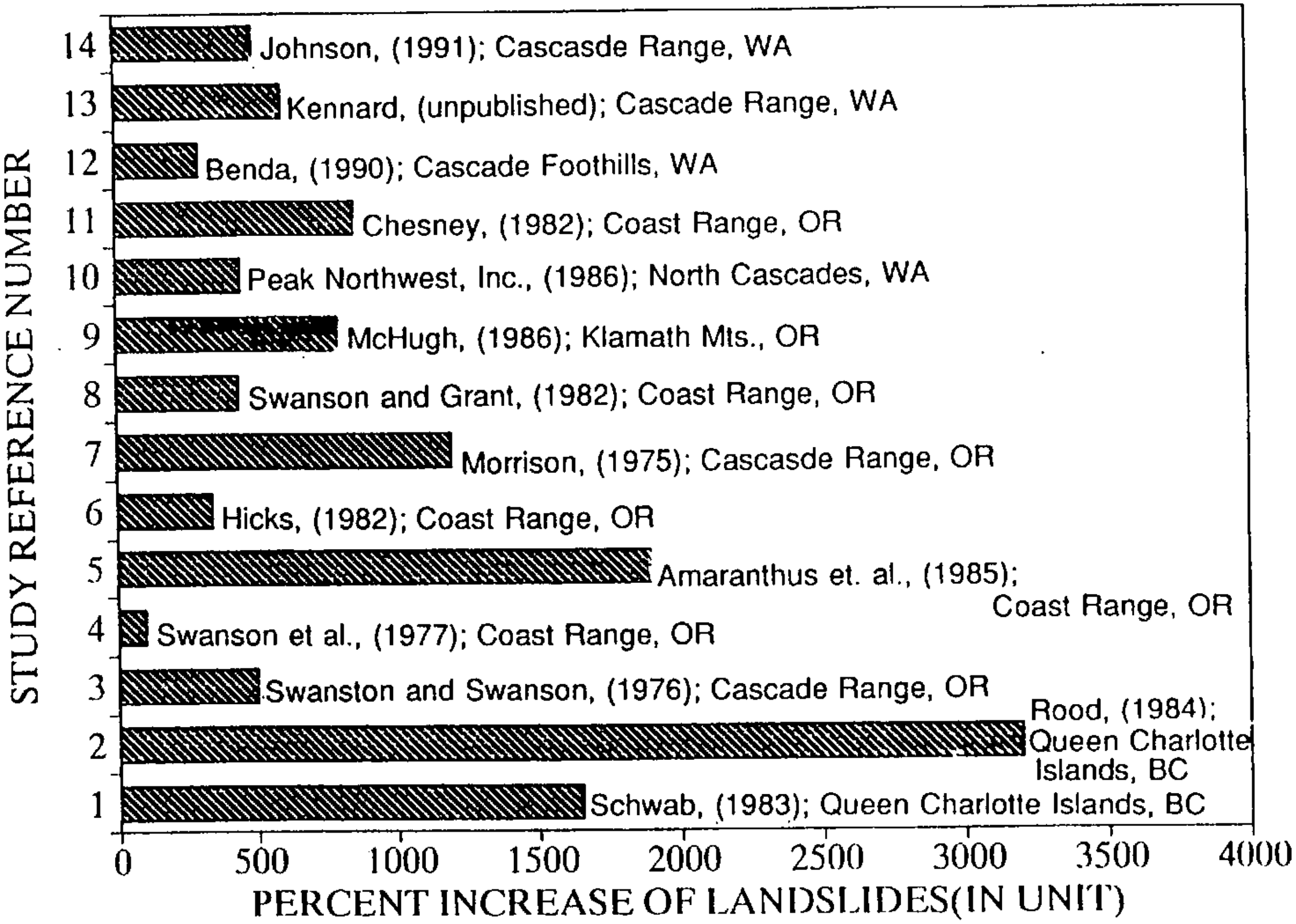

Figure 2.1
Percent increase in occurrence of landslides in clearcuts compared to landslide occurrence in unmanaged forests for 14 studies in the Pacific Northwest.

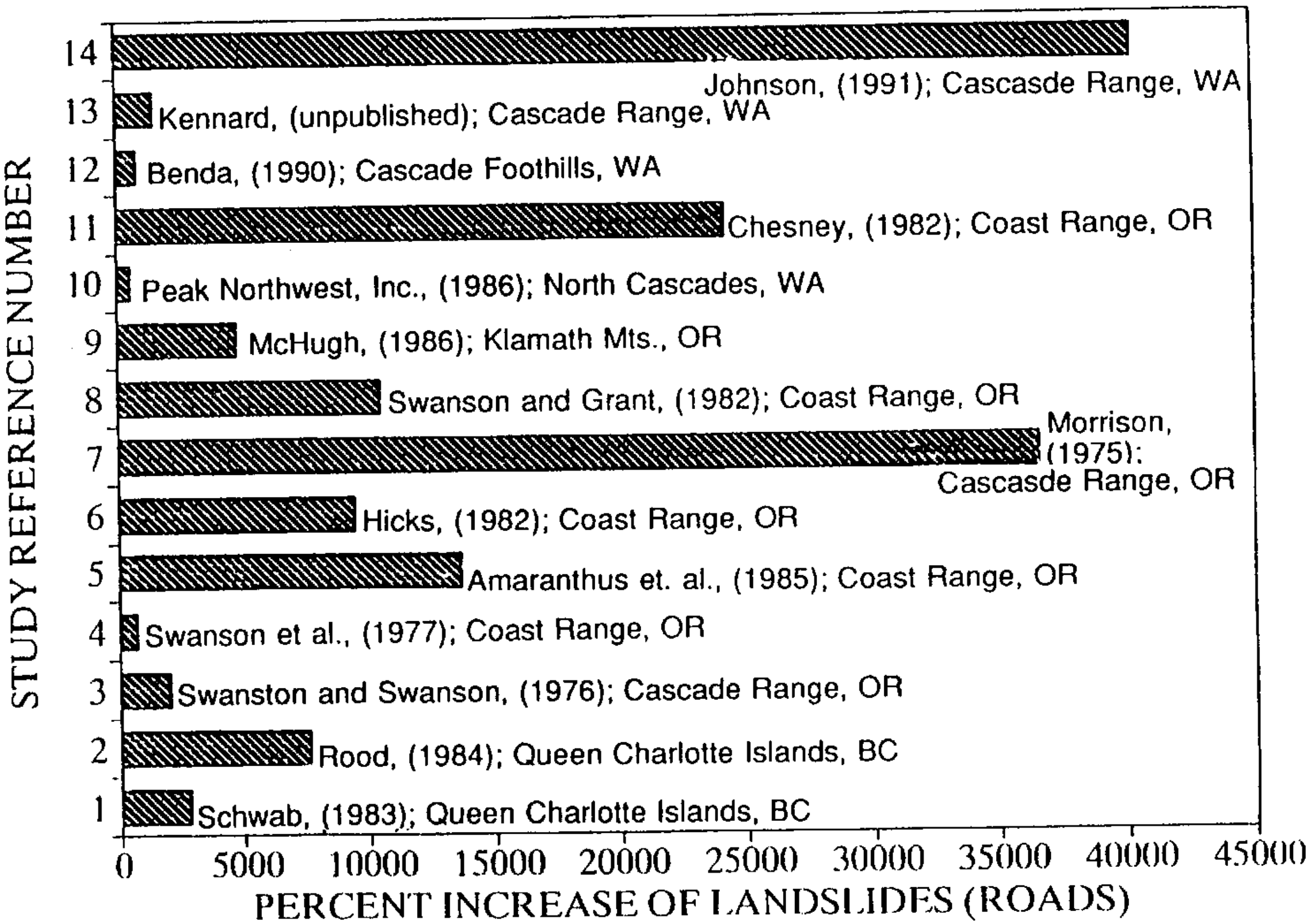

Figure 2.2
Percent increase in occurrence of landslides in logging roads compared to landslide occurrence in unmanaged forests for 14 studies in the Pacific Northwest.

In summary, all landslide inventories conducted in Washington and Oregon show that landsliding associated with clearcuts and logging roads in the last three decades has been greater than in uncut and unroaded forest by hundreds to thousands of percent. Hence, any methodology for assessing BMPs must explicitly consider landslides associated with both clearcuts and logging roads.

Soil Transfer Studies

Landsliding in managed forest landscapes is also measured in terms of the rate of soil movement in a given area over a given time. This "soil transfer rate" does not necessarily involve sediment transfer to a stream.

Thirteen studies in the region show that soil transfer rates in clearcuts ranged between 400 and 5,500 percent and average 1,000 percent more than in unmanaged forests (Figure 2.3). The percentage increase of soil transfer was much higher for landslides in logging roads. The eleven studies in Figure 2.4 showed increases between 400 and 50,000 percent (average of 16,650 percent).

Sediment Budget Studies

Five sediment budget studies have been conducted in managed watersheds in the Pacific Northwest and Idaho. These budgets were constructed in the Queen Charlotte Islands, British Columbia (Roberts and Church, 1986); the Clearwater River, Olympic Peninsula, Washington (Reid et al., 1981); the Cascade Range of Oregon (Swanson et al., 1982); the Idaho Batholith, central Idaho (Megahan, 1982; Megahan et al., 1986), and the north central Cascades of Washington (Eide, 1990). A summary of four of these sediment budgets is shown in Table 2.1.

In all of the sediment budgets shown in the table except the one from Idaho, mass wasting (including deep-seated failures) dominated other sources of sediment contributed to streams: mass wasting accounted for 80 to 89 percent in the Queen Charlotte Islands, 52 to 64 percent in the Olympic Mountains, 81 percent in the Cascade Range of Oregon, 95 percent in the Washington Cascades, and 19 to 23 percent in the Idaho Batholith. Because mass wasting is such an important component of sediment budgets in mountainous terrains of the Pacific Northwest, increased rates of landslides and debris flows associated with forestry can greatly accelerate erosion computed over entire watersheds. For example, forest management activities were responsible for a 37 to 76 percent increases in erosion in the Queen Charlotte

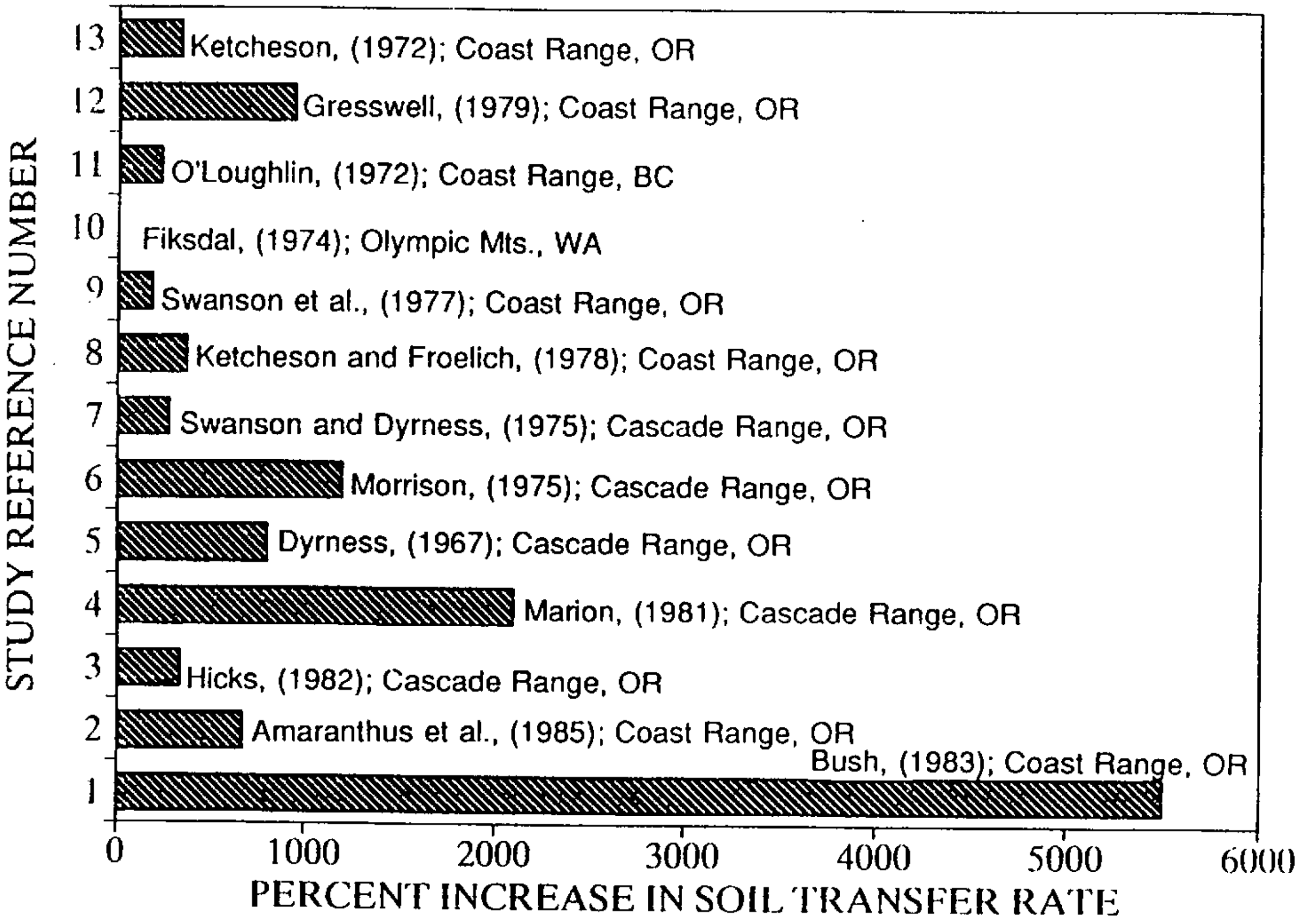

Figure 2.3
Percent increase in soil transfer rates due to landslides in clearcuts compared to soil transfer rates from clearcuts in unmanaged forests for 13 studies in the Pacific Northwest.

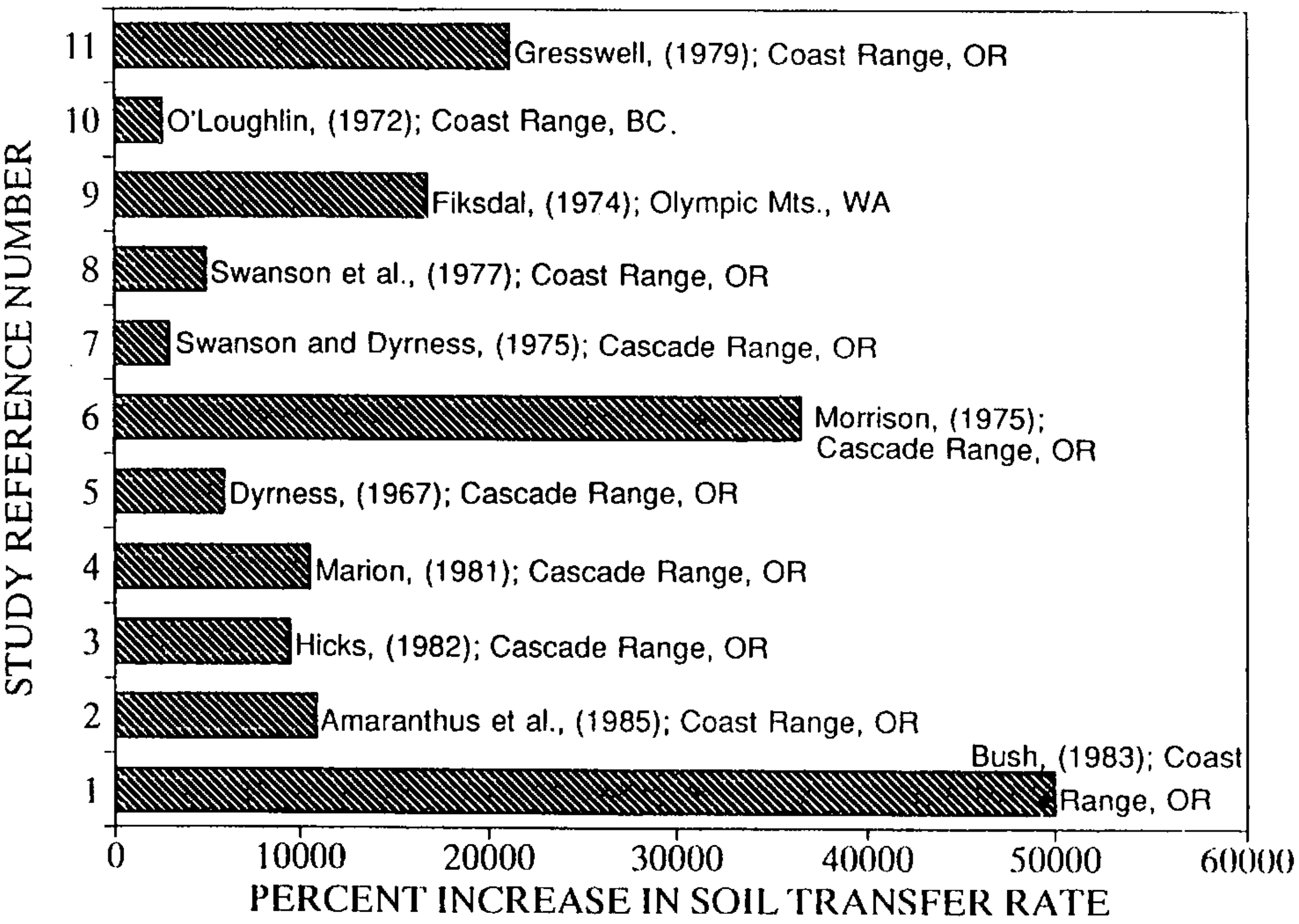

Figure 2.4
Percent increase in soil transfer rates due to landslides in clearcuts compared to soil transfer rates from landslides in unmanaged forests for 11 studies in the Pacific Northwest.

Table 2.1
Sediment budgets for small watersheds following timber harvest in the Pacific Northwest (from MacDonald and Ritland, 1989)

	Queen Charlotte Islands, British Columbia[a]	Clearwater River, Olympic Peninsula, WA[b]	Watershed (WS) 10, Cascade Range, OR[c]	Idaho Batholith, Central Idaho[d]
Forest Type	Sitka spruce, western red cedar	western hemlock, silver fir	Douglas fir	Douglas fir, ponderosa pine, grand and subalpine firs
Geology	Triassic sedimentary and volcanic	Miocene sedimentary	Tertiary volcanics, volcaniclastics	Cretaceous granitics
Drainage Area	1.4 km^2	10 km^2	0.1 km^2	1.26 km^2 (average)
Road Density (km/km^2)	0.3	2.5	0	?
Hillslope Sediment Delivered to Streams (t/km^2/yr):				
Mass wasting	926-1480	136-235	126	17
Soil creep/treethrow	42-102	29/9	11/1	7-22 (total, all 4 rows)
Slope wash/ravel	12-18	16	17	
Gullying (slide scars)	54-217	0	0	
Other (bioturbation, etc.)	0	4	0	
Road surface, backcut	6	65-74	0	49
Total	1040-1823	259-367	155	73-88
Fluvial Erosion (t/km^2/yr):				
Stream banks	223-463	29 (72% from 1st- and 2nd-order channels)	31	< 3-10
Debris flows	—	26	494	0
Total (t/km^2/yr):	1263-2286	555	680	76-98
Total yield above background (t/km^2/yr):	469-1708	191-309	597	66

[a] Roberts and Church (1986); synthetic, based upon regional rates, aerial photography 1936 to 1967, field measurements; 60 percent of sediment production from unlogged portion of the basin.

Table 2.1 (continued)

[b] Reid et al. (1981); synthetic, based upon field measurements 1977 to 1979, geologic and dendrochronologic interpretation, regional rates.

[c] Swanson et al. (1982; 1987a); synthetic, from process measurements in H. J. Andrews with 2- to 25-year periods of record, 1957 to 1982.

[d] Megahan (1982) and Megahan et al. (1986); based on measurements 1973 to 1978, 1980.

Islands, 34 to 56 percent in the Olympic Mountains, 88 percent in the Oregon Cascades, and 67 to 86 percent in the Idaho Batholith (Table 2.1).

Geographic Variation in Occurrence Rate

Some generalizations can be made from the landslide studies listed above about the importance in Washington State of regionally varying factors such as geology, climate, and vegetation.

Fiksdal and Brunengo (1980) mapped landslides in five physiographic regions of the State. The regions, based on soils and geology, vegetation, and precipitation, were North Cascades, South Cascades, Olympic Peninsula, Willapa Hills, and Puget Lowland. Fiksdal and Brunengo also mapped landslides in more detail within five drainage basins selected from these regions (1981).

They identified several general associations between regional geology and susceptibility to mass movement. In the North Cascades, bedded sandstone and shale were highly prone to shallow-rapid landslides, earthflows, and debris torrents, particularly on slopes greater than 20 to 25 degrees and when rock strata dipped in the direction of the land slope. In the South Cascades, soft, altered pyroclastic rocks, especially interbedded with harder flow rocks, had the greatest instability. In the Olympic Peninsula's Hoh and Clearwater drainages, high relief and precipitation were thought to have a dominant influence, although slopes parallel to the dip of fractured and faulted sedimentary and volcanic rock layers were also common there. The Willapa Hills was considered to be more prone to failure than the other regions because of the prevalence of soft marine sediments and of contacts between soft sediments and harder volcanics, and because of the deep, weathered soils.

Studies by Fiksdal and Brunengo (1980) did not include areas within the Puget Lowland, where thick layers of sediments were deposited by continental glaciation. Eide's (1990) sediment budget study, which covered a site partially within an area of thick glacial deposits, and Heller's (1981) landslide inventory in the Skagit River drainage are among the few studies to examine mass wasting in glacial sediments. Debris flows, large slump-earthflows, and chronic stream erosion following the passage of debris flows and dam-break floods are common sediment sources in this area.

We are not aware of landslide inventories from the northeast Cascades and northeastern ranges of Washington State. However, inventories conducted in central Idaho (Megahan et al., 1978) are relevant to much of the northeast Cascades and Okanogan-Washington Rockies region, because these areas are dominated by granitic material similar to that of central Idaho and have a similar climate. As indicated above, landsliding in central Idaho accounts for a much smaller proportion of total watershed erosion than in western Washington and Oregon. In Idaho's Clearwater National Forest 88 percent of landslides were associated with vegetation removal, 9 percent with roads, and 3 percent with undisturbed sites. The majority of landslides inventoried by Megahan occurred on slopes of about 60 percent. In some cases, rock fracturing and mid-slope position are important indicators of failures in the Idaho Batholith (Megahan et al., 1978).

Throughout the State, slope steepness and the lateral divergence or convergence of hillslopes is often more important than regionally varying geology in determining landslide occurrence. Soils and saprolite on slopes greater than about 35 degrees and located in laterally convergent topography (often referred to as swales, bedrock hollows, zero-order basins, and headwalls) are inherently unstable (Sidle et al., 1985; Fiksdal and Brunengo, 1981). Landslides are concentrated in steep bedrock hollows in diverse geologic terrains from Alaska to California.

Occurrence Rate of Debris Flows

Because debris flows (or torrents) play a particularly important role in delivering sediment to streams, studies in Figures 2.1 and 2.2 that noted the occurrence of debris flows in managed forests are discussed separately here. Swanston and Swanson (1976) found that debris torrents in clearcuts and in logging roads in the H. J. Andrews Experimental Forest occurred at rates 450 and 4,100 percent higher than in unmanaged forests. Their results are similar to Morrison's (1975), which found 880 and 13,000 percent increases in debris torrents associated with clearcuts and logging roads in the Alder Creek drainage of Oregon.

In the Oregon Coast Range, Benda (1988) inventoried 44 debris flows that had occurred in a fifth-order, 52-square-kilometer basin between 1952 and 1982. Though there was evidence of historic debris-flow activity at the mouth of many steep first- and second-order basins, 50 percent of the debris flows that occurred during the study period originated from logging roads and 45 percent originated from clearcuts; the remaining 5 percent of debris flows initiated in old-growth forests. In the Deer Creek basin of the western Washington Cascades, Eide (1990) showed that all of the 15 debris torrents that occurred between 1935 and 1990 were associated with either clearcuts or logging roads.

