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A Risk Analysis Approach for Using Discriminant Functions to Manage Logging-Related Landslides on Granitic Terrain

RAYMOND M. RICE
NORMAN H. PILLSBURY
KURT W. SCHMIDT

ABSTRACT. A linear discriminant function, developed to predict debris avalanches after clearcut logging on a granitic batholith in northwestern California, was tested on data from two batholiths. The equation was inaccurate in predicting slope stability on one of them. A new equation based on slope, crown cover, and distance from a stream (retained from the original equation) predicted stability on all three batholiths with an overall accuracy of 83 percent. A procedure is described that can be used to decide how to harvest slide-prone slopes. The procedure uses the manager's estimates of contending resource values and environmental risks together with data from a proposed harvest area. By the algorithm presented, the manager can determine the landslide risk threshold to follow and achieve the greatest net benefit from a timber harvest. *FOREST SCI.* 31:772-784.

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THE OBSERVATION that accelerated landsliding may follow logging is not new. In 1950, Croft and Adams (1950) observed a greater frequency of landslides in second-growth timber than in old-growth timber in the Wasatch Mountains in Utah. They attributed the increase in landslides largely to loss of mechanical support by roots, assuming that old-growth stands had more extensive root systems than did second-growth stands. Similar findings have been reported throughout the world (Bishop and Stevens 1964, Cappuccini and Bernardini 1957, Kawaguchi and others 1959, Zaruba and Mencl 1969, Fugiwara 1970, Swanson and others 1981). The hypothesis that the increase in landslide incidence is attributable to root decay has been supported by the work of Endo and Tsuruta (1969), Swanston (1969), and Ziemer (1981).

Increased erosion from debris avalanches appears to be a possible unwanted side-effect of timber harvest on steep terrain. It is incumbent on the forest manager, therefore, to attempt to estimate the risk of landslides and to strike an appropriate balance between timber utilization and hazard to soil and water. If the hazardous areas in a proposed harvest area can be identified, most of the timber can be utilized with slight increase in the risk of landslides. Typically, only a small proportion of a clearcut area will actually experience slides. Two studies in north-

The authors are, respectively, Principal Hydrologist, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Arcata, CA 95521; Head, Natural Resources Management Department, California Polytechnic State University, San Luis Obispo, CA 93407; and Geologist, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Arcata, CA 95521. Manuscript received 3 January 1984.

western California have found only 1.4 percent (Furbish 1981) and 2.7 percent (Pillsbury 1976) of the harvest slopes scarred by landslides. Frequently, land managers attempt to map high-risk areas on the basis of geomorphic and vegetative indicators of instability (for example: Hicks and Smith 1981). The mapping procedures, however, are susceptible to two weaknesses. First, they may overestimate landslide risk. One study found that experts tended to overestimate the risk of mass erosion by a factor of 2 or 3 orders of magnitude, presumably because of their disproportionately large exposure to problem areas compared with the norm (McGreer and McNutt 1981). A second weakness of the mapping approach is the difficulty of constructing an objective test of its accuracy. We know of only two instances in which mapping was objectively tested. A procedure for predicting landslides after fire in chaparral was objectively tested (Kojan and others 1972), and later the procedure was tested in another area (Foggin and Rice 1979). In both instances, about 80 percent accuracy was achieved. These predictions, however, related to whether slides would occur in second order basins (averaging about 4.5 ha). Slide sites were not located.

Discriminant analysis (Fisher 1936) has been used as an objective method for estimating landslide risk in grass and brush environments (Waltz 1971, Rice and Foggin 1971). Recently, two studies used discriminant analyses to identify potential landslide sites after clearcut logging (Pillsbury 1976, Furbish 1981). The equation used (Pillsbury 1976) correctly identified 80 percent of the sites in the developmental data and another equation (Furbish 1981) achieved a 76 percent accuracy. The accuracy dropped only slightly, to 74 percent, when Furbish's equation was used to classify 159 sites not used in its development. A subset of Pillsbury's data was used to develop a new discriminant function having a logarithmic form (Rice and Pillsbury 1982). The new equation had an overall classification accuracy of 90 percent with the developmental data (Rice and Pillsbury 1982).

Although linear discriminant functions seem to be effective in the identification of slide-prone sites, their use is not without problems. Whether they are used for prediction or as an interpretive tool, their reliability depends on how well they describe the operable processes and conditions affecting slide occurrence. The greatest weakness in a linear discriminant function lies in the rigidity and simplicity of the model: the effect of all variables in the equation must be considered either additive or multiplicative. Thresholds in variables are also difficult to deal with. We feel that the advantages of a linear discriminant function outweigh its weaknesses. If variables are carefully chosen, they can be acceptable surrogates for the processes they represent. The relationship between the variables is explicit and it is possible to estimate the relative magnitude of their roles in slide generation. Lastly, and most importantly, a linear discriminant function leads to a prediction procedure with estimatable precision and accuracy.

