CHARACTERISTICS OF MANAGEMENT-RELATED DEBRIS FLOWS, NORTHWESTERN CALIFORNIA[1]

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Abstract: An inventory of landslides in the lower Redwood Creek basin, California showed that erosion due to shallow landslides has been accelerated by logging-road and skid trail construction. The analysis of landslides occurring during the 1981-82 rainfall season showed that all debris flows (40) originated from roads or skid trails on slopes with gradients of at least 30 degrees. Furthermore, 90 percent of the inventoried features originated less than 30 meters below a major convex break-in-slope and 87.5 percent of the failures occurred in a poorly drained soil having a mottled horizon less than one meter from the surface. These site characteristics commonly occur at the headwaters of ephemeral drainages or in streamside gorge slope positions. Results of this study are being applied in an erosion control program to selectively identify road reaches with high failure potential.

Since the expansion of Redwood National Park in 1978 to include nearly 13,000 hectares of cutover forest lands in the lower Redwood Creek basin, no severe storms ($T_r \geq 5$ yrs) have impacted the area. However, the winter of 1981-82 produced several moderate precipitation events which resulted in numerous shallow hillslope failures on steep forest land in the area. An inventory and analysis of the resultant debris slides, avalanches, flows and torrents was accomplished in 1982. These failures are hereafter collectively referred to as debris flows, reflecting the dominant type of failure (Varnes, 1958).

The purpose of the study was to develop a better understanding of the hillslope processes and to develop criteria useful for selecting mass erosion prone sites for treatment in an ongoing erosion control program. Previous studies in the northwestern United States have described and quantified characteristics of shallow landslides on forest steeplands (Dyrness, 1967; Swanson and others, 1981; Gresswell and others, 1979). Computer assisted multivariate analysis of a wide spectrum of site characteristics has been used to predict the loci of landslide occurrence (Rice, 1967; Furbish and Rice, 1983; Neely, 1983). This study examined some common field associations recognized by other researchers as well as additional factors which were associated with debris flow location and hillslope failure in the study area.

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STUDY AREA

The study area comprises 200 km^2 of Redwood National Park located in the lower Redwood Creek basin, northwestern California (fig. 1). Approximately 34 percent of the study area is virgin redwood forest, 51 percent has been clearcut and tractor yarded and 7 percent has been clearcut and cable yarded. The Redwood Creek basin lies within the rugged Coast Range province and is underlain by folded and sheared sandstones, mudstones and schists of the Franciscan assemblage (Harden and others, 1982). The region is subject to high erosion rates due to geologically rapid tectonic uplift, the pervasively sheared and faulted condition of the underlying lithologies and the imprint of complex, highly disruptive landuse activities (Janda and others, 1975). The Mediterranean climate results in an annual average precipitation of 205 cm occurring mostly as rain during a single eight-month period.

METHODOLOGY

A total of 40 recently activated debris flows, visible in June 1982 during low altitude aerial reconnaissance flights, was included for this analysis. The entire study area was aerially searched to avoid biases created by reliance on ground observations which tend to miss failures in non-roaded terrain. Locations of debris flows were plotted on a master inventory map (1:48000). True color (1:6000), color infrared (1:25000) and black and white (1:12000) aerial photographs were examined to gain topographic, hydrologic and historical information. A field inventory addressing 39 variables was completed for each failure. Lengths, widths, and runout distances were measured with an optical range finder. Failure depths were estimated. Aspect and hillslope gradients were measured with compass and clinometer, respectively. Distance to streams and

