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Title: Landslide Occurrence in the Blue River Drainage, Oregon

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Rapid, shallow soil mass movements (landslides) are examined for a 6,000 ha managed forest area in the Oregon Western Cascades. Analysis of landslide occurrence considers the physical characteristics and frequency, the influence of clearcutting and road construction, and some resource impacts. Nonparametric statistical methods are employed to test the significance of the observed variations in landslide characteristics.

Landslide size and site characteristics appear highly consistent. Fifty-five to eighty percent of all landslide length, width, depth, area, and volume measurements fall within the lower 15% of their respective dimension ranges. Landslides occur most frequently at slope angles of 30° - 40°, in northern aspects (NW - NNE), and in smooth slope locations. Landslide occurrence does not vary significantly ($\alpha = 0.05$) with relative hillslope position.

Clearcutting and road construction appear to strongly affect landslide frequency and location. Landslides occur 24 and 253 times more frequently (relative to forest rate) in clearcut and road areas, respectively. Significant variation in landslide geomorphic setting

with land use suggests that clearcutting and road construction may increase the landslide susceptibility of hillslope nose and hollow locations. They do not influence landslide size, slope angle, slope aspect, or hillslope position.

Resource impacts from landslides are varied. Although on-site disruption is generally substantial, total ground area affected by landslides is small (approximately 0.5%). Roads stand out as an important resource consideration because landslide frequency and the number of stream entries by landslides are significantly higher for road-related failures. Road location, drainage, and fill slope construction methods are the probable causes of this accelerated landslide activity.

Landslide Occurrence in the Blue River Drainage, Oregon

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LANDSLIDE OCCURRENCE IN THE BLUE RIVER DRAINAGE, OREGON

I. INTRODUCTION

"Landslide" is a general term used in this paper to describe rapid, shallow soil mass movements. Such mass movements have been classified elsewhere as slumps, debris slides, and debris avalanches (Varnes, 1978). Landslide events occur when the factors of geology, weathering, water content, slope angle, and internal cohesion are such that shear strength can no longer withstand shear stress. The resulting failure produces a distinctive spoon shaped scar and an area of displaced slope material below.

Landslides are a common phenomena in the managed forests of the Western Cascades and deserve attention for several reasons. As a mass wasting process, they shape the landscape by transporting weathered material downslope. As a natural hazard, they pose a threat to human life and property. Landslides also possess a high potential for natural resource degradation through the removal of soil, the destruction of vegetation, and the deposition of sediment. Therefore, an understanding of the characteristics of landslide occurrence will help to explain the role of landslides in landscape development, and to identify areas which require special management procedures.

Landslides in mountainous forests can also be affected by human action. Past research has indicated that timber harvest activities, specifically road construction and clearcutting, can influence the characteristics of landslide occurrence (Dyrness, 1967; Fredriksen, 1970; Morrison, 1975; Swanston and Swanson, 1976; Megahan, Day and Bliss, 1978; Gresswell et al., 1979; and others). Road construction and clearcutting can disrupt the balance of forces acting on an undisturbed, forested hillslope. One of three situations will result from these harvest activities: the disruption will be sufficient to allow failure to occur; the disruption will be insufficient to allow failure to occur; or failure may occur regardless of the disruption due to the natural instability present. Thus, a fundamental problem in assessing the effect of road construction and clearcutting is establishing when these activities are responsible for landslide occurrence.

This study was conducted to gain an increased understanding of landslide occurrence in a forest area managed primarily for timber production. The Blue River Drainage in the Willamette National Forest (WNF) is such an area. The objectives of this study are to: (1) examine the physical characteristics and frequency of landslide occurrence; (2) assess the relationships between road construction, clearcutting, and landslide occurrence; and (3) examine some characteristics of resource impacts resulting from landslide occurrence.

II. LITERATURE REVIEW

Past work on mass wasting theory and landslide occurrence in the mountainous forests of North America, especially the Oregon Western Cascades, is summarized below. Most of the research has been done in the last ten years. Many workers have investigated the relationship between road construction, clearcutting, and landslide occurrence. However, few statistical techniques have been employed to verify the observed associations and few attempts have been made to identify those topographic forms or geomorphic settings most prone to landslide failure. In general, the analysis of resource impacts has rarely extended beyond the descriptive level.

General Mass Wasting Theory

General mass wasting theory focuses on the physical processes involved in mass movements. Early descriptive studies by Ladd (1935) and Sharpe (1938) attempt to determine process from analysis of landslide form. Ward (1945), Skempton (1945), and Terzaghi (1950) are credited with developing the fundamental theories in mass wasting dynamics (Carson and Kirkby, 1972). Recent efforts include a comprehensive treatment of slope development models (Carson and Kirkby, 1972) and a "state of the art" review of recognition, classification, and analysis techniques (Transportation Research Board, 1978). In addition, morphometric techniques developed by Crozier (1973) promise more accurate diagnosis of post failure evidence to determine the processes involved. However, the usefulness of Crozier's methods have yet to be established in a mountainous forest situation.

North American Forests (excluding the Oregon Western Cascades)

Landslide research in several steepland forests has revealed a similarity in landslide failure situations and mechanisms. In Virginia, Hack and Goodlett (1960) were among the first to recognize the association between landslide occurrence and geomorphic setting, taking a step beyond simple correlation to geology or slope angle. Their observation that most failures occur within topographic hollows has been supported by recent work in the Oregon Coast Range by Dietrich and Dunne (1978).[1] The latter authors emphasize the significance of hollows as sediment production areas. Other workers have focused on the mechanisms of failure, particularly the role of vegetation roots in maintaining slope stability. The work of Swanston (1969, 1970), Ziemer and Swanston (1977), and Wu and Swanston (1980) in Southeastern Alaska demonstrates the decline in measured root strength and the rise in piezometric levels which occur after clearcutting. Both conditions increase the probability of failure occurrence.

Numerous studies have considered the influence of road construction and clearcutting on landslide occurrence in several different areas. Bishop and Stevens (1964) were among the first to observe an increase in debris avalanche occurrence after clearcutting in South-

[1] The two studies differ somewhat in which hillslope forms they classify as "hollow". Both studies include those forms which occur at the heads of streams and are represented by concave contours on a topographic map. However, Dietrich and Dunne also consider bedrock depressions as hollows. These depressions often lack topographic expression but function in the same manner as topographic hollows. Both forms are areas of subsurface water and slope debris accumulation.

eastern Alaska. Subsequent research efforts in the Idaho Batholith (Gonsior and Gardner, 1971; Megahan et al., 1978), British Columbia (O'Loughlin, 1972), Washington (Fiksdal, 1974), and the Oregon Coast Range (Swanson et al., 1977; Ketcheson, 1978; Gresswell et al., 1979) have all recognized notable increases in landslide occurrence following road construction and vegetation removal. Swanston and Swanson (1976) observe that despite a wide variety of geologic and geomorphic settings and harvest activities, landslides are fairly consistent in terms of size and correlation to storm events. However, the relative influence of road construction and clearcutting on landslide frequency is much more variable.

The impact of landslides on both natural and developed resources has been observed frequently but rarely quantified. Hack and Goodlett (1960) note vegetation disruption and gully formation within slide scars. Flaccus (1959) and O'Loughlin (1972) make similar observations as to the slow recovery of vegetation within landslide scars. Using a different time perspective, Moss and Rosenfeld (1978) suggest that random disturbance of vegetation communities by mass wasting events may help to promote long term community stability by maintaining ecological diversity. Impact to developed resources is addressed within Megahan et al. (1978). This work analyzes landslide occurrence for different road classes and components, and documents the cost of road repairs over the three-year study period.

Oregon Western Cascades

Landslide research has been most intensive in the forests of the

Oregon Western Cascades. Results of these studies have supported findings elsewhere. Geologic units especially susceptible to landslide occurrence have been identified, most notably volcaniclastics and the soils derived from them (Dyrness, 1967; Swanson and James, 1975; Swanson and Dyrness, 1975; Shulz, 1980). The influence of road construction and clearcutting has been addressed repeatedly (Fredriksen, 1970; Morrison, 1975; other works cited immediately above). Results show that landslide activity generally increases after road construction and clearcutting, but the average volume per event within both areas is generally smaller than the average for undisturbed forest events.

Only Morrison (1975) has looked closely at the effect of landslides on natural resources in this area. From an examination of vegetation within slide scars of various ages, Morrison concludes that conifer growth rates are consistently and substantially reduced. However, confidence in the generality of this observation is limited by the small sample size Morrison considered.

III. STUDY AREA DESCRIPTION AND METHODOLOGY

Location

The area designated in this study as the Blue River Drainage (BRD) lies at the eastern edge of the Western Cascades, approximately 80 km east northeast of Eugene, Oregon. Its 6166 ha area is contained within the northern half of the Blue River Ranger District. The study area encompasses all of Tidbits, Mona, and Ore Creek watersheds, and Blue River watershed between Blue River Lake and Wolf Meadow (see Figure 1). It is bordered on the south and east by the H. J. Andrews Experimental Forest (HJA); on the northwest by the Sweet Home Ranger District; and on the north and northeast by Cook, Quentin, and Mann Creek drainages.

Climate

The maritime climate of the Western Cascades is marked by mild temperatures and high annual precipitation. Mean monthly temperature extremes for the BRD range between -5.0°C and 27.0°C (Franklin and Dyrness, 1973). Precipitation results primarily from eastward moving cyclonic storms and averages 2304 mm annually (calculated from HJA climatological data, 1952 - 1980). Approximately 75% to 85% of this amount falls between October 1 and March 31 (Franklin and Dyrness, 1973). Frequently rainfall occurs in intense bursts, with maximum 6-hour intensities of 56-66 mm occurring approximately once every ten years (determined from SCS, 1971). Although snow accounts for only 10% of the total annual precipitation in the BRD (calculated from

Lahey, 1973), its presence during rain storm (ie., rain-on-snow occurrences) can greatly affect peak flow amounts. During most of the year, winds are from the southwest in the BRD; however, eastern winds are common during summer months (Lahey, 1973).

Geology

Peck et al. (1964) distinguish three major stratigraphic units within the BRD (Figure 2). The Little Butte Series is the oldest and covers the greatest area. Rock types within this series include basaltic flows, mud and ash flows, breccias, and tuffs of upper-Oligocene to lower-Miocene age. Overlying the Little Butte Series is the Sardine Formation of middle- to upper-Miocene age. This younger formation consists of ash flows, tuffs, breccias, andesitic and basaltic flows which form the major ridges surrounding Tidbits, Ore, and Mona Creeks. The High Cascade Volcanics, or "Pliocascade" volcanic rocks, overlie the Sardine Formation and are the youngest unit present. Andesitic and basaltic lava flows and breccia of Pliocene age make up this unit which occurs along the eastern border of the BRD.[2] Intrusive rocks are exposed below the confluence of Tidbits Creek and Blue River, and along the middle reach of Tidbits Creek (see Figure 2). Swanson and James (1975) classify the former outcrops as ranging from basaltic to rhyolite, whereas Peck et al. (1964) consider the latter granodiorite.

Close proximity to known volcanic vents and the presence of

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[2]Swanson and James (1975) credit Dr. E.M. Taylor of Oregon State University with the designation of "Pliocascade" for the rock unit overlying the Sardine Formation.

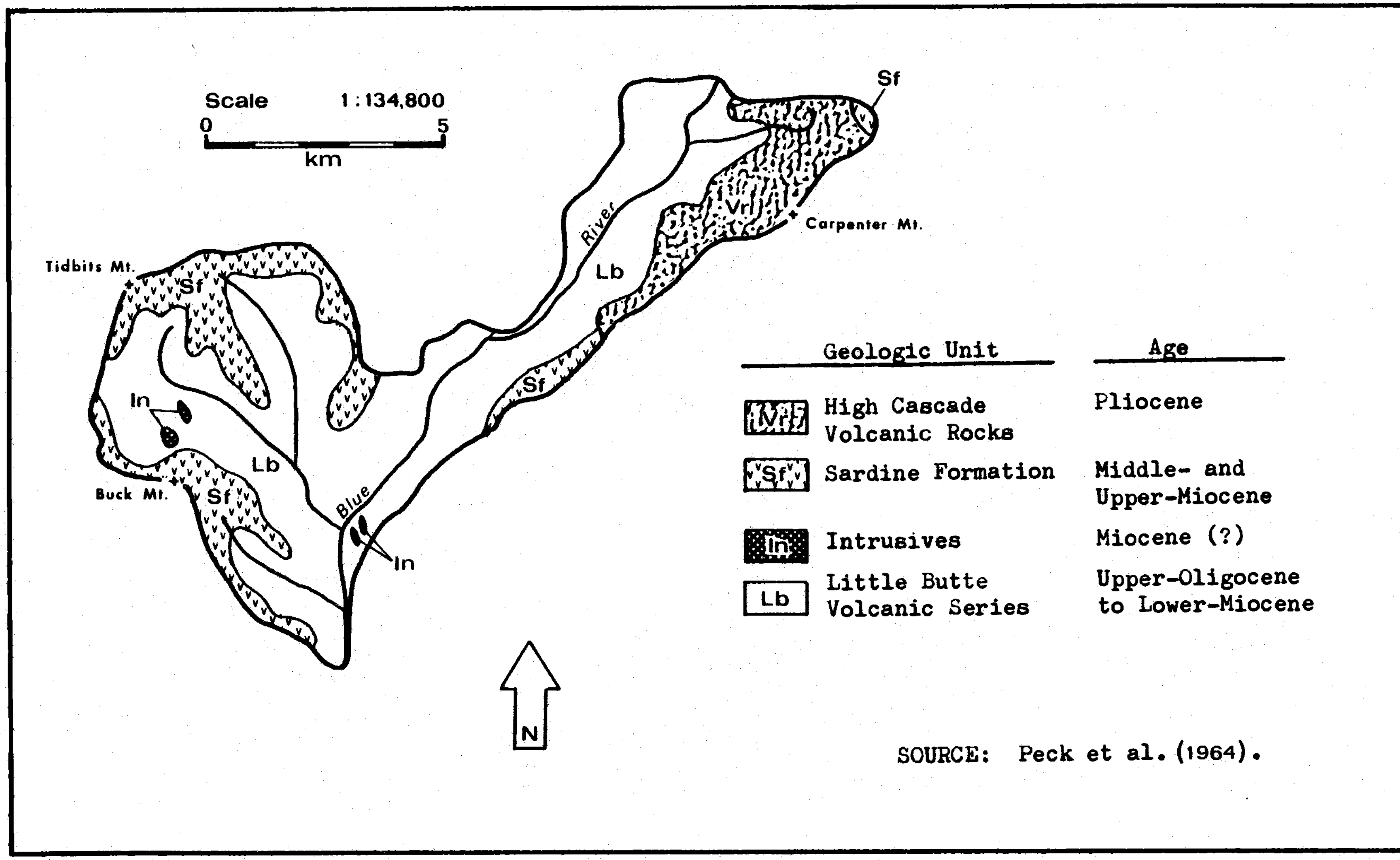

Figure 2. Geology of the Blue River Drainage

intrusive bodies strongly suggests that the volcanic rocks of the BRD have been altered, in some cases repeatedly. Peck et al. (1964) state that most volcaniclastic rocks of the Western Cascades have been thoroughly altered, especially those of Miocene age or older. The work of Dyrness (1967) and Paeth et al. (1971) suggests that these altered volcaniclastic rocks weather quickly and produce unstable soils.

Geomorphology

The landscape of the BRD is for the most part composed of erosional landforms with rugged relief. Elevations range from 413.6 m (1357 ft) at Blue River Lake to 1630.3 m (5349 ft) on Carpenter Mountain (Figure 1).[3] Slopes are steep with average gradients between 25° and 30°. Convex slope profiles are predominant, and footslopes are lacking except along the upper reaches of Blue River. Slope aspects are asymmetrically distributed with southwestern (SSW, SW, and WSW) and northwestern (WNW, NW, and NNW) aspects occurring over 46% of the study area (Table 1). Although soil properties vary widely within the BRD, soils are generally brownish, gravelly to clay loams, with rapid permeability.[4]

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[3] The mixing of English and Metric units is unavoidable. Figure 1 was compiled from sources using English units and conversion to metric units was impracticable. Therefore, to prevent confusion in references to elevations in Figure 1, English units are used.

[4] This observation is based on a summarization of soil characteristics contained in Legard and Meyer (1973, Table of Soil Characteristics of Modal Sites, n.p.) for principal soil-landtype associations in the BRD.

Table 1. Areal Coverage of Slope Aspects for the Blue River Drainage

Aspect Class[a]	Areal Coverage (%)
N	4.3
NNE	4.3
NE	2.9
ENE	7.1
E	4.3
ESE	4.3
SE	10.0
SSE	2.9
S	7.1
SSW	7.1
SW	14.3
WSW	2.9
W	5.7
WNW	1.4
NW	14.3
NNW	7.1

NOTE: Areal coverage was determined by a random sample of 75 slope aspects from a map similar to Figure 1. This sample size insures a 95% chance that the actual slope aspect distribution will be contained within a confidence interval of ± 15.7% (Dixon and Massey, 1969, p. 346).

[a]Each aspect class covers a range of 22.5° centered on the respective compass point bearing (e.g., N = 0.0°, E = 90.0°).

The present form of the BRD is primarily a product of stream dissection, mass movements and past glaciation. Mass movement terrain is apparent in several places along Blue River, and active deep-seated slumps are shown on Figure 1. Pleistocene glaciation is evident from cirque features on the northern flanks of Carpenter, Buck, and Tidbits Mountains and scattered till deposits observed above Blue River. These deposits all occur above 730 m, which is in agreement with Swanson and James' (1975) findings for pre-latest Wisconsin glaciation in the HJA.