This paper reports a study to test how successfully the Rice and Pillsbury (1982) equation can be applied in other areas and explores how its performance is altered by differences between areas. It also describes a method for utilizing the results of a discriminant analysis, together with quantitative estimates of the values and risks at stake, to arrive at an optimum management strategy.

STUDY AREAS

The discriminant function we are testing was developed from data collected from 62 ha of clearcut patches on the English Peak Batholith, 7 km northwest of Sawyers Bar, California (Table 1). The two test data sets also come from granitic batholiths of the Klamath Mountains. One is the White Rock Batholith, 12 km south of Tiller, Oregon; the other is the Ashland Batholith, 8 km south of Ashland, Oregon.

TABLE 1. Variables defining conditions on three batholiths.

Variable and units		Batholiths						All	
		English Peak		Ashland		White Rock			
Study area	(ha)	62.00		162.00		119.47		343.47	
Slide area	(ha)	1.68		.78		1.34		3.80	
Slide area	(pct)	2.73		.48		1.12		1.11	
Number of slides		68		20		43		131	
Frequency	(ha ⁻¹)	1.10		0.12		0.36		0.38	
Average condition		Stable	Slide	Stable	Slide	Stable	Slide	Stable ^a	Slide ^a
Number of sites	66	68		25	20	44	43	135	131
Slide area	(m ²)	304.0			391.2		311.2		319.7
Slide volume	(m ³)	395.9			644.4		671.4		524.3
Slope									
(SLOPE)	(pct)	41.5	83.0	43.3	53.7	48.1	66.8	44.0	73.2
Distance to stream									
(HORSTM)	(m)	47.2	39.2	174.6	153.8	88.4	68.6	84.2	66.3
Crown cover									
(DOM)	(pct)	62.9	87.4	43.0	63.0	46.5	65.3	53.9	76.4
Drainage area									
(DRAREA)	(m ²)	645	209	1,438	6,115	1,445	1,388	1,052.6	1,497.7

^a Each batholith's contribution to the average is weighted by its number of study sites.

Granitic plutons make up about 17 percent of the Klamath Mountains. The slopes of all three study areas were steep (Table 1), soil depths were shallow, generally less than 1 m, but were often underlain by 1 m or more of weathered parent material. On the English Peak Batholith (the only one we studied in the field) a gradient of weathering of the parent rock exists, beginning with relatively unweathered rock high on the slopes and ending in areas of deep laterized soil near the stream (Durgin 1977). All of the slides were found on the 62 percent of the study area on intermediate weathering stages beginning with the development of core stones and ending with deep decomposed granite (Pillsbury 1976).

The histories of the three batholiths are similar. Shortly after each study area was logged it was struck by a storm exceeding Caine's (1980) landslide threshold for rainfall duration of 24 h or more. It has been proposed (Rice and others 1982) that storm severity as a producer of landslides could be indexed by its distance from Caine's threshold in two dimensional space bounded by log (intensity) and log (duration) (Fig. 1). On that scale, the Ashland storm had a severity (S) of 0.05, the English Peak batholith storm (measured at Sawyers Bar, CA) 0.05, and the White Rock storm (measured at Glendale, OR) 0.09. The mean severity of the storms in Caine's data was 0.40, a value which suggests that these were only marginally severe landslide producing storms or that logging had greatly reduced the stability of the slopes. Shallow snow may have been on the ground in each area and, if that were the case, the rate at which water entered the soil may have been considerably above that indicated by the rainfall intensities.

The frequency and volume of sliding differed considerably among the study areas on the three batholiths (Table 1). On the English Peak Batholith, where the prediction equation was developed, there was a little more than 1 slide per ha, while on the White Rock Batholith there was 1 slide per 2.8 ha and on the Ashland Batholith 1 slide per 8.1 ha. The shorter distances from sample points to streams and smaller drainage areas above points on the English Peak Batholith (Table 1) suggest that it was more dissected than the two test batholiths. The greater disparity