Further discussion of debris flows is found in Section 2.2, Transfer of Sediment from Hillslopes to Stream Channels.

2.1.1.2 Mechanisms Triggering Landslides and Debris Flows from Harvest Units

Soil stability on slopes is influenced by the composition and strength of soil and fractured bedrock, hydrologic characteristics of soils, soil thickness, slope angle, and roots of vegetation (Sidle et al., 1985). Forestry activities variously affect these factors, as described below.

Loss of Root Strength

Tree and shrub roots stabilize soil by contributing to the soil's effective cohesion and by anchoring the soil mantle to underlying bedrock. Numerous studies have shown that root decay following timber harvest causes soil strength to decline. For example, tree cutting caused root strength in soils to decrease by 60 percent in Northern California (Ziemer, 1981) and by 85 percent in the Oregon Coast Range (Burroughs, 1984). Many other studies of root strength conducted worldwide have consistently shown a loss of root strength following timber cutting (for example, Wu et al., 1979; Gray and Megahan, 1981; Tsukamoto, 1987; O'Loughlin and Watson, 1979; 1981).

Tree roots do not decay enough to affect soil stability until several years after trees are cut. For this reason, landslide inventories typically show increased landsliding beginning three to five years after harvest. Conversely, revegetation of the harvested site with shrubs and conifers slowly increases the rooting strength in soils, although 20 to 50 years may be needed for sites to recover fully (Ziemer, 1981; Burroughs and Thomas, 1977). Hence, the period of reduced root strength following cutting but prior to growth of new roots often extends from 5 to 15 years after harvest and has been referred to as the "window of vulnerability" for slope failures (Sidle et al., 1985). Many landslide inventories show that landslide incidence peaks during this period.

Increased Soil Moisture Due to Decreased Evapotranspiration

Removal of trees reduces evaporation and transpiration, thereby increasing soil moisture. Evapotranspiration is small during large storms that promote landsliding, and therefore reduced evapotranspiration does not contribute significantly to soil water during failure (Sidle et al., 1985).

Broadcast Slash Burning: Loss of Root Strength

Broadcast burning on steep slopes destroys understory trees and shrubs, thereby eliminating the rooting strength they provided to the soil. As discussed above, tree harvesting reduces the root strength of the soil, and burning seriously compounds that effect by essentially eliminating the remaining root strength. Research has shown that roots of both trees and shrubs impart significant strength to the soil (Ziemer, 1981). Loss of this root strength through timber harvest and broadcast burning may promote landslides and debris flows on unstable slopes.

Increased Soil Moisture Due to Rain-on-snowmelt

The term rain-on-snow is commonly applied to snowmelt during rainfall. The snowmelt portion can be a significant component of the total water delivery (rain plus snowmelt) to the soil and streams during storms. Rain-on-snow runoff is an integral component of fluvial and hillslope processes operating in Washington and elsewhere in the central west coast of North America (Harr, 1981; Beaudry and Golding, 1983; Toews and Gluns, 1986).

Timber cutting can increase both snow accumulation and subsequent melt during rainfall, and plot-scale studies have confirmed the linkage between reduced forest cover and increase in timing and amount of water available for runoff (Beaudry and Golding, 1983; Berris and Harr, 1987). Preliminary results from ongoing research in Washington support these findings (Harr et al., 1989).

Increased melt rates can in turn influence local groundwater levels during rain-on-snow events. For example, studies in the Idaho Batholith showed that groundwater elevations as measured by piezometer, rose following clearcutting and fires (Megahan, 1983). A large portion of this increase was attributed to increased snow accumulation and melt in the large openings created by clearcutting.

Greater soil saturation during rain-on-snow events has the potential to promote greater slope instability. Though many landslide inventories reveal numerous landslides in the transition snow zone (i.e., the area most likely to be affected by rain-on-snowmelt), the magnitude of that effect on slope stability is not well understood.

2.1.1.3 Mechanisms Triggering Landslides and Debris Flows from Roads

Road construction on hillslopes affects soil stability by adding weight to the slopes in the fill section, by steepening and undercutting the slopes above the road, and by altering drainage characteristics. Road location, construction, and maintenance affect the relative importance of the above factors in determining the stability of the slope and road prism.

Road-fill Failure

Several studies show that landsliding of road fills is the most common type of road failure. Gonsior and Gardner (1971) reported that fill failures accounted for 77 percent of road-related failures in an area of the Idaho Batholith. Fill-slope failures occurred more frequently than cut-slope failures in the Blue River drainage of Oregon's western Cascades (Marion, 1981). In Alder Creek, also in Oregon's western Cascades, fill-slope failure contributed 90 percent of the sediment delivered by road-related failure as opposed to 9.7 and 0.3 percent for cut-bank and washout failures (Morrison, 1975). In the Stequaleho and Christmas basins of the Clearwater River basin in the Olympic Mountains, Reid (1981) found that fill failure dominated road-related erosion. O'Loughlin (1972) showed that most landslides were associated with road fills, sidecast, and poor drainage. In the H. J. Andrews Forest in the western Oregon Cascades, fill failures were approximately 2.5 times more common than cut-slope failures (Dyrness, 1967a).

Fill failure occurs either through shallow sloughing or when the entire fill slides along the underlying ground. This latter mode is common for loose, sidecast fills on steep ground.

Roads promote fill failure by recharging the groundwater within the road prism (Megahan, 1972) as a result of surface saturation and interception of subsurface flow (for example, Gonsior and Gardner, 1971). Fills also fail because misdirected road drainage undercuts fill (Fredriksen, 1963) or because culverts plug and pond water on the upslope side. The decay of organic matter in road fill can also trigger failure (Amaranthus et al., 1985).

Cut-slope Failures

Cut-slope failures in road prisms typically have had a lower frequency than fill-slope failures and account for 4 to 10 percent of road-related failures (Dyrness, 1967a; Gonsior and Gardner, 1971). This lower frequency is thought to be due to the lower soil density of the fill slopes and their saturation by road-surface runoff.

Concentration of Drainage by Logging Roads onto Steep Slopes

Logging roads have infiltration capacities two to three orders of magnitude less than those of undisturbed forest floors (Reid, 1981). As a consequence, even moderate rainfall intensities may result in large amounts of surface flow on road surfaces. Surface runoff can be concentrated and diverted through culverts onto steep slopes. Concentration of drainage in this way can saturate soils to a much greater degree than would occur naturally during large rainstorms or rain-on-snow events (Megahan 1972; Sidle et al., 1985). Drainage concentration has been observed by numerous investigators (Reid, 1981; Megahan, 1972; Sidle et al., 1985; Curran et al., 1990), but this mechanism has not been formally incorporated into predictive slope-stability evaluations.

2.1.2 Slump-earthflows

A slump is a movement of a block of earth over a broadly concave failure plane involving relatively little breakup of the failed mass (Swanston and James, 1976). Slumps are typically triggered by the build up of pore water pressure in mechanically weak, and often clay-rich, rocks (Swanston, 1974). The plane of failure is a few to tens of meters below the ground surface. The main scarp is generally bare and concave toward the toe. The toe is hummocky or broken by individual slump blocks (Swanson and James, 1975; Swanson and Swanston, 1977).

Where the failed mass is broken up and transported by the flowing or gliding of a series of blocks, the movement is termed an earthflow. Earthflows move through a combination of slumping and slow flow; they can remain active for thousands of years, with periods of activity and dormancy (Swanson et al., 1987) and move at rates ranging from imperceptible to more than a meter a day (Swanston and Swanson, 1976). The toe of an earthflow is typically lobate and hummocky. The term *slump-earthflow* is used in the Northwest because many features have slump characteristics in the headwall area and develop earthflow characteristics downslope (Swanston and Swanson, 1976).

Slumps and earthflows can initiate on slopes as gentle as 4 to 20 degrees (Sidle, 1980), and in Washington they occur in altered sedimentary and volcaniclastic rocks and glacial sediments of the western Cascades, Olympics, and coastal ranges (Fiksdal and Brunengo, 1980). Sites have also been identified and studied in the drier eastern Cascades (Swanston, 1981).

Studies in the Pacific Northwest indicate that deep-seated failures move most rapidly during the wet season, and unlike shallow failures, which are influenced by individual storms, deep-seated failures are controlled by the seasonal buildup of groundwater at the base of the failure (Iverson and Major, 1986). Movement thus can accelerate as the wet season progresses (Swanston and Swanson, 1976).

Roads can destabilize slumps and earthflows in several ways, and identifying and avoiding such features is the best way to minimize the potential for accelerated movement (Swanston, 1974). Sidle (1980) recommends that fill amounts be limited, especially at the upslope ends of slump features, which could be destabilized by loading. Road cuts can also destabilize earthflows and slumps by undercutting the features' toe. Sidle (1980) also recommends using additional cross drains on insloped roads to avoid excessive saturation of the road prism and installing horizontal drains in cut and fill slopes.

The effect of removing trees on slump and earthflow behavior is not well established. Several field studies in the Pacific Northwest have demonstrated that when trees are cut, slumps and slump-earthflows can be reactivated or accelerated (Swanston et al., 1988; Swanston, 1981; Ziemer, 1984; Benda et al., 1988). Because failure takes place several meters below the ground surface, the loss of anchoring by tree roots is probably less important, although lateral roots may play a role in reinforcing across planes of weakness such as headwalls and tension cracks surrounding earthflows and slumps (Swanston and Swanson, 1976).

Hydrologic changes associated with tree cutting are thought to affect the behavior of slumps and earthflows. Removing trees reduces evapotranspirative water loss, and this reduction can increase pore water pressures at the failure zone and accelerate the downslope movement of deep-seated failures seasonally (Swanston, 1981). In the one study where data are available for a sufficiently long period, movement was accelerated by tree cutting but returned to the pre-harvest rate within three years (Swanston et al., 1988). Another study in the Cascades of Washington revealed a good correlation between harvest in the groundwater recharge area of a large, deep-seated landslide and accelerated activity (Benda et al., 1988).

2.1.3 Channel-bank Erosion

Forestry practices that increase bank erosion are (1) logging in and adjacent to streams, thereby decreasing stream-bank stability; (2) removing large organic debris from stream channels, thereby triggering bed and bank erosion; (3) increasing bedload; (4) increasing peak flows; (5) increasing the incidence of debris flows; and (6) dam-break floods and migrating organic dams.

2.1.3.1 Streamside Logging

Within the context of a sediment budget study of four logged watersheds in the Queen Charlotte Islands in British Columbia, Roberts and Church (1986) documented the effects of logging within riparian areas. In three of four studied basins, bank erosion following logging contributed from more than 50 to as much as 85 percent of the total sediment influx. Following logging in the early to mid-1960s, streams in three of the basins widened by 50 to 100 percent by 1976. In the fourth basin, the channel widened by 190 percent during the period from 1970 to 1976. These impacts resulted from felling, yarding, and skidding near and in streams, practices which, the authors report, are now outmoded in Canada. Channel banks had not stabilized in one to two decades following logging disturbance.

2.1.3.2 Removal of Inchannel Organic Debris

Several studies have evaluated the effects of removing organic debris from streams (for example, Klein et al., 1987; MacDonald and Keller, 1987) and have shown that doing so contributes previously trapped sediment to stream sediment loads.

2.1.3.3 Increased Bedload

Forestry can also accelerate bank erosion by increasing the amount of coarse bedload in channels. Madej (1982) evaluated the effects of intensive forest management on the channel of Big Beef Creek, a Puget Lowland stream. In response to an increase in sediment yield from forestry operations, bedload transport increased from 500 to 4,200 tons per year. In the absence of channel surveys made prior to increased sediment influx, Madej compared measured channel widths in Big Beef Creek with a survey of channel geometries in other streams of the region. This comparison and a comparison with a survey of Big Beef Creek made eight years previous led to the conclusion that the channel had widened as a result of the increased bedload input.

Beschta (1984) summarized two similar studies on the effects of forestry-related coarse sediment influx on channel banks conducted in Oregon (Lyons and Beschta, 1983) and New Zealand (Beschta, 1984). In both cases, an extreme flood combined with increased sediment influx caused persistent channel widening. Channel widening was most pronounced at and immediately downstream of sediment inputs. Beschta argues that sediment influx rather than peak flow was the key element that destabilized banks.

2.1.3.4 Increased Peak Flows

Increased accumulation and melt rates can also influence stream flows, which can in turn cause channel-bank erosion. Using long-term flow records, Cristner and Harr (1982) noted apparent increases in stream flow in large watersheds in western Oregon that related to the timber harvest history of the basins. As indicated previously, the effect of enhanced rain-on-snowmelt on stream flow at a variety of spatial scales has not been studied in great detail.

The effects of deforestation and roading on runoff and attendant increased channel erosion by floods have not been studied.

2.1.3.5 Increased Incidence of Debris Flows

Two recent studies of landsliding in the western Cascades of Washington have quantified the effects of debris flows on the triggering of channel-bank erosion and landslides on steep slopes adjacent to stream channels. Eide (1990) constructed a sediment budget for Deer Creek, a tributary of the North Fork Stillaguamish River, and found that 51 percent of stream bank erosion was the result of debris torrent erosion in first-, second-, and third-order streams; a direct relation was found between the incidence of debris torrents (debris flows and dam-break floods) and forestry activities between 1942 and 1989.

Gowan (1989) studied landsliding in Boulder Creek, a tributary of the North Fork Nooksack River drainage. Logging roads in the vicinity contributed to the instability of steep slopes on mechanically weak rocks and sediments adjoining the channel of Boulder Creek. Debris deposited into the channel by landsliding diverted the stream to the base of slope failures, perpetuating the instability of the failures.

2.1.3.6 Landslide/Dam-break Floods

An important process that promotes bank erosion and accelerated erosion of valley walls is the landslide/dam-break flood. Landslides and debris flows that deposit in narrow valley floors in mountainous terrains often create temporary dams that quickly impound water, creating a small lake. Rapid failure of the dam may lead to an extreme flood that may cause extensive downstream erosion and sedimentation along entire stream-order segments in the

Cascades, Olympics, and coast ranges; these events are referred to as landslide/dam-break floods (Benda and Zhang, 1989).

These extreme floods can be one to two orders of magnitude greater in discharge than normal runoff floods and have been observed in valleys of third- through sixth-order in the Washington Cascades (Benda, Zhang, and Dunne, research in progress, University of Washington). The floods, freighted with large amounts of large and small organic debris, are capable of destroying entire riparian zones and causing major valley-wall erosion. Subsequent erosion of the devegetated floodplains and valley floors by streamflow can lead to accelerated erosion for many years following the event.

Landslide/dam-break floods have been referred to as debris torrents in the Pacific Northwest. Because dam-break floods result from the failure of dams formed by landslides and debris flows, it follows that they occur at an accelerated rate in managed forests. Because debris flows and dam-break floods often have been referred to as debris torrents, however, inventories of dam-break floods have not been conducted.

A second, related process is the migrating organic dam. Landslide/dam-break floods that occur in small mountain basins often entrain enormous amounts of live and dead organic debris. Under certain circumstances this debris will form the leading edge of a flood wave and slow the event, allowing the stream to catch up. As a consequence, the organic debris acts as a "migrating dam," capturing the incoming streamflow and creating a migrating lake. The organic debris dam continues to destroy and entrain additional live and dead vegetation, including entire trees from the floodplains and valley floors. These events can enlarge dramatically as they progress downvalley and have been referred to as migrating organic dams (Benda, Zhang, and Dunne, research in progress).

Migrating organic dams also form from the collapse or migration of a previously stationary woody debris jam in streams. This process of initiation is not well understood and is currently a research topic at the University of Washington (Burges and Coho, Department of Civil Engineering).

2.1.4 Surface Erosion

2.1.4.1 Surface Erosion of Roads

Processes included under the category of surface erosion are dry ravel, sheetwash, rilling and gullying, and shallow sloughing.

Numerous studies have examined the effects of roads on sedimentation on a basin scale (for example, Beschta, 1978; Sullivan, 1985, 1987; Anderson and Potts, 1987); these studies are summarized elsewhere (for example, McDonald and Ritland, 1989; Swanson et al., 1987). This review is restricted to studies that have examined surface erosion on individual components of roads. These components are broken into road construction, road surface, cut bank, and road fill.

2.1.4.2 Road Construction

Construction usually produces high rates of erosion that decline rapidly with time. Megahan and Kidd (1972) found that almost 84 percent of all sediment produced from road-surface erosion was generated during the first year after construction. Fredriksen (1970) reported similar results from Oregon.

Megahan et al. (1986) studied erosion during construction of standard USDA Forest Service roads and roads with upgraded erosion control in Idaho. The study showed that sediment yields from basins increased by an average of five times and that all but 7 percent of eroded sediment was stored in channels and slopes.

Other studies have looked at basin sediment yields without evaluating sediment storage and have shown significant increases in sediment yield temporally associated with periods of road building. For example, Sullivan et al. (1987) found in southwestern Washington that sediment yields were increased by 10 to 30 times by road building. The effects of storage within watersheds (e.g., Duncan et al., 1987) and of other sediment sources, however, complicates interpretation of these studies. Similar studies include Anderson and Potts (1987), Krammes and Burns (1973), Megahan and Kidd (1972), Fredriksen (1965), Beschta (1978), and Rice et al. (1979).

2.1.4.3 Road Surface

Studies of road-surface erosion have monitored the effects of natural events and simulated rainfall experiments on road segments. Erosion rates have been reported by a number of researchers, including Swift (1984b), Burroughs et al. (1984), Burroughs and King (1989), Sullivan et al. (1987), Reid et al. (1981), and Reid and Dunne (1984).

Road surfaces can provide large amounts of fine sediment, depending on road use level. Reid et al. (1981) and Reid and Dunne (1984) found that heavily used roads produced 1,000 times more sediment than abandoned roads and 100 times more than a lightly used road. In a typical basin in the Clearwater River drainage located in the western Olympic Mountains, heavily used roads accounted for 71 percent of road-related surface erosion even though they account for only 6 percent of total road length. Road surface accounted for 19 percent of all road-related sediment production, with landslides and debris flows accounting for most of the rest (72 percent). Road-surface erosion accounted for 40 percent of fine sediment.

Bilby et al. (1985, 1989) measured sediment runoff from road segments in basins of southwestern Washington, where annual rainfall is significantly less than in the western Olympics. They found that erosion rates from heavily used roads were an order of magnitude less than in the Clearwater study. They also found that the thickness and competence of surfacing materials appeared to influence erosion rate. Swift (1984a) and Kochenderfer and Helvey (1989) made similar observations on the importance of gravel thickness and composition on erosion.

2.1.4.4 Road Fill

Megahan (1974, 1978) measured fill-slope erosion in Idaho and found that initially high erosion rates declined rapidly with time. Reid et al. (1981) found that fill erosion accounted for only a small percentage of total road-related erosion. Chronic road-fill erosion can be severe, however, depending in part on the steepness and length of fill slopes. Rilling and gullying of road fill can also be severe if road surfaces are drained onto fill (Burroughs and King, 1989), or if roads intercept drainage, which then runs uncontrolled along the road surface and onto the fill slope (Hagans and Weaver, 1987).

2.1.4.5 Cut Slopes

Because of the steepness of cut slopes relative to fill slopes, dry ravel can dominate erosion on cut slopes, especially on noncohesive soils (Megahan, 1978). In Oregon, Dyrness (1975) found that dry ravel from cut slopes in tuffs and breccias was almost as large as rain-generated sediment. Shallow sloughs of saturated fill material can also be a dominant process (Burroughs and King, 1979).

Reid et al. (1981) found that cut-bank erosion accounted for about 2 percent of road-related sediment in a hypothetical basin. Cutbanks and ditches of active roads accounted for 4.5 percent of average road-surface erosion. Most eroded sediment accumulated at the base of the slope and protected the lower slope from further erosion (Reid and Dunne, 1984). Of the amount that is transported to slope bases, most appeared to be trapped in the ditch.

Road maintenance can thus trigger continued cut-slope erosion by removing debris from the slope base. Megahan and others (1983) measured long-term rates of cut-bank erosion on a 45-year-old road by reconstructing its original profile from tree roots. They recommended that grading of undercut material deposited at the base of roadcuts be avoided.

2.1.5 Surface Erosion from Harvest Units

2.1.5.1 Landslide Scars

Erosion of bare soils exposed by landslides can represent a significant portion of the overall sediment budget of a forested drainage basin. Sediment eroded from landslide scarps and scars represented 6 percent of all sediment production in a managed, 20-square-kilometer watershed in the Clearwater River drainage of the Olympic Mountains (Reid et al., 1981), and up to 9 percent of total sediment production in four small (3.9- to 12.6-square-kilometer) watersheds of Canada's Queen Charlotte Ranges (Roberts and Church, 1986). Data by Smith et al. (1984) cited by Roberts and Church indicate that landslide-scar erosion continues as a significant source for 20 years after initial failure.

2.1.5.2 Tractor-skidder and Cable Yarding

Timber harvest can increase erosion and sedimentation by disturbing vegetation and soils, thereby exposing soil to water erosion and dry ravel, and by compacting soil, thereby decreasing the infiltration capacity. Tractor yarding causes more soil disturbance compared to cable systems (see Anderson et al., 1976 for review). Rice and Datzman (1981) found that erosion from tractor yarding was four times that of cable systems on a number of sites in California. Skyline crane systems disturb soil less than high-lead yarding (Dyrness, 1965, 1967b; Ruth, 1967; Anderson et al., 1976).

Assessments of sediment eroded from harvest units have concentrated on measuring suspended sediment transport in streams. This approach masks several dominant factors that influence sediment influx and transport. The amount of eroded sediment that reaches stream channels is dependent in large part on the extent to which soil and vegetation disturbance is isolated from the channels. Moreover, as research reviewed by McDonald and Ritland (1989) indicates, low-order streams (Types 4 and 5 in Washington State) include many storage sites and act as potential buffers between sediment influx and downstream-measured transport. Finally, operator performance may play as great a role as site characteristics and operation type (Rice and Datzman, 1981).

O'Loughlin et al. (1980) found that sediment yield in a tractor-yarded basin in New Zealand was 8 times that in a comparable, undisturbed basin, and cable yarding resulted in about 1.5 times that of the undisturbed basin. Brown and Krygier (1971) found in an Oregon Coast Range basin that cable logging did not elevate suspended sediment yields. Dyrness (1970) found no increase in suspended sediment from a watershed in the western Cascades of Oregon in the two years prior to slash burning, although he points out there could have been some sediment storage in low-order tributaries. Megahan (1975), working in granitic terrain in central Idaho, found that felling and skidding resulted in 1.6 times the sedimentation in a six-year period from an undisturbed basin. Furthermore, sedimentation declined exponentially. Eighty-four percent of the erosion occurred in the first post-logging year, and 93 percent in the first two post-logging years.

2.1.5.3 Slash Burning

Slash burning can promote erosion in several ways. Fire can consume the organic litter layer that covers the soil, thereby exposing the mineral soil to erosion by water and gravity (dry ravel). Some of the organic matter in soil can also be volatilized, destroying soil structure and reducing infiltration. Finally, in some situations, fire can create a hydrophobic chemical surface. Whether any of these effects are important in a given situation depends on the severity of the burn, the soil erodibility, the potential for vegetative recovery, and the physiographic region. Under most conditions, slash burning does not create erosion problems.