Presently all streams are actively downcutting. A general dendritic drainage pattern is apparent, though Blue River shows indications of structural control. Though overland flow is rare, streams respond quickly to precipitation (Harr, 1976). Rain-on-snow occurrences are not rare (Harr, in press), and increase streamflow response to a given size precipitation event. Harr (in press) finds that most of the larger peak flows in a 60 ha watershed within the nearby HJA result from rain-on-snow occurrences. Furthermore, he concludes that rain-on-snow peak flows of a given magnitude have shorter return periods than equivalent peak flows resulting from rainfall alone. Rain-on-snow events have often been associated with increased landslide occurrence in the Western Cascades (Fredriksen, 1963, 1965; Dyrness, 1967; Harr, in press).

Vegetation

The BRD lies primarily within the Tsuga heterophylla Vegetation Zone, but above 1000 meters forest vegetation is more closely associated with the *Abies amabilis* Zone.[5] Dominant species of the former are Douglas fir (*Pseudotsuga menziesii*), western hemlock (*T. heterophylla*), and western red cedar (*Thuja plicata*) with red alder (*Alnus rubra*) and bigleaf maple (*Acer macrophyllum*) occurring within riparian zones or disturbed sites. Major understory species include giant chinquapin (*Castanopsis chrysophylla*), vine maple (*Acer circinatum*), salal (*Gaultheria shallon*), Oregon-grape (*Berberis nervosa*), bracken fern (*Pteridium aquilinum*), and swordfern (*Polystichum munitum*). Pacific silver fir (*A. amabilis*), noble fir (*Abies procera*), and occassional western white pine (*Pinus monticola*) occur along with the above species in the *Abies amabilis* Zone.

Forest cover within the BRD is typically dense, uneven age stands, 75 to over 500 years old (F. Swanson, per comm.). Past wildfires have influenced the age and composition of the forest, but today wildfire occurrence is strongly suppressed. Exposed soil is rare except along unstable stream channels or where the vegetation is disturbed by mass wasting or blowdown.

Management History

Prior to 1946, the BRD was essentially undisturbed. Road construction first began around 1955 along the lower end of Blue River. Between 1955 to 1967 an average of 5.4 km of road were built each year; from 1968 to 1979 the average was 3.4 km. Figure 3 shows the cumulative trends in road construction and clearcutting since that

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[5]Based on Franklin and Dyrness's (1973) classification of natural vegetation communities for Oregon and Washington. Scientific and common names also follow Franklin and Dyrness (p. 352-376).

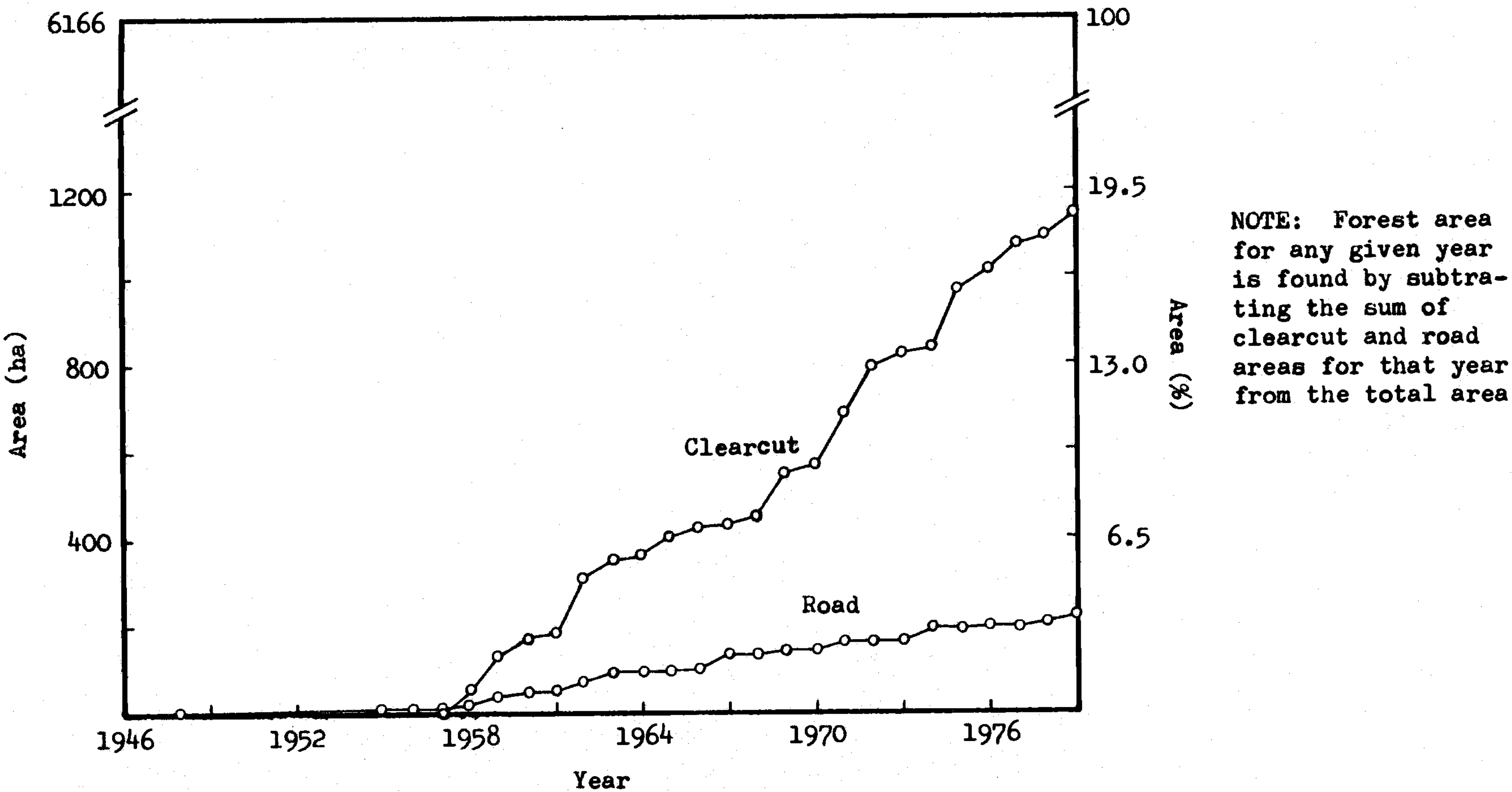

Figure 3. Areas Associated with Forest, Clearcut, and Road Right-of-ways in the Blue River Drainage during the Period 1946 - 1979

time. Road construction techniques have varied with time and also vary in design standards. Cut-and-fill techniques were used extensively in the past, with fill slopes frequently being constructed over sidecast debris. Full-bench designs have been increasingly used to overcome the stability problems inherent in cut-and-fill designs.

Logging is accomplished primarily by clearcutting in the BRD, for both economic and silvicultural reasons (Franklin and Dyrness, 1973). Timber harvest began in 1958 along lower Blue River. From 1958 until 1967 approximately 7.9 ha were clearcut each year. After 1967 until 1979 the average has been 54.7 ha, a substantial increase. Skyline yarding systems are predominantly used; however, tractor yarding is employed on gentle slopes.

Methodology

Data gathering for this project included an air photo survey, a complete field inventory, and office compilation of supporting data. The compiled data were analyzed using the Oregon State University CYBER 70/73 computer and the Statistical Interactive Programming System (SIPS).

Air photos from flights in 1946, 1955, 1959, 1967, 1972, and 1974 were used to locate possible landslides and to determine the fate of the displaced slope material.[6] Comparison of successive air photo flights allowed maximum and minimum dates of occurrence to be extablished. For very large events, air photos were used to deter-

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[6] See Appendix I for air photo specifications

mine failure length and width when field measurements were not possible. Finally, air photos allowed preliminary assignments of geomorphic setting and land use association.

Land use association was determined for each landslide based on the location of the failure. Failures occurring within undisturbed forest areas were termed Forest events.[7] Those occurring within marked or inferred clearcut boundaries were termed Clearcut events. Road events were those which occurred within the road right-of-way, defined as extending 10 m on either side of the road centerline (this is consistent with past research, e.g., Swanson et al., 1977).

Field work included locating and verifying each failure identified by air photo interpretation, collecting data, and making final determinations of geomorphic setting and land use association. Only failures equal to or greater than 100 m^3 were considered. Additional events of sufficient size which were encountered in the field were also inventoried. Numerous transects were conducted through large forest areas to insure adequate forest coverage. This work was accomplished during the summers of 1979 and 1980.

The sample data sheet included in Appendix II demonstrates the type of information collected. Measurements were taken using the instruments listed in Table 2. Dendrochronological dating was done using a 5 mm in diameter increment borer and occassionally a small saw. Vegetation density was estimated visually to the nearest 20%.

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[7]A few Forest events are located in areas which have been thinned or partially disturbed. In every case, failure occurred before any harvest activity took place.

Table 2. Field Instrument Measurements used for Landslide Data Collection in the Blue River Study Area

Measurement Taken	Instrument	Accuracy
length, width of failure	tape measure	nearest 0.5 m
length, width of failure	Toko Duo-Sight range finder	nearest 1.0 m
slope aspect	Silva Compass	nearest 5°
slope angle	Suunto Clinometer	nearest 5°
% vegetation cover	visual estimate	nearest 20%
depth of failure	visual estimate	nearest 0.5 m

A 10X hand lens or 40X Tasco microscope was used for rock identification.

Complementary data included land use change dates, clearcut unit size, associated WNF Soil Resource Inventory (SRI) landtype, and stream and/or road class affected. This information was obtained from various sources provided by the WNF including: the Total Resource Inventory (TRI) system, the _Soil Resource Inventory Atlas of Maps and Interpretive Tables_ for the WNF (Legard and Meyer, 1973), and resource maps prepared by WNF personnel. Finally, a map of landslide location compiled by this author (Figure 1) was used to determine hillslope position based on a three part division of slope length (see Appendix III for method).

IV. CHARACTERISTICS OF LANDSLIDE OCCURRENCE IN THE BLUE RIVER DRAINAGE

Analysis Procedure

The purpose of this section is to examine landslide size and site characteristics, landslide timing, and frequency of occurrence for the BRD. A total of 118 events were inventoried in this study, covering a 34 year period of record. Location and land use association of each event are shown in Figure 1.

Landslides are divided into four groups. One group contains all 118 events found in the BRD. This is done so that data from this study may be compared to other studies. The remaining three groups separate landslides according to their land use association. Only variation within each sample group will be considered in this section. Variations between sample groups will be examined later.

Table 3 indicates the measurement scale of each size and site characteristic considered. One characteristic, slope aspect, is not easily classified. Though it may be defined as a continuous variable (Daniel, 1978) it does not meet the criteria necessary to be ordinal scale data (Stevens, 1946) because observations cannot be ranked relative to one another. Therefore, for this study, slope aspect is considered nominal data.

Size Characteristics

To characterize landslide size measurements were taken of average length, width, and depth for each failure. Estimates of the area and volume of displaced slope material were calculated from these average

Table 3. Measurement Scales for Landslide Data Collected in the Blue River Drainage

Measurement scale[a]	Characteristic measured
nominal	slope aspect (?), SRI, geomorphic setting, geology
ordinal	hillslope position
interval/ratio	all size measurements, slope angle

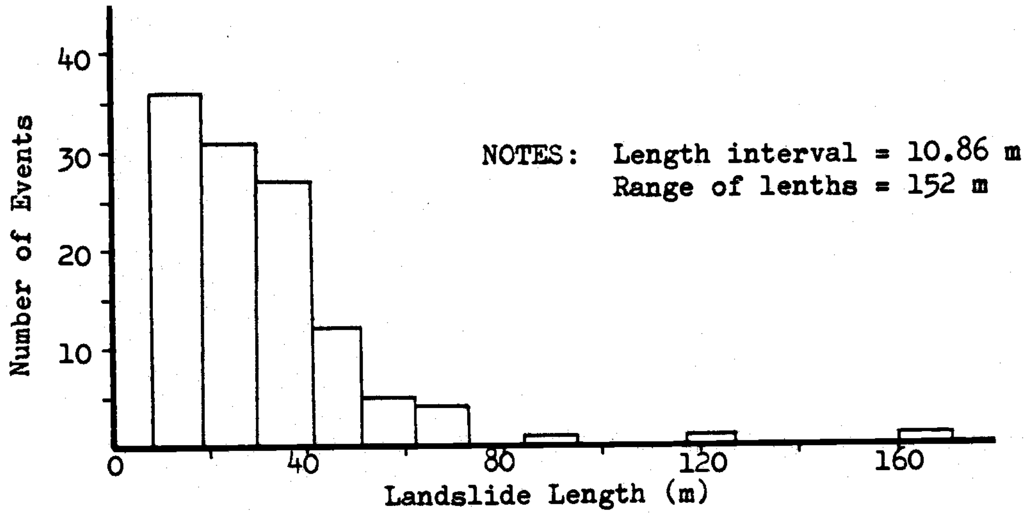
[a]Measurement scales follow Stevens (1946).

values. Average length was calculated from measurements along three or more parallel lines of sight in the direction of slope movement. Average width was determined in a similar manner from measurements orthogonal to length measurements. The average depth was estimated visually.

Landslide size characteristics are highly consistent in the BRD. All four landslide groups are very similar in their respective distributions of size parameters. The distribution of size characteristics for the All event sample group is shown in Figure 4, and generalizations made concerning its size distributions are applicable to the three land use groups.

Each size characteristic falls within a narrow band of values (Figure 4). Fifty-seven percent of all landslides have lengths between 8 m and 30 m. This represents only 14% of the overall range of landslide lengths. Similarly, 64% of landslide widths fall between 4 m and 20 m, again representing only 14% of the respective width range. Fifty-three percent of the BRD landslides are less than 1.25 m deep, an interval which covers 12% of the range. Landslide areas and volumes are even more closely grouped, with 67% and 80% of all events measuring from 76 m^2 to 515 m^2 and 100 m^3 to 1270 m^3, respectively. Both of these area and volume bands account for only 4% of their respective ranges.

It is also obvious from Figure 4 that landslide size characteristics are not normally distributed. The shape of the distributions for each size parameter is asymmetric. Skewness and kurtosis statistics (Table 4) for all event groups are much greater than zero, indi-



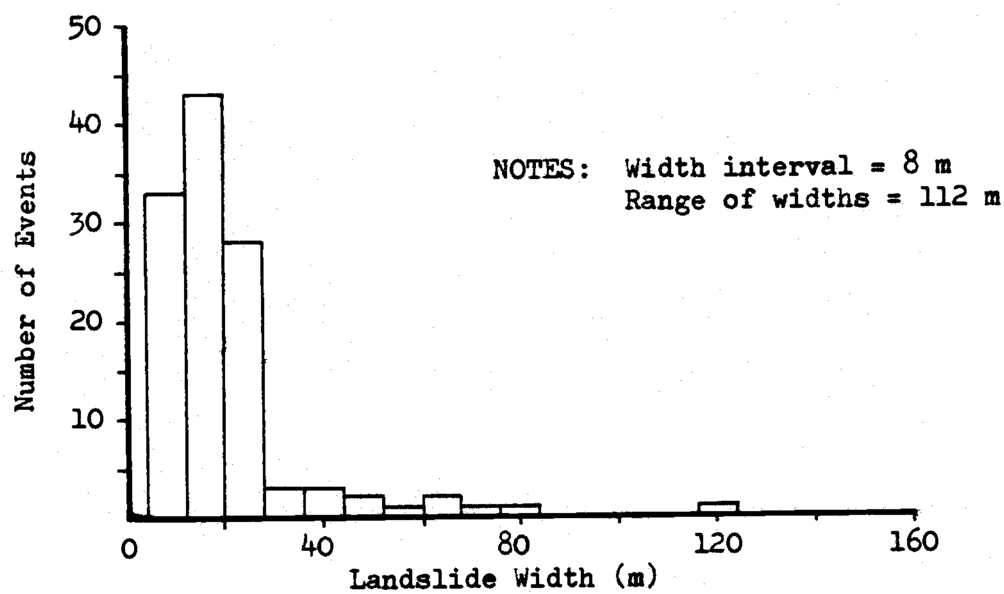
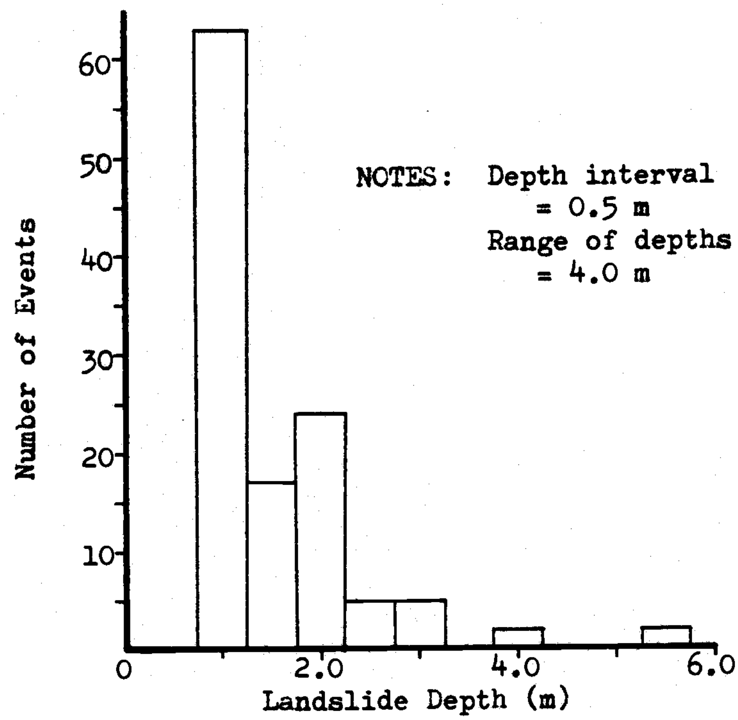


Figure 4. Frequency Distributions of Size Characteristics for All Landslides within the Blue River Drainage



