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PREDICTING LANDSLIDES RELATED TO CLEARCUT LOGGING, NORTHWESTERN CALIFORNIA, U.S.A.

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ABSTRACT Landslides related to clearcut logging are a significant source of erosion in the mountains of northwestern California. Forest managers, therefore, frequently must include assessments of landslide risk in their land-use plans. A quantitative method is needed to predict such risk over large areas of rugged mountainous terrain. From air photographs, data were collected of conditions associated with a sample of logging-related slides and randomly located stable sites. Discriminant analyses were used to develop an equation that distinguishes the two types of sites-slide and non-slide-with 81 percent accuracy. The equation can be used to provide an assessment of risk for undisturbed terrain. Results showed that post-logging failure is most likely to occur near actively scouring streams, just below major convex breaks of slope and within drainage depressions.

RÉSUMÉ *La prédiction des glissements de terre liés à la coupe à blanc dans les foréts de la Californie du Nord-Ouest, U.S.A.* Les glissements de terre liés à la coupe à blanc constituent une source importante de 1'érosion dans les montagnes de la Californie du nor-ouest. L'aménagement des terres doit donc fréquemment inclure une évaluation du danger de glissements. L'élaboration d'une méthode quantitative s'impose si l'on veut aboutir à des prévisions de risques propres aux terrains raboteux. A l'aide de la photographie aérienne, on a mesuré les conditions associées à un échantillon de glissements se rapportant à l'exploitation forestière et aux sites stables situés à proximité et prélevés au hasard. On s'est servi d'analyses discriminantes pour développer une équation qui distingue entre les deux sortes de sites avec une exactitude de 81 % . On peut utiliser cette méthode pour mesurer le danger des terrains non affectés. Selon les résultats il existe une plus forte probabilité que les glissements qui suivent la coupe de bois se produiront près des ruisseaux active ment érosifs, juste au-dessous des grandes interruptions de pente convexes et à l'intérieur des dépressions de drainage.

ZUSAMMENFASSUNG *Die Vorhersage von Erdrutschen als Folge von Kahlschlag in Nordwestkalifornien, USA*. Erdrutsche, die mit Kahlschlag in Verbindung gebracht werden, sind eine wichtige Erosionsursache in den Bergen von Nordwestkalifornien. Aus diesem Grund muß in Landnutzungsstudien das Erdrutschrisiko berücksichtigt werden. Um dieses Risiko für ein ausgedehntes, zerklüftetes, gebirgiges Gelände vorherzusagen, bedarf es einer quantitativen Methode. Durch Luftaufnahmen wurden Daten von Gebieten gesammelt, deren Erdrutsche mit Kahlschlag verbunden waren and ebenso Daten von willkürlich ausgewählten, stabilen Gebieten. Aus dem Vergleich beider Daten wurde eine Gleichung abgeleitet, die es erlaubt, die beiden Geländearten (stabil and instabil) mit 81 % Genauigkeit zu unterscheiden. Diese Methode ist nützlich, um das Erdrutschrisiko in unberührtem Terrain abzuschätzen. Man findet Erdrutsche häufiger in der Nähe von auswaschenden Bächen, unterhalb konvex gewölbter Hänge and in Einzugsbereichen.

INTRODUCTION

Erosion in the form of landslides is a critical problem for forest managers who must frequently assess landslide risk as a significant part of land-use planning. In rugged mountainous terrain the risk of landslides is naturally high. As humans expand their land-resource base to include the mountains, it becomes increasingly necessary to use quantitative methods to evaluate landslide risk over large areas (Caine and Mool, 1982).

Landslides of the debris-avalanche type frequently occur after clearcutting of steep hillslopes because soil-regolith strength is lost as a result of root decay (Fujiwara, 1970; Burroughs and Thomas, 1977; Ziemer, 1981a and b). Of lesser importance, in most environments, is increased soil moisture as a result of reduced evapotranspiration (Gray, 1969; Rice, 1977). Existing hillslope stability models, pioneered by Terzaghi (1950), can be used to evaluate the risk of soil or rock failure at specific sites with reasonable confidence. But such models are impractical for assessing landslide risk over large areas.

This paper discusses a method for predicting where landslides of the debris-avalanche type are likely to occur after clearcutting of steep slopes in northwestern California. The techniques are based on discriminant analysis of conditions associated with slide and non-slide sites, and are similar to those described by Rice (1967) and used by Rice and Pillsbury (1982). The method can be modified for use in landslide situations not associated with logging or in areas where geomorphic factors are significantly different from those of northwestern California.