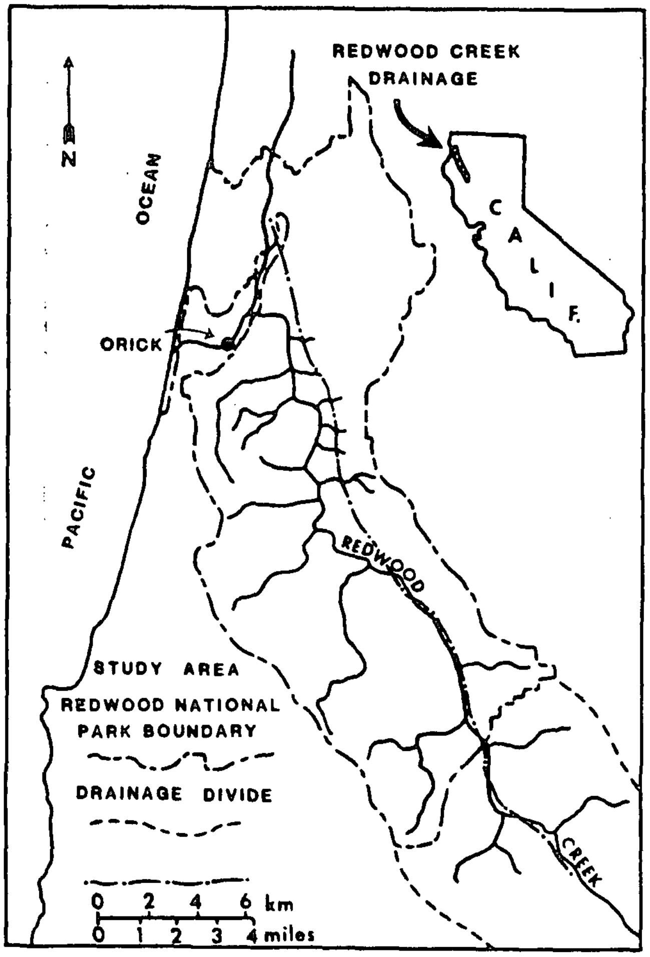

Figure 1--Location map of the lower Redwood Creek basin, Northwestern California, U.S.A. Study area is encompassed by Redwood National Park boundary.

major convex breaks in slope were estimated and hillslope morphology was categorized as planar, concave or convex along horizontal and downslope axes. Spatial relationships of the landslides to roads, skid trails and harvest units were also noted.

Soil characteristics were identified from exposures of the soil profiles at landslide scarps or adjacent road cutbanks. Soil texture was judged by feel and diagnostic surface and subsurface soil horizons were determined. Where exposures permitted observation of the underlying lithology, total depth of the regolith, bedrock competency and dip of bedding or foliations was documented.

Continuous rainfall records were obtained from two tipping bucket precipitation recorders located within the study area. Additional hydrologic data collected during field inspections included the location of surface water flow routes, ponded water, springs, and the presence of vigorous hydrophilic vegetation.

RESULTS

The inventoried debris flows deposited about 14,000 cubic meters of sediment into intermittent and perennial streams. Two thirds of that volume was deposited by a single debris torrent (fig. 2F and 3).

The first and most intense storm known to have induced many of the slope failures occurred on 19 December 1981. The maximum recurrence interval for the storm was only 3 years for the 24-hour total of 160 mm. However, that storm was preceded by 80 cm of rain over the preceding 38 days (fig. 4). The recurrence intervals for shorter durations for the same storm were less than 2 years (Miller and others, 1973).

Although the failure dimensions varied widely (fig. 2), the debris flow source areas exhibited several important similarities (table 1). The most prominent similarity was that all of the debris flows originated in landing, road or skid trail sidecast material where the local hillslope gradients exceeded 30 degrees. More than half of the failures had multiple skid trails crossing the source area.

A bimodal distribution of failures on the hillslope profile was found to coincide with the typical occurrence of two convex slope breaks in the area. Ninety percent of the failures occurred less than 30 meters below these major convex slope breaks. The two steep, convex sections of the hillslope, illustrated in figure 5, are inherently geomorphically active zones. The upper convexity is formed as a result of headward downcutting of an uplifted surface by first and second order streams. The lower "inner gorge" areas are formed by rapid incision of higher order streams into stream valleys. Consequently, the oversteepened slopes at both locations are prone to landsliding.

Another important topographic relationship noted was the tendency for failures to originate in minor swales at the heads of ephemeral drainages (figs. 5 & 6). At these locations, culverts or other drainage provisions through the road prism were noticeably absent.

Eighty-eight percent of the features were located in a single soil type characterized as a moderately deep (>1.5 meters) inceptisol having a fine-loamy texture overlying saprolitic schist. This soil exhibits mottling in a subsurface g-horizon within one meter of the surface. The mottled g-horizon is significant because it develops in poorly drained soils as a result of periodically saturated conditions (Brady, 1974).

The inherently wet conditions of most of the failure sites were often revealed by the presence of springs and unusually dense and vigorous hydrophilic vegetation including Red alder (*Alnus rubra*) and rushes (*Juncus* sp.). Color infrared aerial photographs highlighted vigorous vegetative growth on wet sites indicative of persistently shallow groundwater.