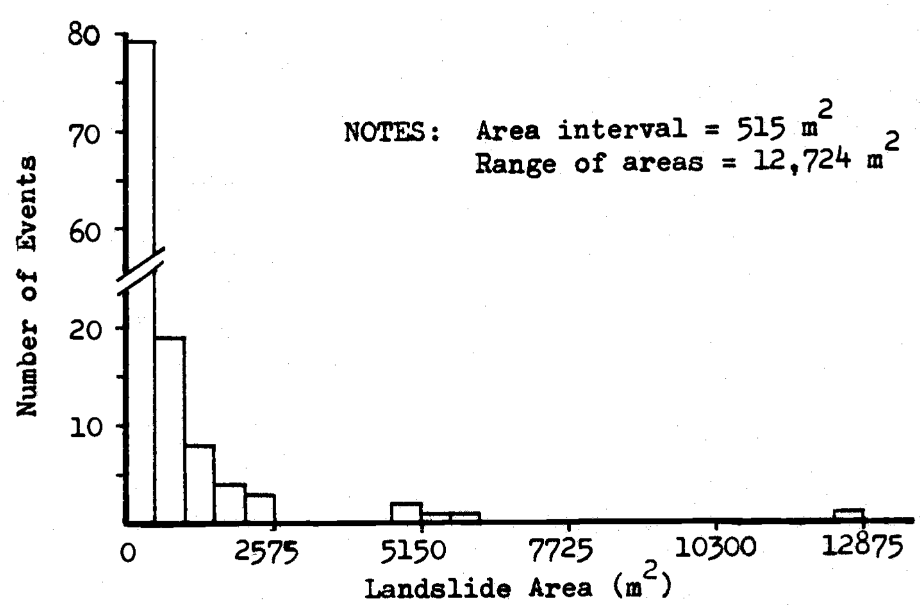


Figure 4. continued

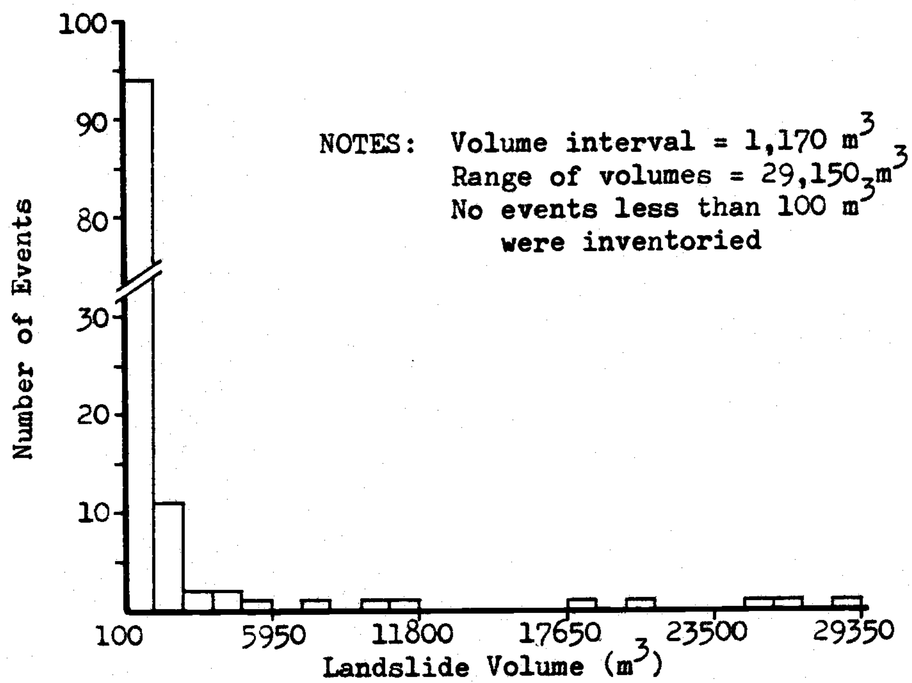


Figure 4. continued

Table 4. Descriptive Statistics for Size Characteristics of Landslides in the Blue River Drainage

Size characteristic	Statistic[a]	Units[b]	Landslide group: All	Forest	Clearcut	Road
	N	-	118	19	30	69
	mean	m	30.4	31.2	33.4	28.8
	maximum	m	160	160	117	70
Length	minimum	m	8	8	12	9.5
	st. dev.	m	21.1	34.3	22.2	15.4
	skewness	-	2.9	3.0	2.3	0.9
	kurtosis	-	15.8	11.7	8.5	3.0
	N	-	118	19	30	69
	mean	m	19.7	24.6	18.7	18.8
	maximum	m	116	116	62	73
Width	minimum	m	4	8	7	4
	st. dev.	m	16.1	27.6	13.3	12.6
	skewness	-	3.1	2.5	1.9	2.4
	kurtosis	-	15.5	8.0	6.0	9.9
	N	-	118	19	30	69
	mean	m	1.5	1.7	1.7	1.4
	maximum	m	5.0	4.0	5.0	3.0
Depth	minimum	m	1.0	1.0	1.0	1.0
	st. dev.	m	0.8	0.8	1.2	0.6
	skewness	-	2.1	1.1	1.8	1.13
	kurtosis	-	8.3	4.0	5.4	3.3
	N	-	118	19	30	69
	mean	m^2	780.8	1297.9	859.5	604.2
	maximum	m^2	12800	12800	5850	5110
Area	minimum	m^2	76	96	104	76
	st.dev.	m^2	1493.5	2997.5	1368.3	742.9
	skewness	-	5.4	3.3	2.9	3.8
	kurtosis	-	39.1	12.8	10.2	21.3
	N	-	118	19	30	69
	mean	m^3	1939.3	3114.7	2683.8	1291.9
	maximum	m^3	29250	25600	29250	26875
Volume	minimum	m^3	100	144	108	100
	st. dev.	m^3	5068.4	6996.3	6548.5	3449.4
	skewness	-	4.1	2.5	3.2	6.3
	kurtosis	-	19.4	7.7	12.0	45.8

[a]Abbreviations used: N = sample size; st. dev. = standard deviation.

[b]The symbol "-" indicates that units are not applicable.

cating a consistent displacement of observations to the left of the mean and a sharp peakedness to the distribution curves.[8] Mean values are consistently low relative to the respective range of each characteristic for all four sample groups. In a normal distribution the mean is roughly equal to one-half the range value. Even when extremely high observations are disregarded, the distribution of size characteristics do not resemble normal ones.

Three possible explanations for the observed size characteristics are: a measurement bias; restriction of size parameters due to topography; or the characteristic of the landslide failure mechanism. Since only those events greater than 100 m^3 were included, the bottom half of the distribution curves may have been excluded from measurement. Several failures smaller than 100 m^3 were observed. However, I feel that the number of such events would be insufficient to substantially change the distribution functions observed above.

Landslide dimensions may also be restricted by the topography in which failure occurs. Because BRD is highly dissected by streams, many events entered stream channels below the failure site. Size measurements taken under these circumstances only considered the hillslope part of the landslide area. Topographic benches and roadbeds can also act to reduce runout length by catching sliding debris from upslope failures. It is possible then, that frequent landslide occurrence within these areas of topographic restrictions could produce a preponderance of low observations for landslide length, area, and

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[8]Skewness and kurtosis statistics equal zero for normally distributed sample groups.

volume. However, such restrictions cannot explain the preponderance of low observations for landslide width and depth.

The observed size characteristics may possibly be explained by the mass wasting process being considered. The mechanism which produces landslide failure can only operate when shear stress is sufficient to overcome shear strength. Stress is partly dependent on the mass of the soil material involved. Assuming that the soil material fails as a unit or block, then the preponderance of events on the low end of the various distribution curves may indicate the dimensions of a soil block which occurs most frequently to produce landslide failure. Therefore, the distributions may reflect realistic characteristics of landslide size, and identify a geomorphic threshold above which landslide failure occurs readily.

Site Characteristics

The variation in site characteristics is discussed below. In each case, chi-square (X^2) goodness-of-fit tests are used to test the variations observed. Appendix IV contains the tabulated frequency distributions, X^2 test statistics, and degrees of freedom for all four landslide groups in each test. Unless otherwise noted, the null hypothesis (H_0) for all tests is that the site characteristic in question is drawn from a population with a uniform frequency distribution. The alternative hypothesis (H_a) is that the population frequency distribution is not uniform. Significance level is 0.05 for all tests.

Tests producing significant results are further evaluated to determine which values account for the greater part of the observed variation. Those values which are felt to be important are removed and the X^2 test repeated. This procedure continues until the X^2 test statistic falls below the $\alpha = 0.05$ level. It should be noted that this exclusion procedure is not a precise measurement technique, nor is it used for hypothesis testing. Rather, it is intended to better indicate which values are important in explaining the observed variation from a uniform distribution.

Slope angle. Slope angle was measured to approximate the general hillslope gradient before failure. Measurements were made facing downhill, in the direction of slope movement, and were recorded to the nearest 5° (e.g., 5°, 10°, 15°, etc.). Figure 5 shows the distribution of slope angles observed.

The slope angle at which failure occurs appears very consistent for the All, Clearcut, and Road event groups. Initial goodness-of-fit tests reveal that slope angles for these groups are not uniformly distributed. Exclusion of angles 40° and 35° produces a X^2 statistic for the Road events group which is insufficient to reject H_0. Removal of angles 40°, 35°, and 30° is necessary to produce nonsignificant X^2 statistics for the All and Clearcut groups.

In contrast to the three previous groups, the variation in the Forest event group is not sufficient to reject the null. Possibly the frequency of slope angles between 30° to 40° is less in the forested areas than in road or clearcut areas. It is more likely, however, that the relative importance of slope angle to failure occurrence is less in the forest than in road or clearcut areas.

Other research in the Western Cascades has also found slope

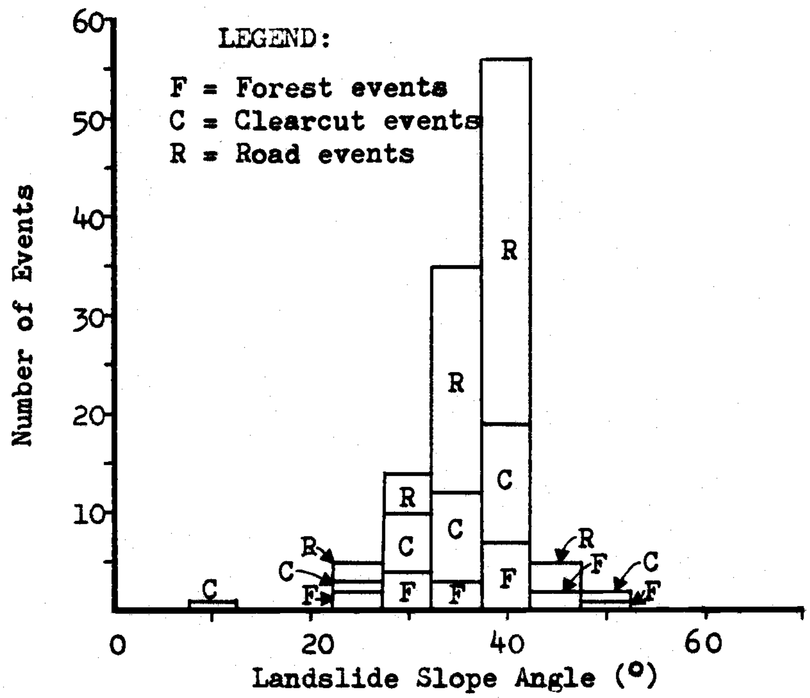

Figure 5. Landslide Occurrence by Slope Angle in the Blue River Drainage

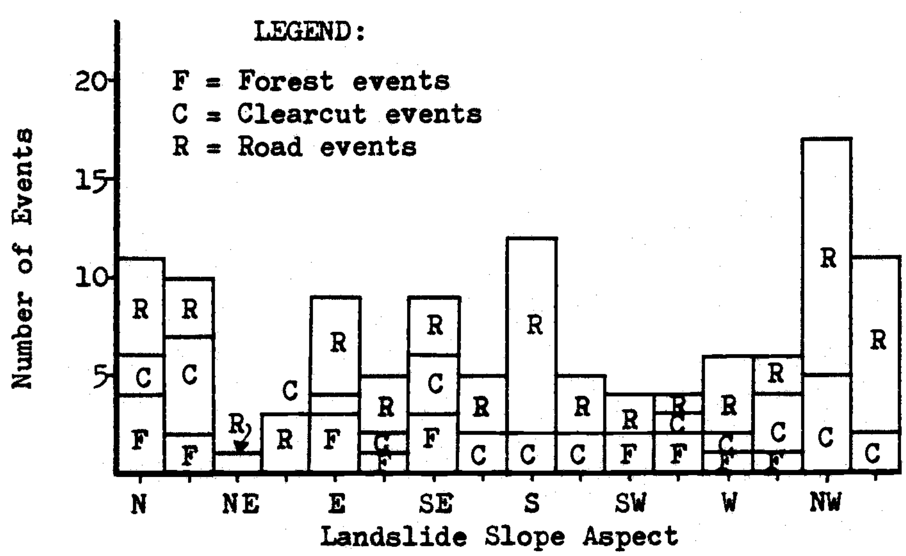

Figure 6. Landslide Occurrence by Slope Aspect in the Blue River Drainage

angles between 30° to 40° to be important in landslide occurrence. Table 5 compares BRD observations to those made at three other locations: the HJA, adjacent to the BRD; Alder Creek, approximately 37 km to the southwest; and Bull Run, 135 km to the north. Both the HJA and Alder Creek possess similar geomorphic environments and management histories. Values for the HJA may be lower than BRD and Alder Creek values due to differences in the compared slope angle ranges, and also because the HJA inventory only considered failures resulting from a single, very large storm.[9] Such a storm could have produced conditions which allowed failures to occur at lower than normal slope angles. The Bull Run area is somewhat different in geology and management history than the three areas above. However, the average slope angle for Bull Run landslides is comparable to those for the BRD and Alder Creek. It appears then that the slope angles at which landslides occur is fairly consistent throughout much of the Western Cascades.

Slope aspect. Slope aspect was determined by compass facing downhill. Bearings were recorded to the nearest 5°, and grouped into 16 aspect classes equivalent to the ones shown in Table 1. Each class covers a range of 22.5° (e.g., N = 348.75° - 11.25°) with North defined as 0.0°.

The distribution of slope aspects for all BRD landslides is significantly different from the aspect distribution of the entire study

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[9]This storm occurred between December 20 -24, 1964, and has generally been classified as a 50-year event (Dyrness, 1967).

Table 5. Comparison of Landslide Slope Angles for Selected Areas in the Western Cascades

Area	Period of record (yrs)	Slope angle	Mean slope angle (°)	% of Total Events Inventoried
Blue River Drainage (BRD)	34	30° - 40°	37	89
Alder Creek	25	27° - 42°	40	71
H. J. Andrews	15	31° - 42°	n/a	47
Bull Run	40	n/a	40	n/a

SOURCES : Alder Creek, WNF (Morrison, 1975); H. J. Andrews, WNF (Dyrness, 1967); Bull Run, Mt. Hood National Forest (Schultz, 1980).

NOTES: (1) Due to differences in measurement techniques, the inclusive endpoints of the slope angle ranges used above are not the same. However, the ranges used for comparison come as close to the BRD range as possible.
(2) n/a = data not available.

area (Table 1). The distribution of landslides by slope aspect class is shown in Figure 6. A X^2 goodness-of-fit test using expected probabilities derived from Table 1 results in rejection of the null hypothesis. The difference between the two distributions lies in their respective frequencies for particular aspects. The All event group has a large number of observations with northern aspects (NW, NNW, N, NNE) and in the South class, whereas the BRD does not show this preference.

Of the three land use groups, only the Road event group appears predisposed to certain slope aspects. Assuming a uniform expected frequency distribution for each landslide group, X^2 analysis shows that only the Road event group is sufficiently different to reject the null. Removal of those events with northern aspects produces a Road event X^2 statistic for slope aspect which is not significant at $\alpha = 0.05$. The frequent number of road-associated landslides in northern aspects also accounts for most observations recorded in the All landslide group for these aspects. Northern aspects may be more susceptible to disruption by road construction due to the higher water inputs and weathering rates which occur in these areas.

Aspect control in landslide occurrence has also been noted by Dyrness (1967) and Morrison (1975). Although differences in measurement techniques prevents direct comparisons between the BRD data and these works, both reveal higher landslide occurrence in northern aspects (NW - NE) than any other similar grouping of consecutive aspect classes. Both authors attribute this tendency to reduced weathering and shallower soils on southern aspects rather than to any special characteristics of northern aspects. However, their analyses only consider all events together. The further break down of events into land use association groups shows that only 32% of Forest events occur in northern aspects (NW, NNW, N, NE), whereas 47% and 42% of Clearcut and Road events occur in these aspects, respectively. This would seem to indicate some interaction between land use and northern aspects versus an explanation of increased failure resistance in southern aspects.

Hillslope position. The technique used to determine the hillslope position class of each landslide is described in Appendix III. This method removes subjectivity from this classification. The bar graph in Figure 7 shows the occurrence frequency for each class.

Hillslope position does not appear to affect landslide occurrence in the BRSA. A X^2 analysis of all sample groups shows there is insufficient variation present in any group to reject H_0.

SRI landtype. Legard and Meyer (1973) have mapped soil-landtype associations (SRI units) for the BRD as part of a reconnaissance level survey of the entire WNF. The SRI unit for each landslide was determined from the Legard and Meyer maps. Landslide frequency for all SRI units within the study area is shown in Table 6. The areal extent of each SRI unit was determined using the SRI maps and a sonic digitizer. Note that many units have experienced no landslide occurrences over the 34 years of record.