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STUDY AREAS

Clearcut patches from the entire Six Rivers National Forest (the SRNF) and the combined catchments of Hurdygurdy and Jones Creeks (the HJC) were sampled (Figure 1). The HJC as used for a pilot study to develop a risk-rating method.

The SRN lies within the Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) region of the Klamath and Coast Range Mountains. The northern half is in the Klamath Province and the southern half is within the Coast Range. The mean annual precipitation ranges from 100 to 315 cm (Rantz, 1968).

The HJC catchment, 140 square kilometres in area, in the northern part of the SRNF, is 32 km from the Pacific Ocean (Figure 1). Terrain is rugged-elevation ranges from 180 to 1,615 m. Precipitation averages 240 cm annually.

Structurally complex, heterogeneous, and highly frac-

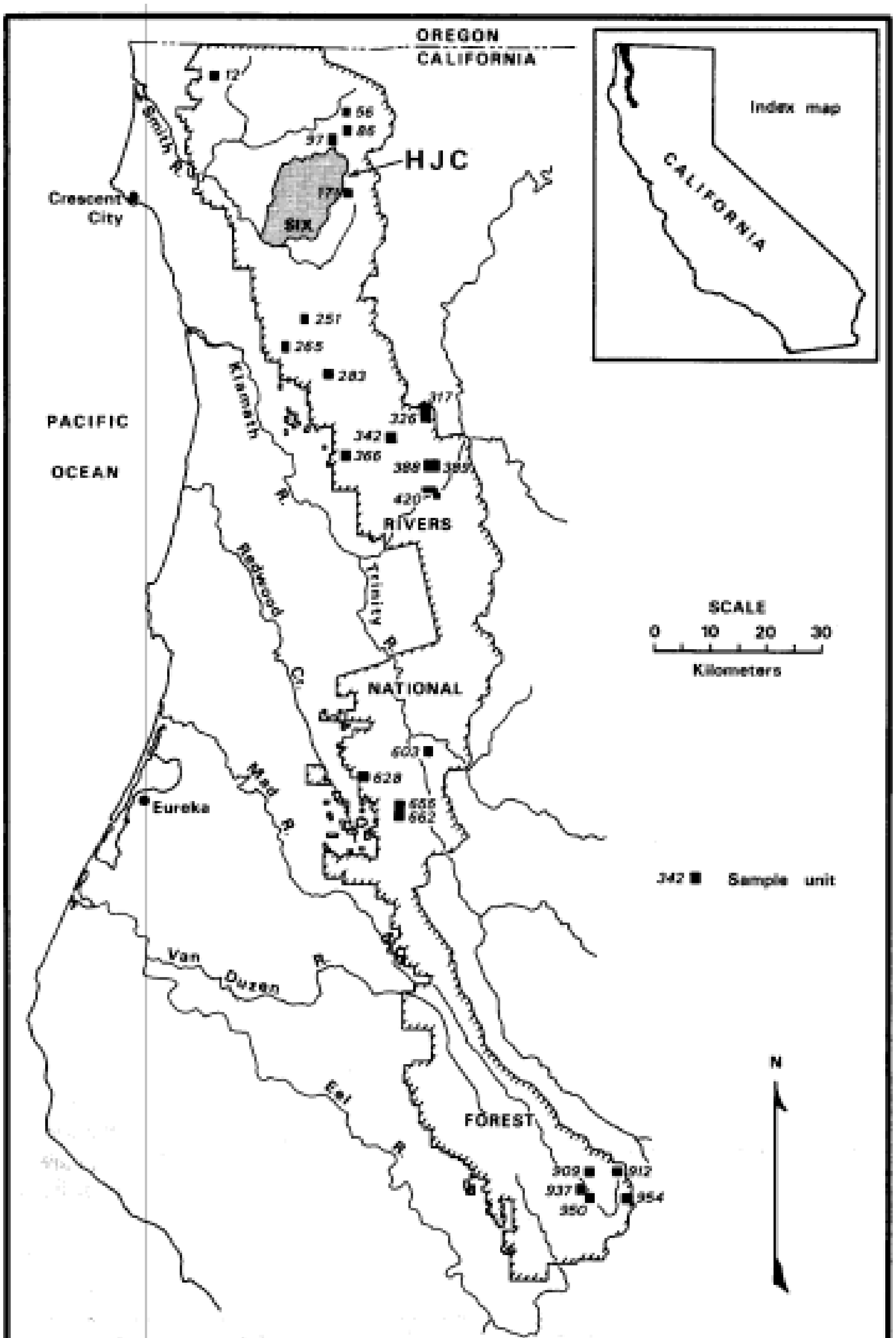

FIGURE 1. Hurdygurdy Jones Creeks (HJC) and Six Rivers National Forest (SRNF) study areas (showing sampled sections).