Severity of burn influences the extent to which mineral soil is exposed. In the western Cascade Range of Oregon, Mersereau and Dyrness (1972) found that after clearcutting and before broadcast burning, 12 percent of a western Cascades watershed was bare soil. After burning 55 percent was bare. Revegetation occurred rapidly, and erosion, primarily by dry ravel, occurred only during the first post-fire growing season prior to significant revegetation. Dyrness (1973) found that only 3 to 8 percent of the total area of a typical broadcast burn was burned severely enough to cause ongoing erosion problems. Dry ravel can also be a chronic source of sediment in areas where revegetation is slow for other site reasons (Mersereau and Dyrness, 1972). Dyrness (1970) found that the burning did not result in increased sedimentation except in a watershed that was entirely cut over, and then the sedimentation increase was speculatively attributed to the release of channel sediments when channel organic matter burned. Fredriksen (1970) and Beschta (1978) similarly found that little sedimentation resulted from slash burning, although, like Dyrness, Beschta found that in a watershed with no riparian vegetation and subject to a very hot fire, sedimentation did result, either from the mechanism suggested by Dyrness or by streamside erosion associated with logging.

Two studies of prescribed burning on dry ponderosa pine forests in Arizona and California showed no noticeable effect on overland flow and erosion because a sufficient layer of organic material remained after the fire to protect the soil (Anderson et al., 1976).

Erosion problems can be more significant on granular soils, such as those found in the granitic terrain of central Idaho and in much of north central and eastern Washington, and on soils derived from volcanic tephra (Anderson et al., 1976). Most of the studies in the published literature, however, were conducted on these granular soils following wildfire, which is considerably hotter and more devastating to the soil organic litter layer and the soil structure than slash burning fires (Megahan and Molitor, 1975; Helvey et al., 1985; Helvey, 1981).

Fire can create chemicals on the soil surface that give the soil water-repellency, a decreased infiltration rate, and greater susceptibility to erosion (DeBano, 1981). DeByle (1973) studied the effects of slash burning on a larch and Douglas fir forest in Montana with fine- to medium-textured soils. He concluded that the moisture content of soils and fire temperature in most broadcast slash burns did not cause significant development of water-repellency. McNabb et al. (1989) studied a broadcast burn of fine-textured soils in the mixed evergreen forest of southwest Oregon and found that resulting water-repellency was slight and lasted for only five months.

Piling and burning of slash as an alternative to broadcast burning can have a greater impact on soil water-repellency (DeByle, 1973) and erosion (Geppert et al., 1984) than broadcast slash burning because of the effect of the high heat on the soil underlying the pile and because of soil disturbance and compaction by heavy equipment.

2.1.5.4 Mechanical Site Preparation

The effect of intensive mechanical site preparation on erosion has been the subject of several studies in forests of the southern and southeastern U.S. (Dissmeyer and Stump, 1978; Blackburn et al., 1986; Beasley, 1979). These studies have generally shown increased erosion following activities such as tree crushing, chopping, shearing, disking, bedding, and ripping (NCASI, 1988).

2.2 TRANSFER OF SEDIMENT FROM HILLSLOPES TO CHANNELS

2.2.1 Landslides and Debris Flows

The debris flow is the most efficient geomorphic process at transferring sediment to streams in the Pacific Northwest. A single debris flow can transport thousands of cubic meters of sediment and organic debris directly into a third- or higher-order channel and can have a direct impact on fisheries. Debris flows are particularly significant in this regard because they travel through first- and second-order channels, which comprise 80 to 90 percent of the entire channel length in a large watershed.

Impacts to streams along the path of travel of the debris flow or at its site of deposition are unambiguous and are usually characterized by devastated riparian vegetation and severely eroded channels and valley floors. This type of sudden debris-flow impact poses serious risks to lives and property (Kellerhals and Church, 1990) and to streams and fish habitats (Swanson et al., 1987).

Often, the transition of shallow-rapid landslides to debris flows is governed by the topographic position and geometries of the landslide site and the channel network, and these factors have been incorporated into a model for predicting the downstream movement and deposition of debris flows in Oregon and Washington (Benda and Cundy, 1990).

Predicting debris flows enables an estimation of the length of the channels that will be impacted by a debris flow and the final depositional zone. This allows recognition and prediction of resources likely to be impacted by a debris flow. Benda and Cundy (1990) developed an empirical model of debris-flow deposition in confined mountain channels that does not require information on the rheological properties of the debris. The model employs two topographical criteria for deposition: channel slope (less than 3.5 degrees) and tributary junction angle (greater than 70 degrees); these criteria were based on field measurements of 14 debris flows in the Oregon Coast Range. For a more complete discussion of the derivation, test, and use of the model, refer to Benda and Cundy (1990).

2.2.2 Slump-earthflows

Slump-earthflow features often involve long slope segments that end at stream channels. Toes of slump-earthflows can oversteepen channel banks, which then fall or slide into the channel. Steep, lower portions of slumps and slump-earthflows can also cause repeated shallow debris slides. This mass wasting and erosion of slump and slump-earthflow toes can in turn trigger the continued failure. Sediment production by these processes has not been the subject of systematic study.

Fluvial erosion of the broken up surface of slump-earthflow features can also be an important mechanism for contributing sediment to streams. Kelsey (1978) found that sediment from this source equalled that from toe erosion on earthflows in a northern California drainage.

2.2.3 Surface Erosion

2.2.3.1 Roads

Sediment has been routed to streams by various mapping approaches. For example, Megahan et al. (1986) mapped the fate of total road-related sediments. They measured travel distance and deposition of granitic sediments below roads in three basins as well as sediment storage in channels and sediment transported from the basin. They concluded that during road construction, about 7 percent of the road-eroded sediment left the basin, and the majority (85 percent) remained in storage on hillslopes.

Megahan et al. (1986) later examined sediment delivery from a 45-year-old road for a basin within the Idaho Batholith. By reconstructing the original profiles of road banks from exposed tree roots, they estimated the long-term erosion and compared this to measured stream yields. They concluded that about 10 percent of the eroded sediment exited the basin.

Others have used a mapping approach to route culvert outfalls to streams. Bilby et al. (1989) mapped road drainage points on five road segments in three Washington and Oregon drainage basins. They found that 34 percent of drainage points entered a stream channel; the remainder were judged to empty onto the forest floor at a great enough distance from a stream for the water to infiltrate the soil. Reid and Dunne (1984) found that road drainage from 75 percent of culverts contributed directly to streams in a sub-basin of the Clearwater River in the western Olympic Mountains.

2.2.3.2 Logging and Site Preparation

Disturbed sites generate overland flow and erosion but do not contribute sediment to streams unless disturbance is contiguous to the stream. Assessment of sediment influx from logging and site disturbance is made by mapping the continuity of erosion features and disturbed soils up to streams.

2.2.3.3 Landslide Scars

Most landslides occur in topographic hollows at stream channel heads and along stream banks. Thus, the chronic erosion of most landslide scars results in the introduction of sediment directly to channels. Assessment of the contribution of landslide scars is made by mapping the location of scars relative to channels.

2.3 EFFECTIVENESS OF METHODS TO MITIGATE EROSION IN MANAGED FORESTS

2.3.1 Shallow-rapid Landslides

2.3.1.1 Approaches to Minimizing Landslide Hazard

There exist numerous methods for predicting relative slope stability based on natural hillslope characteristics such as gradient, slope form and soil depth, and forestry activities such as vegetation removal and road construction. The objective of these methods is the avoidance of particular combinations of site characteristics and forestry practices to reduce the likelihood of landslides (and debris flows).

The types of methods include:

1) Terrain or landform mapping (e.g., Ryder and Howes, 1984; Rollerson et al, 1986; Fiksdal and Brunengo, 1980; 1981).

2) Predictive, hazard-rating systems that incorporate such variables as gradient, geology, slope position, and slope form (e.g., Duncan et al. 1987; Hughes and Edwards, 1978; Ketcheson and Froehlich, 1978; Bush, 1982).

3) Deterministic mathematical slope stability computations, which attempt to take into account site parameters at a basin scale (e.g., Burroughs, 1984; Ward et al., 1981).

4) Simulation models, which predict probabilities of failure over large areas (e.g., Hammond et al., 1988; Benda and Zhang, 1989).

We are not aware of any studies that have tested the effectiveness of these methods except for the headwall leave area approach developed in the Mapleton Ranger District

(Bush, 1982). This method involved identification of a potentially unstable headwall (bedrock hollow) based on a rating system developed from the personal experience of several soil scientists in the district. To mitigate the landslide potential due to logging of that site, a buffer area of trees (no-cut zone) was left at that site, and often it was surrounded by clearcuts. This method was tested for its effectiveness at reducing landslides, and the test either was inconclusive or revealed higher frequencies of sliding in leave areas than in unmanaged headwalls (Swanson and Roach, 1987).

Other workers have concentrated on engineering improvements to road design and location. Using a factor-of-safety approach, Schroeder and Brown (1984) showed that for Oregon Coastal soils, translational failures can be avoided in the absence of seepage by keeping the fill depth to less than 5 meters (the vertical distance from subgrade to toe of fill) for soils with friction angles of 35.4 degrees, and soil densities of 1.82 milligrams per cubic meter on ground slopes of up to 70 percent. Rotational failure of fill material is also unlikely for fill heights of less than 5 meters. For unprotected fill toes, however, exiting seepage can cause backward erosion that eventually results in an over-steepened face that triggers a failure.

Prellwitz (1985) developed a three-level approach for analyzing landslides on forest lands. Using the concept of critical height and a factor-of-safety approach, the stability of cut-slope heights can be evaluated.

Changes in policies and practices regarding road location, design, and construction may be resulting in reduced road-induced failures (Barnett, 1983; Schwab, 1983; Gresswell et al., 1979; McCashion and Rice, 1983), although clear conclusions have yet to be drawn. Sessions et al. (1987) investigated the effect of improved road location and construction practices on road-related failure frequencies. They noted that the use of endhaul/fullbench construction on slopes of greater than 50 percent showed a significant reduction in road failures in comparison to historical road location and construction practices.

Roads in USDA Forest Service sites have shown lower failure rates than comparable sites on nearby private lands, and Spiesschart (as quoted in NCASI, 1985) speculated that the lower rates were due to higher design and construction standards.

Sessions et al. (1987) showed that using steep grades to place roads on ridgetops and avoiding mid-slope locations resulted in a significant reduction in road-induced failures in comparison to historical locations on mid-slopes.

In the last 10 to 15 years, the use of hydraulic excavators rather than bulldozers has increased rapidly, primarily because of the excavators' versatility and efficiency in right-of-way clearing, subgrade pioneering, and culvert installation (Gilman, 1987). The hydraulic excavator operates by digging, swinging, and depositing material, and the excavated material is placed, as opposed to being pushed and/or sidecast. Fill-slope lengths can be shortened by constructing a catch wall of boulders along the toe of the fill. This feature is particularly important when side slopes increase to more than 40 percent.

The excellent placement control of hydraulic excavators means that a balanced cross section can be constructed with considerably less excavation. Raveling disturbance and erosion is reduced as well because of lesser excavation and little or no downhill drifting of embankment material.

2.3.2 Debris Flows

The previous discussion of landslides is applicable to the debris-flow process because debris flows are triggered by landslides. The only addition is a model that predicts debris-flow travel distance and depositional area developed by Benda and Cundy (1990). The debris-flow model allows recognition of the highest hazard areas among numerous landslide sites, as previously described.

2.3.3 Slump-earthflows

Identifying and avoiding slumps and slump-earthflow terrain is the best way to minimize the potential for accelerated movement (Swanston, 1974). Terrain and landform mapping can be used to identify the most sensitive areas in a watershed, thus allowing more detailed field evaluation and alternative forest management practices.

When features must be crossed by roads, Sidle (1980) recommends that fill amounts be limited, especially at the upslope ends of features, which could be destabilized by loading. Road cuts can also destabilize earthflows and slumps by undercutting the features' toes. Sidle (1980) also recommends using additional cross drains on insloped roads to avoid excessive saturation of the road prism and installing horizontal drains in cut and fill slopes.

Scheduling the timing of tree cutting in deep-seated-failure terrain could limit the effects of cutting on increased groundwater pressures, but this practice has not been tested or evaluated.

2.3.4 Channel-bank Erosion

When triggering mechanisms are prevented, channel erosion is prevented. The integrity of riparian soils and vegetation needs to be protected, and landslides — and therefore debris flows/dam-break floods — need to be prevented.

2.3.5 Surface Erosion From Roads

The recent literature on the effectiveness of various road-erosion control measures has been summarized by Burroughs and King (1989).

2.3.5.1 Road Surface

Gravel-surfaced roads erode significantly less than unsurfaced roadways; two field studies showed that a gravel surface reduced erosion by 70 to 80 percent (Swift 1984; Burroughs et al., 1984). Gravel-layer thickness substantially affects erosion reduction; Swift (1984) found that a 2-inch layer was ineffective, whereas a 6-inch layer reduced erosion by 92 percent, and an 8-inch layer by 97 percent. Kochenderfer and Helvey (1987) found 88 and 97 percent reductions from 6- and 3-inch layers, respectively.

Dust oil and bituminous surface treatment reduced sediment production by 85 and 97 percent in a study conducted on granitic soils in Idaho (Burroughs et al., 1984).

2.3.5.2 Fill Slopes

Because fill-slope erosion is most rapid soon after construction, the effectiveness of measures to protect fill slopes from erosion is increased when implemented immediately after construction (Burroughs and King, 1989). Similarly, the effectiveness of all measures is increased when roads are insloped, and thus the amount of road-surface-generated runoff that is diverted onto the road fill is reduced (Burroughs and King, 1989).

Seeding alone has been found ineffective in controlling erosion from steep, granitic fill slopes (Bethlahmy and Kidd, 1966). Studies by Wollum (1962) and Swift (1984) measured erosion reductions from seeding of 68 and 58 percent, respectively, but their studies did not evaluate erosion during the most rapid period of erosion, the months immediately following construction.

Burroughs and King (1989) compared the effectiveness of six types of material applications. Effectiveness of the six materials in decreasing order was: straw with asphalt tack; straw with a net or mat; straw alone; erosion-control mats; wood chips or rocks; and hydromulch. Hydromulch, the least effective measure tested, produced no reduction in sediment production at 56 percent ground cover, about 16 percent effectiveness at 80 percent ground cover, and a maximum of 80 percent effectiveness at 100 percent groundcover. Straw with asphalt, the most effective measure, showed 56 percent effectiveness at 20 percent cover, 84 percent effectiveness at 60 percent cover, and 100 percent effectiveness at 100 percent cover.

Compaction by rolling of fillslope material reduced infiltration and increased erosion by 107 to 532 percent in an Idaho study (Boise State University, 1984). Similarly, application of a polymer soil binder in the same study increased erosion by a factor of about two because more runoff was generated, and the runoff detached soil in the cracked polymer surface.

Filter windrows constructed of logging slash on or below the fill slope slow the velocity of surface runoff and cause sediment deposition (Burroughs and King, 1989). Various studies (Cook and King, 1983; Burroughs et al., 1985; Swift, 1985) have shown that filter windrows can reduce erosion by 75 to 90 percent. When combined with mulch, windrows were 99 percent effective (Burroughs and King, 1989).

2.3.5.3 Cut Slopes

In reviewing the literature on the effectiveness of dry grass seeding of cut slopes, Burroughs and King (1989) concluded that for slopes of 0.75 to 1 with vertical height greater than 8 feet, first-year erosion reduction could be expected to be 10 percent; for cut slopes of 1 to 1 or less, expected first-year sediment reduction is 36 percent.

First-year sediment reductions for new 1-to-1 cut slopes on tuffs and breccias treated with 2 tons per acre of straw mulch averaged about 85 percent in Oregon (Dyrness, 1975). For the second through seventh years following construction, effectiveness declined to about 77 percent on 20- to 25-foot long slopes. Straw mulch with a tackifier is substantially more effective in reducing cut-slope erosion than is mulch alone (King, 1984).

A variety of net and mat treatments evaluated or reviewed by Burroughs and King (1989) showed effectiveness ranging from 60 to 98 percent.

Terracing cut slopes can be highly effective at reducing erosion. Studies by Megahan (1984) and Wagner et al. (1979; quoted in Burroughs and King, 1989) showed 86 and 94 percent effectiveness in granitic soils in Idaho and California, respectively.

Hydromulching is ineffective on steep cut slopes (Burroughs and King, 1989) and gives about a 10 percent reduction for 0.75-to-1 slopes and 30 percent for 1-to-1 and less cut slopes. Seeding can be very effective once a stand of grass has been established (Burroughs and King, 1989) but may be ineffective during the initial months following construction, when erosion is highest.

2.3.5.4 Road-surface Drainage and Culvert Spacing

Reducing the erosive power of water can be achieved by reducing its velocity. If, for practical reasons, water velocity cannot be reduced, surfaces must be hardened or protected as much as possible to minimize erosion from high-velocity flows. Road-surface drainage attempts to remove the surface water before it accelerates to erosive velocities and/or infiltrates into the road prism and destroying soil strength by increasing pore water pressures. This is especially true for unpaved, gravel, or dirt roads.

Water moves across the road surface laterally or longitudinally. Lateral drainage is achieved by crowning or by in- or out-sloping of road surfaces. Longitudinal water movement is intercepted by dips or cross drains. These drainage features become important on steep grades or on unpaved roads where ruts may channel water longitudinally.

Sloping or crowning significantly reduces sediment delivery from road surfaces. Reid (1981) showed a reduction in sediment delivery when the transverse road surface grade was increased. In this particular case the road surfaces insloped from 5 to 12 percent and were compared with conventionally constructed road surfaces at transverse slope grades of 0 to 2 percent. Sediment yield was reduced by a factor of 3.0 to 4.5 (from 970 to 400 to 260 tonnes per hectare per year) when compared to a conventionally insloped road.

Insloping of roads is also important to prevent surface waters from entering onto fill slopes. Gullying of fill slopes from road drainage can be a dominant process (Burroughs and King, 1989).

Reid (1981) calculated possible sediment production rates for various culvert spacings from field data and the Universal Soil Loss Equation (USLE). Washington Forest Practices Board guidelines require culvert spacing of less than 305 meters for roads with grades of 0 to

7 percent, less than 245 meters for grades of 8 to 15 percent, and less than 185 meters for road grades steeper than 15 percent. Calculations based on the USLE for a heavily used logging road indicated a sediment yield of 29.4 tonnes per road kilometer per year, or 10 percent of that of a 9.6 percent road grade with 245-meter culvert spacing. A 185-meter-long ditch line on an 18 percent road grade would produce about 806 tonnes per road kilometer per year or 2.7 times the rate of the 9.6 percent road grade. (A conversion rate of 1290 tonnes per hectare equal to 520 tonnes per kilometer was used based on a 4-meter road width.)

Sullivan et al. (1987) noted that the single most important characteristic that determines the magnitude to which truck traffic contributes to sediment deliveries to streams is the road surface area that drains directly into a stream. The greatest impact on water quality was from the direct entry of ditch lines or relief culverts into larger streams (Types 1 to 3).

Reid et al. (1981) report a typical sediment delivery ratio of 0.62 for road-surface sediment production. They estimate, however, that about 43 to 49 percent of basin suspended sediment load comes from road-surface erosion. No information on culvert outfall in relation to stream proximity was given.

Burroughs and King (1989) developed a cumulative frequency of sediment travel distances below fill slopes with the influence of relief culverts for roads in the Horse Creek basin in central Idaho. They stated that if the objective were to prevent 80 percent of the relief culverts from contributing sediments to streams, a distance of at least 175 feet must be provided between culvert outfall and the nearest live stream.

2.3.5.5 Discussion

After the initial construction period, sediment production and delivery is primarily a function of road-surface material, road grade, traffic load, the draining of road-surface areas directly into larger streams, a transverse or insloping gradient of the road surface, culvert spacing, and proximity of culvert outfalls to live streams. Measures addressing these areas would appear to have the greatest effect. One has to recognize, however, the sometimes opposing or neutralizing effects of certain processes. For example, with increasing road grade, sediment production from the traveledway portion will increase. On the other hand steeper road grades will decrease overall road length in a basin. More importantly, steeper grades may allow a better road location.

Quality of ballast and surfacing material determines to a large extent the amounts of fines (less than 2 mm) produced from traffic. Paving results in the elimination of this source of fines. On very steep grades, however, paving may not be appropriate because of reduced traction coefficients and the result of wetness and/or dirt on the pavement surface.

Concurrent, preventive erosion practices during construction appear to have a high potential for significantly reducing sediment export from road construction right-of-ways, especially on fill slopes. Windrowing of debris and slash at the toes of fills is an effective method. Changes in equipment type used for road construction appear to facilitate windrowing slash at the base of the construction sites. As noted under the mass wasting section, road construction equipment and practices may positively affect sediment production from cut and fill slopes.

2.3.6 Surface Erosion From Harvest Units

2.3.6.1 Erosion Associated with Logging Systems

O'Loughlin et al. (1980) recommend that tractor tracks be reseeded immediately and that track surface runoff be carefully cut off and diverted onto permeable open spaces instead of tributary gully bottoms. Isolating soil and vegetation disturbance from streams is also important.

Kidd (1963) studied the effects of erosion-control structures on erosion of skid trails on granitic and basaltic soils in Idaho. Findings were that erosion was greater and slower to heal on the coarser-grained granitic soils than on the basaltic material, but erosion on both could be significantly reduced with wooden control structures. Control structures that divert water off skid trails onto the undisturbed forest floor were more effective than those that only retarded water movement. The erosion rate was sensitive to the distance between control structures; the effective distance varied with the slope steepness, the lateral slope convergence, and the geologic parent material of soil.

2.3.6.2 Erosion of Landslide Scars

Ice (1981) reviewed strategies for mitigating erosion from landslide sites. Four general strategies include: stabilizing to prevent further failure; control of surface erosion; downslope sediment trapping; and instream treatment. Stabilization can include a variety of means specific to the particulars of an individual failure. Surface-erosion control can make use of standard technologies. Downslope sediment trapping can include debris jams, terraces, sediment filters, and revegetation. Instream treatments can include dams and devices to remove sediment from channels.

2.4 METHODS FOR EVALUATING THE EFFECTIVENESS OF BEST MANAGEMENT PRACTICES

2.4.1 Types of Methods Previously Used

NCASI (1988) recently summarized several states' approaches to assessing the effectiveness of best management practices in protecting water quality. NCASI categorized the methodologies into (1) widespread water quality monitoring efforts; (2) planned watershed studies; and (3) qualitative field surveys of compliance and effectiveness. According to NCASI, only the State of Georgia has carried out a broad water quality monitoring program. In the Georgia program, begun in 1981, water quality samples were collected too infrequently to effectively indicate effects of forestry on streams (NCASI, 1988, p. 10). A monitoring program was also planned in California in the mid-1980s but was not carried out.

The second type of approach has involved the intensive monitoring of research watersheds; such an approach has been taken in Pennsylvania and Kentucky (NCASI, 1988). In both cases, suspended sediment and turbidity from watersheds subjected to unrestricted forestry methods were compared to measurements from watersheds logged using the states' BMPs. In both cases, sediment levels were lower in the watersheds where BMPs were implemented. Such results do not yield much information on the effectiveness of particular management practices, however, nor can they locate particular problem spots within the stream network.

The third and most common method is the "qualitative assessment and implementation survey" (NCASI, 1988). This approach has been used in Alabama, Arkansas, California, Colorado, Florida, Idaho, Maine, Oregon, Utah, Washington, and West Virginia. Surveys in all states involved visits to a sample of forestry operations by an interdisciplinary team of watershed and forestry practitioners. A similar study was carried out in Montana in 1990 (Schultz, no date).

The Washington State study is summarized below in detail because of its relevance and because it illustrates strengths and weaknesses of the qualitative assessment approach.

2.4.2 Previous Assessments in Washington State

In 1979, the Washington Department of Ecology undertook a comprehensive field evaluation of the effectiveness of BMPs in maintaining water quality (Sachet et al., 1980a; 1980b). The study also emphasized compliance and made some recommendations for improvements to the BMPs.

To initiate the study, 102 forest operations were randomly selected from all Forest Practice Applications submitted between January 1, 1977, and May 10, 1979. These operations were visited in the field between May and October 1979. These 102 sites represented 219 forest practices, and 1,476 evaluations of individual regulations. The forest practices included clearcutting, partial cutting, salvage logging, road construction, road maintenance, rock or gravel pit excavation, and site preparation for reforestation.