Landslide occurrence within each SRI landtype is not simply related to the areal extent of each landtype. Using the areas in Table 6 to calculate the expected occurrence probability, a X^2

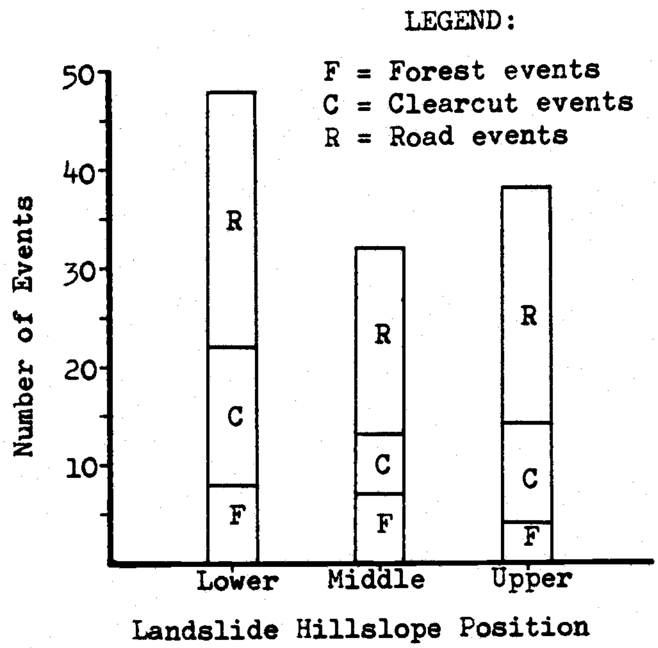

Figure 7. Landslide Occurrence by Hillslope Position in the Blue River Drainage

Table 6. Landslide Occurrence by SRI Landtype in the Blue River Drainage

SRI landtype[a]	Area (ha)[b]	Total number of landslides	Areal frequency (events · ha^{-1} of SRI)
1	27	0	-
2	13	0	-
3	314	1	0.003
6	22	0	-
8	384	15	0.039
13	345	3	0.009
14	57	1	0.018
15	89	0	-
16	296	2	0.007
21	302	36	0.119
23	161	6	0.037
25	30	0	-
33	18	0	-
44	31	0	-
61	17	1	0.059
132	90	1	0.011
168	204	10	0.049
201	743	4	0.005
202	26	0	-
203	581	8	0.014
210	561	3	0.005
212	245	12	0.049
231	267	8	0.030
233	25	0	-
235	351	2	0.006
310	264	0	-
313	239	3	0.013
441	257	0	-
610	79	1	0.013
614	12	0	-
646	6	0	-

[a]Legard and Meyer (1973) mapped SRI landtypes for the Blue River Drainage.

[b]Summation of the above areas does not equal the total area of the Blue River Drainage because a 5 ha area was not classified by Legard and Meyer and was therefore excluded from this analysis.

goodness-of-fit test of the All event group shows there is sufficient variation present to reject the null.

Certain SRI landtypes appear very susceptible to landslide occurrence after road construction and clearcutting. Chi-square analysis of the three land use groups reveals that the null hypothesis cannot be rejected for the Forest event group, but is rejected for both the Clearcut and Road event groups. Removal of SRI units 21, 8, and 212 is necessary to reduce the Road event X^2 statistic below the $\alpha = 0.05$ level. Only removal of SRI unit 21 is needed for the Clearcut event X^2 statistic to be insufficient to reject H_0. These results, plus the observation that Forest landslide occurrence is very low for SRI units 21, 8, and 212 (Table 6), suggest that these SRI units are more vulnerable to disruption by harvest activities.

As landslide occurrence is one characteristic used in delineating SRI units, the preceding results are not unexpected. However, the results do indicate that SRI unit 21 is perhaps more sensitive to harvest activities than was previously believed. Legard and Meyer (1973) classify the landslide hazard of SRI unit 21 as moderate. Data in Appendix IV show that unit 21 accounts for 31% of all landslide events and 34% and 35% of clearcut- and road-associated events, respectively. For the BRD at least, the failure potential of SRI unit 21 is substantial.

Geomorphic setting. Five different geomorphic settings were defined for the BRD based on the topographic character and hydrology of a given hillslope location. Descriptions of the five settings are listed below.

Hillslope Nose: Area of convex contour lines, located along or directly adjacent to ridge lines. No surface drainage evident.

Hollow: Area of concave contour lines, located at head of stream valleys above stream source. Occasional surface drainage evident or inferred only in downslope end of setting.[10]

Incipient Drainage: Source area of streamflow, either perennial or intermittent. Surface drainage evident or clearly inferred. Always associated with hollows but can occur elsewhere.

Smooth Slope: Area of straight, parallel contour lines, located along valley sides above streamside or hollow. No surface drainage evident.

Streamside: Channel area adjacent to and containing perennial stream, below incipient drainage. Area extends uphill to first major slope break. Surface drainage well developed.

Each landslide was also classified by whether that setting was possibly or definitely within deep-seated earthflow-slump terrain. This was determined through field observations and the use of air photos. The frequency of landslide occurrence in each geomorphic setting is shown in Figure 8.

Smooth slopes are the geomorphic setting most prone to landslide failure in the BRD. An overall X^2 test of all possible settings for each sample group allows rejection of H_0 for the All, Clearcut, and Road event groups at the $\alpha = 0.05$ level. Removal of both types of smooth slope events produces X^2 statistics for All, Clearcut, and Road event groups which are below the $\alpha = 0.05$ level. Though the variation in the Forest event group is insufficient to reject the null, it too has its greatest number of landslides in these settings.

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[10]This definition is in keeping with that used by Hack and Goodlett (1960) but is different from that used by Dietrich and Dunne (1978).

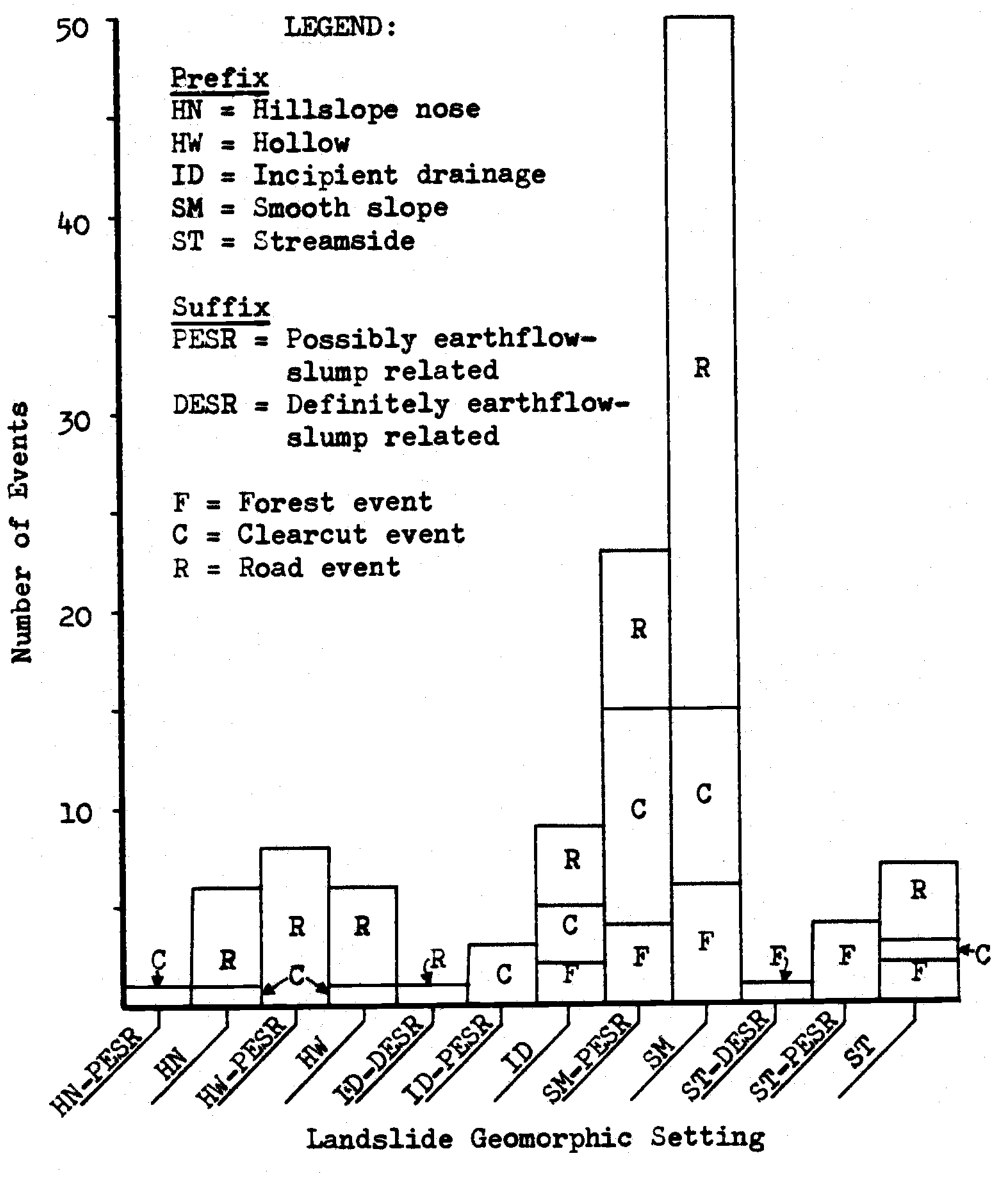

Figure 8. Landslide Occurrence by Geomorphic Setting in the Blue River Drainage

Smooth slope failures are also the most frequent type of landslide to occur within earthflow-slump terrain. A second X^2 analysis considering only those events possibly or definitely related to deep-seated mass movements produces the same results as the previous tests. It is first assumed that all possible earthflow and slump related events are definite and these two classifications are combined for each setting. The resulting All event X^2 statistic ($X^2 = 36.44$) is significant at the $\alpha = 0.05$ level (df = 4) and H_0 is rejected. Exclusion of those smooth slope events within earthflow-slump terrain produces an All event X^2 statistic that is insufficient to reject the null ($X^2 = 5.56$, df = 3). Therefore, the location of landslides within deep-seated mass-movement terrain does not appear to affect which geomorphic settings landslides occur in most frequently.

The reason for the importance of smooth slope locations in landslide occurrence is not clear. Research outside the Western Cascades has pointed to hollows as areas with high failure potential due to subsurface water accumulation (Hack and Goodlett, 1960; Dietrich and Dunne, 1978). It is very likely that smooth slope settings cover the greatest area of any setting in the BRD, though no measurements were made to confirm this possibility. A large areal coverage could provide increased opportunities for failure and therefore could partially account for the high landslide occurrence observed. However, it would not completely explain why failure occurs in settings which do not possess apparent slope loading or water accumulation characteristics.

Geology. The distribution of bedrock types found exposed within landslides in the BRD is shown in Figure 9. Only 44 events presented

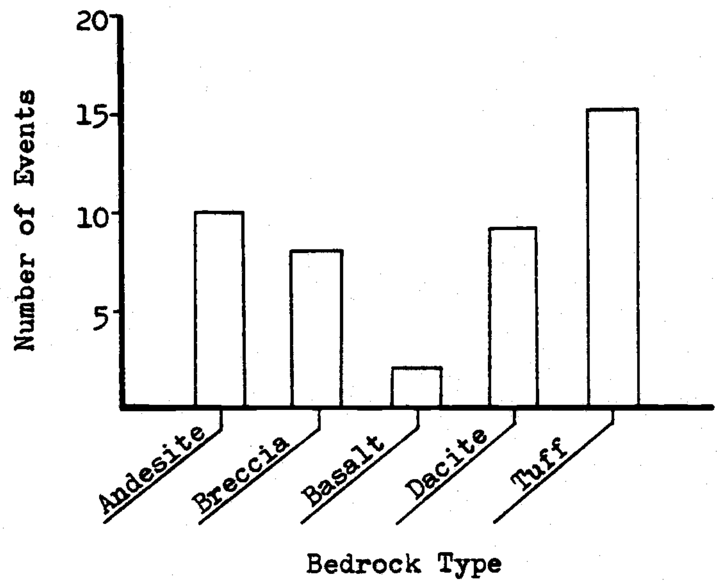

Figure 9. Landslide Occurrence by Bedrock Type for 44 Landslides in the Blue River Drainage

opportunities for collecting samples. Most BRD landslides fail within the soil-regolith layer and do not expose bedrock.

The data indicate that landslides occur rarely in basaltic rock areas, but that failure occurrence is approximately uniform among other rock types. A X^2 test of bedrock type for the All event group demonstrates sufficient variation to reject H_0. In this particular case, most of the observed variation results from the low number of occurrences for basaltic rock types (Figure 9). Exclusion of this rock type results in a X^2 statistic which is insufficient to reject the null.

Interpretation of the BRD geologic data leads to conclusions which are different from past research in the Western Cascades. Whereas landslide occurrence in the BRD appears uniform in many different rock types, other authors have identified breccias and tuffaceous rocks as being especially failure prone (Dyrness, 1967; Morrison, 1975; Swanson and Dyrness, 1975). Unfortunately, none of these researchers specify how their samples were collected. Identifying which rock type is associated with a landslide is difficult in the BRD because of the lack of good bedrock exposures, and the wide variation in rock types frequently present within landslide scars. The presence and extent of specific bedrock types within the BRD is unknown due to the lack of large scale geologic mapping. These difficulties, plus the consideration that the sample group used in this study is small and incomplete, may explain the lack of correlation between this study and others.

Landslide Timing and Frequency

The time of occurrence for each landslide was determined by air photo dates, field evidence, and the dates of harvest activities. In most cases landslide occurrence could only be narrowed to a range of years, rather than a single year. Only 18 events of the total could be accurately dated to the year.

The lack of specific occurrence dates for each event prevents a direct analysis of landslide timing variation within the All, Forest, Clearcut, and Road event groups. However, the general pattern of landslide occurrence can be evaluated by using a surrogate measurement which approximates the temporal character of landslide occurrence. As an index of the number of landslides occurring each year, I have used the "maximum possible occurrence frequency" (MPOF). The MPOF is the maximum number of events which could have occurred within any year and includes both events with specific occurrence dates, and events dated to a range of years. The yearly MPOF value for each respective landslide group is determined by counting the number of events whose occurrence time range includes the year in question. For comparative purposes, these MPOF values are expressed as a percentage of the total number of landslides within each event group and are shown in Figure 10.[11]

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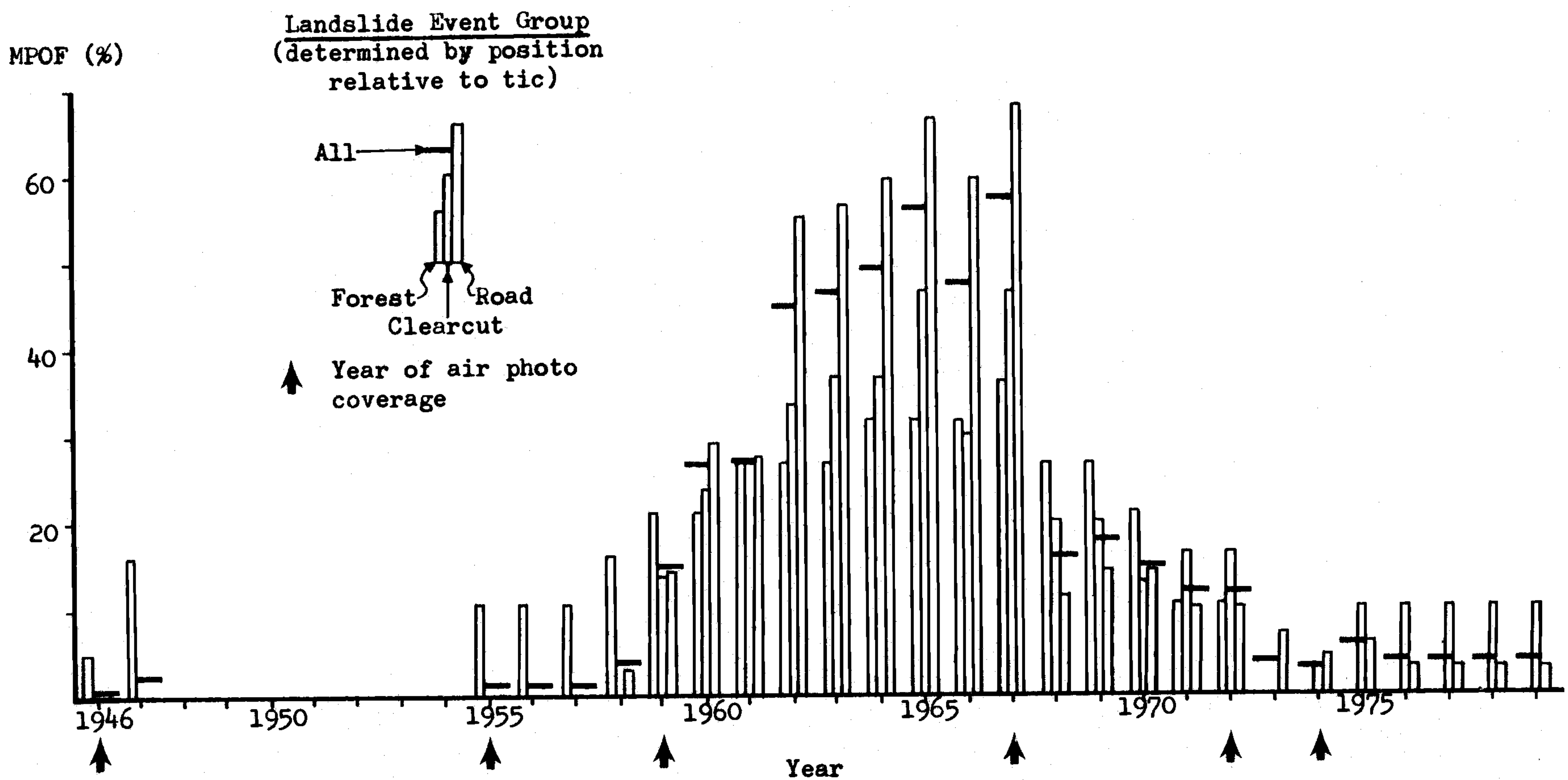
[11]The "resolution" of this technique is limited. The accuracy of all MPOF values is dependent on the size of the various occurrence time ranges. Each landslide occurs only once in nature but may be represented several times in Figure 10, depending on the length of its occurrence time range. The mean time range for the BRD landslides is four years, and the standard deviation is 2.89 years. For this study then, blocks of at least five years should be used to



NOTE: MPOF values are seperated into four event groups: All, Forest, Clearcut, and Road. Yearly MPOF values are expressed as a percentage of the total number of landslides in each events group (118, 19, 30, and 69, respectively).