tured bedrock combine with steep topography and a mediterranean climate to produce exceptionally rapid erosion rates within the Klamath and Coast Range Mountains (Kelsey, 1977; Janda, 1979; Janda and Nolan, 1979). The Galice Formation dominates in the Klamath mountains portion of the SRNF and this formation underlies almost all of the HJC. It consists primarily of sandstones and argillaceous rocks, locally metamorphosed into phyllite. Soils developed on the unit have little or no cohesion. Steep Stream-side hillslopes are particularly prone to shallow mantle failures (Farrington and Savina, 1977; Janda, 1979). The Franciscan Group dominates the Coast Range portion of the SRNF. It consists primarily of sandstone and mudstone, but includes significant amounts of volcanic rocks, serpentinite, chert, and limestone. It is typically highly sheared and fractured and subject to widespread landsliding by shallow mantle failures and deep rotational and earth-flow failures (Kelsey, 1975; Janda, 1979).

METHODS

STUDY SITE SELECTION

The sample included clearcut patches spanning 15 years of age, assuming that landslides resulting from clearcutting would occur within that time (Ziemer, 1981a). It seemed rational to assume that the 15 "sample years" contained several rainfall or snow-melt events of sufficient magnitude to produce landslides after clearcutting. Detailed data of precipitation intensity and duration for the mountains of northwestern California are scarce. On the basis of generalized frequency-intensity-duration maps (Rantz, 1968), however, rainfall in amounts necessary to cause landslides are common. Of the study sites, for example, 39 percent have 2-year 24-hour precipitation amounts exceeding the landslide threshold estimated by Caine (1980). On the basis of data from 13 weather stations in the vicinity of the SRNF (Goodridge, 1972), the probability of having at least one storm greater than Caines threshold during a 15-year interval is about 0.99. More than an even chance exists of having at least one such storm in any 3-year period.

Landslides tend to occur sporadically and to be concentrated within certain geomorphic niches. Samples were taken from an area spanning approximately 2° latitude and ½° longitude, assuming that the sample of clearcut patches represented a reproducible distribution of landslide-controlling factors with respect to both time and space. This is, essentially, a time-independent approach (Hack, 1960; Chorley, 1962).

TABLE 1

Clearcut patches, area of slope classes, and harvest slope slides in sampled sections

Sample Section*	Clearcut patches	Total area	Steepland		Non-steepland	
			Area	Slides	Area	Slides
		(ha)	(ha)		(ha)	
012	1	8.74	0.65	0	8.09	0
056	10	61.76	14.87	11	46.89	3
086	6	34.09	10.46	6	23.63	0
097	3	36.91	10.96	2	25.95	0
171	2	52.45	25.21	2	37.24	0
251	3	55.91	33.57	1	22.34	0
265	2	32.54	15.38	3	17.16	0
283	2	16.51	0.00	0	16.51	0
317	2	40.39	6.23	0	34.16	0
326	3	24.08	3.45	2	20.63	0
342	10	79.53	12.30	17	67.23	1
366	1	2.69	0.70	0	1.99	0
388	1	9.55	0.00	0	9.55	0
389	4	45.40	3.61	8	41.79	1
420	1	29.94	20.07	23	9.87	0
603	2	21.05	7.77	3	13.28	0
628	6	48.54	28.19	8	20.35	0
655	5	48.58	11.84	4	36.74	0
662	3	43.64	19.11	1	24.53	0
909	5	16.31	1.99	0	14.32	0
912	5	28.03	5.11	1	22.92	0
937	3	16.35	8.01	0	8.34	0
950	4	22.47	4.14	5	18.33	0
954	1	3.13	0.70	0	2.43	0
Totals	85	778.59	234.32	97	544.27	5

*Numbers correspond to those in Figure 1.