For each of the 1,476 compliance evaluations, the level of compliance and the degree of impact were evaluated. Impacts were divided into sediment, slash and debris, and temperature. The duration of the impact was evaluated, and the intensity was rated as "negligible," "low," "moderate," or "severe."

Overall, 1,106 of the 1,381 compliance requirement evaluations indicated compliance. In 1,102 cases, no impact on water quality was noted. Of the 275 requirements that were not met, water quality impacts occurred in 191 (69 percent). Of the 195 observed noncompliances judged to have affected water quality, 153 (78 percent) were negligible or low and 42 were moderate or severe. One-hundred one (53 percent) were judged to affect Type 1 to 3 Waters, but 86 percent of those were rated negligible or low.

For road construction, 64 percent of 136 compliance requirements were met, resulting in two water quality impacts. Of the 49 where requirements were not met, 39 (80 percent) resulted in impact on water quality. Of the total 64 impacts, 87 percent were negligible or low. Noncompliance with road and bridge construction and culvert installations were the most frequent causes of water quality impacts.

Road maintenance was evaluated for 92 forest practice applications, but only for haul roads within the boundaries of the application units. Of 100 compliance requirements, 65 were not met, resulting in water quality impacts in 41 cases. Seventy-nine percent of impacts were rated negligible or low. Non- or semifunctional ditches and culverts and lack of water bars were the primary causes of water quality problems. Impacts on active roads were higher in number and in severity than those on inactive roads.

Clearcutting was covered in 58 forest practice applications and 777 compliance requirements. Of these, 661 or 85 percent were in compliance, and no water quality impacts resulted. Water quality was affected in 85 of the 116 cases of noncompliance. Of these, 78 percent were negligible or low. Most problems related to skid-trail maintenance and fire-trail construction, where 40 percent of the 43 cases of noncompliance resulted in impacts. The dominant problem was inadequate or absent water bars. Overall, impacts were predominantly from road maintenance and tractor trail drainage.

This type of study has distinct advantages over studies that monitor stream sediments. Examining erosion at its source makes it possible to evaluate particular BMPs. Sampling a large number of site conditions allows for a representative sampling of the range of conditions statewide.

Several factors limit the study's validity, however. First, visits were made on only one occasion, so data are limited in several respects. That visits were made in summer limits the evidence for many sediment-producing processes because the soil would be dry and subject to modification since active erosion took place, and thus field evidence of erosion would be obscured. That visits were made up to two years after the forest activity also limits evidence of surface erosion, which could be completely obscured by revegetation or succeeding maintenance operations. Perhaps more important, visits were made too soon after forest practices for many of the most potentially serious problems — landslides and debris flows from clearcuts and roads, for example — to arise. Older sites, where these processes would more likely be in evidence, were not sampled.

Impacts were described in subjective and qualitative terms and did not include such quantitative information on the nature or magnitude of sediment input that would allow a better assessment of the importance of the effect.

Finally, as the report indicates, some BMPs could not be evaluated because compliance was too low: ". . . Effects of properly maintained roads on water quality were not thoroughly determined because the incidence of noncompliance with road maintenance regulations was high (65 percent)" (Sachet et al., 1980).

2.4.3 Geomorphic-process-oriented Methods

Some of the limitations of the 1979 Washington State approach stem from the study's not having been conducted in a framework in which individual erosion processes were separately considered. This type of framework would have pointed the field sampling strategy toward measuring the right things at the right times. In spite of the widespread availability of methods to conduct such field assessments oriented toward particular geomorphic processes, no states have carried out such an evaluation.

McCrea (1984) made a theoretical evaluation of the effectiveness of the forest practice rules according to their interaction with individual sediment-producing processes, but it was not applied to a sample of field sites. Because the regulations do not extend to Type 4 and 5 Streams, where forestry activities and sediment-producing processes are clustered, and because these streams can comprise greater than 80 percent of the cumulative channel length in a mountain watershed, McCrae concluded that the rules are not adequately protecting streams and water. In particular, she concluded that regulations that govern fill and debris disposals, culverts, and streamside management zones for Type 1 to 3 Streams need to be extended to Type 4 and 5 Streams.

3.0 SCOPE OF SEDIMENT PROBLEM
TASK 2

3.1 VARIATION IN EROSION AMONG PHYSIOGRAPHIC REGIONS OF WASHINGTON

Four generalized categories of erosion processes have been used in this report. The controlling variables and relative magnitude of each varies with the geology, soils, topography, and climate in different regions of the State. For the purposes of the following discussion, the State has been broken into nine regions (Figure 3.1).

The five regions in western Washington are from Fiksdal and Brunengo (1980): North Cascades, South Cascades, Olympic Peninsula, Willapa Hills, and Puget Lowland. Eastern Washington has been broken into four regions, based on an EPA classification (Omernik and Gallant, 1986): Eastern Cascades, Blue Mountains, Okanogan Highlands, and Columbia Basin. The western Washington classification was used because Fiksdal and Brunengo have described the geology and stability of these regions. The eastern Washington categories are broader because there is less detailed information available on erosion and stability in the east of the State.

3.1.1 North Cascades

The rocks of the North Cascades region include early Paleozoic gneisses; late Paleozoic marine sandstones, shales, and volcanics (Chilliwack Group), and phyllite and greeschist (Shuksan Suite); Mesozoic marine sandstones, shales, conglomerates, and volcanics (Nooksack Group and others); early Tertiary continental sandstones (Chuckanut or Swauk Formation), and felsic and intermediate volcanics and plutonic intrusions of a variety of compositions and ages, most importantly, middle Tertiary granodiorites of the Snoqualmie and Index batholiths. These units have been sutured together by a series of thrust faults, as well as being cut by other faults. Mt. Baker and Glacier Peak have erupted repeatedly within the last half million years, and some of their pyroclastic material has been deposited in the valleys of the Nooksack, Skagit, Suiattle, and Sauk rivers.

The area north of the Skykomish River was covered by continental ice during the last glaciation; most of the southern part was covered by alpine glaciers. Tills are ubiquitous, and outwash and glacial-margin deposits are common and extensive along the mountain front and in the river valleys. Fluvial erosion has cut deep gorges into the mountains,

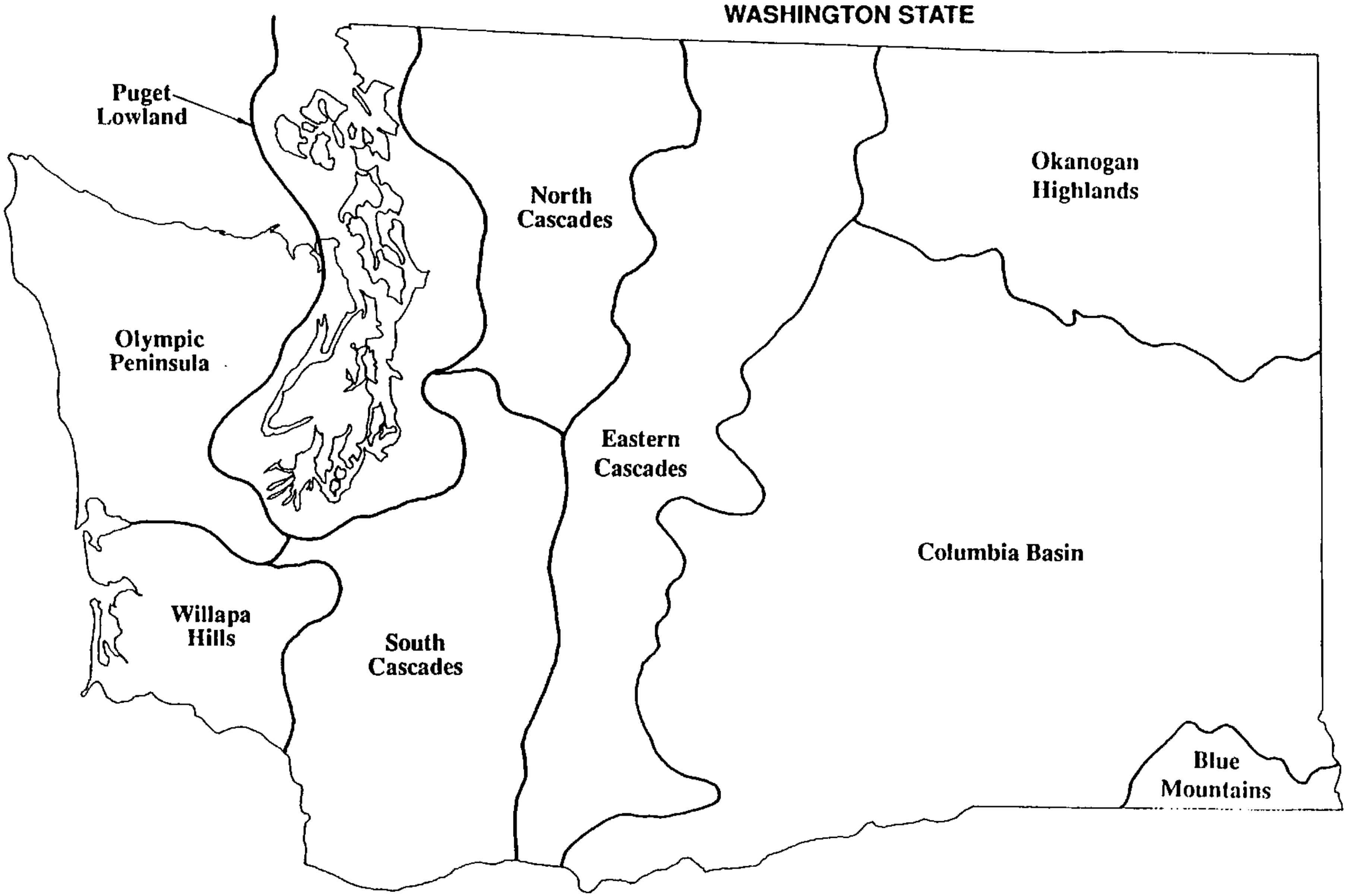

Figure 3.1
State of Washington partitioned into general physiographic regions based on Fiksdal and Brunengo (1980), Omernik and Gallant (1986) and McDonald and Ritland (1979)

forming steep slopes and high relief with generally thin soils, especially in the eastern section.

Average annual precipitation in the North Cascades ranges from 180 centimeters to about 300 centimeters on most of the higher mountains.

The rock types most susceptible to landslides, debris flows, and dam-break floods are the Chuckanut sandstones (e.g., in the Clearwater Creek drainage, west of Mt. Baker, and in the Sultan basin), the phyllites, the Mt. Baker pyroclastics, and the early Tertiary volcanic rocks in the Skykomish and Snoqualmie basins. Because of the steep slopes and glacial tills in this province, shallow-rapid landslides can occur on practically any rock type.

3.1.2 South Cascades

The rocks of this terrain include early to middle Tertiary volcanic flows, breccias, and pyroclastics (both marine and continental contained in the formations of: Keechelus, Ohanapecosh, Stevens Ridge, Fife's Peak, Goble), early Tertiary marine sandstones, shales, and continental deposits (contained in Puget Group coals, conglomerates, and sandstone), late Tertiary fluvial and glacial-outwash sediments in the Chehalis-Centralia basin and Clark County, and young volcanic flows, pyroclastics, and mudflows from Mt. Rainier and Mt. St. Helens. There are many small Tertiary plutonic intrusions scattered in the region.

This area has not been as intensely glaciated as the North Cascades. Pleistocene continental glaciation reached the mountains surrounding the Puget Lowland, and large alpine icecaps covered the range from Mt. Rainier south, extending into the valleys of the Cedar, Green, White, Puyallup, Nisqually, and Cowlitz rivers. South of the Cowlitz, the alpine icecap was smaller, but valley glaciers occupied the Toutle, Kalama, and Lewis rivers.

The less-intensive glaciation has allowed longer weathering and somewhat deeper soils to develop than in the North Cascades. Stream erosion, aided by glacial scour in many valleys, has formed high relief and steep slopes in the South Cascades, however.

Annual precipitation in this province ranges from about 130 to 200 centimeters.

Landslide activity in the South Cascades is only partly related to rock type and is more often related to rock structure. Volcanic rocks are by far the most susceptible to deep-seated slumping, but some areas are more susceptible than others, even of the same mapped formation. In general, units with a greater proportion of volcaniclastics such as tuffs and breccias are the most unstable. A related factor is the amount of interbedding of dense, hard flow rocks (andesites and basalts) with softer volcaniclastics (which often weather to weak, clay-rich layers). When such interbedded layers dip out of the hillslope, failure is likely to occur.

Unconsolidated glacial sediments are also subject to slump failure in this region. Continental glacial margin deposits at the mountain front are collapsing in the Puyallup and Nisqually valleys, and fluvial and outwash sediments commonly fail in terrace scarps along the Cowlitz River and near Chehalis.

Shallow-rapid landslides and debris flows occur wherever there are steep slopes. Concentrations of landslides are located in volcanic and volcaniclastic rocks along the White River; in both sedimentary and volcanic rocks west and south of Mt. Rainier National Park and the Tilton River basin north of Morton; and in young pyroclastic deposits east of Mt. St. Helens. Elsewhere, landslides and debris flows have taken place in granitic rocks, volcaniclastics, sedimentary rocks, andesites, and basalts. Again, in addition to lithology, weathering, slope gradient, interbedding, and the dip of strata have much to do with failure.

3.1.3 Olympic Peninsula

The geology of the Olympic Peninsula consists of highly folded, faulted, and fractured marine sediments in the core and on the west side of the peninsula. These sediments are bordered on the north, east, and south by the peripheral Crescent Formation, consisting of submarine basalt flows and sedimentary rocks. Along the northern edge of the peninsula paralleling the Strait of Juan de Fuca are folded sandstones, siltstones, and conglomerates, and along the southern margin are tuffaceous and micaceous siltstones, sandstones, and mudstones. During the Pleistocene there was extensive valley glaciation, and on the western side the valley glaciers coalesced to form piedmont glaciers past the mountain front. The northern and eastern edges of the peninsula were covered by the continental ice sheet emanating from Canada.

Precipitation varies dramatically in the Olympic region. Along the western mountain slopes there is as much as 500 or more centimeters of rainfall per year, but on the lee side of the mountains, near Sequim, there is as little as 35 centimeters per year.

In the northern Olympic region, mass wasting events seem uniform in intensity over most of the area. Rock type does not seem to be a significant factor because igneous and sedimentary rock types show no difference in number of deep-seated landslides. Slope steepness is probably the determining factor for stability. There are a few large landslides found near Lake Crescent. These slides were probably the result of deglaciation or climatic or hydrologic factors related to the glacial period or some time after. There are numerous slump-earthflows mapped along the shoreline of the Strait of Juan de Fuca. These are mostly in areas of steep banks being actively undercut by shoreline erosional processes.

The largest concentrations of mass wasting events is in the Clearwater-Hoh block of land on the western slopes of the Olympic Mountains. Underlain by highly fractured and faulted siltstone, sandstone, and mudstone, this area has intense topographic relief, thin colluvial soils, and rainfall of up to 500 centimeters per year. It is currently undergoing intense forest management and is known for its high concentration of landslides and debris flows.

In the southern portion of the Olympic region, subdued topography (resulting from easily eroded tuffaceous and micaceous sediments and glacial outwash) gives little chance for landslides and debris flows to occur; some slump-earthflows are present, however. This region appears to have relatively good stability except in the steep, rugged, mountainous terrain near the Olympic National Forest boundary. In this area, numerous landslides occur on steep slopes.

3.1.4 Willapa Hills

The geology of the Willapa Hills area is generally is characterized by tuffaceous, micaceous, and carbonaceous marine and nonmarine sediments with basalt flows overlying them in some areas. Skookumchuck, Astoria, Lincoln Creek, and Cowlitz Formation form most of the sedimentary rock types, and the Cowlitz, Crescent, Goble, and Yakima basalts make up the volcanic rock types.

Precipitation in this region varies markedly with elevation and east-west location. Annual rainfall rises from 180 centimeters on the coast to 300 in the Centralia-Chehalis basin.

The Willapa Hills region is quite different from the other areas of western Washington in terms of geologic and geomorphic history, and slope stability problems are significant. Three basic factors result in the great instability of this area. These are 1) the easily-weathered, soft tuffaceous marine sediments; 2) inherent unstable contacts between sedimentary and volcanic rock types; and 3) the deep soils.

The large number of landslides mapped west and east of Centralia are located in very easily weathered Skookumchuck sandstones and siltstones. In this area drainages have undergone extensive mass wasting. To the south, slope angle seems to dictate the type of mass wasting. In the steep areas most events are landslides and debris flows, and in the less steep areas slump-earthflows are most common. Also in this area, one lithology seems to have no more susceptibility than another, at least at the 1-to-250,000 scale. Both sedimentary and igneous rock types have mass wasting features.

The contact between the overlying volcanic rocks and the sediments below forms another very unstable condition. Because of the mineralogy of the sediments, they usually weather faster than the overlying volcanic rocks when exposed. This differential weathering causes the underlying rock to lose strength when the minerals weather to clay. Slope failure results.

The Willapa Hills region has deep, clay-rich soils. The area has not undergone glaciation like most other parts of western Washington, so soil development has been able to proceed for the past several million years. Soil depths can reach as much as 2 to 3 meters. Most slopes have developed to their natural angle of stability, forming in equilibrium among gravity, internal soil strength, and vegetation. When these slopes are altered by forest activities, instability may result.

3.1.5 Eastern Cascades Slopes and Foothills

The Eastern Cascades are a transition between the wet, rugged western Cascades and the drier Columbia Basin and Blue Mountains to the east. Precipitation ranges from about 160 centimeters near the Cascade Crest to about 30 centimeters to the east.

The geology south of about Snoqualmie Pass is dominated by Miocene-age volcanic rocks and Pleistocene and Holocene volcanic rocks. The older, Miocene rocks are mostly dark, fine-grained, jointed basalt flow rocks. The more recent Pleistocene and Holocene rocks, localized near Mt. Adams and to the east, are predominantly a vesicular basalt, with some andesitic and pyroclastic flow rocks and cinder cones. Near the Cascade Crest, Tertiary volcanic rocks (see Section 3.1.2) dominate from about Mt. Rainier south, and granodioritic rocks (see Section 3.1.1) dominate north to Snoqualmie Pass.

North of about Snoqualmie Pass, the geology varies across a series of northwest-southeast trending lineaments. Rock types include arkosic sandstones in the Wenatchee area and the Methow River area, with crystalline gneissic and granitic rocks between.

3.1.6 Northern Rockies

The Okanogan Highlands reach across the north of the State from the Eastern Cascades to Idaho and range in elevations from about 1,300 to 8,000 feet. The area is relatively dry with precipitation ranging from about 30 to 60 centimeters.

Granitic rocks dominate the forested parts of the region; sedimentary and metamorphic rocks are less common. Glacial deposits are widespread in valleys.

Surface erosion is aggravated by timber harvest, roads, and livestock grazing (Omernik and Gallant, 1986); no surveys of mass wasting have been conducted. Stream disturbance may also result locally from placer, shaft, and open pit metal mining.

3.1.7 Blue Mountains

A small portion of the Blue Mountains is contained within the southeastern corner of the State. Elevations range to more than 6,000 feet, and precipitation ranges between about 40 and 80 centimeters. Soils are derived from Miocene basalts and volcanic ash.

Surface erosion in the area is aggravated by timber harvest, roads, and livestock grazing (Omernik and Gallant, 1986); no surveys of mass wasting have been conducted. Stream disturbance may also result locally from placer, shaft, and open pit metal mining.

3.1.8 Comparison of Erosion among Regions

Total erosion amounts differ greatly among the regions described above. The nature of differences in erosion rates can be discerned from the published literature on suspended sediment transport in streams (for example, Sidle, 1980; Nelson, 1973).

Suspended sediment loads in large streams draining forested and mixed-use areas tend to cluster within distinct ranges for each region. Sediment yields in the Olympic Peninsula range between 500 and 2,000 tons per square mile per year, between 100 and 700 tons per square mile per year in the western Cascades, and between 10 and 80 tons per square mile per year in the eastern Cascades and the Okanogan Highlands. We know of no comparable data from the Willapa Hills and Blue Mountains.

We do not know of published, regional surveys in which the proportion of management-related erosion and sedimentation is compared to natural erosion. Moreover, the data summarized above were collected over a period ranging from the late 1960s through the 1980s, and land use changes could have brought about change in erosion rates in some regions.

Several sediment budget studies from managed forests, discussed earlier in the Literature Review (Section 2.0), do indicate the relative significance of erosion caused by forest management versus the natural background rate. There have not yet been an adequate number of sediment budget studies conducted to generalize the results to a regional scale, but a few broad statements can be made. In studies of the Olympics and the wet, west side of the Cascades, road-related landslides and debris flows with attendant channel erosion dominate sediment production. Road surface erosion is also locally important.

Erosion on the east side of the State is poorly documented, and no sediment budgets have been carried out there to our knowledge. The sediment budget created by Megahan et al. (1982; 1986) for central Idaho has some relevance for the east side of the State, as indicated in Section 2.0, because the climate and geology are similar to parts of the northeast Cascades and Okanogan Highlands. That overall erosion rates in the Idaho study are similar to those documented for the northeast Cascades and Okanogan Highlands may support the comparison of the Idaho results to the northeastern Washington region. The Idaho study suggested that surface erosion from roads and harvest units was more important than mass wasting. It is not known to what extent this holds true in the east of this State.

The impact of livestock grazing on stream-bank stability in eastern Washington is mentioned in published regional descriptions (e.g., Omernik and Gallant, 1986), but we know of no published data on the topic.

Finally, the occurrence of deep-seated failures, documented by Fiksdal and Brunengo (1980, 1981) for the western portion of the State, is not documented within the published literature on eastern Washington forestlands, and no generalizations can be made about this important sediment source.

4.0 CONCEPTUAL EFFICACY OF BEST MANAGEMENT PRACTICES
TASK 3

4.1 INTRODUCTION

This section evaluates individual Washington State Forest Practice Rules with respect to their theoretical (conceptual) effectiveness in minimizing the sediment production of forestry activities. The focus is the rules' expected effectiveness rather than their actual effectiveness as determined in field evaluation. Individual forest practice rules are evaluated in relation to each major erosion process listed in Table 1.1. Table 4.1 summarizes an assessment of the effectiveness of the forest practice rules (BMPs) in preventing erosion and sediment introduction to streams.

Forest practice rules that are inadequate or require comments, additions, or recommendations are discussed below, according to the erosion processes they affect. Comments and recommended changes or additions follow each rule, and recommendations are referenced by a number (e.g., R2). Because some rules are relevant to more than one erosion process, some rules are found in more than one category.

4.2 LANDSLIDES/DEBRIS FLOWS/DAM-BREAK FLOODS

For this report, landslides, debris flows, and dam-break floods are considered within one grouping (see Process Definitions and Terminology, Section 1.4).

WAC 222-16-050 Classes of Forest Practices (1)

Rule (1) is potentially highly effective because it recognizes that catastrophic stream impacts can originate from slope failures (e.g., debris flows). A forest practice designated as "Class IV - Special" would provide the protective measures needed to minimize the risk of a debris flow. The effectiveness of the BMPs, however, will depend on an adequate evaluation of slope stability and debris-flow potential.

R1 Trained personnel should conduct slope stability and debris-flow analyses and assess the need for designating an FPA "Class IV - Special."

Table 4.1
A summary of the evaluation of the conceptual effectiveness of forest practice rules.