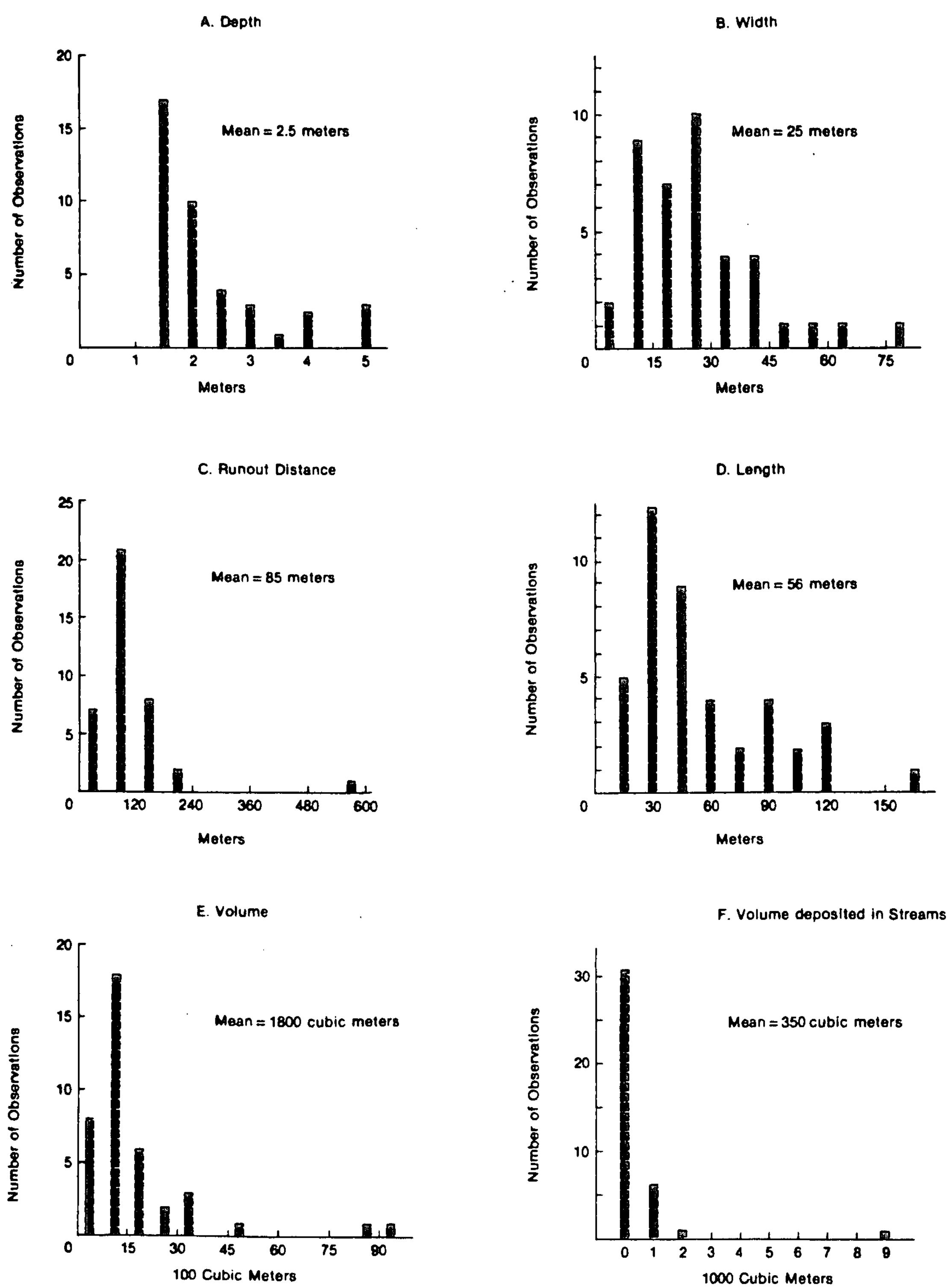

Figure 2—Histograms of A) depths, B) widths, C) runout distances, D) lengths, E) volumes and F) sediment delivery to intermittent and perennial streams. Data collected from 40 debris flows active during Winter, 1981-1982, lower Redwood Creek basin, California.

Figure 3—Debris torrent which deposited 9000 cubic meters of sediment into a perennial stream over 500 meters downslope. Note: 1) the failure originated below a major convex slope break at the headwaters of an ephemeral stream, 2) the road is totally sidecast fill with no cut.