In northwestern California, valley walls typically have basal portion (steeplands) that slope 30° or more and are bounded above by major convex-upward slope breaks. Because the study began as a test of the hypothesis that most debris avalanche failures related to clearcutting occur within these steeplands, the emphasis was to develop a risk-rating methods for steeplands. Two reasons dictated this emphasis: debris avalanches from steeplands, are more likely to contribute sediment directly to streams than are slides from flatter or higher areas; and, this restriction limited consideration to steep, cable-yarded sites. Therefore, much o the variability due to site was eliminated. More importantly, it was possible to avoid much of the variability in operator performance that is found with tractor yarding but that is not easily quantified (Rice and Datzman, 1981).

The HJC as selected for a pilot study to develop a discriminant function for distinguishing unstable from stable steepland areas. The HJC contained 21 clearcut patches having steepland slides visible on 1:15,840 colour air photographs (Forest Service, 1975). A scanning stereoscope and parallax bar were used to delineate steeplands from non-steeplands within each patch. Patch areas and slope-class areas (Table) were estimated with a dot grid. All debris avalanches not associated with roads, landings, or firelines were located. Non-slide sites were randomly located points in steepland reas. A point was discarded if it fell within 20 m of the centre of any slide or if it fell on any part of a road, landing, or fireline. The patches included a range of geomorphic, meteorologic, and vegetative conditions and were relatively accessible for field verification. Site variables at 35 slide sites and 79 non-slide sites were measured. A discriminant function developed for this area was to be tested with data collected from the SRNF. The extensive exposure of Galice rocks in both study areas influenced the choice of the HJC.

A map of the SRNF (Forest Service, 1977), subdivided into one-square-mile public lands survey sections, served as a sampling base, and 44 sections were randomly selected. Twenty-four of these sections (Figure 1) contained at least one cable-yarded clearcut patch observable on the 1975 photographs. There was a total of 85 clearcut patches.

VARIABLE MEASUREMENT AND ANALYSES

Nineteen variables describing environmental conditions at slide centroids and non-slide points were estimated. Eight additional variables were derived from transformations (Table 2). Variables selected were those that could be easily measured on air photographs or maps and that required no field verification.

The study used a series of discriminant analyses (Fisher, 1936; Jerlnri and Sampson, 1979) and multiple regression analyses Douglas, 1979; Frane, 1979) to screen variables. Variable combinations were evaluated by R^2, adjusted R^2 (Kerliinge and Pedhazur, 1973; Green, 1978), Mallows' C_P (Gorman and Toman, 1966; Daniel and Wood, 1971), and percentages of correctly classified sites (Green, 1978; Jennric and Sampson, 1979). Variable and model stability were evaluated with split-sample tests and “jackknife classification” (Jennrich and Sampson, 1979)–a

TABLE 2
Variables tested in discriminant analyses

Acronym	Variables measured at sample sites Definition	Code or Units
SITE	Site type:	
	Non-slide	
	harvest slope proper	0
	slide	
	harvest slope proper	1
	road associated	2
	landing associated	3
	fireline associated	4
PTAREA	Planimetric photo area of slide (not used in analyses)	m^2
AGE	Age of cutblock relative to date (year) of 1975 aerial photographs (USDA Forest Service 1975)	Months
ROCK	Rock type:	
	Quaternary terrace	1
	Franciscan Group	2
	granitic	3
	Galice Formation	4
	ultramafic	5
	metavolcanics	6
	metasedimentary	7
MOR	Hillslope-contour morphology:	
	planar	1
	convex	2
	bank of draw with contour radii less than 20 m	3
	thalweg of draw with contour radii less than 20 m	4
	thalweg of first-order stream	5
SLOPE	Slope of ground surface	degrees
LASP	Local, first-order aspect	degrees
RASP	Regional, second-order aspect	degrees
ORD	Order of downslope stream	1-3
DOM	Dominant canopy closure in a 1,000 m^2 circle centred on site	percent
DISDVD	Horizontal distance to upslope divide	m
DISUCB	Horizontal distance to upper cutblock boundary	m
DISUP	Horizontal upslope distance to first convex slope break	m
DISST	Horizontal downslope distance to stream	m
ELV	Elevation above mean sea level	m
ELVBDVD	Elevation below divide	m
ELVAST	Elevation above stream	m
MAP	Mean annual precipitation (Rantz, 1968)	mm
MAE	Mean annual evaporation (Rantz, 1968)	mm
MAR	Mean annual runoff (Rantz, 1968)	mm
TY24H	Two-year 24-hour storm depth	mm