Rule Number	Rule Description	Landslides/ Debris flows	Slump-earthflows	Surface erosion	Channel-bank erosion
222-08-035(1)	Annual evaluations.	EP[1]	EP	EP	EP
222-12-040	Alternative plans.	EP	EP	EP	EP
222-12-045	Adaptive management.	EP	EP	EP	EP
222-16-010	General definitions.	NA[2]	NA	NA	NA
222-16-045	Watershed screening and analysis.	EP	EP	EP	EP
222-16-050	Classes of forest practice.	NA	NA	NA	NA
222-16-050(1bii)	Class IV—Special—critical habitat.	NA	NA	NA	NA
222-16-050(1e)	Class IV—Special—roads in slide-prone areas.	PO[3]	PO	NA	PO
222-16-050(1f)	Class IV—Special—slope instability from harvest.	PO	PO	NA	NA
Road Location					
222-24-020(2)	Avoid canyons and riparian areas.	PO	PO	PO	PO
222-24-020(3)	Minimize stream crossings.	PO	PO	PO	PO
222-24-020(4)	Cross streams at right angles	NA	NA	PO	PO
Road Design					
222-24-025(5)	Surface drainage.	I[4]	I	PA[5]	NA
222-24-025(6)	Cross drain outfall.	I	I	E[6]	NA
222-24-025(7)	Locations of cross drains.	PA	PA	E	NA
222-24-025(8)	Relief culvert specifications.	PA	PA	NA	NA
222-24-025(9)	Divert ditch water onto forest floor—Type 1 to 3 Waters.	I	I	PO	E

Evaluation Key

[1] EP = Effective Planning. Though not directly applicable to BMPs, these rules are potentially effective at limiting erosion.

[2] NA = Not Applicable. The rule pertains to definitions, policy, administration, or procedure.

[3] PO = Potentially Effective. The rule is effective if personnel are trained.

[4] I = Ineffective. The rule does not address an erosion process or is inadequate.

[5] PA = Partially Effective. The rule does not specify which process or triggering mechanism it is intended to limit, or the rule is partially inadequate for limiting erosion.

[6] E = Effective. The rule effectively limits a particular erosion process or triggering mechanism.

Table 4.1 (continued)

Rule Number	Rule Description	Landslides/ Debris flows	Slump-earthflows	Surface erosion	Channel-bank erosion
Road Construction					
222-24-030(2)	Organic debris burial in road fill.	PA	NA	NA	NA
222-24-030(4)	Stabilize soils.	I	I	PO	NA
222-24-030(5)	Clear channel of debris and slash.	NA	NA	NA	E
222-24-030(6)	Timing of drainage installation.	NA	NA	E	NA
222-24-030(7)	Soil moisture during construction.	NA	NA	E	NA
222-24-030(8)	Endhaul/side-casts.	PO	PO	PO	PO
222-24-030(9)	Waste and spoil disposal.	PO	PO	PO	PO
222-24-035(1)	Landing location and construction.	PO	PO	PO	PO
Water Crossing Structures					
222-24-040(1)	Bridge construction.	NA	NA	NA	E
222-24-040(2)	Culvert installation.	PA	PA	PA	E
222-24-040(3)	Culverts in anadromous fish streams.	NA	NA	E	E
222-24-040(4)	Temporary water crossings.	E	E	E	E
Road Maintenance					
222-24-050(1)	Road maintenance and abandonment plan.	NA	NA	NA	NA
222-24-050(1)	Active roads.	E	E	E	E
222-24-050(3)	Inactive roads.	E	E	E	E
222-24-050(4)	Additional culverts/maintenance.	PA	PA	PA	PA
222-24-050(5)	Abandoned roads.	PA	PA	E	E
Rock Quarries, Gravel Pits, Borrow Pits, and Spoil Disposal Areas					
222-24-060(1)	Location of pits.	E	E	E	E
222-24-060(2)	Location of spoil disposal areas.	PO	PO	E	PO
222-24-060(3)	Pit drainage.	I	I	E	NA
222-24-060(6)	Major spoil disposal operations.	NA	NA	E	E

Table 4.1 (continued)

Rule Number	**Rule Description**	**Landslides/ Debris flows**	**Slump-earthflows**	**Surface erosion**	**Channel-bank erosion**
Harvest Unit Planning and Design					
222-30-020(2)	Landing locations.	PO	PO	PO	PO
222-30-020(3c & e)	Landing construction.	I	I	E	NA
222-30-020(4)	Riparian management zones.	NA	NA	NA	NA
222-30-020(5)	Western Washington riparian management zones.	NA	NA	NA	NA
222-30-020(6)	Eastern Washington riparian management zones.	NA	NA	NA	NA
222-30-030	Stream bank integrity.	NA	NA	PA	PA
Felling and Bucking					
222-30-050(1)	Falling along water.	NA	NA	PA	PA
222-30-050(2)	Bucking in water.	NA	NA	PA	PA
222-30-050(3)	Falling near riparian management zones.	E	E	E	E
Cable Yarding					
222-30-060(1)	Type 1, 2, and 3 Waters.	NA	NA	PA	PA
222-30-060(2)	Deadfalls.	NA	NA	PA	PA
222-30-060(3)	Riparian management zone.	NA	NA	PA	PA
222-30-060(4c)	Yarding parallel to Type 1, 2, or 3 Streams.	NA	NA	PA	PA
Tractor Skidding					
222-30-070(1)	Streams.	NA	NA	PA	PA
222-30-070(2)	Riparian management zones.	E	E	E	E
222-30-070(4)	Moisture conditions.	E	E	E	E
222-30-070(6)	Skid-trail construction.	E	E	E	E
222-30-070(7)	Skid-trail maintenance.	NA	NA	PO	PO
222-30-070(8)	Slope restriction.	PO	PO	PO	PO
Landing Cleanup					
222-30-080(1)	Drainage.	E	E	E	E

Table 4.1 (continued)

Rule Number	Rule Description	Landslides/ Debris flows	Slump-earthflows	Surface erosion	Channel-bank erosion
Slash Disposal					
222-30-100(1c)	Location of slash piles.	PA	PA	PA	NA
222-30-100(4)	Removing slash from streams.	NA	NA	PA	PA
222-30-100(5)	Fire trails.	E	E	E	E
Site Preparation and Rehabilitation					
222-34-040(1)	Heavy equipment.	E	E	E	E
222-34-040(2)	Surface water drainage.	E	E	E	E
222-34-040(3)	Stream channel alignment.	NA	NA	PO	PO

WAC 222-24-020 Road Location (6)

R2 Rule (6) should be made a water quality BMP because it pertains to reducing landslide erosion by limiting road construction on steep and unstable slopes.

WAC 222-24-025 Road Design (5)(6)(7)(8)(9)

These forest practice rules do not address the diversion of road-generated runoff onto steep, potentially unstable slopes. Many landslide inventories show a dramatic increase in the rate of landsliding and debris flows associated with logging roads. One cause of logging-road-related failures is the concentration of drainage on steep and inherently unstable slopes.

R3 Rule 5 establishes procedure to minimize or avoid erosion from road traveledways and/or fill slope by requiring outsloping or ditching on the uphill side. In light of new information (see Section 2.3.5.4, Literature Review), water from outsloped roads that drains onto fill slopes actually causes significant gullying and under such conditions should not be considered.

R4 Rule (6)'s requirement that flow not be discharged onto erodible soils is vague, and it is not clear whether it refers to surface erosion or to slope failure. Diversion of flow onto steep slopes should be avoided, particularly onto those slopes identified by 222-16-050 as having a high debris-flow potential. Furthermore, the numbers and locations of culverts should be designed so that drainage areas are not enlarged.

R5 Rule 7 tries to mitigate the erosive powers of moving waters by reducing the culvert spacing for steeper grades. The erosive power of water is governed by the elevation difference (change of potential energy to kinetic energy) and not by distance. The present rules result in a vertical elevation difference of 70 feet for the 0- to 7-percent grade range (maximum distance of 800 feet) and 90 feet for road grades greater than 15 percent (maximum distance 600 feet). The current rules try to address this problem by providing additional culvert spacing recommendations (Table 2, Part 5, *Forest Practices Manual*).

R5 The present spacing rule, (7), should be replaced with a rule specifying the maximum vertical distance between culverts. The proposed maximum allowable elevation difference between culverts is between 40 and 70 feet. The proper value should be determined based on a careful review of existing practices and theories. The vertical allowable distance between culverts may be different for the west and the east sides.

R6 Rule (8a) should be changed to require a diameter of at least 15 inches for relief culverts. Most landowners, notably the DNR and the US Forest Service as a practice use 15-inch-diameter culverts as a minimum. The cost difference between 12- and 15-inch culverts is minimal, and the larger size is more effective in handling debris, a major cause of culvert blocking and subsequent failure.

R7 Rule (9) is designed to reduce surface runoff and sediment into Type 1 to 3 Streams by diverting ditch flow onto hillslopes. This is a good practice but may promote hillslope instability unless recommendations R4 and R5 are adopted.

WAC 222-24-030 Road Construction (2)(4)(8)

Rule (2) prohibits the burial (or inclusion) of logs, and loose stumps in the load bearing portion of the road, "except as a puncheon across swampy ground or for culvert protection." The rule recognizes the future problems that result from decay. In that context, the exclusion should also apply to culverts in particular (Rule 2a, i - iii).

R8 The language of Rule (2a) that allows incorporation of organic debris, slash, or stumps in load-bearing section of roads for culvert protection should be dropped. Especially around culverts, care should be taken during installation to ensure such impermeable conditions that water is forced into the culvert. Over time decaying material opens voids that allow water to bypass and eventually undermine culverts.

Rule (4) misrepresents the ability of grass and clover to stabilize soils along roads. Grass and clover may reduce surface erosion, but they have little effect in controlling landslides or slumps greater than approximately 1 meter in depth.

R9 The gradient of the cut slope should be reduced to less than the angle of repose of the material, and trees or shrubs should be used to stablize the slopes.

R10 Rule (8) requires endhauling when there is an increased potential for mass soil movement but does not specify or quantify how the increased potential for soil-mass movement is to be determined. Slope-gradient and slope-form criteria should be specified according to existing landslide prediction methodologies and landslide inventories.

WAC 222-24-035 Landing Location and Construction (1)(2)

Rule (1) does not specifically define where landings will cause the most damage (steep slopes and convergent slope forms) or where unstable sites have a high potential for creating debris flows (see 222-16-050).

R11 Published methods for assessing slope stability and debris flows should be used to determine safe locations for landings.

WAC 222-24-040 Water-Crossing Structures (2)

R12 Rule (2a ii) should be amended to read: "18 inches or the equivalent for the resident game fish streams and/or all other water crossings." Rule (2a iii) should be dropped in order to maintain consistency with the relief-culvert-sizing recommendation [222-24-025 (8)] under the Road Design section.

WAC 222-24-050 Road Maintenance (5)

Rule (5), concerning conditions for abandoning roads, fails to specify the removal of culverts and fills in swales and hollows. Removal of culverts and fills is required only for all streams (Types 1 to 5). Though Type 5 Waters include some wet swales, not all convergent, slide-prone topography is included in the Type 5 designation. In addition, spacing of water bars is not specified with respect to road-surface-runoff generation and diversion onto steep slopes.

R13 Culverts should be removed from swales and hollows as in other water categories. Moreover, the number and location of water bars should be designed so that drainage areas are not increased.

Rule (5) is an important and effective rule because old, unmaintained, and abandoned roads have been sources of debris flows in recent times in Washington State.

WAC 222-24-060 Rock Quarries, Gravel Pits, Borrow Pits, and Spoil Disposal Areas (2)

This rule indicates that spoil disposal areas should be placed where risk of soil erosion and mass soil movement is minimal. This rule lacks specific definitions of potentially unstable slopes.

R14 Individual forest practices designed to assess slope stability, such as this one and 222-16-050, 222-24-030, and 222-24-035, should include guidelines (contained in the *Forest Practices Board Manual*) on how slope stability and the risk of debris flows can be adequately appraised using published methodologies. Though the *Forest Practices Board Manual* contains a short section on slope stability, this section needs to be updated and referenced directly in the pertinent forest practice rules.

WAC 222-30-020 Harvest Unit Planning and Design (2)(3)

Rule (2) does not adequately specify what constitutes safe landing locations in terms of such hillslope properties as slope gradient and slope form and the potential for debris flows.

Rule (3) does not address failure of landing sidecast material.

R15 Personnel trained in slope stability should employ published methodologies to identify safe landing sites and determine what constitutes safe landing sidecast.

Numerous studies have shown that landslide rates are hundreds to thousands of percent greater in clearcuts than in unmanaged forests (see Section 2.0, Literature Review). The much higher rate for clearcuts has been attributed to reduced root strength following timber harvest on steep and unstable slopes. Though this rule addresses harvest unit planning and design, it fails to make any mention of the potential slope stability problems that may arise because of logging on steep slopes.

R16 Some form of slope-stability assessment including risk of debris flows should be conducted during evaluation of proposed timber harvest units.

WAC 222-30-070 Tractor and Wheeled Skidding (6)

Rule (6) does not address forest-floor compaction, which may lead to concentration of drainage. In addition, skid trails can intercept surface runoff from trails (and logging roads) and subsurface flow, thereby causing enlargement of drainage areas. Unnatural surface and subsurface flow magnitudes may result in increased slope instability.

R17 Tractor skidding should be minimized or eliminated in areas where road-surface-generated runoff can be routed onto steep slopes, particularly in areas prone to debris flows. Furthermore, if skid trails are constructed, they should be located so that they will not divert other surface runoff and will not intercept subsurface flow. This provision for skid-trail location will help prevent drainage areas from being enlarged.

WAC 222-30-080 Landing Cleanup (2)

R18 Rule (2) does not specify a stable angle. The angle should be specified, so that, in the absence of soil cohesion, the angle is less than the angle of internal friction.

R19 Rule (2b) should include a recommendation that trees and shrubs be used to stabilize hillslopes.

WAC 222-30-100 Slash Disposal (1)

Broadcast burning on steep slopes destroys understory trees and shrubs, thereby eliminating the rooting strength they provide to the soil. Tree harvesting reduces the root strength of the soil, and burning seriously compounds that reduction by essentially eliminating the remaining root strength. Research has indicated that roots of both trees and shrubs impart significant strength to the soil. Loss of this root strength due to timber harvest and broadcast burning may promote landslides and debris flows on unstable slopes.

R20 Broadcast burning on slopes greater than 25 to 30 degrees should be discontinued.

4.3 SLUMP-EARTHFLOWS

WAC 222-16-050 Classes of Forest Practices (1)

R21 Slope-stability criteria specific to earthflows and deep-seated slumps should be referenced to aid the accurate assessment of potential for mass soil movement. It is further recommended that earthflows be mapped in the context of watershed analysis programs to delineate slump-earthflow terrain as an aid to field interpretation by untrained personnel.

WAC 222-24-020 Road Location (6)

A main objective is to avoid building roads on slump-earthflow terrain. Rule (6), which is not a water quality rule, indicates that "where feasible" roads should not be located on "excessively steep or unstable slopes or known slide-prone areas."

R22 This rule should be included as a water quality BMP and given more specific language. The effectiveness of this rule is dependent on the level of geotechnical and geomorphological skill of the road system engineers and on the level of interpretation of "where feasible." The occurrence and mechanics of slump-earthflows are not widely known, and it is important that forest practice regulators and road designers be given specific guidelines on avoiding this terrain.

WAC 222-24-025 Road Design (9)

Road drainage should not be directed onto slump-earthflow features. No regulations specifically address this need. Rule (9) requires that culverts be diverted onto the forest floor rather than into streams.

R23 Rule (9) should include the need to avoid diverting road drainage onto slump-earthflow terrain. This is particularly pertinent where roads may intercept runoff and increase the upslope drainage area, thus increasing drainage to downslope unstable areas.

WAC 222-24-030 Road Construction (all)

In preventing the acceleration of slump-earthflow movement, a main objective is to avoid sidecast loading, especially on the upslope portion of slump-earthflows with sidecast from roads or from landings. This rule, 222-24-030, fails to consider this objective in any detail. A second objective is to avoid undercutting slump-earthflow features, particularly their toe slopes.

R24 The section should include or refer to instructions to the road designer on recognition of slump-earthflow terrain and provide measures to avoid loading or undercutting.

WAC 222-24-035 Landing Location and Construction (1)

Landing locations should avoid slumps and earthflows.

R25 Rule (1) should be more explicit about the need to avoid loading and undercutting unstable terrains as described above.

WAC 222-24-050 Road Maintenance (all)

No regulations specifically address the need to prevent drainage onto slump and earthflow areas.

R26 The effectiveness of road maintenance on drainage depends on the location and design of the road. For example, on earthflow or other unstable terrain, it is paramount that drainage structures be maintained in order to reduce the possibility of drainage blockages. Blockage of upslope drainage structures may increase drainage onto downslope unstable terrains as a result of drainage-area enlargement.

WAC 222-24-060 Rock Quarries, Gravel Pits, Borrow Pits, and Spoil Disposal Areas (2)(3)(6)

R27 Rule (2) requires that spoils be located where the risk of mass movement is minimal. Foresters and other resource professionals should be trained in recognition of these unstable areas.

There is no regulation addressing the need to avoid diverting runoff onto slump-earthflow terrain. Rule (3) requires that drainage from rock quarries and pits be diverted onto the forest floor. Rule (6) requires that drainage from major spoil areas be discharged onto the forest floor.

R28 Explicit mention should be made of the need to avoid diverting runoff onto slump-earthflow terrain, which is similar to the landslide terrain discussed above.

WAC 222-30-020 Harvest Unit Planning and Design (2)(3)

R29 Rule (2) duplicates 222-24-035 (1), and the same comments made there apply here (see above).

Research indicates that timber removal can be associated with an acceleration of soil movement in earthflows. The acceleration in soil movement is thought to arise from reduced evapotranspiration, which may lead to increased pore pressures and therefore increased instability (see Section 2.0, Literature Review, on earthflows). No rules address the potential that timber harvest enhances movement of slump-earthflow features by reducing evapotranspirative loss. Rates of movement of identified earthflows in the vicinity of proposed harvest areas should be measured using historical aerial photographs to determine the potential for accelerated movement in the portions of a proposed harvest area located on an earthflow.

R30 A rule addressing the alteration of subsurface hydrology in slump-earthflow terrain by timber cutting should be added.

4.4 CHANNEL-BANK EROSION

Channel-bank erosion can arise in any waters of Types 1 to 5. Debris flows may cause extensive bank and streambed erosion in first- and second-order channels (Type 4 and 5 Waters). This form of erosion is considered under debris flows, which are part of the landslide erosion process (see Section 4.2).

Another process that causes erosion of channels is a dam-break flood (see Section 2.0, Literature Review, for definition). Dam-break floods may cause severe erosion of channel banks and valley walls throughout entire stream-order segments of third- and higher-order channels. Because this process is typically initiated by landslides or debris flows, it is also included in Section 4.2, which covers the landslide erosion process.

Stream-bank erosion may also occur as a result of 1) erosion of bank sediments due to increased discharge; 2) bank disturbance by forest machinery which causes higher susceptibility to erosion, and 3) riparian vegetation removal, which leads to weakening of the banks.

WAC 222-24-030 Road Construction (5)

Rule (5) requires that debris generated during harvest operations be removed from stream channels but fails to mention the potential impacts of debris removal.

R31 Extreme care should be taken not to remove existing, embedded organic debris. In addition, debris should not be yarded across channels where such yarding will cause channel erosion.

WAC 222-30-020 Western Washington Riparian Management Zones (5)

R32 Rules (5) and (4) should be included as water quality BMPs.

WAC 222-30-030 Stream-bank Integrity (all)

These rules, which include avoiding disturbance of brush and stumps and leaving of high stumps and trees with large, embedded root systems, apply only to Type 1, 2, and 3 Waters, which are approximately equivalent to stream orders of third and higher. Type 4 and 5 Waters, or first- and second-order streams, typically make up more than 80 percent of the cumulative channel length in mountainous terrains and therefore dominate the bank area available for erosion. Hence, 222-30-030 does not fully protect bank erosion for most of the channel length in a watershed.

R33 Type 4 and 5 Waters should be covered under rules (1), (2), (3), and (4).

WAC 222-30-060 Cable Yarding (2)(3)(4)

Rule (2), which specifies that firmly embedded logs not be removed in Type 1, 2, 3, and 4 Waters, does not include Type 5 Waters (first-order channels). Because Type 5 Waters make up a large portion of the channel length of the Water Types (as discussed above), Rule (2) is inadequate for protecting channel disturbance.

R34 Type 5 Waters should be included in 222-30-060 (2).

R35 Type 4 and 5 Waters should be included in Rule (3).

R36 Type 4 and 5 Waters should be included in Rule (4).

WAC 222-30-100 Slash Disposal (1)

Rule (1c) specifies that slash burning not take place in stream Types 1 to 4 but fails to include Type 5 channels. Type 5 channels constitute a large proportion of the stream length in a watershed, and burning slash in these headwater channels can promote surface erosion and, more importantly, destroy shrubs and understory tree vegetation, thereby reducing root strength and promoting landslides. Landslides occurring in close proximity to Type 5 Waters can initiate debris flows, which are one of the most damaging forms of mass erosion in forested watersheds.

R37 Type 5 Streams should be included in Rule (1c), particularly those Type 5 Streams that are at a high risk for landslides and, more importantly, debris flows.

WAC 222-34-040 Site Preparation and Rehabilitation (3)

Rule (3) requires that stream channel alignment work on Types 1, 2, and 3 requires consultation and permits. The implication is that Type 4 and 5 Waters are not covered.

R38 Type 4 and 5 Waters should be included in this rule. Significant channel-bank erosion could ensue if these stream types are not protected.

4.5 SURFACE EROSION

Surface erosion includes rainsplash, sheetwash, rilling, gullying, and dry ravel of exposed mineral soil. Those sites most susceptible in areas undergoing forest harvesting activities are fill slopes and cut banks of roads, road surfaces, and recent landslide and debris-flow scars.

WAC 222-24-025 Road Design (9)

Rule (9) requires diversion of ditch water onto forest floors rather than into streams, but it fails to caution against gully erosion caused by the diverted water.

R39 Diversion of surface runoff generated from roads should be avoided on steep slopes because of the potential for gully erosion. This recommendation was made earlier in the context of landslide and debris-flow erosion. Energy deflectors would be useful in minimizing gully erosion.

WAC 222-24-030 Road Construction (4)(8)(9)

Rule (4) requires grass seeding to prevent soil erosion on exposed soils, but as stated earlier, grass cannot stabilize soils against small or large landslides.

R40 The gradient of cut slopes (other than bedrock) and fill slopes should be reduced to less than the friction angle of the soil. The gradient should be vegetated with a combination of trees, shrubs, and grasses. Moreover, because grass seeding is not effective in slowing erosion in the short term, guidelines for other erosion-control measures should be given (see Section 2.0, Literature Review).

R41 Rules (8) and (9) should include clauses specifying 1) the replanting of construction spoils with a combination of trees, shrubs, and grasses to reduce surface erosion; and 2) the incorporation of organic debris embedded in the soil surface to retard flow and filter sediments.

WAC 222-24-040 Water Crossing Structures (4)

R42 Rule (4) should include replanting of all abandoned temporary approaches and crossings. This is important because of the close proximity to streams. Vegetation should include not only grass but also shrubs or trees.

WAC 222-24-050 Road Maintenance (5)

R43 Rule (5) should include revegetation of road surfaces (and cut and fill slopes if necessary) as part of the abandonment program.

WAC 222-30-070 Tractor and Wheeled Skidding Systems (7)

R44 Abandoned skid trails should be revegetated to reduce surface erosion.

R45 Scars from landslides induced by roading and harvest should be rehabilitated to mitigate the long-term erosion of fine sediment from these sites.

4.6 SUMMARY

There are several major problems regarding the conceptual effectiveness of the forest practice rules that need to be emphasized. Though these problems have been discussed in the previous section, they will be summarized here.

1) All of the forest practice rules that involve reducing the likelihood of landslides (and therefore debris flows and dam-break floods) depend on accurate recognition of

inherently unstable sites (i.e., those that could become destabilized or produce debris flows). The effectiveness of these rules depends wholly on whether the observer is trained in state-of-the-art, published geotechnical assessment methods. The lack of a trained observer is equivalent to the absence of forest practice rules covering slope stability. It cannot be overstressed, therefore, that personnel applying these forest practice rules be adequately trained in geotechnical assessment methods.