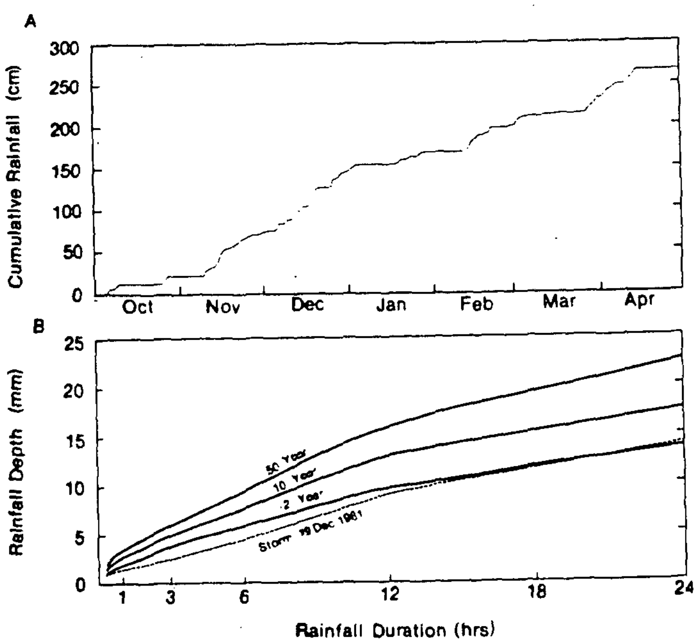

Figure 4--A) Cumulative precipitation for the lower Redwood Creek basin, 10Oct1981 through 30Apr1982. B) Precipitation depth versus duration showing storm recurrence intervals and the rainfall of 19Dec1981. That storm triggered numerous road failures and was preceeded by 80 cm of rain over 38 days.

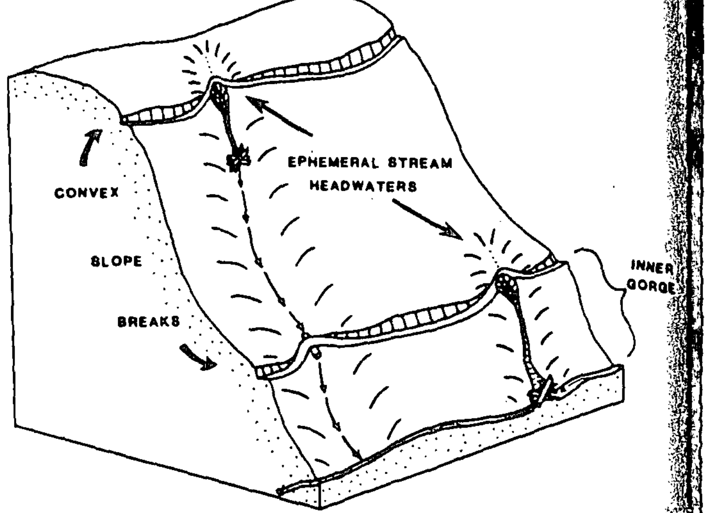

Figure 5—Diagrammatic view illustrating debris flow prone locations in ephemeral stream headwater and inner gorge areas below convex slope breaks.