TABLE 2. Continued

Variables created from transformations Achronym	Definition/Transformation
MORPH	Hillslope-contour morphology: 1) planar or convex (from variable MOR) 2) bank or thalweg of draw or thalweg of stream (from variable MOR)
SINLASP	Sine (LASP)
COSLASP	Cosine (LASP)
SINRASP	Sine (RASP)
COSRASP	Cosine (RASP)
LASOUTH	|180–LASP|
RASOUTH	|180–RASP|
SUMDIS	1/DISUP + 1/DISST

method to estimate correctly classified cases with virtually zero bias (Green, 1978). An individual variable was considered valuable if it significantly and consistently contributed to the correct classification of sites in a series of analyses and if, after split-sample testing, it maintained its relative value. Certain variables were eliminated from further consideration (i.e., they were not collected in the SRNF study phase) because of poor statistical performances during the HJC study phase and because of relative measurement difficulty. The SRNF data were used to test the HJC discriminant function, and were used later to develop a geographically more general, "improved" discriminant function. The final equation was incorporated into a method for assessing landslide risk for unlogged terrain.

RESULTS

DEBRIS-AVALANCHE DENSITY

The debris-avalanche density was found to be about one slide per square kilometre of non-steep land (5 slides) and about 41.4 slides per square kilometre of steeplands (97 slides). Therefore, 95 percent of the slides originated within steeplands, constituting less than one-third of the clearcut area in the SRNF. The most obvious control over this variation in density is gradient. Gradient, however, is a necessary, but not necessarily sufficient, condition for landsliding. Only 1.4 percent of the steepland area was affected by debris avalanches. It is to this small area that further analyses were addressed.

DISCRIMINANT ANALYSES

On the basis of the HJC data, the final discriminant equation was:

$$Y = 3.439 + 4.350 \log \text{SUMDIS} + 0.882 \log \text{LASOUTH} + 1.593\ \text{MORPH} \quad (1)$$

where SUMDIS and LASOUTH are defined in Table 2, and MORPH (also defined in Table 2) equalled 0.825 if a site was located with a draw, or - 0.175 if it was located on a convex or planar hillslope (the unequal weights compensate for the relative frequency of the two conditions). Also, if LASOUTH was zero (log 0 is undefined), it was arbitrarily assigned a value of 1.0. Y is a discriminant (canonical) score. If Y was positive, the site was classified as a slide site; if Y was negative, the site was classified as a non-slide site. Equation (1) correctly classified 27 of 35 slide sites and 60 of 79 non-slide sites, for a total correct classification of 76.3 percent.

SRNF data were entered into equation (1) to compute Y scores. It correctly classified 82 of 97 slide sites and 81 of 124 non-slide sites, for a total correct classification of 73.8 percent. Equation (1) was then tested with only SRNF Galice data, with the thought that classification might improve because of similar rock types. Improvement was slight–68 of 81 slide sites and 54 of 79 non-slide sites were correctly classified, for a total correct classification of 76.7 percent. Later analyses of SRNF data suggested that the variable ROCK gave little or no additional discriminating power to test models. A Chi-square test compared tables of correct and incorrect classification with HJC, SRNF, and SRNF-Galice data. Differences between the tables were not statistically significant. From the Chi-square test, the performance of equation (1) was found to be consistent in the three data sets.

The variables of equation (1) were forced into a discriminant model with SRNF data. Results suggested that the variables SUMDIS and MORPH were significant discriminators, but LASOUTH was not significant (0.05 level). Furthermore, coefficients of the variables SUMDIS and MORPH remained essentially the same with or without the presence of LASOUTH in the model. Analyses of SRNF data, where the entry of variables into models was unrestricted, indicated that SUMDIS and MORPH were, in fact; the most useful of the variables sampled in the SRNF. The analyses were completed with the development of the following equation based on SRNF data:

$$Y = 3.245 + 3.017 \log \text{SUMDIS} + 1.312\ \text{MORPH} \quad (2)$$

MORPH equalled 0.837 (draw) or - 0.163 (planar-convex) in equation (2). Equation (2) was highly significant. It correctly classified 73 of 97 slide sites and 106 of 124 non-slide sites, for a total correct classification of 81.0 percent.