2) The majority of forest practice rules designed to protect watercourses from erosion generally cover only Water Types 1 to 3. A few rules include Type 4. The paucity of rules including Types 4 and 5 is a fundamental flaw. Type 4 and 5 Streams, otherwise known as first- and second-order channels, generally make up greater than 80 percent of cumulative channel length in mountain watersheds. Therefore, the vast majority of erosion or sediment production is carried out in or through Type 4 and 5 Streams. It is paramount that equal protection be given to Type 4 and 5 Streams in recognition of the significant role they play in erosion and transport of sediment in mountain watersheds. MacDonald and Ritland (1989) explain the role of Type 4 and 5 Waters in greater detail.

3) Many forest practice rules encourage diversion of road-surface-generated runoff onto forested hillslopes rather than into stream channels as a means to filter sediment. While this is an important strategy for reducing the contribution of road sediment to streams, many geomorphologists believe that diversion of surface runoff onto steep slopes is a major cause of landslides and debris flows associated with road prisms. Concentration of flow from even a 50-foot section of logging road onto a steep slope can create effective precipitation rates on that slope that greatly exceed naturally occurring precipitation intensities by thousands of percent. Therefore, it is necessary to avoid diverting surface flow onto steep hillslopes particularly in those areas prone to debris flows. Trained professionals using state-of-the-art, published methodologies for predicting landslides and debris flows should assess the risk of diverting runoff onto steep hillslopes and recommend alternative culvert placement.

4) Many of the same rules addressed in 3) also fail to identify the potential for expanding upslope contributing drainage areas through poor placement of logging roads and culverts. Often, logging roads and culverts enlarge existing drainage areas. The resulting increased surface and subsurface runoff is then routed downslope onto areas that have never encountered a greater amount of saturation, and failures may result. It is crucial that during road design and construction, upslope drainage areas are not expanded, particularly on steep slopes.

5) Broadcast slash burning destroys the remaining root strength of the soil by killing understory trees and shrubs and thus increasing the instability of an already unstable site. Research indicates that failure rates are higher in burned units than in unburned units. Therefore, broadcast burning should be banned on all hillslopes with gradients of greater than 25 degrees.

5.0 METHODS FOR TESTING THE EFFECTIVENESS OF THE FOREST PRACTICE RULES AT MINIMIZING SEDIMENT PRODUCTION AND ITS ENTRY TO STREAMS

TASK 4

5.1 INTRODUCTION

The methods presented below are designed to test the effectiveness of specific forest practice rules at preventing the individual erosion processes listed in Table 1.1. These processes are landslides/debris flows, slump-earthflows, surface erosion, and channel-bank erosion. Each general forest practice activity that affects an erosion process will be addressed according to process. The relationship between erosion process and forestry activity is summarized in Table 1.1.

The testing methods are based on the sediment budget approach discussed in Section 1.0. The test of rule effectiveness is based on two components: a quantitative measure of erosion (erosion detection) that indicates a potential failure of the forest practice rules or in their application; and a qualitative interpretation of the magnitude of the rule failure, based on number or frequency of erosion incidence, the estimated volume of sediment entering channels, and the lengths of channel portions affected by a particular erosion process. Absence of significant erosion indicates that the rule is effective for the geographic area and time period of the analysis. In some cases the results may be extrapolated in time and space.

Each test may contain up to six general levels of analysis. These are site stratification, measurement of erosion, determination of sample size and time period (summarized in Table 5.1 for all erosion processes), analysis of storm history, tests of the effectiveness of forest practice rules, and interpretation of erosion significance.

The procedure that follows is not a "cookbook" method for conducting a test of the BMPs. Rather, it is a set of guidelines for conducting the test in the context of a geomorphological sediment budget approach. Conducting a test if the BMPs using these guidelines requires personnel trained and educated in the science of geomorphology (see Section 5.6 for further details).

Table 5.1
Time scale for sampling erosion processes by forest practice activity.

Forest Activity	Erosion process			
	Landslide/ Debris Flow	Slump-earthflow	Surface Erosion	Channel-bank Erosion
Roads	Minimum 5 to 7 years after road construction	Beginning of photo record to present	Three categories: 1) during construction 2) during use and temporary nonuse 3) distribution of years since abandonment	Mechanical disturbance: within several years following the forest practice Debris flow/dam-break flood erosion: no time limit
Timber Harvest	3 to 5 years after harvest and buming and no later than 15 to 20 years afterwards	Beginning of photo record to present	Immediately following and 1 year later	Mechanical disturbance: immediately following activity and first several years after Debris flow/dam-break: immediately following event up to several decades later
Reforestation	3 to 5 years after harvest and buming and no later than 15 to 20 years afterwards	Not Appplicable	Immediately following and 1 year later	Not Applicable

5.2 LANDSLIDES (INCLUDING DEBRIS FLOWS AND DAM-BREAK FLOODS)

The landslide erosion category includes landslides, debris flows, and dam-break floods (see Section 1.4 for definitions and terminologies of erosion processes). A landslide inventory is recommended for evaluation of BMP effectiveness in minimizing erosion due to landslides. This inventory computes the number of landslides per unit area per unit time (see Section 2.0, Literature Review, for details) and can be used to evaluate either landslides or debris flows. Because dam-break floods are difficult to differentiate from debris flows on aerial photos and in the field, this method treats them as debris flows, which are treated later with regard to interpreting erosion significance.

The three major categories of forest practice rules apply to the erosion process of landslides and debris flows. These categories are: 1) roads (hereafter referred to as logging roads), including design, location, construction, and maintenance, along with forest practices relating to landings, rock quarries, gravel pits, borrow pits, and spoil disposal area; 2) timber harvest (clearcuts and partial cuts); and 3) reforestation.

5.2.1 Testing Effectiveness of Logging Road BMPs

The forest practice rules that apply to logging roads include Classes of Forest Practices 222-16-050 (1e); Design, 222-24-025 (5)(6)(7)(9); Construction, 222-24-030 (4)(8); Landing Location, 222-24-035 (1); Water Crossings, 222-24-040 (2)(4); Maintenance, 222-24-050; Landing Drainage and Erosion, 222-30-080 (1)(2); and Skid Trails, 222-30-070 (6).

Landslides associated with logging roads may originate from a variety of factors including 1) a natural failure that includes damage to the capital improvement; 2) design failure (e.g., faulty location or design); 3) construction failure (e.g., not as designed); and 4) maintenance failure (e.g., not as planned).

To test the effectiveness of the forest practice rules and regulations, it is important to determine first whether landslides occurred in association with roads, and second, the cause(s) of landslides (e.g., general categories 1 to 4).

5.2.1.1 Site Stratification

There are four levels of stratification designed to reduce site variability and allow for more accurate detection of erosion associated with specific forest practices. The four levels include general physiographic region, geology, hillslope gradient, and forest practice.

General Physiographic Region

Landform heterogeneity caused by climate, vegetation, and geomorphology in Washington State results in variability of locations, triggering thresholds, and frequencies of landslides (and debris flows). Rule testing should therefore be conducted within areas with minimal site variability. Physiographic region is the first level of site stratification; other levels may be required depending on the erosion process.

The west side of the Cascades has been divided into five physiographic regions (see Section 3.1). These are the North Cascades, South Cascades, Olympic Peninsula, Willapa Hills, and Puget Lowland (Figure 3.1). The eastern portion of the State contains three general physiographic regions where forest practices are of concern (see Section 3.1). These regions are the Eastern Cascades, Northern Rockies, and Blue Mountains (Figure 3.1).

Geology

Shallow-rapid landslides usually involve the failure of a thin layer of colluvium on steep bedrock. The stability of colluvium is governed by such factors as hillslope gradient; depth of colluvium; hillslope form, which controls degree of saturation; soil mechanical properties including friction angle and cohesion; and vegetative root cohesion. Though lithology may influence soil mechanical properties, colluvium is often considered generally cohesionless, and studies have indicated that factor of safety is not very sensitive to changes in friction angle of the soil (Gray and Megahan, 1981).

Fiksdal and Brunengo (1981) determined that geologic structures such as hillslopes that are parallel to the dip of the underlying bedrock influence landslides in Washington State, especially when the dip slope exceeds 20 degrees. They concluded, however, that "there was a poor correlation of mass movement to the mapped geologic units."

For the purpose of testing the forest practice rules with regard to shallow-rapid landslides, therefore, landslide inventories should be contained within a uniform lithology whenever feasible. The test can still be conducted if this is not possible or indeterminate, however.

Late Pleistocene continental glaciation created extensive glacio-fluvial deposits including lacustrine sediments along all the major river valley floors within the North Cascades physiographic region. These deposits are sculpted into terraces, valleys, and ridges, and they have numerous types of soil-mass movements associated with them, including shallow-rapid landslides (refer to Section 2.0, Literature Review). Because of the unique hydrological and geomorphological characteristics of these deposits, a landslide inventory should be stratified by glacial and nonglacial areas.

Hillslope Gradient

The infinite slope stability model demonstrates that stability rapidly declines as gradient increases; this relationship is supported by numerous landslide inventories that have shown the majority of landslides occurring on slopes greater than 25 degrees (Sidle et al., 1985; NCASI, 1985). Therefore, because physiographic regions have a variety of slope gradients, only those hillslopes with gradients in excess of 25 degrees should be selected for landslide or debris-flow inventories.

Forest Practices

To evaluate forest practice rules, the actual forest practice (e.g., logging roads) should be consistent over the area and time of the evaluation. For example, road design specifications and construction practices should be the same over the entire road length in question. Otherwise, separate evaluations for each significant variation in forest practice must be made. Therefore, evaluators must know the age of the road and the forest practice rules that were in effect at the time of construction. Equipment and practice changes that may not be included in the forest practice rules also need to be researched.

5.2.1.2 Measurement of Erosion: Landslide (and Debris Flow) Detection

Measurement of erosion by landslide (and debris flow) is accomplished through landslide inventories. An inventory for logging roads consists of a count of the total number of landslides per road length (or area) within the field of study during a particular time period (see Site Stratification, Section 5.2.1.1). This inventory produces a landslide occurrence rate, which is expressed as the number of events per square kilometer per year. The investigator should know how to identify landslide scars from aerial photographs without confusing them with bedrock outcrops, sidecast material, or surface erosion. Hence, the investigator should be a geomorphologist, hydrologist, or soil scientist familiar with analysis of aerial photos and identification of geomorphic features.

Landslide inventories developed primarily from aerial photos — and to a lesser extent, field surveys — have been the method of choice for the investigation of mass wasting in managed forests. Many of these studies have been summarized in the Literature Review (Section 2.0).

Identification criteria for associating a landslide with a road from an aerial photo must be determined. These criteria have varied among existing inventories and often are not stated. One possible criterion is that landslides whose scars merge with the road prism at its upslope point in either the cut or fill slope should be considered as originating from the road. Though some landslides triggered by roads may occur downslope from them, these can be identified only from field surveys, which will be discussed below.

Landslides and debris flows (including dam-break floods) generally create large erosional scars that are visible in aerial photographs, particularly when they occur in timber harvest areas. Aerial photos with a scale of 1 to 24,000 have been found to be sufficient for detecting landslides that are significant contributors to erosion (NCASI, 1985). Landslides in mature forests are more difficult to detect, and therefore field surveys are necessary to verify the photo inventory. This detection problem in mature forests can be lessened significantly by inventorying debris flows, which have much larger erosional scars and are therefore much easier to detect, both in photos and in the field.

Landslides detected in aerial photos should be verified in the field to determine whether they actually merge with road prisms and have not been misinterpreted. In addition, field analysis of landslide scars can ascertain the cause(s) of a landslide and therefore determine more specifically whether the landslide was part of a natural event that destroyed a road segment or whether it was caused by the ineffectiveness of a particular rule.

Determination of the causes of failure often requires that investigators be experienced in geomorphology, geotechnical engineering, and logging road engineering. Because this combination of training and experience is rare in one individual, it is recommended that field analysis be conducted by a team, including, but not limited to, at least one geomorphologist or geologist familiar with mass wasting in the Pacific Northwest and one logging road engineer.

Because of the variety of geomorphic conditions and the multiplicity of road location, design, and construction characteristics that could be encountered at landslide sites, it is not feasible to detail here the nature of the field surveys that could be used to determine the cause(s) of failures. Field surveying and interpretation techniques are often based on an investigator's unique experience and education.

The forest practice rules pertaining to logging roads listed at the beginning of this section can be divided into three general categories: Road Design (including location), 222-16-050 (1e), 222-24-025 (5)(6)(7), 222-24-035 (1), 222-24-040 (2)(4), 222-24-060 (2), 222-30-080 (2), and 222-30-070 (6); Road Construction, 222-24-030 (4)(8), 222-24-035 (1), and 222-30-070 (6); Road Maintenance, 222-24-050 (1-5); and Landing Cleanup, 222-30-080 (1)(2).

Optimally, field analysis can determine which forest practice rules were ineffective and contributed to the landslides. In some cases local knowledge will be necessary to discover the cause of a failure. For example, a DNR area manager may know if culverts were cleaned or maintained during a specific storm or period of time. The investigator can then discover whether the failure was due to maintenance or design.

Landslide rates can be used to determine the severity of the erosion problem or the ineffectiveness of certain forest practice rules. Rates can also be used to compare different time intervals, physiographic areas, slope classes, geologies, and road types. Landslide rates for roads are usually given in events per square kilometer per year (NCASI, 1985; Sidle et al., 1985), though rates can also be estimated per linear road length (e.g., events per kilometer per year).

Landslide rates within an area are very sensitive to such climatic conditions as large storms or rain-on-snow events. Therefore, rates calculated over relatively short time intervals, such as 5 to 20 years, are generally poor indicators of the long-term rate (e.g., more than 100 years). This is particularly true of unmanaged forests where the magnitude of the threshold storm is high, and less applicable to roads and clearcuts where the threshold storm has been shown to be smaller. Nevertheless, in general the rate based on 10 to 20 years' data should not be extrapolated over much longer time periods, particularly when the rate is used to calculate sediment production in the context of a sediment budget.

Comparison between rates obtained from roads, timber harvest areas, and unmanaged forests is useful and more accurate if all the rates were measured during the same time interval. Hence, the relative difference between landslide rates is much more accurate than the absolute rate for each category.

The determination of a landslide rate is best shown by example. Table 5.2 displays a hypothetical data set obtained during an aerial-photo-based analysis of 13 kilometers of logging road over a 20 year-period; the landslides have been field verified. In the table the estimated average landslide rate for the time period 1970 to 1990 is computed. Optimally,

Table 5.2

An example computation of a weighted landslide rate for a hypothetical landslide inventory from logging roads.

Photo Year	Photo Interval (years)	Road Segment		
		4 kilometers 1973 to 1990	6 kilometers 1977 to 1990	3 kilometers 1988 to 1990
1970				
	1970 to 1975 (5)	0	—	—
1975				
	1975 to 1978 (3)	4	2	—
1978				
	1978 to 1988 (10)	1	3	0
1988				
	1988 to 1990 (2)	2	4	2
1990				
	Total Landslides	7	9	2

Landslide Rate (segment 4 kilometers): 7 / 4 km / 17 years = 0.103 / km / year
Landslide Rate (segment 6 kilometers): 9 / 6 km / 13 years = 0.115 / km / year
Landslide Rate (segment 3 kilometers): 2 / 3 km / 7 years = 0.095 / km / year

Weighted Average Landslide Rate:

$$\frac{(0.103 \times 4\text{ km} \times 17\text{ yrs}) + (0.115 \times 6\text{ km} \times 13\text{ yrs}) + (0.095 \times 3\text{ km} \times 7\text{ yrs})}{(4\text{ km} \times 17\text{ yrs}) + (6\text{ km} \times 13\text{ yrs}) + (3\text{ km} \times 7\text{ yrs})} = 0.1076$$

the exact dates of road construction would be known; otherwise, roads can be assumed to have been completed by the middle of the photo interval, as in the table.

The photo interval is the period of time between consecutive aerial photo years, such as 1970 to 1975 and 1978 to 1988 in Table 5.2. Three road length segments corresponding to their ages (when they first appeared on the photos) are listed. Counts of landslides are arranged on the table corresponding to the photo interval and road segment. Next, the landslide rate for each photo interval is estimated by dividing the number of landslides by the length of the road segment and the years in the photo interval. Each landslide rate must then be time and length weighted to compute the average landslide rate. The weighted mean is estimated by the following equation:

$$\frac{(R_1 \times T_1 \times A_1) + (R_2 \times T_2 \times A_2) + \ldots (R_n \times T_n \times A_n)}{(T_1 \times A_1) + (T_2 \times A_2) + \ldots (T_n \times A_n)}$$

where $R_1 \ldots R_n$ equals the landslide rate, $T_1 \ldots$ Tn equals the photo interval, and $A_1 \ldots A_n$ equals the area.

The weighted average landslide rate is computed for the hypothetical example in Table 5.2.

5.2.1.3 Sample Size and Time Period

There are two purposes for conducting a landslide inventory to test the forest practice rules. The first is to evaluate whether any landslides have occurred. Field verification of landslides indicates that one or more forest practice rules was ineffective in design or application. The absence of landslides indicates that the rules were effective with regard to this form of erosion. The second purpose is to compare the occurrence rate obtained from the landslide inventory to previous inventories to determine whether changing construction practices, equipment, and timber harvest methods not included in the forest practice rules have reduced the number of landslides. The absolute landslide rate is an important indication of the magnitude of the ineffectiveness of the rules, particularly when it is compared to rates in unmanaged forests and timber harvest areas.

Selection of a landslide sample size depends on the types of analyses conducted on the data collected at each landslide. Types of analyses may involve scar size, sediment volume, sediment routing to channels, and measurement of the erosion, in this case computation of occurrence rates. The quantitative portion of the methodology is the computation of the landslide rate; the qualitative portion is the estimate of the magnitude of erosion or the numbers of channels affected. Where population distributions of these factors are unknown, sample sizes of greater than or equal to 30 are suggested (Spiegel, 1961). Hence, a minimum of 30 landslides will adequately characterize population statistics and occurrence rates in a landslide inventory.

Previously calculated landslide rates can be used to estimate the combination of area (or road length) and time period necessary to inventory 30 landslides. Ten landslide inventories from the Pacific Northwest (six published in the first half of the 1980s and the remainder in the late 1970s) provide an estimation of the average occurrence rate of landslides (studies summarized in Peak Northwest, Inc., 1986). The average rate of landslides originating from logging roads is 10.2 events per square kilometer per year. Given a road-area-to-road-length conversion of 1 square kilometer equal to 50 kilometers of road length (Peak Northwest, Inc., 1986), this area rate is equivalent to a linear rate of 0.2 events per kilometer per year, or 1 event per 5 kilometers per year. This average rate is used to estimate the road length and time combination necessary to characterize the road-originated-landslide rate adequately.

The road length and time period combination necessary to obtain 30 landslides using the average rate of 1 event per 5 kilometers per year is shown in Figure 5.1. For example, using an aerial photo record of 10 years would require investigation of a minimum of 15 kilometers of road. If approximately 30 landslides are inventoried, the resulting rate should be representative of the entire area under analysis (the particular road segment over that time period). In addition, the rate may also characterize the occurrence of landslides in other similarly designed, constructed, and maintained segments of road on similar geology and slope in the physiographic region. Actual numbers of landslides inventoried using the area/time guidelines given here may be more or less than 30.

If significantly fewer than 30 landslides are counted, an additional length of similar road should be inventoried to increase the number of slides and thereby increase the accuracy of the rate and confidence in the analysis. If after the second inventory, the total count continues to be less than 30, the analysis can be terminated. If the landslide rates of the two inventories are very different, the investigator may wish to conduct a third analysis.

Certain magnitudes of storms are necessary to trigger landslides, including those originating from roads. The recurrence interval of triggering storms has been estimated to vary between 2 and 10 years (Sidle et al., 1985). Therefore, when evaluating road forest

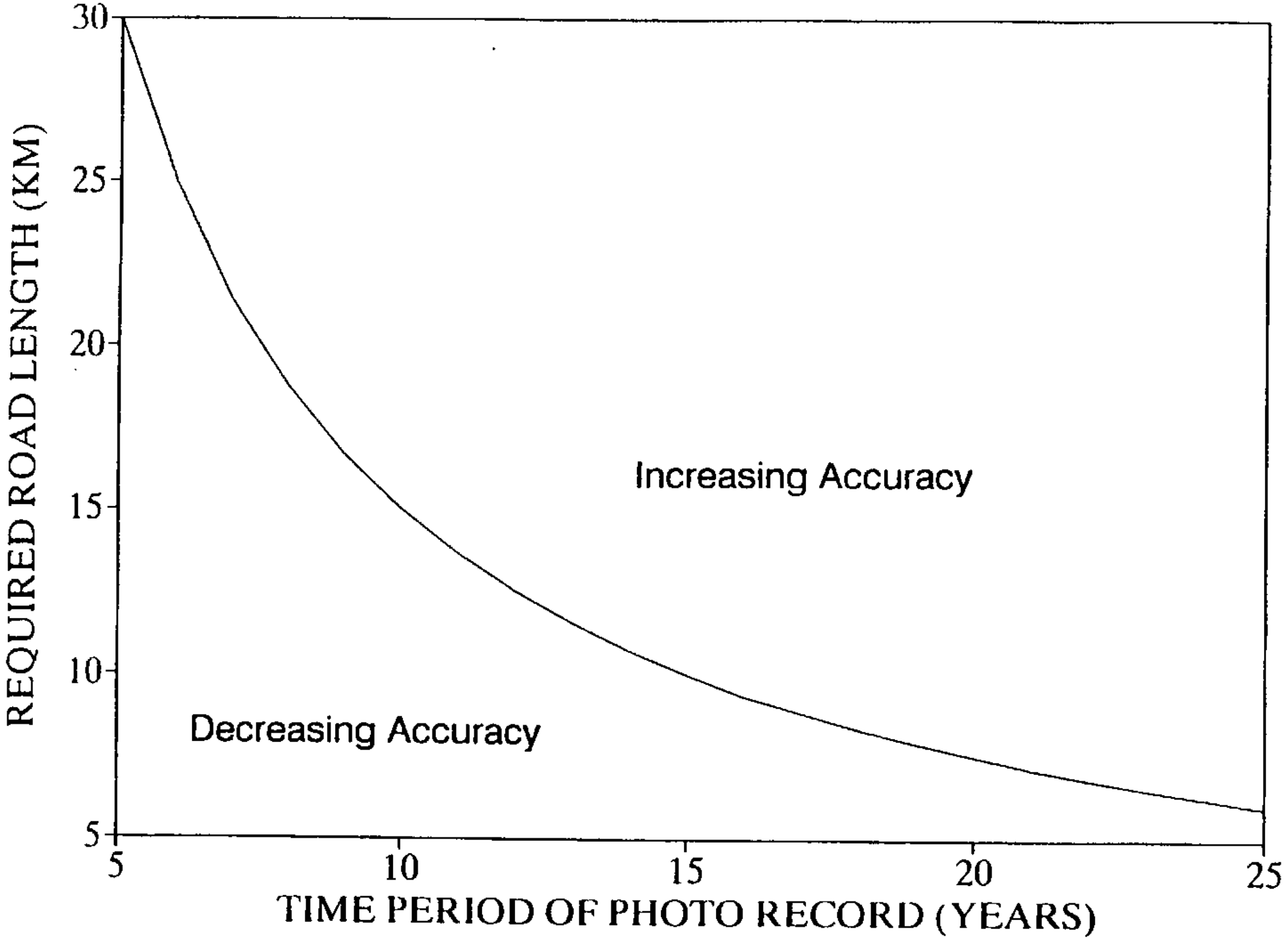

Figure 5.1
Relationship between time period of analysis and required road length necessary for landslide inventory along logging roads.

practice rules, investigators should cover roads over a minimum of 7 to 10 years; longer time periods increase the confidence of the test. This sample time constraint is summarized in Table 5.1. Of course, when specifying an investigation time period, which is often determined by the aerial photo record, investigators must know the distribution of road construction within the period. Three general cases are displayed in Figure 5.2. Normal and left-skewed distributions of road constructions are acceptable for the analysis since they allow time for sufficiently large storms to trigger landslides. The right-skewed distribution is unacceptable because it does not allow sufficient time for large storms to trigger landslides. For example, the distribution of roads in the hypothetical case shown in Table 5.2 is plotted in Figure 5.3. In this hypothetical case they are skewed to the left, so this is an acceptable test case.