Figure 10. Comparison of the Yearly Maximum Possible Occurrence Frequency (MPOF) Values for Landslides in the Blue River Drainage

The general pattern of landslide occurrence with time is consistent of all four event groups (Figure 10). In each group the period 1962-1967 has the greatest number of landslides. This is probably due to the occurrence of a very large rain-on-snow storm in December of 1964 (Fredriksen, 1965). Forty-seven mass soil movements resulted from this storm in the HJA (Dyrness, 1967) and no doubt brought about similar results in the BRD. This correlation between large storms and increased landslide occurrence has been well documented elsewhere (Hack and Goodlett, 1960; Bishop and Stevens, 1964; Swanston, 1969; O'Loughlin, 1973; Gresswell et al., 1979; and others). The three land use groups in the BRD appear to be affected in a similar manner by very large storms.

Landslide erosion rates for the three BRD land use groups are compared to similar groups from different areas in Table 11. The three areas are similar in areal frequency, size, and soil transfer rate for each land use group except the Road group. Although average landslide volumes are approximately the same for the three areas, a much higher soil transfer rate occurs in the Alder Creek Road event group due to more frequent landslides per unit area. In general, though, landslide erosion rates for each land use group appear fairly consistent for these different areas of the Western Cascades.

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insure meaningful comparisons of MPOF values. I have used the MPOF technique in preferrence to time blocks determined by air photo dates because the MPOF technique incorporates more information (e.g., harvest activity dates) and therefore has a somewhat higher "resolution" level than air photo dates alone.

Table 7. Comparison of Landslide Erosion Rates for Selected Areas in the Western Cascades

Land use	Period of record (yrs)	Areal frequency (events$\cdot$km$^{-2}\cdot$yr^{-1})	Average volume per event (m^3)	Soil transfer rate (m$^3\cdot$km$^{-2}\cdot$yr^{-1})
Forest				
Blue River Drainage	34	0.012	3,115	37
H. J. Andrews	25	0.025	1,460	36
Alder Creek	25	0.023	1,990	45
Clearcut				
Blue River Drainage	22	0.120 (10.0)	2,684 (0.86)	322 (8.7)
H. J. Andrews	25	0.097 (3.9)	1,340 (0.92)	132 (3.7)
Alder Creek	15	0.267 (11.6)	440 (0.22)	117 (2.6)
Road				
Blue River Drainage	25	1.26 (105)	1,292 (0.41)	1,628 (44)
H. J. Andrews	25	1.38 (55)	1,380 (0.95)	1,770 (49)
Alder Creek	15	8.33 (360)	1,870 (0.94)	15,600 (350)

SOURCE: H. J. Andrews Experimental Forest, WNF (Swanson and Dyrness, 1975); Alder Creek, WNF (Morrison, 1975).

NOTE: Values in parentheses are the factor by which the adjacent value exceeds its comparable Forest group value.

The technique used in Table 7 for the calculation of areal frequency, though common in the literature (Morrison, 1975; Swanson and Dyrness, 1975; Swanston and Swanson, 1976; Swanson et al. 1977, 1981), is not entirely accurate. In evaluating landslide areal occurrence over time, it fails to account for changes in the size of the land use area associated with each landslide group during the period of record. Instead, one area value, the area existing at the end of each respective record period, is used to calculate areal frequency. From Figure 3 it is clear that area values at the end of the record period represent the minimum area associated with the Forest group, and the maximum areas associated with the Clearcut and Road groups. Therefore, calculations using these particular areas tend to distort the "real" areal frequencies by using too small an area for the Forest group, and too large an area for the Clearcut and Road groups. The calculated Forest group frequency is too high (because the divisor is too small) and the Clearcut and Road group frequencies are too low (because the divisors are too large).[12]

Swanson et al. (1977, 1981) have proposed a calculation method which corrects most of the shortcomings in the method discussed above. This new technique accounts for the change in associated land use areas over time by using "cumulative area per unit time" (CAT) units in place of the conventional "final area per unit time" units. Instead of multiplying the respective final area values by record

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[12]See Appendix V for an expanded discussion of this subject.

period lengths to determine the divisor components for the areal frequency calculations, the CAT method sums the yearly area values associated with each landslide group over the entire record period. The CAT sums for each land use group are then used as the respective divisor components. Use of the CAT method requires a detailed record of timber harvest activities for the area in question. Such a record is available for the BRD.

An examination of areal frequency and soil transfer rates calculated using the CAT method (Table 8) reveals that the rates for the Clearcut and Road groups are much higher than those determined by the conventional method (Table 7). Both rates are approximately twice as large as the comparable rates in Table 7. The rate for the Forest group decreases a small amount from the value previously calculated.

Table 8. Landslide Erosion Rates for the Blue River Drainage Based on the Cumulative Area per unit Time (CAT) Method

Land Use	Period of record (yrs)	Areal frequency calculated by CAT method ($events \cdot km^{-2} \cdot yr^{-1}$)[a]	Average volume per event (m^3)	Soil transfer rate ($m^3 \cdot km^{-2} \cdot yr^{-1}$)
Forest	34	0.010	3,115	31
Clearcut	22	0.240 (24)	2,684 (0.86)	644 (21)
Road	25	2.534 (253)	1,292 (0.41)	3,274 (105)

NOTE: Values in parentheses are the factor by which the adjacent value exceeds the comparable Forest group value.

[a]This method was developed by F. Swanson, M. Swanson, and C. Woods (1977, 1981).

V. INFLUENCE OF CLEARCUTTING AND ROAD CONSTRUCTION ON LANDSLIDE OCCURRENCE

Analysis Procedure

In the preceding section, the differences in landslide characteristics within each landslide group were examined. The differences between groups is examined in this section. Only the three land use groups, Forest, Clearcut, and Road, are considered. The analysis procedure is to first compare between-group variation for all three groups together. If results from this test are significant at the $\alpha = 0.05$ level, then variation between each pairing of land use groups (e.g., Forest vs. Clearcut) is tested.[13] Causality between land use association and landslide occurrence is assumed to be implied whenever variation between groups is statistically significant.

Influence on Size Characteristics

It was established in Section IV that the size characteristics of BRD landslides are not normally distributed. Therefore, a non-parametric teohnique, the Kruskal-Wallis one-way analysis of variance test, is used to evaluate between-group variation for each size characteristic.

Results from the Kruskal-Wallis test indicate there is insufficient evidence to imply that clearcutting and road construction affect landslide size characteristics. In each case the variation in size

[13] See Appendix IV for specific information regarding each test.

parameters between the three land use groups is not great enough to reject the null hypothesis. This consistency in landslide size suggests that shear and normal stresses within the soil unit which failed were very similar in the three land use areas. If clearcutting and road construction have an affect on slope stability, then it must be on one or more of the other components affecting shear strength.

Influence on Site Characteristics

The variation in site characteristics between the Forest, Clearcut, and Road event groups is evaluated below. Except for slope angle, X^2 tests of homogeneity are used throughout. As slope angle measurements are interval level, the Kruskal-Wallis test is appropriate for evaluating slope angle variation among the three groups.

Slope angle, slope aspect, and hillslope position. The evidence is insufficient to infer that land use association affects the slope angle, aspect, or hillslope position at which landslides occur. For all three site characteristics, the variation present between the land use groups is not great enough to reject the null hypothesis. This indicates that within-group variation (Section IV) is fairly consistent. In particular, landslide occurrence in the BRD appears uniform with respect to hillslope position despite clearcutting and road construction activities.

SRI landtype. Chi-square analysis of between-group variation for SRI units is not appropriate due to an unacceptably large number of expected frequencies less than one (Cochran, 1954). No other statistical techniques are available which can utilize nominal data, therefore no analysis of SRI landtype variation is attempted.

Geomorphic setting. It was demonstrated earlier that landslides ralated to possible deep-seated earthflows occur in geomorphic settings similar to non-earthflow related events. Therefore, comparable settings are combined for the following analyses.

Results of X^2 analysis of the variation in landslide geomorphic setting suggest that clearcutting and road construction may influence the susceptibility of certain geomorphic settings to landslides. Comparison of the Forest, Clearcut, and Road groups together yields a X^2 statistic that is significant. Subsequent tests of land use pairs show the Forest group to be significantly different from the Road and Clearcut groups. The null cannot be rejected for the test between Clearcut and Road groups. The latter group of tests suggests that Forest failures occur in different geomorphic settings than Clearcut and Road failures in the BRD. Comparison of the observed frequencies for the three groups shows that despite the prominence of smooth slope landslides in all three groups, differences do exist. The number of Forest failures in streamside settings relative to other settings is greater than in either the Clearcut or Road group. Conversely, the relative frequencies recorded for hillslope nose and hollow settings in the Clearcut and Road groups are greater than in the Forest group. No immediate explanations are available for the relative lack of streamside failures in clearcut or road areas. The increased occurrences in hillslope nose and hollow settings indicates that clearcutting and road construction may cause changes to occur which increase landslide susceptibility in these locations.

Control test: SRI plus slope aspect. Up to this point the analysis procedure has been to isolate one characteristic and test the variation of the three land use groups with respect to that characteristic. Stated another way, the procedure has been to control the sample groups in question (Forest, Clearcut, and Road) and let the landslide characteristic vary. A reverse procedure is possible in which landslide characteristics are held constant and variation in landslide occurrence within each land use group is observed. A limited application of this last technique is possible in the BRD. Specific values for two landslide characteristics, SRI landtype and slope aspect, are selected to produce the control situation. SRI unit 21 and northern aspects (NW, NNW, N, NNE) are used because together they cover a larger portion of the BRD than most other combinations (≈91 ha), and because the All event observations for both are large (see Table 6 and Figure 8). Therefore, only events occurring within northern aspects in SRI unit 21 are tabulated.

Test statistics generated from X^2 goodness-of-fit tests strongly indicate that clearcutting and road construction influence landslide occurrence in the BRD. Uniform failure occurrence is assumed for the three land use groups to test the variation in land use association. Comparison of the three groups together results in rejection of the null. Testing of the land use pairs shows the Forest group to be significantly different from either the Clearcut or Road group. Variation between the latter two groups is not significant. Thus, landslide occurrence is definitely changed by clearcutting or road construction in areas covered by SRI landtype 21 and northern aspects.

Influence on Landslide Frequency

Landslide frequency is examined in two ways. The first compares the number of occurrences for each land use group over the record period. The second relates areal frequency rates for Clearcut and Road groups to the Forest rate. Both methods strongly suggest that clearcutting and road construction have increased the rate of landslide occurrence.

A statistical comparison of the landslide frequency reveals that significant differences exist between the three land use groups, with Road events appearing to occur most frequently. Once again, landslide frequency is assumed to be constant among the groups compared. Comparison of the three groups together produces a X^2 statistic which is significant at the $\alpha = 0.05$ level. Comparison of the three group pairings shows that both the Forest and Clearcut groups vary significantly from the Road group, but insufficient variation exists between the former two to reject H_0. As the record period for the Road event group is noticeably less than that for the Forest group, the difference between these two is probably even greater than this comparison shows.

Numerical comparisons can also be made to examine the relative differences in landslide areal frequencies between the Forest group and the Clearcut and Road groups. The values in parentheses in Table 8 show the factor by which the Clearcut and Road frequencies exceed the comparable Forest rate (rates calculated by CAT method). It is clear that for the BRD the Clearcut and Road groups have much higher landslide occurrence frequencies than the Forest group. The Road group demonstrates the greatest instability, with a frequency in excess of 253 times that of the Forest group. The Clearcut group is more stable, but records a frequency 24 times that of the Forest group.

Table 7 contains a comparison of the relative influence of these harvest activities for other areas in the Western Cascades. Areal frequencies for the respective BRD groups fall between those for Alder Creek and the HJA.[14] Consideration of soil transfer rates, a measure which combines landslide size and frequency, suggests that the BRD clearcut areas are affected to a greater degree than corresponding areas in Alder Creek or the HJA. The effect on road areas appears very similar for the BRD and the HJA, however both are affected to a lesser degree than road areas in Alder Creek. The last difference may be due to more extensive road construction in the unstable areas of Alder Creek, than in similar areas of the BRD or the HJA. Morrison (1975) cites the influence of SRI landtype 8 on Road failure occurrence in Alder Creek. He further points out that while this landtype covers over 50% of Alder Creek, it covers only a small portion of the HJA. SRI unit 8 occupies only 6% of the BRD, therefore, Morrison's explanation above may also account for the difference between Alder Creek and the BRD.

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[14]Areal frequencies calculated by the conventional method are used here because that is the method used in the other two studies.

VI. CHARACTERISTICS OF LANDSLIDE IMPACTS ON RESOURCES AND LAND USE INFLUENCES

Landslide occurrence in managed forests affects many natural and developed resources. Impacts to forest vegetation is often the most apparent, but is only one of the many impacts possible. In this section some general characteristics of impacts to vegetation, soil, stream, and transportation resources will be examined. Where appropriate, the influence of land use is considered as it affects landslide caused resource impacts. All statistical tests use the $\alpha = 0.05$ level as indication of statistical significance.

Hillslope and Channel Area Affected

In addition to the failure area, the hillslope area below a landslide is often severely impacted. Passage or deposition of the displaced slope material can strip off or bury soils and thereby drastically reduce subsequent plant establishment. This is demonstrated for the BRD by the values shown in Table 9. Although these measurements are crude representations of site disruption, they do indicate that soil and vegetation disruption has occurred. Some vegetation recovery over time is evident from these values, however plant establishment is still clearly reduced after 20 years.

The size of the area affected by landslides in the BRD does not appear to be influenced by land use association. The sums of the areas affected by landslides are shown in Table 10 for each land use group. A Kruskal-Wallis test is performed to determine if land use association has an influence on the total ground area affected by

Table 9. Vegetation Characteristics Within Landslide Scars in the Blue River Drainage

Age class of event (yrs)	Mean vegetation cover, all species (%)[a]	Mean maximum age of conifer revegetation (yrs)
1 - 9	20 (14)	1 (10)
10 - 19	20 (67)	6 (64)
20 - 35	40 (36)	10 (32)

NOTE: Values in parentheses are the number of observations (i.e., landslides) upon which the adjacent value is based. Total number of observations does not equal the total number of events (118) because some data is missing.

[a]Determined for each site by visual estimate of total vegetative cover by trees, shrubs, forbs, sedges, herbs, and grasses. Natural vegetative cover is 100%.

Table 10. Ground Area Affected by Landslides in the Blue River Drainage

Land use	Total failure area (ha)	Total down-slope area affected (ha)	Total channel area affected (ha)	Total ground area affected (ha)	Percent of total drainage basin area (%)[a]
Forest	2.47	1.47	6.35	10.29	0.17
Clearcut	2.58	1.66	1.71	5.95	0.10
Road	4.17	4.65	6.76	15.58	0.25
				Total	0.52

[a]Total draingae basin area is 6166 ha.

landslides. Hillslope and channel area affected are combined for those events affecting both. Results show that insufficient evidence exists to reject the null hypothesis.

It is also apparent from Table 10 that the total area affected by landslides in the BRD is not substantial. Though on-site disruption is impressive, the impact to the total vegetation and soil resource is minimal.

Landslides which enter stream channels often continue downstream as debris torrents. Streamside soil and vegetation impacts for the BRD are similar to those shown in Table 9. The water quality impacts of events which entered stream channels in the BRD are unknown, but research elsewhere suggests the impacts can be great (Fredriksen, 1963, 1965, 1970; Gardner, 1979).

Stream Class Affected

The United States Forest Service recognizes that certain streams or stream reaches have greater resource value than others. Therefore, stream reaches have been classified within the BRD according to water supply, fisheries, and recreational value (U.S. Forest Service Manual, 1972 Revision). Class I has the highest value and Class IV the lowest. The classifications for streams in the BRD are shown in Figure 1.

A X^2 goodness-of-fit test is used to determine whether the frequency of stream entry by landslide is proportional to the total length of each stream class. Total stream lengths of Classes I, II, and III are used to calculate the respective expected entrance frequencies. These lengths are determined from "Stream Class Map for the Blue River Ranger District" (compiled by resource specialists of the WNF) using a sonic digitizer. Class IV streams are not considered because the total length of Class IV streams is not yet known.

The result of the X^2 test strongly suggests that the frequency of stream entries is dependent on stream class lengths. Variation is too small to reject H_0. Since stream lengths for the different stream classes are similar (Figure 1), one might expect this test also indicates that channel and water quality impacts are distributed fairly equally among the three stream classes. However, this test does not consider the number of times a Class I or II stream is entered by a debris torrent which initially began in a Class III or IV stream. Because stream class generally goes from lower class (III or IV) to higher class (I or II) as one moves downstream, upstream entries in lower class streams can affect higher class streams as well. Therefore, this test is very conservative in its evaluation of how frequently higher class streams are affected by landslide occurrence.

Road related landslides enter streams more frequently than landslides associated with other land use areas. Once again, a X^2 goodness-of-fit test is used to evaluate the influence of land use association on the frequency of stream entries by landslides. All stream classes are considered as one for this test. The initial comparison of all land use groups together reveals significant differences exist at the $\alpha = 0.05$ level. Subsequent comparisons of each land use pair show that both the Forest and Clearcut group vary significantly from the Road group, but vary little between each other.

To determine if land use influences the stream class entered by a landslide, a X^2 test of homogeneity is performed. Results indicate that there is insufficient variation between land use groups to reject the null. Apparently, land use does not influence which stream classes are entered by landslides.

Road Class Affected

Roads are important as a transportation resource and because previous analyses have indicated landslides occur more frequently within road areas. How roads are constructed may help explain why particular road sections fail. The design standards used in road construction vary depending on surfacing, width, maximum grades, sight distance on curves, and vehicle speed specifications (Mifflin and Lysons, 1979). In general, variation in design standards can be represented by the U.S. Forest Service classification assigned to each road (Jim Reeves, WNF Engineer, per comm.). Therefore, the variation in landslide occurrence between different road classes is examined to determine if design standards influence landslide activity.

A X^2 goodness-of-fit test is again used for analysis. General relative descriptions of each road class considered in this test are listed below.