DISCUSSION

LANDSLIDE LOCATIONS

In addition to their statistical utility, the variables appear reasonable as expressions of geomorphic factors related to slope stability. The discrimination of sites by the variable SUMDIS indicates that a high proportion of the sampled slides occurred near streams and immediately below major convex break in slope (usually the upper boundary of the steeplands). the high proportion of slides near streams likely reflects general, continuous oversteepening of hillslopes by stream undercutting. It may also reflect a greater susceptibility of stream-side areas to the build-up of destabilizing pore-water pressures, as predicted by contemporary models of storm-flow generation in humid, forested terrain (see Chorley [1978] for an overview of the "partial area" runoff models). Specific evidence of this mechanism of landsliding as been described (Pierson, 1977). Similarly, high moisture levels likely account for the high proportion of landslides associated with draws, as indicated by the variable MORPH.

Major slop breaks mark a discontinuity where material is nearer to failure-threshold conditions below the break than above. The regolith is thinner below the break because, due to steeper slopes, erosion can more nearly keep pace with weathering. Weathering of the parent material on the gentle slopes above the break will tend to cause strata to form parallel to the surface. These strata will conduct subsurface water to a point beneath the slope break. The thicker regolith above the slope break may be capable of delivering subsurface water to the slope break more rapidly than the thinner regolith below the break can transmit it to the stream. High pore-water pressures may result, causing debris avalanches. Farther down the slope, there is less 1ikelihood of high pore-water pressures developing in this manner and, consequently, less likelihood of debris avalanches.

The high proportion of slides on north-facing slopes in the HJC (as indicated by LASOUTH) may reflect locally pervasive orientations of rock foliations conducive to failure or .aspect-related variations in the relative availabilty of moisture, or both. Because moist northerly aspects tend to support heavier forests than do southerly aspects, slide frequencies may reflect a greater dependency of such aspects upon denser tree-root networks for their strength. Loss of root strength after logging, therefore, would be more destabilizing to northerly aspects than to southerly aspects. By considering a much greater range of conditions in the SRNF data, the local usefulness of LASOUTH was masked by other sources of variability. Changes in moisture conditions over 2° latitude, for example, likely masked the effects of local changes with aspect.

LANDSLIDE RISKS

Bayes' Theorem, used to estimate the posterior probability of a slide occurring at a site given its discriminant score (Y) as computed by equation (2), may be written as:

$$P(S \mid Y) = \frac{P(Y \mid S)P(S)}{P(Y \mid NS)P(NS) + P(Y \mid S)P(S)} \qquad (3)$$

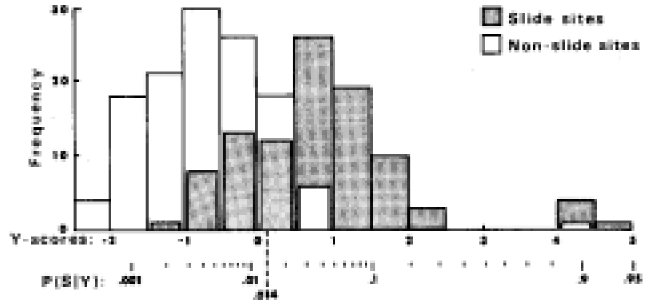

FIGURE 2. Slide and non-slide site Y-scores associated with landslide probabilities.

where: P(S) is the prior probability of a slide as determined from the proportion of the steepland area in slides; P(NS) is the prior probability of a non-slide; P(Y | S) is the conditional probability (posterior probability) that a site with score of Y came from the same population as the slide group of the developmental data; and P(Y | NS) is the probability that it came from the non-slide group.

The proportion of the logged area in SRNF steeplands that contained slides was extremely small (P(S) = 0.014). The slide probabilities calculated by equation (3), therefore, appear to be low for known slide sites (Figure 2). The probability assigned to the average slide site, for example, is only about 0.04. A practical way to evaluate such a probability is to consider the relative improvement it offers to a risk assessment (Rice and Pillsbury, 1982). Relative risk may be calculated by dividing the slide probability determined from equation (3) by the prior probability of a slide (P(S)). Considered in this way, conditions associated with the average SRNF slide site would be nearly nine times more likely to lead to failure than conditions associated with the average stable site.

The use of equation (2) to assess landslide risk for uncut terrain would be valid only if the new sites came from the same population as did the developmental data; that is, only if they came from the same environmental setting and were subjected to identical weather conditions. Such a repetition is unlikely. Nevertheless, certain situations may be sufficiently similar to warrant verification and use of these results.

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