It is important to note that failures originating from roads have no counterpart in unmanaged forests. Hence, any landslides detected from aerial photos indicate a preliminary failure of those forest practice rules that pertain to road-generated landslides. A field survey is required to determine the actual cause of failure and thereby specify which forest practice rule or application was not effective. If no landslides are detected, the rules can be considered effective over the segment of road during the specified time.

The magnitude of the landslide occurrence rate in comparison with the rate of landslides in unmanaged forests and in recent timber harvest areas and also in comparison with the rates of other erosion processes, can provide an indication of the extent and seriousness of the ineffectiveness of the rule. In addition, other important factors include the size and volume of landslides and whether they entered stream channels or transformed into debris flows (and dam-break floods).

5.2.1.4 Analysis of Storm History

Estimating the storm history for the landslide inventory period can be useful for the interpretation of the landslide time series, for the comparison of rates obtained at different time intervals, and because certain road engineering design requirements are given in storm-recurrence intervals. For example, 222-24-035 (2) requires culvert size to pass flows of the 50-year recurrence interval. If a larger-than-50-year storm was estimated, that rule could not be adequately tested. The procedure for determining the recurrence intervals of storms or flows is beyond the scope of this report; for details refer to Dunne and Leopold (1978) and Linsley et al. (1975).

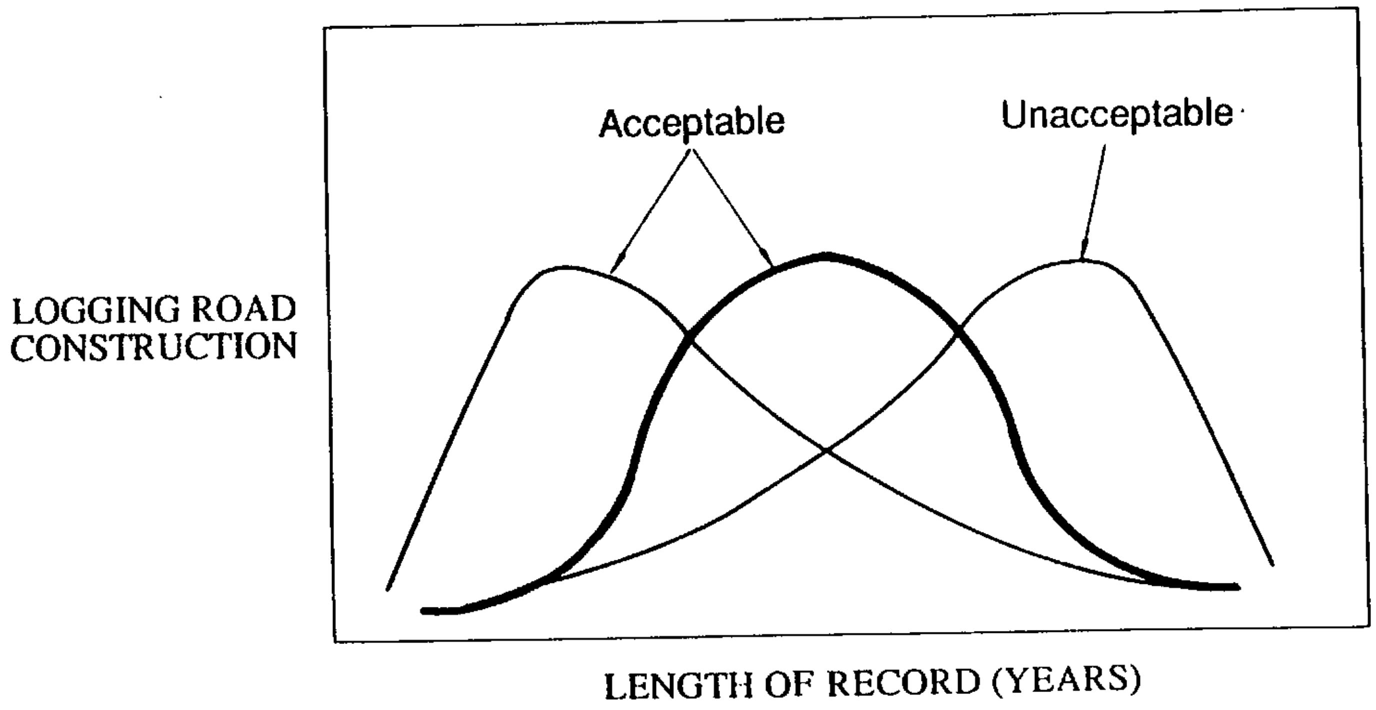

Figure 5.2
Three hypothetical distributions of road construction during the time period selected to conduct a landslide inventory along logging roads.

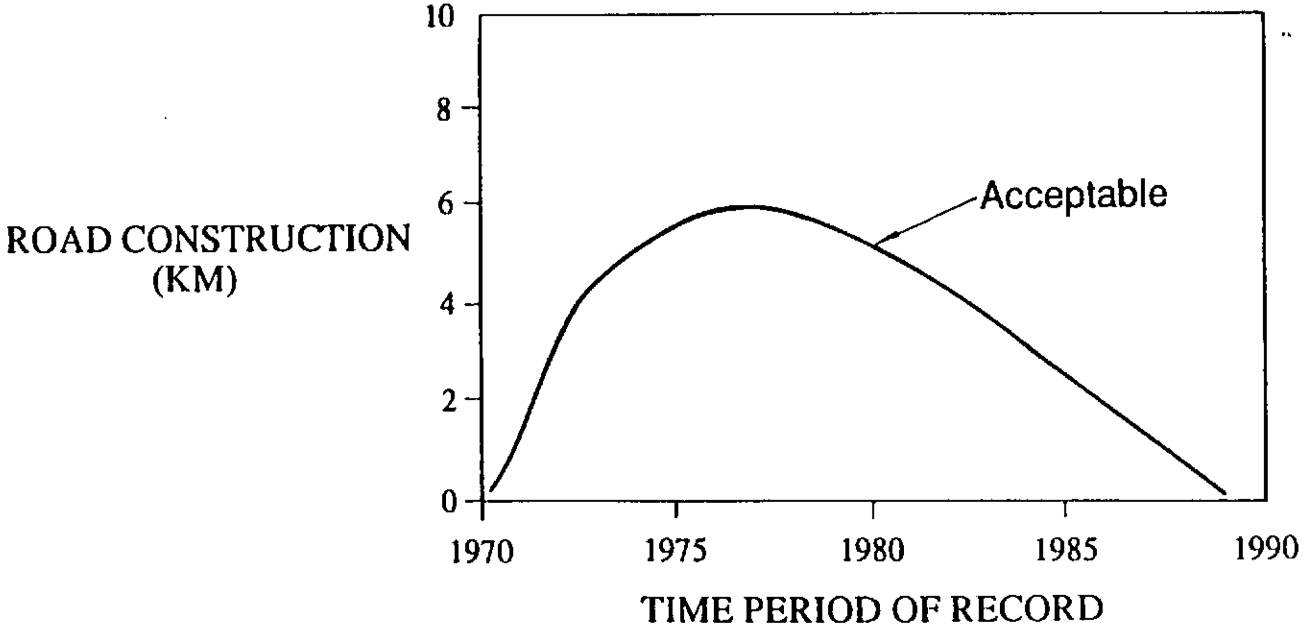

Figure 5.3
Distribution of road construction for the example used to compute a landslide rate along roads in Table 5.2

5.2.1.5 Testing the Effectiveness of Forest Practice Rules

Any landslide detected in photos and verified in field surveys as originating from a road constructed in compliance with BMPs indicates that certain forest practice rules or their applications were ineffective. Because landslides originating from road prisms have no counterpart in unmanaged and unroaded forests, they are not compared to unmanaged forest landslide rates.

Trained personnel should conduct field surveys to determine the cause(s) of these landslides and to discover which forest practice rules may be ineffective (see beginning of section for listing of pertinent forest practice rules). Responsibility for the landslides may be assigned to several forest practice rules that apply generally.

5.2.1.6 Interpreting Erosion Significance

This section is designed to produce a qualitative indicator of erosion significance that can be used as a crude surrogate for assessing environmental impacts or degradation of water quality (including turbidity).

The entry of sediment to stream channels is a good indicator of erosion significance and an increase in turbidity. Sediment deposition in higher-order channels (Types 1 to 3) is more significant than entry into first- and second-order channels (Types 4 and 5). The magnitude of sediment volume is important; several thousand cubic meters of sediment is more significant and can do more damage than several hundred cubic meters. Grain size is important but depends on the resource in question and will not be listed here.

Significant impacts may arise from landslides that result in debris flows and dam-break floods. Inventories of debris flows directly from aerial photos (as with landslides) may be important. Debris flows are identified on aerial photos through location of erosion scars in steep first- and second-order channels. A few other mass wasting features such as snow avalanche tracts and talus appear similar to debris flows on aerial photos; care should be taken not to inventory these. Typically, occurrence rates for debris flows are lower than for landslides because not all landslides initiate debris flows.

A large number of debris flows in a large watershed is more significant than a single event with respect to sediment transfer to streams. In small catchments, however, a single debris flow or dam-break flood may destroy the majority of stream habitat. Thus, the significance of these events needs to be determined from a biological perspective.

Determining erosion significance — that is comparing the amount of erosion to other erosion processes in a particular area over a specific time period — is best done in the context of a sediment budget. A sediment budget is a key component of the proposed watershed analysis, and therefore, defining erosion significance should be done at the watershed scale (see Section 5.6 for further details).

5.2.2 Testing Effectiveness of Timber Harvest BMPs

Timber harvest can entail complete removal of the trees (clearcutting) or some form of partial removal of the trees (partial cutting). Clearcut harvest is the method of choice on the west side of the Cascade Mountains of Washington; partial cutting is more common in the eastern portion of the State.

There are several forest practice rules that pertain to slope stability concerns during timber harvest on steep and unstable slopes. These include Class IV - Special, 222-16-050 (1f) and Slash Disposal, 222-30-100 (1). In addition, landslides (and debris flows) may also occur in clearcuts in response to concentration of drainage by logging roads and diversion of that runoff onto steep and unstable slopes. Though no forest practice rules mention this specifically (see Section 4.0), the absence of pertinent guidelines may implicate those rules when landslides occur below roads within clearcuts because of drainage diversion.

The method for testing the effectiveness of forest practice rules in minimizing landslides in timber harvest areas is very similar to that for logging roads and is based on a landslide inventory. The difference is that rule effectiveness is based on a comparison of landslide rates in timber harvest areas and rates in unmanaged forests.

5.2.2.1 Site Stratification

Stratification of landscapes to inventory landslides in timber harvest areas is similar to that done for logging roads, discussed above. The sample area should be contained within one physiographic region, and if possible it should be contained within a single, relatively homogeneous geologic mapping unit. The sample area must be on hillslopes having gradients greater than 25 degrees because few landslides occur on slopes of less.

An additional site stratification criterion is vegetation age. Because tree-root strength is important to slope stability and because it increases with forest age following harvest, selecting inventory areas with similar vegetation ages is important; this is particularly applicable to clearcuts.

There does not exist a definitive division of stand ages with respect to landslide probabilities. It has been observed that root strength is at its lowest approximately three to seven years following clearcut harvesting and that root strength increases with time fairly rapidly (Ziemer, 1981; Burroughs and Thomas, 1977). It has been hypothesized that tree root strength recovers to pre-cut values no earlier than age 16 to 20.

For the purpose of testing the forest practice rules, therefore, we recommend that landslide inventories take place three to five years following harvest. Landslides should not be inventoried in clearcuts with revegetation greater than approximately 15 years old. Though landslides may occur in units greater than 15 years old, they should be considered as having a different vegetation age class, and should be referred to as a second-growth, managed forest. These sampling time constraints are summarized in Table 5.1.

5.2.2.2 Measurement of Erosion: Landslide Detection

Analysis of aerial photos for the purpose of inventorying landslides in timber harvest areas is similar to that done for logging roads, discussed above. Special care should be taken not to attribute pre-existing landslides (those that existed under forest cover) to timber harvest.

Verifying landslides detected from aerial photos is an important part of the methodology. Field surveys are necessary to check the accuracy of photo interpretation and build confidence in the aerial photo analysis. In addition, field surveys are necessary to collect further information concerning the relationships between landslides and upslope roads, sediment from landslides reaching stream channels, hillslope characteristics such as gradient and slope form, and landslide volumes. Landslides considered to predate the clearcut (possibly not detected on early air photos because of canopy closure) or confused with bedrock outcrops, fill slopes, etc., should be deleted from the field survey. Landslides discovered during the field survey should be added to the landslide inventory.

The occurrence rate of landslides in timber harvest areas is computed similarly to that of logging roads. Landslides are associated with specific harvest areas and time periods (often determined by the photo interval) and then are area and time weighted to produce an average rate for the entire area. Because some of the inventoried landslides in timber harvest areas are possibly due to natural events, the actual landslide rate is determined by subtracting the landslide rate from that of an equivalent unmanaged forest. Landslide rates are expressed in units of events per square kilometer per year (see example for computation of landslide rates in clearcuts in Table 5.3).

Table 5.3

An example computation of a weighted landslide rate for a hypothetical landslide inventory from clearcuts.

Photo Interval	Harvest Year	Area (acres)	Analysis Time Interval	Number of Landslides	Landslide Rate
1964 to 1968	1964	40	64 to 80 (17 years)	2	2 / 40 acres / 17years = 0.0029
1968 to 1972	1967	60	68 to 80 (13 years)	1	1 / 60 acres / 13 years = 0.0013
1972 to 1980	1978	100	80 to 86 (7 years)	0	0 / 100 acres / 7 years = 0
1980 to 1986					
	Total	200 acres		3 landslides	

Weighted Average Landslide Rate:

$$\frac{(0.0029 \text{ x } 40 \text{ acres x } 17 \text{ years}) + (0.0013 \text{ x } 60 \text{ acres x } 13 \text{ years})}{(40 \text{ acres x } 17 \text{ years}) + (60 \text{ acres x } 13 \text{ years})} = 0.0021$$

Individual timber harvest areas should be investigated no earlier than approximately three to five years after harvest, and no later than approximately 10 to 15 years following harvest; this time scale assumes that the tree plantation is approximately the same age as the unit. If the user desires to extend the analysis over longer time periods (e.g., greater than 15 years), a break should be made to delineate the more mature age of trees, and a separate landslide rate should be computed. This rate may be referred to as a landslide rate for second-growth forests.

5.2.2.3 Sample Size and Time Period

Clearcuts

The minimum area recommended for investigation of landslides in clearcuts is based on the average area that was required to detect 30 landslides from 10 previous landslide inventories in the Pacific Northwest; all 10 studies examined clearcuts. If possible, as with logging roads, a minimum of 30 landslides should be inventoried in timber harvest areas. The average occurrence rate of landslides based on the 10 studies in the Pacific Northwest is 1.8 per square kilometer per year. The recommended time period for the analysis is approximately 10 to 12 years (e.g., approximately three to five years following harvest to year 15). Based on the average occurrence rate of 1.8 per square kilometer per year and an analysis period of 10 years, approximately 2 square kilometers (500 acres) of clearcuts is the recommended minimum inventory area. Increasing the area increases the accuracy and confidence of the analysis.

It is likely in certain areas that 30 landslides may not be counted in a 2-square-kilometer area because many of the studies on which the sample area was based may have been conducted in some of the most unstable terrain in the Pacific Northwest. In less erodible landscapes, the landslide rate will probably be lower. Therefore, in the event that less than 30 landslides are counted in 2 square kilometers, the analysis should be conducted again in an additional 2-square-kilometer area of clearcuts of a similar age to ensure that an accurate rate is computed for later comparison to rates in unmanaged forests. If the combined count of landslides continues to be less than 30 following the second inventory, the analysis can stop. If, however, the landslide occurrence rates for the two inventories are significantly different (by a factor of 5 or more), a third inventory may be conducted.

Partial Cuts

We are not aware of existing landslide inventories in partial cuts in the Pacific Northwest. Because not all trees are removed in partial cuts, root strength should be greater and landslide rates should be lower. Nevertheless, we recommend the same minimum sample area of 2 square kilometers (500 acres). Because fewer than 30 landslides will probably be detected in partial-cut areas, an additional inventory of another 2-square-kilometer area will most likely be necessary.

5.2.2.4 Testing the Effectiveness of the Forest Practice Rules

Detecting landslides in timber harvest areas alone is not sufficient to measure of the effectiveness of forest practice rules. Some landslides that occur in timber harvest areas may have occurred naturally, as they do in unmanaged forests. Landslides are a natural process in unmanaged forests, and they occur in response to large storms and other disturbances such as blowdown and fires. Hence, landslides in unmanaged forests must be inventoried and a background or control rate of landslides computed for comparison to rates from timber harvest areas.

Like landslides elsewhere, landslides in natural forests can be counted with aerial photos and field surveys. Detection of landslides in forested areas by aerial photos may be complicated by dense vegetative cover, which conspires to mask landslide scars and depositional zones. Landslide inventories in dense, unmanaged forests should rely heavily on field surveys to verify photo results and to augment the landslide count. One way around this detection problem is inventorying debris flows, which can be detected much more easily in unmanaged forests using aerial photos. Inventorying debris flows also addresses directly the issue of sediment delivery to stream channels, because debris flows move through and severely erode first- and second-order streams (Type 4 and 5 Waters), and typically deposit large volumes of sediment directly into lower-gradient channels (Type 1 to 3 Waters).

Site stratification is as important in unmanaged forests as it is for timber harvest areas. The forests to be surveyed should be similar to timber harvest areas with respect to physiographic region, geology, hillslope gradient, and age of vegetation. Areas burned within the last 100 years or so may have numerous old landslide scars, and if so these should be dated by dendrochronological methods to determine the time of failure. Optimally, only those landslides that occurred during the same time period as the inventory in the harvest areas should be counted; consecutive aerial photos and field survey methods can be used to determine dates of occurrence.

To determine whether landslides were caused by timber harvest requires that the rate of landslides in unmanaged forests be subtracted from the rate of landslides in the harvest area. This revised rate for a harvest area is then multiplied by the area (square kilometers) and time period (years) of the original inventory in the harvest area. The result is an estimate of the number of landslides attributable to forest practices.

The existence of landslides attributable to timber harvest may indicate the ineffectiveness of forest practice rules, a failure in the application of the rules, or noncompliance on the part of the timber operator. To determine effectiveness, the investigator should examine the location of landslides in timber harvest areas with respect to the original forest practice permit. Refer to the specific forest practice rules listed above regarding slope stability issues in timber harvest areas.

5.2.2.5 Interpreting Erosion Significance

Determination of erosion significance in clearcuts is done as it is for logging roads, discussed above. Inventorying debris flows may be more suitable; they are more easily detected in dense, unmanaged forests because their erosional scars encompass entire lengths of first- and second-order channels. Thus the comparison between harvest units and forests is more accurate and the need for extensive field work in unmanaged forests is reduced.

As described previously, erosion significance is best determined through a sediment budget at a watershed scale; this level of analysis is a key component of the proposed watershed analysis.

The number or location of debris flows and dam-break floods can be used as an indicator of the significance of erosion. Field surveys of channels or water quality, however, are required to accurately determine impacts and significance.

5.2.3 Testing Effectiveness of Reforestation (BMPs)

The only forest practice considered under reforestation is site preparation by Broadcast Slash Burning, 222-30-100, or Scarification, 222-34-040. To test for the effects of broadcast burning or scarification, a landslide inventory similar to that for clearcuts is conducted with additional site stratification by surface treatment (slash burning and scarification).

5.3 SLUMP-EARTHFLOWS

This section covers testing of BMPs for their effectiveness in preventing new slumps and slump-earthflows from being triggered or existing features from being activated.

Unlike landslides (defined in this document as "shallow-rapid processes"), slump-earthflows are generally confined to specific geologic terrain. They are usually long-term features in the landscape, and forestry activities reactivate or accelerate their movement. For this reason, the objective of the sampling strategy is to inventory existing features and analyze the way in which forest management may have influenced or be influencing their behavior.

The same categories of forest practices that apply to landslides also apply to slump-earthflows: logging roads, timber harvest, and reforestation. These categories are considered separately in the following discussion.

5.3.1 Testing Effectiveness of Logging Road BMPs

The forest practice rules that apply to logging roads and site instability include Classes of Forest Practices, 222-16-050 (1e); Location, 222-24-020 (2); Design, 222-24-025 (5)(6)(7)(9); Construction, 222-24-030 (4)(8); Landing Location, 222-24-035 (1); Water Crossings, 222-24-040 (2)(4); Maintenance, 222-24-050; Landing Location and Erosion, 222-30-080 (1)(2); and Skid Trails, 222-30-070 (6).

The physical mechanisms through which logging roads can cause new or destabilize existing deep-seated failures include 1) loading, especially in the upslope portion, by road fill, sidecast, landings, and spoils; 2) undercutting, especially in the downslope portion, by excavation for roads, landings, and borrow pits; and 3) disruption of natural drainage so that it is focused on unstable locations.

Policies that govern logging roads can be implicated in the triggering or acceleration of slump-earthflows when 1) the location of the road contributes to instability in a way that design and drainage measures cannot mitigate; 2) construction is such that design and drainage provide inadequate mitigation; and 3) maintenance measures provide inadequate protection.

5.3.1.1 Site Stratification

The following levels of stratification are designed to locate and sample a distribution of slump-earthflow terrain across the State.

Physiographic Region

Sampling should be made separately within each physiographic region of the State, as described in Section 5.2.1.1.

Geology

Unlike landslides, slump-earthflows are not widespread across the spectrum of geologic terrain. Deep-seated failures are localized in the following geologic settings: deeply weathered and mechanically weak rock types; thick, glacially-derived sediments; and zones of structural weakness, such as major fault zones.

Watersheds or landscape polygons should be selected within this range of geologic terrain. Selection must be made by a skilled geologist familiar with the geologic conditions that promote deep-seated failure, knowledgeable about Washington State geology, and able to interpret geologic and slope-stability maps for the occurrence of such terrain. The geologist would make the selection using geologic and slope-stability maps published by the US Geological Survey, the State Department of Natural Resources, and other sources.

Hillslope Gradient

Earthflows can occur on slopes as gentle as 4 degrees. For this reason, sampling should not be restricted by slope gradient.

Land Management

The inventory in each selected watershed should be confined to the areas that have undergone roading and harvest.

5.3.1.2 Measurement of Erosion

The objectives in analyzing slump-earthflow features are to determine the frequency of failures triggered by some aspect of logging roads and to determine the frequency with which logging roads accelerate feature movement.

It should be made clear that though inventories of slump-earthflows have been made, to our knowledge, no systematic, landscape-scale inventory of the role of logging roads or other forestry activities in activating or accelerating slump-earthflows has been made. The literature on the interaction of forestry activities with slump-earthflow features has focused on the detailed study of the mechanics of individual features. Because there has been so little previous work to guide the effort described herein, it should be undertaken by a geologist who is skilled in the identification and interpretation of deep-seated failures.

The triggering of new or dormant slump-earthflows should be identified through examination of the complete aerial photographic record of the area of interest. Each incidence of slumping and of an event in spatial association with a road should be noted. The criteria for associating a failure with a road should be detailed and should include the identification of a possible mechanism by which the road could have influenced the failure. These features can be subtle, and identification requires a skilled photogeologist. Depending on the quality of the photographic record, a ground survey may be necessary to determine whether some features are deep-seated failures.