Arterial: Highest intensity of use, highest road speeds, widest roadbed, and lowest grades.
Collector: Medium use intensity, lower road speeds, narrower roadbed, and moderate grades.
Local: Lowest use intensity, lowest road speeds, narrowest roadbed, and steepest grades.

The expected failure frequency for each road class is determined using the respective total road lengths. This procedure corrects for any variation in landslide frequency due solely to differences in road lengths.

Landslide frequency seems to increase with decreasing design standards in the BRD. Test results show that sufficient variation exists to reject H_0. However, before it is concluded that arterial road design standards are superior, it should be noted that Megahan et al. (1978) report different results for road failures in the Northern Rocky Mountain Physiographic Province in Idaho. Their work (Table 11) shows landslide frequency to decrease with decreasing road design standards. The increased excavation associated with higher design standards is their explanation for this result.

Personal observations made while collecting field data may explain some of the observed differences in landslide occurrence for different road classes. The one arterial road in the BRD was constructed in a very stable area along the valley bottom of Blue River (see Figure 1). Much of the road is located on alluvial terraces or gentle slopes, therefore extensive excavation was unnecessary. Road drainage is very good with frequent large culverts which appear well maintained. In contrast, collector and local roads traverse more unstable ground, and are primarily constructed by cut-and-fill techniques which result in steep cut and fill slopes. Culvert spacing is much greater on these roads and road maintenance was obviously lacking in many places. It was not uncommon to observe road ditches filled with sediment while the culverts draining these ditches were plugged with debris. Inefficient road drainage coupled with less stable road prisms could explain the higher incidence of landslide occurrence on

Table 11. Comparison of Landslide Frequencies for Road Classes in the Blue River Drainage (Oregon) and the Northern Rocky Mountain Physiographic Province (Idaho)

	Frequency (events/km)	
Road class	Blue River Drainage	Northern Rocky Mtn. Physiographic Province[a]
Arterial	0.17	2.2
Collector	0.39	1.2
Local	1.00	0.6

[a]Source: Megahan et al. (1978)

collector and local roads.

Road Component Affected

Determining which components of the roadway are most affected by landslide failure is another means of assessing road construction methods, as well as evaluating impacts to the road itself. The roadway is divided into three parts: the cut slope, the roadbed, and the fill slope. Roadbed failures are not evident in the BRD, therefore this component is excluded. Analysis of landslide occurrence within the remaining components follows below.

Fill slope failures occur more frequently than cut slope failures in the BRD. Results of a X^2 goodness-of-fit test indicate the difference in landslide occurrence between the two components is significant. This relative instability is probably due to fill construction over sidecast debris. Decomposed organic material, mostly stumps, roots, and logs were frequently exposed within fill slope failures in the BRD. Fill construction over sidecast debris has been previously identified as promoting fill slope failures (Gonsior and Gardner, 1971). Such construction methods are likely to be responsible for many of the BRD fill slope failures.

A reverse order of importance for cut and fill slope failure occurrence is reported for Idaho forests. Megahan et al. (1978) find cut slope failures are the more frequent, as shown in Table 12. It seems doubtful that road construction methods for the two areas are sufficiently different to account for these opposite results. However, differences do exist in the climate, bedrock geology, soils, and

Table 12. Comparison of Landslide Frequencies for Road Components in the Blue River Drainage (Oregon) and the Northern Rocky Mountain Physiographic Province (Idaho)

Road component	Frequency (% of total)	
	Blue River Drainage	Northern Rocky Mtn. Physiographic Province[a]
Cut slope	29	66
Fill slope	71	34

[a]Source: Megahan et al. (1978)

vegetation. In addition, Megahan et al. inventoried all events equal to or greater than 8 m^3, whereas this study only considers events at 100 m^3 or above. Several cut bank failures less than 100 m^3 were observed in the BRD, but I doubt their number would substantially change the relative difference between cut and fill slope failure occurrence. It appears that a complete resolution of this disagreement is not possible with the data available.

In addition to being more frequent, fill slope failures also appear to affect a greater downslope area than cut slope failures. A comparison of the respective downslope (hillslope and channel) areas affected by road component failures is possible using a one-tailed, Mann-Whitney test. The computed test statistic indicates there is not enough variation present to reject H_0 at the $\alpha = 0.05$ level. However, since the probability of exceeding the test statistic under the null hypothesis is 0.0735 (Appendix IV), it would not be unreasonable to suggest that fill slope failures do affect a larger area than cut slope failures.

It is not surprising that fill slope failures appear to have a greater impact than cut slope failures. The roadbed acts to catch much of the displaced mass from a cut slope failure, thereby reducing the amount of debris available to continue downhill. Megahan et al. (1978) note a similar relationship between the resource impacts of cut and fill slope failures in Idaho.

VII. SUMMARY AND CONCLUSIONS

The preceding sections have examined: landslide characteristics and timing; the influence of clearcutting and road construction on landslide occurrence; and some characteristics of resource impacts resulting from landslide failures. Results and interpretations are summarized below. The adequacy of the analysis techniques used in this paper is also considered.

Despite the wide variety of factors involved, landslide characteristics are remarkably consistent in the BRD. Failure dimensions generally occur within a narrow range of values regardless of land use association. Landslides within all land use groups occur most frequently at slope angles between 30° to 40°, in northern aspects, and in smooth slope settings. Hillslope position has no apparent influence on landslide frequency. Only the relationship between SRI landtype and landslide occurrence varies among the three land use groups.

This consistency of landslide characteristics has implications for geomorphology and forest management. The frequency of events with size characteristics falling within a narrow range of values indicates a fairly consistent amount of soil material is displaced by each landslide failure. This is true even in clearcut and road areas. Clearcutting and road construction produce a number of environmental changes which affect the balance of forces present within a hillslope (Table 13). Despite these changes landslide size remains consistent. This fact, plus the observation that the dominant size ranges all occur at the low end of the distribution curves, strongly suggests

Table 13. Some Environmental Changes Resulting from Clearcutting and Road Construction and their Affect on Landslide Dynamics

Environmental change	Result of change	Effect of change on hillslope force component
Road excavation	removal of lateral support to upslope soil	decreased shear strength
Road fill construction	increased slope angle	increased shear stress
Vegetation removal	decreased evapotranspiration = increased soil moisture content	decreased shear strength
	decreased root strength	decreased shear strength
	removal of overlying biomass	decreased shear stress

the presence of a geomorphic threshold. Such a threshold would represent the amount of material which must be present to produce a landslide failure. If not initially present, this necessary amount of material would have to accumulate before a landslide could occur. Surficial creep, weathering, and debris accumulation are processes which could supply this material. Thus, active landslide sites should be those areas having geomorphic situations which encourage these processes, i.e., steep slopes with plentiful soil moisture. Steeply inclined areas in northern aspects appear to produce these conditions most frequently in the BRD.

Consistency in landslide site characteristics further suggests that risk areas can be identified. Special management provisions could be established to avoid disruptions of areas with the characteristics specified above. At the very least, such avoidance would prevent an acceleration of landslide occurrence in these areas.

The influence of clearcutting and road construction on landslide occurrence can only be strongly implied for landslide frequency and the geomorphic location of failure. Both statistical and numerical comparisons show that landslide rates in clearcut and road areas are much greater than rates in forest areas. Use of the CAT technique suggests even greater differences exist. However, the most conclusive demonstration of land use affects may be the control test with SRI land type 21 and northern aspects. Results show that under similar site conditions, landslide frequency is greater in clearcut and road areas than in the forest area.

The effect of clearcutting and road construction on landslide location is more subtle but still significant. Except for smooth slope locations, there appear to be differences in how other geomorphic settings react under different land uses. Hollow and hillslope nose positions, which are apparently stable within forest or clearcut areas, are frequently affected by landslides within road areas. This suggests a reduction in site stability due to some impact of the road. Reduced stability in a hillslope nose setting could be explained by road excavation which removes toe support from uphill soil blocks. The failure or inefficient operation of road drainage systems could reduce stability in hollows where natural water accumulation magnifies the drainage problem.

It cannot be demonstrated that clearcutting or road construction influence landslide size characteristics, slope angle, slope aspect, or hillslope position. Although road construction and, to a lesser degree, clearcutting, affect the frequency of landslide failure, they do not affect how landslides will occur. Moreover, aside from certain geomorphic settings, they do not generally affect where landslides occur. Most likely the sites which fail are already very unstable. The site changes resulting from clearcutting and road construction (Table 13) accentuate the inherent instability rather than destabilize sites which normally would not fail.

Areas which are sensitive to timber harvest activities have already been identified to a limited degree. Legard and Meyer (1973) have classified SRI landtypes according to sensitivity to road construction and clearcutting. Quantification of sensitivity may be possible using a technique like that used in the control test with

SRI landtype 21 and northern aspects. Such a refinement would improve the forest planner's ability to foresee potential impacts and anticipate when unacceptable erosion levels will occur.

Characteristics of landslide resource impacts and land use considerations in the BRD are documented in Section VI. Impacts to both soil and vegetation is clearly apparent, but the areal extent of these disruptions is not substantial relative to the drainage basin area. Though it cannot be demonstrated that any particular stream class is disproportionately affected, it is apparent that land use influences the frequency of landslide entries into streams. Road failures are once again indicated as the most frequent landslide source.

Section VI also considers how road design and construction methods affect road failures. Landslide frequency is shown to increase with a decrease in road class. Less stable terrain and less efficient road drainage are more likely the cause of this result than the decrease in design standards employed for collector and local roads. Fill slopes, frequently constructed on sidecast debris, are statistically shown to fail more frequently and result in greater downslope disruption than cut slope failures. It seems certain then, that road location, drainage, and construction methods have a definite influence on whether roads will fail in the BRD.

Any conclusions based on the results of this paper should consider the adequacy of the testing methods used. Methods used in the previous sections have indirectly evaluated landslide characteristics and land use effects. These methods can only imply that relationships exist. However, environmental variability and data restrictions prevent use of more direct and precise evaluation methods. Tests which attempt to control environmental variation or interactions, such as the control test with SRI landtype 21 and northern aspects, usually lack sufficient observations within the specified conditions to make statistical analysis reliable. Use of nominal data also severely restricts the types of evaluation methods which are applicable.

There are benefits in the approach used in this paper, however. It does consider a large area. Though the interpretation of results must be generalized, it is more applicable to the needs of the forest manager. It also helps to identify relationships which require further investigation. The consistency in landslide size, frequent occurrence in particular aspects, and the influence of land use on failures in different geomorphic settings are all examples of topics identified in this paper which deserve further study.

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APPENDICES

APPENDIX I
AIR PHOTO SPECIFICATIONS

Specifications of Air Photos Which Cover the Blue River Drainage

Year	Flight name	Flight dates	Scale (approximate)	Film type	Coverage
1946	DEK	8-15-46 9-12-46	1:24,000	black & white panchromatic	complete
1955	WASM	8-3-55 8-17-55	1:70,000	black & white panchromatic	complete
1959	EGI	5-59 6-59	1:13,000	black & white panchromatic	40% - only Blue River itself
1967	ESF	6-14-67 6-15-67 6-30-67	1:14,500	black & white panchromatic	complete
1972	F16	7-18-72 7-15-73	1:20,000	color	80% - upper Tidbits watershed missing
1974	F70	8-25-74 8-26-74	1:74,000	black & white panchromatic	complete

APPENDIX II

Landslide Data Collection Sheet

SE= self-explanatory

DATA SHEET

Collected by: SE

Date: SE

No. SE

Event No. SE

Photo No. SE

Photo date SE

Type: SE Slide/Slump-earthflow/debris torrent

Location: T. SE R. Sec.

SRI Classification No. **all SRI units involved; verify in field**

Not identifiable in air photos: SE

Probable time of occurrence: **Id dating techniques used; tree scars age, reveg. age, D.F. decomposition class, air photo bracketing, personal comm.**

For debris torrents: Associated slide? Yes / No SE Slide No. SE

LAND USE: ✔ **Failure** ✘ **Surrounding area**

Forest

Road when built SE

sidecast / full bench

cutslope / fill slope / other

Clearcut Cutting date SE

Vegetative Cover: **Areal extent (±20%), veg. types w/in; surrounding veg. types physical state (health, density)**

STAND AGE **w/in slide; surrounding slide**

GEOMORPHIC SETTING:

Aspect: SE

Slope Angle: **Hillslope and w/in slide if signif. different**
or Channel Gradient

(slope position: Upper 1/3 Mid 1/3 Lower 1/3

Headwall:

Streamside: **Position of failure on hillslope**

Smooth slope:

Incipient drainage:

Other: **eg. nose of hillslope, ridge saddle,**

SLIDE GEOMETRY: **Failure / Slide path**

Avg. length: SE

Avg. width: SE

Est. Avg. Depth: SE

Est. Volume: SE

Est. Area: SE

BEDROCK: **Material in which failure occurred; nearby exposures**

FATE OF DEBRIS: Into stream SE

Other **where deposited, est. of amt.**

REMARKS:

SLUMP OR EARTHFLOW-RELATED? SE

- **Amt. of material which could possible fail later or presence of cont'd instability.**
- **% area in active dry ravel or spalling.**
- **Departures from natural drainage characteristics.**
- **% area being gullied.**
- **est. of amt. of gullying having already occurred.**
- **% area having revegetated.**
- **% area covered by soil or regolith.**
- **% area covered by loose gravel or road fill material.**
- **% area of exposed bedrock**
- **Cracks present? Type, depth, extent.**
- **Was area burned before failure (re cc.)?**
- **Signs of contributing water sources.**
- **Distance to nearest uphill culvert. Tendency of culvert plugging evident?**
- **Location in snow zone?**
- **Sidecast material present in road fill?**
- **For DT's: Height of debris wash.**
  - **Physical description of debris, impact on stream.**
- **Confidence in measurements (1=very poor to 5=very good)**
- **Scarp angle if significantly different from above.**
- **Exposed roots present?**

SKETCH:

Boundary of failure /-clear /inferred

Road

Culvert

Drainage

Slope break

Scarp of failure

Crack

Tipped trees

Dist. measures 30

Rooted stumps

Rooted conifers

Rooted deciduous

Large organics

Root wads

Debris deposits

Exposed bedrock

Gullys

Boulders

Tree scars

Bedrock samples

General veg cover

APPENDIX III

A METHOD FOR DETERMINATION OF LANDSLIDE HILLSLOPE POSITION

This method was developed to provide an objective procedure for establishing the relative hillslope position of landslides. Hillslope position is established by dividing the basin area into three zones (upper, middle, and lower), and then noting in which zone a given landslide is located. These zones do not distinguish position by absolute elevation; rather, they mark hillslope position relative to the major valley bottoms and ridge tops.

Hillslope position zones are constructed by establishing the elevations of the interzone boundaries on reference hillslope lengths, and then connecting the respective elevation points on successive hillslope lengths to form continuous boundaries. This procedure is divided into four parts:

1. Plotting of reference hillslope lengths.
2. Determination of slope length for each reference hillslope.
3. Determination of interzone boundary elevations on each reference hillslope.
4. Connection of respective boundary elevation points on successive reference hillslopes.

The equipment required to perform this procedure includes:

1. Topographic map covering the area of concern;
2. Ruler;
3. Straightedge;
4. Marking pen or pencil;
5. Programmable calculator.

A program for a Hewlett Packard 34C calculator is included for making the calculations necessary in parts 2 and 3 above.

Plotting of Reference Hillslope Lengths

Reference hillslope lengths are used to establish the interzone boundary elevations at given locations in the basin. These hillslope lengths are plotted as straight lines on the topographic map as shown in Figure 11. However, before these lines can be plotted it is necessary to establish a top and a bottom for a given hillslope length. The bottom, or base level, of a hillslope length is defined as the second order or larger stream channel which lies in the valley bottom. To determine stream order it is necessary to delineate the entire stream network. This is accomplished using the method outlined in Marston (p. 7, 1978). Streams are ordered using the Strahler method (Strahler, 1957). Once the stream network is ordered the top of a hillslope length is defined as the ridge line which separates third order or larger watersheds. All ridge lines are drawn in freehand as shown in Figure 11 to approximate the location of watershed divides.

With hillslope bottoms and tops established, reference lines are plotted with a straightedge according to the following guidelines.

1. Try to put one reference line down each significant interflueve. (Significant interflueves are those with sharply bending, convex contours. These contours appear consistently from valley bottom to ridge line along a given interflueve.)

2. Only straight lines are plotted, therefore lay the straightedge in a position which best approximates the axis of the interflueve.