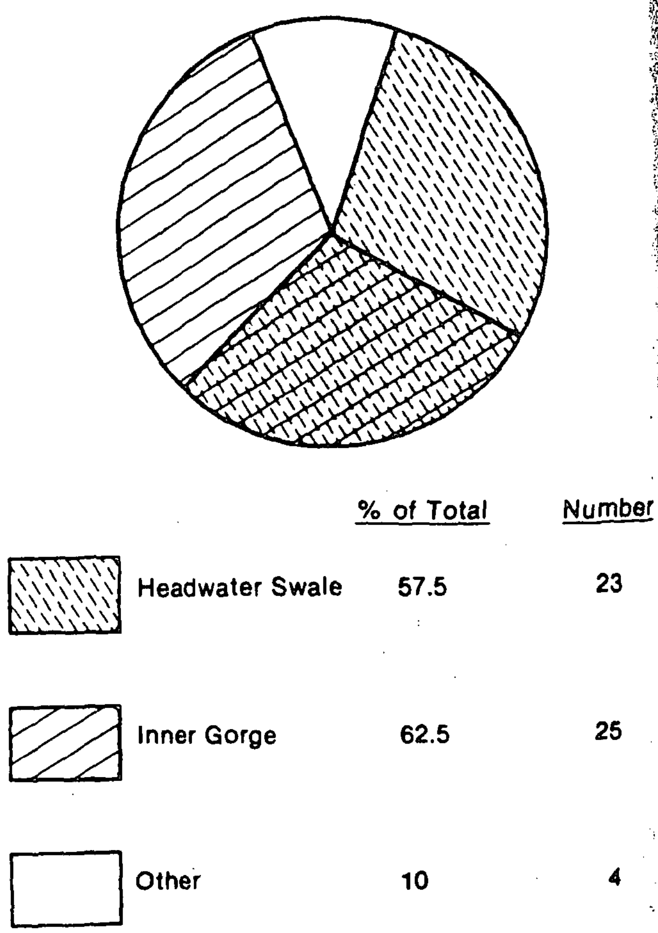

Figure 6--Topographic position of debris flows, lower Redwood Creek basin, Winter 1981-1982.

Table 1--Common associations of debris flows and other site variables in the lower Redwood Creek Basin, Winter 1981-1982.

Site Variables	Number of Debris Flows	Percent of Total
1) Origin at:		
a. Road or Landing	22	55
b. Skid Trail	18	45
Total	40	100
2) Hillslope Gradient>30°	40	100
3) <30 Meters Below Slope Convexity	36	90
4) Soil exhibits Mottling<1m Deep	35	88

DISCUSSION

The ability to define specific areas with high failure potential is essential to effectively manage forest steeplands. Through the analysis of various extrinsic and intrinsic factors potentially related to landsliding, high risk areas may be delineated. The methodology employed in this inventory and analysis can be utilized elsewhere to pinpoint sensitive areas and compile an appropriate set of diagnostic criteria for risk classification.

This study has shown that the greatest potential for slope instabilities in the study area occur where roads and skid trials cross steep slopes and wet soils located in headwater swales or along inner gorge slope positions. These findings agree in part with other studies done in the region.

Neely (1983) tested a proposed erosion hazard rating system for logging-related debris slides in Northern California (California Board of Forestry, 1981) and found that only four criteria were significant in predicting debris slide locations in his study area. Those factors were: 1) slope gradient, 2) distance to springs, 3) distance to a major convex break-in-slope, and 4) density of incipient drainages (swales). Neely's results, indicating that the greatest instabilities occur on steep, wet hillslopes beneath major convex slope breaks, corroborate the results of this investigation.

Gresswell and others (1979) pooled data from forest lands which show that 70 percent of landslides in the northwestern United States are related to roads and the greatest number of these are sidecast fill failures. Swanston (1974) contends that roads cause failures due to slope loading, inadequate provision for slope and road drainage and oversteepened cutbanks. Direct severence or burial and subsequent decay of forest root systems also decrease hillslope stability (Ziemer, 1981).

As suggested by this study, an additional factor to be considered is the potential influence of road fills on natural subsurface flow characteristics. As forest roads cross a hillslope, the fill/cut ratio is greatest within swales. The weight of these deep, wide fill wedges may compact underlying soil horizons thus reducing their permeability. Consequently, subsurface flows which naturally concentrate in topographic depressions are restricted causing elevated pore water pressures beneath the road prism (fig. 7). Furthermore, a cap of structureless and permeable sidecast fill prevents exfiltration and relief of building pressures. As a result, continued buildup of pore water pressure beneath and within the road prism may lead to eventual failure.

Although the landslides observed during this study were clearly associated with road