Consistent criteria should be used for the identification of deep-seated failure. These criteria will vary according to geologic terrains, but possible criteria, adapted from Swanson and James (1975), could include the following:

(1) Large-scale features include large, bowl-shaped drainages; topography is hummocky in the central and lower portions of watersheds; drainage systems are poorly developed and include small sets of small parallel streams; the mainstream channel at the foot of the watershed is temporarily blocked or diverted; and there is a steep headwall scarp across the top of the drainage.

(2) Smaller-scale surface characteristics include poorly drained depressions, indicated by ponds, skunk cabbage, and cedar bogs; arcuate, concave-downslope scarps; and hummocky topography.

(3) Vegetative characteristics include "jackstrawed" trees.

Features identified on photos should be verified in the field to determine whether they were caused by roads and to determine mechanisms. Again, the field evaluation should be done by an individual or individuals with credentials in geomorphology and geotechnical engineering.

The second objective is to evaluate the role of roads on or near existing features in accelerating movement of those features. Deep-seated features can move at rates ranging from millimeters to meters per year. It should be repeated that there has not, to our knowledge, been a systematic, landscape-scale survey of the role of forestry activities in accelerating the deformation of existing features. Once again, the analysis to be conducted herein should be undertaken by an experienced geologist.

For rapidly moving features, the rate of movement can be quantified by mapping the feature on a series of aerial photographs. Downslope displacement can be measured by mapping fixed natural or cultural objects such as individual trees or roads relative to the feature. For most features, ground surveys must be used to determine the rate of movement. Ground surveys cannot be used to evaluate the prior history and several years or decades may pass before there is any measurable movement. It is assumed that the intensity and duration of such a field effort is not within the scope of this study.

5.3.1.3 Sample Size and Time Period

Within the watershed or landscape polygon selected for sampling, all slump-earthflow features that occur in association with roads should be inventoried on aerial photographs and evaluated on the ground, as outlined above. The minimum number of features should be 30 (see Section 5.2.1.3 for discussion). It is likely that several watersheds or polygons must be inventoried to achieve this sample size, and so different geologic terrain will be evaluated. All watersheds should be selected from the stratification process used to select terrain prone to deep-seated failure.

The sizes and numbers of watersheds selected will vary according to the geologic terrain and the frequency of deep-seated failures within that terrain. For this reason, the amount of land to be sampled will likely vary from physiographic region to region.

The entire aerial photographic record should be inspected in order to better identify features, to measure the rate of feature movement, and to survey for road-induced triggering or acceleration. The photographic record in the State ranges from 30 years to as much as 70 years. Every effort should be made to find the complete record.

5.3.1.4 Analysis of Storm History

Unlike shallow landslides, deep-seated failures are affected less by the magnitude and occurrence of individual storms than by the seasonal and annual water balance. Detailed field monitoring of deep-seated failures shows that movement is controlled by the seasonal elevation of the groundwater table. There are not sufficient data, however, to relate movement to specific periods of less-than-normal precipitation. Moreover, because a photographic record of several decades will be used for the inventory, it should not be necessary to take into account the history of annual precipitation variations.

5.3.1.5 Testing the Effectiveness of Forest Practice Rules

The inventory will result in a list of all deep-seated failures within the managed portion of susceptible watersheds. From this information, it should be possible to determine:

(1) The extent to which the road network was planned so as to avoid unstable terrain.

(2) In cases where roads were built across or in close association to deep-seated failures, the extent to which roads were designed so as to avoid triggering or accelerating movement.

(3) The extent to which roads on unstable terrain were maintained to prevent triggering or accelerating movement.

5.3.1.6 Interpreting Erosion Significance

For each studied feature, the aerial photo and field evaluations should include an assessment of the extent to which the failure has contributed sediment to the stream system. Features that reach a stream may erode by normal bank-erosion processes, the rate of which can be determined from sequential aerial photographs and converted to a volume using a field-measured bank height.

The presence or absence of fluvial erosion of the slump-earthflow surface should also be noted as an additional, chronic sediment source. Finally, features that terminate in mid-slope or near stream heads should be evaluated for evidence of landsliding of the toe and surface erosion of the bare landslide scars.

Again, evaluation of the significance of an erosion source needs to be conducted in the framework of a sediment budget or watershed analysis. Even if turbidity samples were available, the effect of the earthflow would have to be evaluated.

5.3.2 Testing Effectiveness of Timber Harvest BMPs

The forest practice rule that applies to the effect of timber harvest on deep-seated failure is 222-16-050, which defines as Class IV — Special any timber harvest in areas where canopy removal has the potential for increasing slope instability.

Timber harvest can destabilize slump-earthflow terrain by altering the subsurface hydrologic regime. Several field studies (see Section 2.0, Literature Review) have indicated that cutting reduces evapotranspirative water loss sufficiently to induce existing failures to accelerate.

It should be made clear that, once again, to our knowledge, there has not been an extensive, landscape-scale inventory of the role of tree cutting in slump-earthflow behavior. Knowledge is limited to studies published from several intensively-monitored field sites and based on a limited amount of data. Hence, there is no established methodology for conducting such a survey, which in any case should be undertaken by a skilled geologist.

5.3.2.1 Stratification

Stratification can be incorporated within the approach detailed in Section 5.3.1.1.

5.3.2.2 Measurement of Erosion

Erosion measurement will not differ from the approach indicated in Section 5.3.1.2 except that the spatial and temporal association of interest is clearcuts and partial cuts, not roads.

The main objective is to identify the incidence of clearcutting that appears to trigger the rapid initiation of a dormant or new feature. A second objective is to note the incidence of acceleration of existing features. It may not be possible to detect accelerated movement except in a few extreme cases, however, because the scant literature available suggests that movement may accelerate for only a few years following cutting, and it is unlikely that this change in rate can be detected by aerial photographs.

5.3.2.3 Sample Size and Time Period

See Section 5.3.1.3 for discussion.

5.3.2.4 Analysis of Storm History

See Section 5.3.1.4 for discussion.

5.3.2.5 Testing the Effectiveness of Forest Practice Rules

The result will be an inventory of all deep-seated failures within the managed portion of sampled watersheds susceptible to deep-seated failures. From this inventory, it should be possible to determine the extent to which unstable terrain was avoided.

5.3.2.6 Interpreting Erosion Significance

See Section 5.3.1.6 for discussion.

5.3.3 Testing Effectiveness of Reforestation BMPs

The only rule covering a reforestation activity relevant to deep-seated failure is Broadcast Slash Burning, 222-30-100. Slash burning could potentially affect evapotranspiration, but this effect has not been studied to our knowledge. The method described for testing the effectiveness of timber harvest BMPs (Section 5.3.2) should be used for this assessment.

5.4 SURFACE EROSION

Surface erosion in unmanaged forested watersheds is generally not widespread and is limited to sites where the soil is compacted or devegetated. In managed forests, such disturbed sites are more widespread and are created by logging roads, harvest units, and reforestation. These management categories are treated separately below. In addition, separate consideration is given to road construction, road use, and abandoned roads.

Because the period of erosion following logging or slash burning is typically short-lived, the objective in measuring erosion is to make field inspections at the appropriate times following each disturbance type and after or during the first storm period. Observations also need to be made on a subsequent occasion to evaluate the incidence of chronic erosion. For road surfaces, erosion is associated with road use patterns, and therefore observations need to be scheduled according to periods of use.

The strategy outlined below emphasizes mapping of disturbed areas and erosion processes with respect to their connection with streams, in combination with surrogate rates extrapolated from the published literature, or using published erosion-estimation techniques.

5.4.1 Testing Effectiveness of Logging Road BMPs

In accordance with the approach in Section 5.2.1, the term *logging roads* includes landings, rock quarries, borrow pits, and spoil disposal areas. The forest practice rules that apply to erosion of logging roads are included within Chapter 222-24, Road Construction and Maintenance. Rules relevant to road erosion include Road Location, 222-24-020 (2)(3)(4); Road Design, 222-24-025 (5)(6)(7)(8)(9); Road Construction, 222-24-030 (4)(5)(6)(7)(8)(9); Landing Location and Construction, 222-24-035 (1); Water Crossing Structures, 222-24-040 (1)(2)(3)(4); Road Maintenance 222-24-050 (1)(2)(3)(4)(5); Rock Quarries, Gravel Pits, Borrow Pits, and Spoil Disposal Areas, 222-24-060 (1)(2)(3)(6); Harvest Unit Planning and Design, 222-30-020 (2); and Landing Cleanup, 222-30-080 (1)(2).

5.4.1.1 Site Stratification

For erosion processes described earlier, sampling is stratified according to the following variables.

Physiographic Region

Physiographic regions are described in Section 5.2.1.1.

Geology

Road segments sampled within each physiographic region should reflect the range of geologic materials within the region. The categories selected will vary with the individual region but should be grouped into two or three inclusive categories according to erodibility as indicated by soil surveys published by the State, federal government, and private industry.

Hillslope Gradient

Sampled road segments should reflect both the hillslope gradient and the slope position. Slope steepness should be grouped into approximately three categories by gradient. Road position categories should include mid-slope, ridge, and valley.

Land Management

Management activity categories should include the following three main headings with subgroupings indicated for each:

(1) Roads under construction.

Sampled road construction sites should consider proximity to streams, fill-slope length, erosion prevention practices employed (e.g., mulching, filter windrows, etc.), and construction equipment and practices used.

(2) Active haul roads and roads temporarily not in use but not abandoned.

Sampled roads should be stratified by grade, amount and type of traffic, road prism characteristics such as surface condition and type, and relief culvert location and spacing.

(3) Abandoned roads.

These roads should be chosen to reflect the distribution of length of time since abandonment and grouped into three categories. Length of time will be established by the number of years since policies regarding road abandonment were first initiated.

5.4.1.2 Measurement of Erosion and Timing

Measurement strategies differ for the three main management categories. Roads under construction should be visited during the first major period of storms following or during construction or soon after the storms. For each sampled road, the number and length of road segments that contribute water and sediment runoff to a stream should be measured. Roads in use should be visited during the use period. The time of visit for abandoned roads is less important, but as with roads in use and under construction, observation during or soon after major storm events provides the most information.

For the purpose of determining the effectiveness of BMPs, approximate erosion rates are adequate and can be estimated with a semi-quantitative field index of erosion severity. Index categories will need to be derived by the individual field worker or workers but should be consistent throughout the study. About three categories would be defined by field evidence for erosion severity. For example, criteria to be considered could include number and cross sectional area of rills, approximate depth of sheetwash erosion as indicated by stone pedestals or vegetation, and extent of armoring. Such a rating must be constructed by an experienced geomorphologist or hydrologist.

If a more quantitative measure is needed for evaluation of rule effectiveness, one of the following methods can be used:

(1) The Universal Soil Loss Equation. Description of this tool is beyond the scope of this study; an introduction to the theory and application can be found in Dunne and Leopold (1978).

(2) Extrapolation from measured rates of erosion quoted in published studies (see Section 2.0, Literature Review).

(3) Sampling of water and sediment runoff from road segments. This approach is described by Bilby et al. (1989) and Reid and Dunne (1984).

The method chosen will depend on the precision needed to test the rule; this point will be addressed again in Section 5.4.1.5.

Application of these methods would require personnel with some expertise in hydrology or geomorphology to describe a detailed field protocol. Field evaluations could be carried out by persons versed in the fundamentals of hydrology or geomorphology but without expertise in hydrology.

5.4.1.3 Sample Size

No sample size can be defined because the test of rule effectiveness is dependent on the parameters measured. For example, if the test is based on the presence of surface erosion, all roads within the area of concern should be examined. If the test is based on the severity of erosion, a statistical sample size would have to be determined from a sample set of measurements using standard statistical procedures (Gilbert, 1987).

5.4.1.4 Analysis of Storm History

Construction sites should be visited following or during a storm season for visual observation of erosion. The storm history should be determined for road segments in use and for abandoned roads, as described in Section 5.2.1.4.

5.4.1.5 Testing the Effectiveness of Forest Practice Rules

Surface erosion produces mostly fine sediments, the fate of which varies tremendously in the stream system according to the individual watershed and the location of the road within the watershed. It is beyond the scope of this document to determine a method for routing eroded sediment downstream and to evaluate stream impacts. The approach described above can determine whether and approximately how much sediment is entering a stream.

If rule effectiveness must be tied to downstream impacts, it is possible to evaluate the total sediment loading in a watershed through a synthetic budget of the influx of road-surface-generated sediment to streams. Such an approach was taken by Reid (1981; Reid et al., 1981) and involves determining the number and length of road segments of different management categories in a watershed and applying erosion rates measured or extrapolated from elsewhere to determine a total road-erosion rate for the watershed. Such an approach should be undertaken as part of a program to determine the sediment influx rates from all sediment sources in a watershed and to route the eroded sediment through the stream system.

5.4.2 Testing Effectiveness of Timber Harvest BMPs

Rules aimed at limiting erosion from timber harvest are focused on 1) logging practices near streams, 2) methods to mitigate the disturbance of soil on slopes by skid trails and cable yarding practices. These rules are Harvest Unit Planning and Design, 222-30-020 (4)(5)(6); Stream-bank Integrity, 222-30-030; Felling and Bucking, 222-30-050 (1)(2)(3); Cable Yarding, 222-30-060 (1)(2)(3)(4c); Tractor and Wheeled Skidding Systems, 222-30-070 (1)(2)(4)(6)(7)(8); and Slash Disposal, 222-30-100 (1c)(4)(5).

5.4.2.1 Site Stratification

Physiographic Region

Physiographic regions are described in Section 5.2.1.1.

Geology

Harvest units sampled within each physiographic region should reflect the range in geologic materials within the region. The categories selected will vary with the individual region but should be grouped into two or three inclusive categories according to erodibility as indicated by soil surveys published by the State, federal government, and private industry.

Hillslope Gradient

Units sampled should be grouped according to classes of hillslope gradient. The number of sites sampled should be proportional to the steepness of the unit.

Land Management

Clearcut and partial-cut units should be separately sampled, with the number of clearcut sites versus partial-cut sites reflecting the relative distribution of these sites throughout each physiographic region.

5.4.2.2 Measurement of Erosion and Timing

As described in Section 5.4.1.2, the extent and distribution of disturbed areas relative to streams should be mapped following logging and following or during the first major storm period. The map should include the disturbed area as well as rills or gullies that extend from it to a stream channel.

As described in Section 5.4.1.2, either a semi-quantitative rating of erosion severity or a quantitative estimate of erosion rate can be derived using the methods listed.

Because revegetation often proceeds rapidly, each site should be revisited and remapped after revegetation and following or during the first rainy season subsequent to significant revegetation. The second visit should take place one or two years following the first visit. A comparison of data between visits would lead to a determination of whether any of the previously noted erosion problems had remained as chronic sediment sources.

5.4.2.3 Sample Size

See Section 5.4.1.3.

5.4.2.4 Analysis of Storm History

See the above discussion on timing of field visits relative to the occurrence of storms. The magnitude of storms that occur during the period of the study should be described and taken into account in the analysis of results.

5.4.2.5 Testing the Effectiveness of Forest Practice Rules

See discussion for Section 5.4.1.5.

5.4.3 Testing Effectiveness of Reforestation BMPs

Reforestation activity regulations relevant to surface erosion include Slash Disposal, 222-30-100 (1c)(5), and Site Preparation and Rehabilitation, 222-34-040 (1)(2). Sampling and analysis should be done as described above in Section 5.4.2, but site stratification should include categories for broadcast and pile burning and for scarification.

5.4.4 Landslide Scars

At present, no BMPs address the control of erosion from landslide scars. In the event that a rule concerning landslide scars is added, a sampling strategy should be also added for evaluation. The sampling strategy could be combined with the strategies outlined above for road-related and harvest-unit-related landslides. The measurement strategy would be based on the approach outlined above for surface erosion of harvest units.

5.5 CHANNEL-BANK EROSION

The process of channel-bank erosion includes disturbance of channels by machinery and by timber felling and yarding. In addition, bank erosion includes disturbance or erosion of channels and valley walls by debris flows and dam-break floods, which are the most serious form of bank erosion, particularly in western Washington.

Detection of channel-bank erosion is based primarily on field surveys of areas recently disturbed by logging. Bank erosion in the area of interest is measured, and if significant and unambiguous erosion is observed, forest practice rules are considered to have failed. If bank erosion is not observed or measured, the rules are considered effective. Surveys of bank erosion should include all stream types (1 through 5). Only the forest practice of timber harvest applies to stream-bank erosion.

5.5.1 Testing Effectiveness of Timber Harvest BMPs

The forest practice rules pertaining to bank erosion include Channel Clearance, 222-24-030 (5); Stream-bank Integrity, 222-30-030; Cable Yarding, 222-30-060 (2-4); Skidding, 222-30-070 (2); Slash Disposal, 222-30-100 (1c); and Channel Alignment, 222-34-040.

5.5.1.1 Site Stratification

The same site stratification done for landslides (see Section 5.2.1.1) is done for bank erosion. In addition, sampling streams should be further stratified by stream type or, preferably, by stream order, and drainage area.

5.5.1.2 Measurement of Erosion

Personnel trained in geomorphology should determine whether accelerated erosion along channel banks is due to forestry activities. This is important because the analysis is based on field recognition and interpretation of the causes of erosion. Details on the determination of bank erosion are beyond the scope of this report.

The only form of bank erosion that can be identified from aerial photos is the scouring of first- and second-order channels from debris flows. Typically, debris flows obliterate the original stream channel, and erosion extends to the bedrock (or glacial sediment) of the valley walls. This is also true of dam-break floods in higher-order, lower-gradient channels. In these cases, erosional scars extend from valley wall to valley wall, and they are a source of accelerated erosion for years or even decades because of the absence of vegetation.

These forms of bank erosion can usually be traced upstream to a triggering landslide or debris flow. Testing the forest practice rules with respect to landslides and debris flows is discussed in a previous section. There are no forest practice rules that specifically address bank and valley-wall erosion following debris flows and dam-break floods. Therefore, this important erosion process must be considered in the context of landslides and debris flows, which are addressed in a previous test.

Bank erosion in all channels (including higher-order channels) will need to be identified by ground surveys. The length of bank disturbance can be measured by the method used for the TFW Ambient Monitoring Program (Ralph, 1990).

5.5.1.3 Sample Size and Time Period

There is no minimum or maximum sample size. The test of rule effectiveness is whether bank erosion occurred during or immediately after harvest activities. Observations of channel banks can be made in streams that traverse the harvest unit or units. All channels should be sampled within the harvest unit of interest.

The analysis time period for detecting bank erosion should be the first year or two after harvest. Bank and valley-wall erosion caused by debris flows and dam-break floods can be surveyed many years following the events because these areas tend to stabilize very slowly.

5.5.1.4 Analysis of Storm History

Analysis of storm history is important in the context of measuring bank erosion (particularly non-debris-flow erosion) and determining its cause or causes. Large-magnitude storms may accelerate natural bank erosion, and this erosion could be thought to come from forest management activities. A trained geomorphologist should compare the management history and the storm history and interpret the causes of any detected erosion processes.

5.5.1.5 Testing the Effectiveness of the Forest Practice Rules

Determination of rule effectiveness is based on the presence or absence of bank erosion in the area of interest. Often channels in harvested areas can be compared to those in adjacent, unmanaged forests to aid in detecting erosion due to land use. Significant bank erosion caused by mechanical disturbance indicates that rules are ineffective. Conversely, the absence of erosion indicates rule effectiveness.

5.5.1.6 Interpreting Erosion Significance

Erosion of banks and valley walls from debris flows and dam-break floods is the most intense, and therefore significant, bank erosion found in forested watersheds in western Washington. The number and length of channels so affected indicates erosion significance; the occurrence of many debris flows and dam-break floods indicates that chronic bank and valley-wall erosion will persist for many years and may have a large environmental impact.

Determination of the significance of bank erosion caused by mechanical disturbance within timber harvest units is based on the number of channels affected and the magnitude of the erosion problem. A single eroding channel is probably not significant, whereas numerous eroding channels concentrated in a relatively small area may be a significant source of sediment entry into streams.

As stated previously, the interpretation of channel-bank erosion significance should be based on comparison with all other sources of erosion such as landslides, debris flows, slump-earthflows, and surface erosion. This can best be accomplished through a sediment budget, which is one of the key components in the CMER proposed watershed analyses.

5.6 DISCUSSION OF METHODS AND RECOMMENDATIONS FOR IMPLEMENTATION

The methods discussed above do not provide a "cookbook" approach to a water quality study. Instead, they provide guidance with methodologies for the measurement of each of the four generalized erosion processes used in this report.

It is intended, however, that a water quality study plan be developed from the information presented within this document. The plan must be designed and implemented by skilled investigators in hydrology, geomorphology, and geotechnical engineering.

The study plan developed from this report will differ from the 1979 Washington State study primarily in that it will focus on erosion processes first and on the regulatory framework second. The 1979 study took the opposite approach. The biggest advantage to organizing a study around processes rather than regulations is that the sampling schedule and strategy is more likely to take into account the different rates and controlling variables of individual erosion processes. The Literature Review (Section 2.0) suggests that erosion in managed forests is many times greater than in unmanaged forests. Keying on each erosion process separately should bring into focus the forest practices and BMPs responsible for this accelerated erosion.

A second advantage to concentrating first on erosion processes and second on the regulatory framework is that a field study carried out with this approach is more likely to reveal whether the BMPs fail to address any forestry-induced erosion mechanisms. An example of such an overlooked mechanism is landslides triggered by road runoff; another example is the erosion of landslide scars.

The approach outlined in this report also differs from that in the 1979 study in that it is a more quantitative method for evaluating sediment influx. It should be possible to design and carry out a study that will give quantitative measures of sediment influx from each of the erosion process categories.

The link between sediment influx and channel conditions remains elusive, however. The BMPs' effectiveness in maintaining water quality cannot be evaluated until this connection is made. For this reason, it is recommended that the study be carried out at a watershed scale and include an evaluation of the complete sediment budget. The results should couple hillslope erosion and channel response. The watershed analysis concept now under discussion by the TFW would be an excellent vehicle for incorporating such an approach to a BMP water quality study.

At present, there is insufficient comparative information on erosion and beneficial uses across the State of Washington to justify ranking regions according to overall severity of sedimentation. Clearly, erosion rates are higher to the west of the Cascade Crest than to the east, but there is not sufficient information to determine whether forestry-induced erosion accounts for a proportionately larger or smaller component of total erosion in one part of the State than another, nor is there a survey of beneficial uses that can be used to rank regions.

Some generalizations can be made about the relative importance of different sediment sources, both within and among regions. The few sediment budget studies available for western Washington and similar regions of Oregon and British Columbia (Roberts and Church, 1986; Reid et al., 1981; Eide, 1990; Swanson et al., 1982) indicate that road-related landsliding dominates sediment production and that road surface erosion is also locally important. Deep-seated failures, though poorly documented, are locally important sediment sources.

Studies of erosion on the east side of the State are few, and no sediment budgets have been carried out to our knowledge. The sediment budget created for the Idaho Batholith by Megahan et al. (1982; 1986) has some relevance to the east side of the State, as indicated earlier, because climate and geology in that region is similar to that in the northeast Cascades and Okanogan Highlands-Washington Rockies region. Surface erosion from roads and harvest units dominated erosion in the Idaho study.

Managers' perceptions about sediment problems in different regions of the State are summarized in McDonald and Ritland (1989). These perceptions are consistent with the sediment budget studies summarized above but are too sketchy to provide a basis for generalization.

An additional advantage of conducting a water quality study in conjunction with a method such as watershed analysis is that such a basin-scale approach would begin to generate much-needed information on the relative importance of different erosion processes across the State. Information generated from the initial basins studied could help shape the direction of the water quality study.

Finally, field study planning must provide for two potentially confounding variables. One is BMP noncompliance. In the 1979 study, compliance with some BMPs was so low that effectiveness could not be evaluated. The second complicating factor is the diversity of actual practices. Different managers in different regions have developed varied responses to some of the more general BMP rules, and the study plan will need to take these significant variances into account.

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