3. Extend reference lines from stream channel to ridge line.

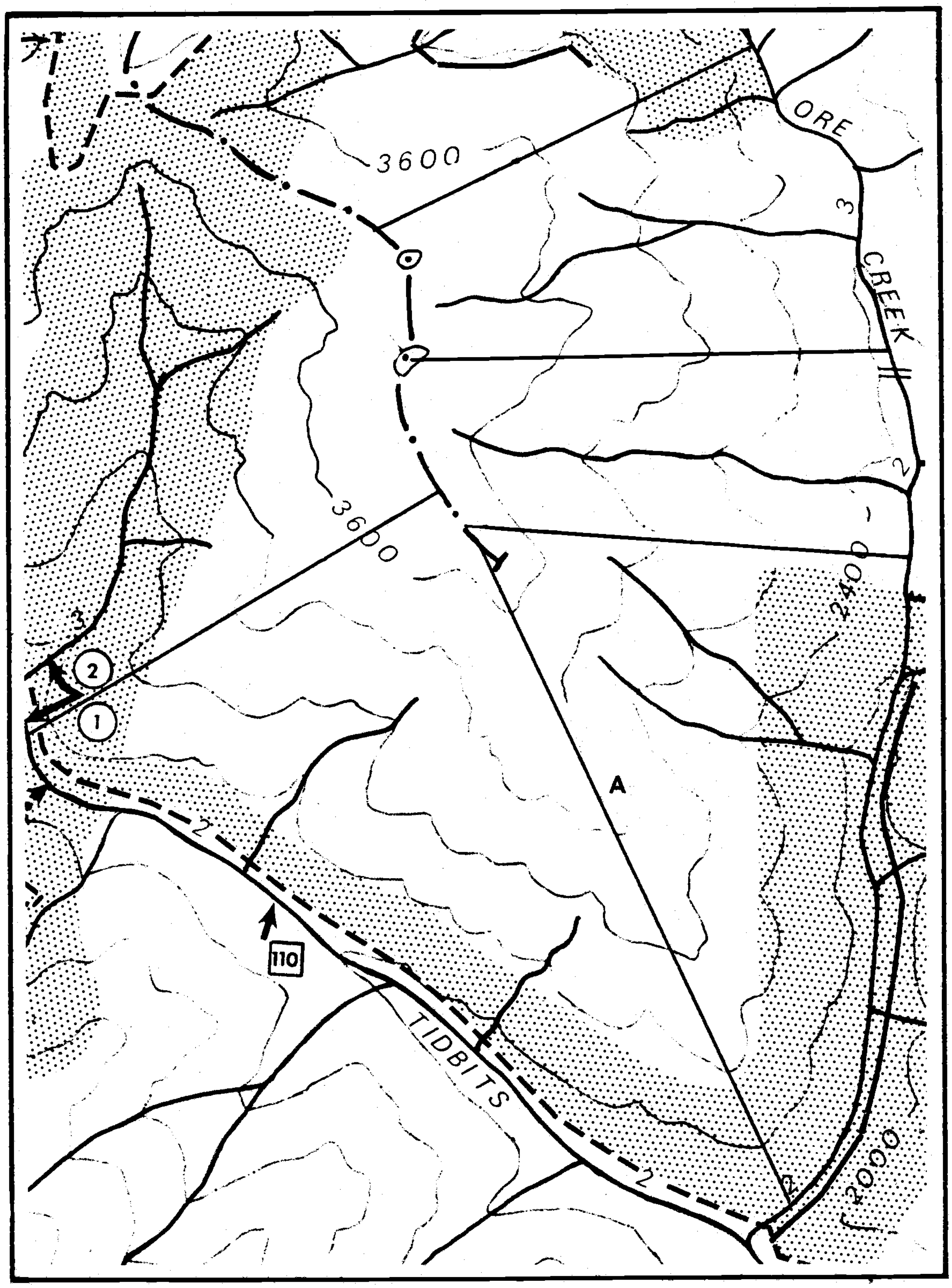


Figure 11. Example of Reference Line Locations in the Blue River Drainage

4. Plot only one reference line along the hillslope nose portion of major ridge lines (i.e., the area where, if the ridge line were continued, it would descend to the valley bottom; e.g., line A in Figure 11).

5. Do not plot any reference lines which would intersect first order streams.

6. Do not plot reference lines such that any two lines intersect between the stream channel or ridge line. Use only one reference line in these areas.

Determination of Slope Length

Each reference line represents a hillslope which has a characteristic length. In order to determine the slope length associated with each reference line it is necessary to first determine the hillslope gradient along this line. Slope gradient or angle is calculated using the following equation:

$$SA = \arctan\left(\frac{Y}{X}\right)$$

where SA = slope angle
Y = vertical distance between top and bottom of reference line
X = horizontal distance between top and bottom of reference line.

The vertical distance between top and bottom is the difference in elevation between the two. The elevation of the reference line top is defined as the elevation of the highest contour line intersected by the reference line. The bottom elevation is defined as the elevation of the lowest contour line intersected by the reference line.

To determine the horizontal distance between the top and bottom, a ruler is used to measure the map distance between the two along the reference line. Map distance is then converted to real distance (same units as vertical distance) by multiplying by the map scale factor.

Once slope angle is established, the slope length is determined using the following equation:

$$SL = \frac{X}{\cos\ (SA)}$$

where SL = slope length.

Determination of Interzone Boundary Elevations

The elevations of the lower zone - middle zone boundary and the middle zone - upper zone boundary on the reference line are established by dividing the slope length into three sections, and calculating the elevations of the two points separating the three sections. The first step is accomplished by dividing the slope length by three.

$$IL = \frac{SL}{3}$$

where IL = incremental slope length for each section (i.e., the slope length of each zone on a given reference line).

This length is then used to determine the elevations of the two boundary points on the reference line. This second step is accomplished using the following equations:

$$E_1 = \sin(SA)(IL) + E_b$$

$$E_b = Z\ (\sin(SA)(IL)) + E_b$$

where E_1 = Elevation of lower zone - middle zone boundary

E_b = Elevation of reference line bottom (i.e., lowest intersected contour)

E_u = Elevation of middle zone - upper zone boundary.

These points are plotted on the reference line by determining which contour line elevation is closest to the given boundary point elevation. The boundary point is then plotted where the reference line intersects that countour line. Determination of slope angle, slope length, and boundary elevations for each reference line is greatly speeded by use of a programmable calculator. The program listed below is designed to calculate these values on a Hewlett Packard 34C calculator.

Program step	Program command	Program step	Program command
1	LBL-A	18	STO 2
2	RCL 0	19	RCL 3
3	×	20	SIN
4	R↓	21	STO 3
5	STO 1	22	×
6	-	23	RCL 1
7	R↑	24	+
8	÷	25	R/S
9	TAN^{-1}	26	RCL 2
10	STO 3	27	2
11	R/S	28	×
12	COS	29	RCL 3
13	R↑	30	×
14	X≷Y	31	RCL 1
15	÷	32	+
16	3	33	RTN
17	÷		

Before running this program it is necessary to store the map scale factor in storage register '0'. This scale factor must be in the same length units as the elevation values on the topographic map.

To run the program, the following data must be inputed for each reference line.

1. Enter the top elevation of the reference line in the Z register.

2. Enter the bottom elevation of the reference line in the Y register.

3. Enter the map distance between the top and bottom of the reference line in the X register.

Once initiated, the program will stop to display (in order) the slope angle, the lower inter-zone boundary elevation, and the upper inter-zone boundary elevation. With the first two stops the program is restarted by pressing the R/S key, while the last stop indicates the program has ended. New data is then entered and the program is restarted.

Connection of Boundary Elevation Points

After the inter-zone boundary elevation points have been plotted for each reference line, they are connected with their counterparts on successive reference lines to form the inter-zone boundary lines. The following are guidelines for joining related elevation points.

1. Boundary lines are drawn freehand between respective elevation points following the general bend of the contours.

2. When two related points are at different absolute elevations the boundary line must cross sufficient contours to join the two points. Draw the line so that the change in elevation is smooth over the distance between the two points. Avoid making abrupt changes in elevation with the boundary line.

3. If the reference line is the last one before the study area border, then continue the boundary line at the same elevation as marked on the last reference line to the border.

Determination of Landslide Hillslope Position

Once the study area has been divided into three zones landslide position is determined by noting in which zone each landslide is located. Landslides are plotted on the same topographic map used to establish the three zones. The position of the main scarp is then used to decide which zone represents the relative hillslope position of the failure. In cases where the main scarp is located directly on the boundary line the higher zone is recorded.

APPENDIX IV
STATISTICAL TESTS

X^2 Goodness-of-fit Analysis of Landslide Slope Angle in the Blue River Drainage

H_o: Landslide slope angles are uniformly distributed for the landslide group in question.

H_a: Landslide slope angles are not uniformly distributed for the landslide group in question.

Slope angle (°)	Observed frequency for each landslide group All	Forest	Clearcut	Road
10	1	-	1	-
25	5	2	1	2
30	14	4	6	4
35	35	3	9	23
40	56	7	12	37
45	5	2	-	3
50	2	1	1	-
X^2 statistic	155.6	7.21	22.8	70.64
Degrees of freedom	6	5	5	4
Probability of observing a test statistic ≥ the above X^2 statistic under H_o	<0.005	>0.100	<0.005	<0.005

NOTE: The symbol "-" indicates landslides did not occur at this particular angle for the group in question. This cell is not included in the X^2 analysis.

APPENDIX IV - continued

X^2 Goodness-of-fit Analysis of Landslide Slope Aspect in the Blue River Drainage

H_o: Landslide slope aspects are uniformly or specifically distributed for the landslide group in question.

H_a: Landslide slope aspects are not uniformly or specifically distributed for the landslide group in question.

Aspect	Areal coverage (%)	Observed frequency for each landslide group: All	Forest	Clearcut	Road
N	4.3	11	4	2	5
NNE	4.3	10	2	5	3
NE	2.9	1	-	-	1
ENE	7.1	3	-	-	3
E	4.3	9	3	1	5
ESE	4.3	5	1	1	3
SE	10.0	9	3	3	3
SSE	2.9	5	-	2	3
S	7.1	12	-	2	10
SSW	7.1	5	-	2	3
SW	14.3	4	2	-	2
WSW	2.9	4	2	1	1
W	5.7	6	1	1	4
WNW	1.4	6	1	3	2
NW	14.3	17	-	5	12
NNW	7.1	11	-	2	9
X^2 statistic		46.25	4.21	9.87	36.51
Degrees of freedom		15	8	12	15
Probability of observing a test statistic $\geq$ the above X^2 statistic under H_o		<0.005	>0.100	>0.100	<0.005

NOTE: The symbol "-" indicates landslides did not occur at this particular aspect for the group in question. This cell is not include included in the X^2 analysis.

[a]In this test the expected frequency was specified using the areal coverage of each aspect.

APPENDIX IV - continued

X^2 Goodness-of-fit Analysis of Landslide Hillslope Position in the Blue River Drainage

H_o: Landslide hillslope positions are uniformly distributed for the landslide group in question.

H_a: Landslide hillslope positions are not uniformly distributed for the landslide group in question.

Hillslope position	Observed frequency for each landslide group All	Forest	Clearcut	Road
Lower third	48	8	14	26
Middle third	32	7	6	19
Upper third	38	4	10	24
X^2 statistic	3.32	1.37	3.20	1.13
Degrees of freedom	2	2	2	2
Probability of observing a test statistic $\geq$ the above X^2 statistic under H_o	>0.100	>0.100	>0.100	>0.100

APPENDIX IV - continued

X^2 Goodness-of-fit Analysis of SRI Landtype Associated with Landslides in the Blue River Drainage

H_o: Landslides occur uniformly or specifically among all SRI landtypes for the landslide group in question.

H_a: Landslides do not occur uniformly or specifically in all SRI landtypes for the landslide group in question.

SRI landtype[a]	Areal coverage (%)	Observed frequency for each landslide group			
		All[b]	Forest	Clearcut	Road
3	5.1	1	1	-	-
8	6.2	15	-	5	10
13	5.6	3	1	1	1
14	0.9	1	-	-	1
16	4.8	2	-	1	1
21	4.9	36	2	10	24
23	2.0	6	-	3	3
61	0.3	1	1	-	-
132	1.5	1	1	-	-
168	3.3	10	5	2	3
201	12.0	4	-	-	4
203	9.4	8	1	-	7
210	9.1	3	-	-	3
212	4.0	12	-	3	9
231	4.3	8	5	1	2
235	5.7	2	1	1	-
313	3.9	3	-	2	1
610	1.3	1	1	-	-
X^2 statistic		186.4	13.11	26.11	92.46
Degrees of freedom		17	9	9	12
Probability of observing a test statistic $\geq$ the above X^2 statistic under H_o		<0.005	>0.100	<0.005	<0.005

NOTE: The symbol "-" indicates landslides did not occur within this particular SRI landtype for the group in question. This cell is not included in the X^2 analysis.

[a]SRI landtypes were determined by Legard and Meyer, 1973.

[b]In this test the expected frequency was specified using the areal coverage of each SRI landtype.

APPENDIX IV - continued

X^2 Goodness-of-fit Analysis of Landslide Geomorphic Setting in the Blue River Drainage

H_o: Landslides occur uniformly among all geomorphic settings for the landslide group in question.

H_a: Landslides do not occur uniformly among all geomorphic settings for the landslide group in question.

Geomorphic setting[a]	Observed frequency for each landslide group All	Forest	Clearcut	Road
Hillslope nose (PESR)	1	-	1	-
Hillslope nose	6	-	1	5
Hollow (PESR)	8	-	-	8
Hollow	6	-	1	5
Incipient drainage (DESR)	1	-	-	1
Incipient drainage (PESR)	3	-	3	-
Incipient drainage	9	2	3	4
Smooth slope (PESR)	23	4	11	8
Smooth slope	50	6	9	35
Streamside (DESR)	1	1	-	-
Streamside (PESR)	4	4	-	-
Streamside	6	2	1	3
X^2 statistic	218.6	5.32	29.73	96.68
Degrees of freedom	11	5	7	7
Probability of observing a test statistic ≥ the X^2 statistic above under H_o	<0.005	>0.100	<0.005	<0.005

NOTE: The symbol "-" indicates that landslides did not occur within this particular geomorphic setting for the group in question. This cell is not included in the X^2 analysis.

[a]PESR indicates the setting occurs within possible earthflow terrain. DESR indicates the setting occurs within definite earthflow terrain.

APPENDIX IV - continued

X^2 Goodness-of-fit Analysis of Landslide Bedrock Geology in the Blue River Drainage

H_o: Landslides occur uniformly among all bedrock type.

H_a: Landslides do not occur uniformly among all bedrock types.

Rock type	Observed frequency
Andesite	10
Breccia	8
Basalt	2
Dacite	9
Tuff	15
X^2 statistic	9.86
Degrees of freedom	4
Probability of observing a test statistic ≥ the above X^2 statistic under H_o	$0.05 < P(X^2) < 0.01$

APPENDIX IV - continued

Kruskal-Wallis One-way Analysis of Variance Test: Landslide Size Characteristics and Slope Angle vs. Land Use Association in the Blue River Drainage

H_o: The frequency distributions of each landslide size characteristic or slope angle for all land use groups are identical.

H_a: The frequency distributions of each landslide size characteristic or slope angle for all land use groups are not identical.

Characteristic tested	Kruskal-Wallis (K-W) statistic	Probability of observing a test statistic ≥ the adjacent K-W statistic under H_o[a]
Length	2.1764	>0.100
Width	0.3372	>0.100
Depth	2.0289	>0.100
Volume	0.3267	>0.100
Area	0.7942	>0.100
Slope angle	2.4840	>0.100

NOTES: (1) Sample sizes for each test: Forest group = 19; Clearcut group = 30; Road group = 69.
(2) Degrees of freedom for each test is two.

[a]Probabilities are determined using a X^2 probability table because the sample sizes are too large to use a standard K-W probability table.

APPENDIX IV - continued

X^2 Homogeneity Test: Landslide Slope Aspect vs. Land Use Association in the Blue River Drainage

H_o: Land use groups are homogeneous with respect to landslide slope aspects.

H_a: Land use groups are not homogeneous with respect to landslide slope aspects.

Aspect	Observed frequency for each land use group: Forest	Clearcut	Road
N	4	2	5
NNE	2	5	3
NE	0	0	1
ENE	0	0	3
E	3	1	5
ESE	1	1	3
SE	3	3	3
SSE	0	2	3
S	0	2	10
SSW	0	2	3
SW	2	0	2
WSW	2	1	1
W	1	1	4
WNW	1	3	2
NW	0	5	12
NNW	0	2	9

Comparison	X^2 statistic	df[a]	Probability of observing a test statistic ≥ the adjacent X^2 statistic under H_o
All groups together	37.58	30	>0.100

[a]df = degrees of freedom

APPENDIX IV - continued

X^2 Homogeneity Test: Landslide Hillslope Position vs. Land Use Association in the Blue River Drainage

H_o: Land use groups are homogeneous with respect to landslide hillslope position.

H_a: Land use groups are not homogeneous with respect to landslide hillslope position.

Hillslope position	Observed frequency for each land use group		
	Forest	Clearcut	Road
Lower third	8	14	26
Middle third	7	6	19
Upper third	4	10	24

Comparison	X^2 statistic	df[a]	Probability of observing a test statistic ≥ the adjacent X^2 statistic under H_o
All groups together	2.542	4	>0.100

[a]df = degrees of freedom.

APPENDIX IV - continued

X^2 Homogeneity Test: Landslide Geomorphic Setting vs. Land Use Association in the Blue River Drainage

H_o: Land use groups are homogeneous with respect to landslide geomorphic settings.

H_a: Land use groups are not homogeneous with respect to landslide geomorphic settings.

	Observed frequency for each land use group		
Geomorphic setting (GS)	Forest	Clearcut	Road
Hillslope nose	0	2	5
Hollow	0	1	13
Incipient drainage	2	6	5
Smooth slope	10	20	43
Streamside	7	1	3

Comparison	X^2 statistic	df[a]	Probability of observing a test statistic ≥ the adjacent X^2 statistic under H_o
All groups together vs. all GS	30.17	8	<0.005
Forest vs. Clearcut vs. all GS	10.91	4	$0.050 < P(X^2) < 0.025$
Forest vs. Road vs. all GS	19.23	4	<0.005
Road vs. Clearcut vs. all GS	6.74	4	>0.100

[a]df = degrees of freedom

APPENDIX IV - continued

X^2 Goodness-of-fit Analysis of Landslide Occurrence within SRI Landtype 21 and Northern Aspects for Land Use Groups in the Blue River Drainage

H_o: Landslides occur uniformly among the land use groups compared below under the conditions specified.

H_a: Landslides do not occur uniformly among the land use groups compared below under the conditions specified.

Land use group	Observed frequency
Forest	1
Clearcut	9
Road	17

Comparison	X^2 statistic	df[a]	Probability of observing a test statistic ≥ the adjacent X^2 statistic under H_o
All groups together	14.22	2	<0.005
Forest vs. Clearcut	6.40	1	$0.025 < P(X^2) < 0.010$
Forest vs. Road	14.22	1	<0.005
Clearcut vs. Road	2.462	1	>0.100

[a]df = degrees of freedom

APPENDIX IV - continued

X^2 Goodness-of-fit Analysis of Landslide Occurrence Among Land Use Groups in the Blue River Drainage

H_o: Landslides occur uniformly among all land use groups.

H_a: Landslides do not occur uniformly among all land use groups.