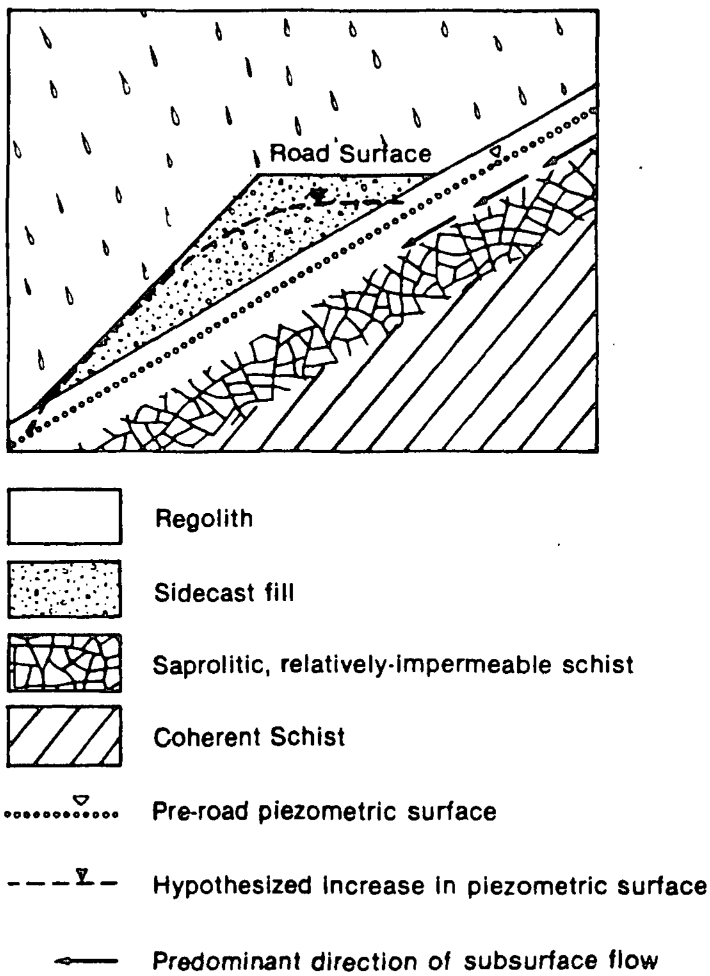

Figure 7--Diagrammatic cross section of forest road having no cut into hillslope. Dual piezometric surfaces show hypothesized conditions before and after road construction.

construction, it should not be inferred that only roaded sites in the study area are unstable. However, this study does confirm that roads decrease the stability of geomorphically active sites. The fact that no debris flows were found in non-roaded areas only indicates that the failure thresholds for these locations were not exceeded.

If a geomorphic threshold for landsliding is defined as a ratio of driving and resisting forces, hillslope failure occurs when the ratio become unity (Bull, 1980). This mechanistic definition, also known as the factor of safety, has been used extensively in slope stability analyses. Ward and others (1981) used a factor of safety model to predict general landslide hazards on forest hillslopes in southeast Alaska. More detailed stability analyses covering large forest management units are impractical. Since the intrinsic variables influencing slope stability such as cohesion and frictional strength vary spatially, attempts to identify absolute threshold values should be approached on a site specific basis. Therefore, it is crucial to identify additional criteria, such as soil characteristics or microtopographic position, which will limit the areas requiring further analysis.

CONCLUSIONS

The short period of record for timber harvesting on steep and unstable hillslopes prevents a direct magnitude-frequency analysis for debris sliding. However, utilizing a mechanistic analysis of hillslope stability, it may be possible to define a set of recurrence intervals for the conditions for which a landslide threshold is attained. The intrinsic variables within the factor of safety equation can be measured or derived for a particular site and act as constants for stability calculations. Because porewater pressure ultimately induces slope failure, it is the recurrence interval of the piezometric surface, not rainfall, for which estimates need to be determined.

Obviously rainfall creates fluctuations in piezometric levels. Where rainfall records are available, precipitation could be a surrogate variable potentially suitable for analysis. However, studies using stochastic methods to directly correlate precipitation with debris flow occurrence (Caine, 1980; Wieczorek and Sarmiento, 1983) have yielded inconclusive results.

A more suitable approach for magnitude-frequency analyses was taken by Swanston (1967), who utilized piezometric data to define a precipitation-piezometric head relationship for some thin soils in southeast Alaska. To develop such a predictive model for deeper colluvium-derived soils, current research at Redwood National Park involves continuously monitoring precipitation and piezometric levels at roads in debris flow prone locations. Through these efforts, we hope to more closely define both the precipitation-pore pressure relationship and the influence of road location on subsurface flow regimes.

There are several methods available to reduce debris flows related to construction of new roads, maintaining existing roads and rehabilitation of abandoned roads. Most obviously, sensitive slopes can be delineated and avoided when new roads are built. Total mileage requirements for new roads can be reduced by increasing road spacing in conjunction with complementary yarding systems (e.g. multiple span skylines, balloon or helicopter yarding). Road alignments which closely follow contours of the slope reduce the volume of sidecast fill placed in swales. Permeable blankets or horizontal drains can be used to improve drainage of the road prism and underlying soils. Finally, structural reinforcement of fillslopes can be an effective means of preventing fillslope failures on new and existing roads.

The erosion control program at Redwood National Park concentrates on erosion control and prevention by the excavation of unstable fill material from abandoned roads and skid trails. Results of this study are being used to selectively identify those road sections with high failure potential. Such specific road or skid trail reaches receive more extensive treatments including total fill removal. The ability to selectively prioritize treatment sites has helped to optimize the cost-effectiveness of logging road rehabilitation.

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