Land use group	Observed frequency
Forest	19
Clearcut	30
Road	69

Comparison	X^2 statistic	df[a]	Probability of observing a test statistic ≥ the adjacent X^2 statistic under H_o
All groups together	35.10	2	<0.005
Forest vs. Clearcut	2.47	1	>0.100
Forest vs. Road	28.41	1	<0.005
Clearcut vs. Road	15.36	1	<0.005

NOTE: Record period: Forest = 34 years; Clearcut = 22 years; and Road = 25 years.

[a]df = degrees of freedom

APPENDIX IV - continued

Kruskal-Wallis One-way Analysis of Variance:
Ground Area Affected vs. Land Use Association
in the Blue River Drainage

H_o: The distributions of ground area (hillslope and channel) affected by landslide occurrence is the same for the three land use groups.

H_a: The distributions of ground area affected by landslide occurrence are not the same for the three land use groups.

Land use group	Sample size
Forest	6
Clearcut	24
Road	55
Kruskal-Wallis statistic	1.18
Degrees of freedom	2
Probability of observing a test statistic ≥ the above K-W statistic under H_o[a]	>0.100

[a]Probability is obtained using a X^2 probability table as the sample sizes are too large to use a standard K-W probability table.

APPENDIX IV - continued

X^2 Goodness-of-fit Analysis of Stream Class Entries by Landslides for Class I, II, and III Streams in the Blue River Drainage

H_o: Stream entries by landslides are proportional to stream class length.

H_a: Stream entries by landslides are not proportional to stream class length.

Stream class	Observed frequency
I	6
II	8
III	6

X^2 statistic	0.28
Degrees of freedom	2
Probability of observing a test statistic $\geq$ the above X^2 statistic under H_o	>0.100

NOTE: Expected frequencies were calculated based on the stream length of each stream class. These stream lengths were determined from a stream class map of the Blue River Ranger District which is on file at the Willamette National Forest Supervisors Office, Eugene, Oregon.

APPENDIX IV - continued

X^2 Goodness-of-fit Analysis of Stream Entries by Landslides for Land Use Groups in the Blue River Drainage

H_o: Stream entries by landslides occur uniformly among the land use groups.

H_a: Stream entries by landslides do not occur uniformly among the land use groups.

Land use group	Observed frequency
Forest	16
Clearcut	14
Road	37

Comparison	X^2 statistic	df[a]	Probability of observing a test statistic ≥ the adjacent X^2 statistic under H_o
All groups together	14.54	2	<0.005
Forest vs. Clearcut	0.13	1	>0.100
Forest vs. Road	8.32	1	<0.005
Clearcut vs. Road	10.37	1	<0.005

[a]df = degrees of freedom

APPENDIX IV - continued

X^2 Homogeneity Test: Stream Class Entries by Landslides vs. Land Use Association in the Blue River Drainage

H_o: The three land use groups are homogeneous with respect to the stream class entered by landslides.

H_a: The three land use groups are not homogeneous with respect to the stream class entered by landslides.

	Observed frequency for each land use group		
Stream class	Forest	Clearcut	Road
I	2	0	4
II	1	4	3
III	0	1	5
IV	13	9	25

Comparison	X^2 statistic	df[a]	Probability of observing a test statistic ≥ the adjacent X^2 statistic under H_o
All groups together	8.49	6	>0.100

[a]df = degrees of freedom

APPENDIX IV - continued

X^2 Goodness-of-fit Analysis of Road-related Landslide Occurrence by Road Class in the Blue River Drainage

H_o: Landslide frequency for each road class is proportional to the length of each road class.

H_a: Landslide frequency for each road class is not proportional to the length of each road class

Road class	Observed frequency	Total road length (km)
Arterial	3	17.94
Collector	18	46.20
Local	45	44.87

X^2 statistic	20.96
Degrees of freedom	2
Probability of observing a test statistic $\geq$ the above X^2 statistic under H_o	<0.005

APPENDIX IV - continued

X^2 Goodness-of-fit Analysis of Road-related Landslide Occurrence in the Blue River Drainage

H_o: Landlside failures are uniformly distributed between fill and cut slopes.

H_a: Landslide failures are not uniformly distributed between fill and cut slopes.

Road component	Observed frequency
Cut slope	20
Fill slope	48
X^2 statistic	11.53
Degrees of freedom	1
Probability of observing a test statistic ≥ the above X^2 statistic under H_o	<0.005

APPENDIX IV - continued

Mann-Whitney Test: Area Affected by Road-related Landslide Occurrence vs. Road Component in the Blue River Drainage

H_o: The size distribution of the area affected by road related failures is the same for both fill and cut slope failures.

H_a: Fill slope failures tend to affect a larger area than cut slope failures.

	Road component	
	Cut slope	Fill slope
Sample size	20	48
Sum of ranks in combined sample	582	1764
Test statistic (T)[a]	372	588
Probability of observing a T statistic ≥ 588 under H_o[b]	n/a[c]	0.0735

[a]This particular one-tailed Mann-Whitney test statistic is described in Daniel, 1978.

[b]Probability was determined using a large-sample approximation for the Mann-Whitney test statistic.

$$Z = \frac{T - n_1 n_2/2}{\sqrt{n_1 n_2 (n_1 + n_2 + 1)/12}}$$

[c]n/a = not applicable

APPENDIX V

LANDSLIDE AREAL FREQUENCY: A COMPARISON OF THE CONVENTIONAL CALCULATION METHOD AND THE CUMULATIVE AREA PER UNIT TIME METHOD

The conventional and cumulative area per unit time (CAT) methods are two techniques for determining landslide areal frequency. The former has been used frequently in past research (Morrison, 1977; Swanson and Dyrness, 1975; Swanston and Swanson, 1976; Swanson et al., 1977, 1981). The latter has only been proposed recently (Swanson et al., 1977, 1981) and, to my knowledge, has only been applied once (Swanson et al., Appendix A, 1977). Both methods contain an implicit assumption that the area for which the landslide areal frequency is calculated is homogeneous with respect to the factors which affect landslide occurrence. To understand how these methods differ and which is the more accurate, it is first necessary to examine what landslide areal frequency represents, and how the factors of time and space are integrated to measure the "opportunity" for landslides to occur.

Landslide areal frequency is the rate of landslide occurrence per unit of associated land area per unit of time. It combines the temporal frequency of landslide occurrence (no. events/time) with the corresponding spatial frequency (no. events/area). It is composed of three factors: (1) the total number of landslides occurring within an area defined as being associated with these landslides; (2) the total size of this associated area; and (3) the time period over which the landslides occurred. Determination of the first and third factors is straightforward; a time period is defined and the number of landslides occurring within that period is counted. When the associated area is constant throughout the time period, its determination is also clear; the area is simply measured to determine its size. Under the condition of constant area size, landslide areal frequency is calculated as follows:

$$\text{Landslide areal frequency} = \frac{n}{a \cdot t} \qquad (1)$$

where n = total landslide number
a = total size of the associated area
t = length of time record.

When the associated area is not constant throughout the time in question, its determination is not readily apparent. How this area is determined when its size changes with time is the fundamental difference between the conventional and CAT methods.

The product of area and time ($a \cdot t$) in Equation 1 may be thought of as a measurement of landslide "opportunity". Opportunity means the chance that landslides have had to occur. Obviously, many factors influence this chance, but, as stated earlier, it is assumed that the area in question is homogeneous with respect to these factors. Under this assumption then, landslide opportunity is controlled by the area size and length of time involved. At any instant in time, the larger the area considered, the greater the chance that landslides will occur within it. Similarly, for any given sized area, the longer the time period over which it is observed, the greater the chance that landslides have occurred.

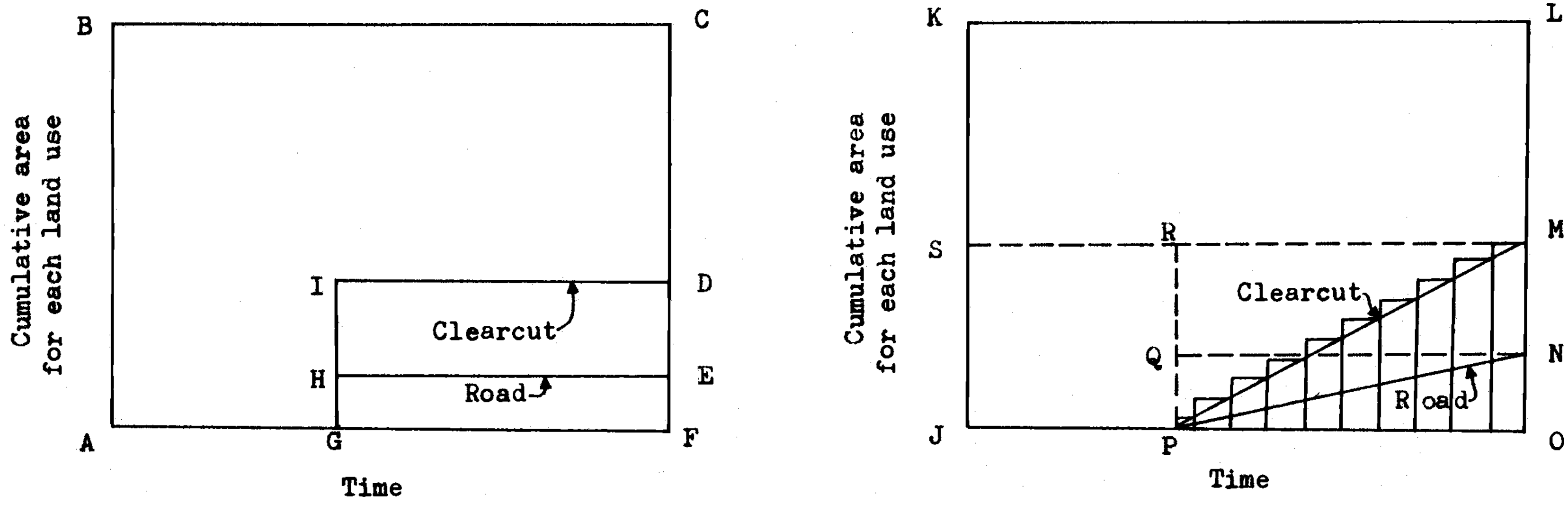
The total chance landslides have had to occur under specified conditions of place and time may be called the total landslide opportunity (TLO). Because this chance increases or decreases with changes in area and time, TLO must be a cumulative measurement which accounts for the passage of time and changes in area size. For example, the TLO for an area which is 30 ha in size for three years, then increases to 45 ha in the fourth year and remains at 45 ha for an additional year, increases in the following manner:

Year	TLO (ha • yr)
1st	30
2nd	60
3rd	90
4th	135
5th	180

For any given year the TLO is larger than the value for the preceding year because of an increase in time and/or area.

The concept of landslide opportunity can also be illustrated graphically. The case where area size remains contant through time for clearcut and road areas is shown in Figure 12(a). $\overline{GI}$ and $\overline{GH}$ represent the size of the clearcut and road areas, respectively, and $\overline{GF}$ represents the time period over which these areas are observed. The graph areas contained within polygons GIDF and GHEF represent the respective TLO values for each land use area at the end of the time period (point F).[15] At any given time before point F the TLO could be determined by plotting the vertical line which represents this new

[15]The actual TLO value is equal to the graph area of each polygon times the scale factor of the graph (a constant). This multiplication is necessary to produce the actual TLO values which are used in calculations to be discussed later in this section. However, this multiplication is not necessary to show relative differences in TLO values. For this discussion it is only necessary to identify general differences. As the polygon areas in Figure 12 accurately represent relative TLO values, comparisons between these graph areas are sufficient.



(a) Clearcut and Road Areas Constant through Time

(b) Areas Vary through Time

NOTES: (1) Forest area for any given year is found by subtracting the sum of the clearcut and road areas for that year from the total area (i.e., $\overline{AB}$ or $\overline{JK}$).

(2) Polygon areas delineated by solid lines (e.g., PNO) represent actual total landslide opportunity (TLO).

(3) Polygon areas delineated by dashed and solid lines (e.g., PQNO) represent TLO determined by the conventional method of landslide areal frequency calculation.

(4) The areas within the series of rectangles intersecting $\overline{PM}$ represent the individual opportunities associated with each time interval of $\overline{PO}$ for the clearcut area as determined by the Cumulative Area per unit Time method of areal frequency calculation (after Swanson et al., 1977). TLO for the clearcut area is represented by the sum of the individual opportunities.

Figure 12. Graphical Illustration of the Difference in Determination of Total Landslide Opportunity with Variation in Land Use Area through Time

ending date and measuring the graph areas of the newly formed polygons. Note that at any given year when area size is constant,

$$TLO = a \cdot t \qquad (2)$$

This is not true for the forest area in Figure 12(a) because forest area size changes through time.

The case where area size varies through time for all three land use areas is shown in Figure 12(b). Area size increases from zero at point P to $\overline{MO}$ and $\overline{NO}$ at the end of the time period (point O) for clearcut and road areas, respectively. The period of record for both of these areas is $\overline{PO}$. Forest area decreases with time, starting from $\overline{JK}$ and ending at $\overline{ML}$ over a record period of $\overline{JO}$. The TLO at the end of the record period is again represented by polygons JKLMP, PMO, and PNO for the forest, clearcut, and road areas, respectively. As before, the TLO values at any particular year can be determined by plotting the new ending date and determining the graph areas of the new polygons in question. However, unlike the constant area situation, Equation 2 cannot be applied for any of the three land use areas to determine respective TLO values.[16]

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[16]It may be possible when area size varies with time to find a single area value which, when used in Equation 2, would yield a TLO value equivalent to that determined from the area of a polygon; however, the accuracy of using a single value would be unknown unless the actual TLO value was determined. To my knowledge, actual TLO values can only be measured graphically or by tabular summation when area varies with time. Therefore the area of Equation 2 would either be inaccurate or redundant.

Landslide areal frequency can now be redefined as the rate of landslide occurrence per unit of opportunity that has existed for each land use area. The TLO for each land use group accounts for the size of area within each land use, the length of time over which the land use area is observed, and any changes in area size during this period. The equation for areal frequency can now be written:

$$\text{Landslide areal frequency} = \frac{n}{\text{TLO}} \qquad (3)$$

When area size is constant through time Equation 2 may be substituted for TLO so that

$$\text{Landslide areal frequency} = \frac{n}{a \cdot t}$$

When area size varies through time then TLO must be determined by some other technique. It is now possible to examine how the conventional and CAT methods determine TLO when area size varies with time, and consequently how accurate these methods are in determining landslide areal frequency.

<u>Conventional Method</u>

Equation 1 is used in the conventional method to calculate landslide areal frequency. The area sizes existing at the end of the record period are used for "a" in this method. These values are represented by $\overline{DC}$, $\overline{FD}$, and $\overline{FE}$ in Figure 12(a) and $\overline{ML}$, $\overline{OM}$, $\overline{ON}$ in Figure 12(b) for forest, clearcut, and road areas, respectively. When area size is constant through time, this single area value can be used in this method to accurately represent the respective TLO values (Figure

12(a)). The resulting areal frequencies are an accurate measurement of landslide rate per unit opportunity.

When area size varies through time, however, the use of these particular area size values results in inaccurate representations of TLO values for the three land use areas. Polygons SKLM, PRMO, and PQNO in Figure 12(b) represent the TLO values as determined using the conventional method for the forest, clearcut, and road areas, respectively. The calculated TLO for the forest area is much smaller than the actual TLO (polygon JKLMP). An areal frequency value calculated using this low TLO value will be too high because the divisor (TLO) is too small. Landslide activity will therefore appear greater than it actually is when the conventional method is used. In contrast, the TLO representations for clearcut and road areas are larger than the actual TLO values (polygons PMO and PNO, respectively). Consequently, the divisors are too large for these areas and their areal frequency values are too low. Landslide activity appears less than what it actually is in these areas using the conventional method.

CAT Method

The following equation is used in the CAT method to compute landslide areal frequency:

$$\text{Landslide areal frequency} = \frac{n}{\sum_{i=1}^{j} a_i t_i} \qquad (4)$$

where a_i = the associated area size during the ith time interval (a_i = area size at time t_i)

t_i = the length of time during the ith time interval

$i=1...j$ = index symbols representing the series of time intervals which subdivide the record period (t). Each time interval is marked by a change in associated area size.

With this method TLO is determined using the following steps:

1. Determine cumulative area size (a_i) at each time it is known to have changed (t_i).
2. Determine the length of the time intervals between each time of known area size change ($t_i - t_{i-1}$).
3. Calculate the individual landslide opportunities associated with each time interval ($a_i t_i$), assuming that the area size for that interval is constant at a value equal to that at the upper time endpoint.
4. Sum the individual opportunities for all time intervals to get the TLO value.

The mechanics of the CAT method are illustrated in Figure 12(b) for the clearcut area. The sum of the rectangle areas, which represent the individual opportunities associated with each time interval, represents the TLO for the clearcut area. This technique is equivalent to approximation techniques for integration.

The CAT method is more accurate than the conventional method when area size varies through time because the CAT method estimates TLO more accurately. As more cumulative area size values are used in the CAT method, it is possible to follow the change in the cumulative area curve (e.g., $\overline{PM}$) more closely and thus estimate the area beneath that curve (polygon PMO) more precisely than the conventional method. A more accurate divisor (TLO) yields more realistic areal frequency values. The only time that the conventional method would approach the accuracy of the CAT method would be when area size changes are very small. When area size is constant, then Equation 4 reduces to Equation 1 and the two methods produce the same result.

The degree of precision available using the CAT method is dependent on the number of times cumulative area size is determined. The greater this number, the more accurate the resulting areal frequency values.

An alternative to the tabular summation which is described above is to plot cumulative area vs. time, directly measure the graph area under the curve representing land use area, and convert this graph area to TLO values using a scale factor (e.g., 1 cm^2 = 100 ha-yr). This alternative method is the one used in this study. Graph areas were measured from Figure 3 using a sonic digitizer. I am not sure which CAT technique, the graphical or tabular, is the most accurate; however, it is certain that either is more accurate than the conventional method.