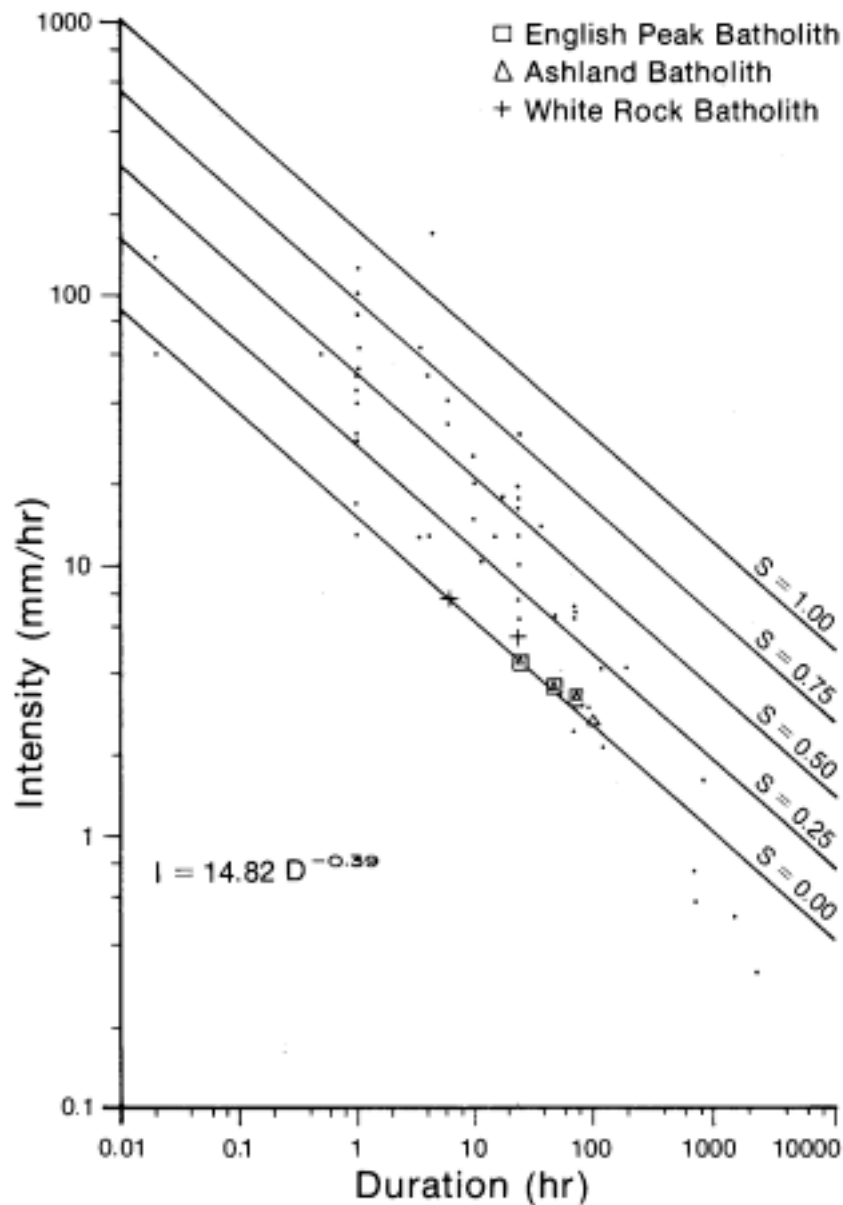


FIGURE 1. Rainfall duration and intensity related to shallow landslides (Caine 1980), with contours of storm severity (S) (Rice and others 1982) superimposed.

in slopes between stable and slide sites on the English Peak Batholith also suggests a more broken terrain. Also, the forest cover (Table 1, DOM) was considerably heavier on the English Peak Batholith than on the two test batholiths.

TEST OF ENGLISH PEAK EQUATION

The test of the Rice and Pillsbury (1982) equation has two aspects. The first addresses the question of whether the relationships developed on the English Peak Batholith have sufficient generality to be useful on other granitic batholiths. The second has to do with methodology. Pillsbury (1976) collected his data using a

stereocomp rator that is capable of considerably greater accuracy and precision than are likely to be available in most instances. The test data were collected with a parallax bar and scanning stereoscope of 4.5-power magnification. All test data were collected on prelogging photographs at a scale of 1:12,000 or less, whereas some of Pillsbury's (1976) data were taken from postlogging photographs at a scale of 1:6,000. The tests evaluate, therefore, both the generality and the practical utility of a discriminant analysis approach to evaluating landslide risk.

The Rice and Pillsbury (1982) equation was based on four variables

$$X = 13.24 - 4.63 \log(\text{SLOPE}) - 3.04 \log(\text{DOM}) - 1.03 \log(\text{HORSTM}) + 0.69 \log(\text{DRAREA}) \quad (1)$$

in which X is the discriminant score of a site: SLOPE is terrain slope of the slide or a 60 m slope segment centered on a stable site, expressed as a percent; DOM is the ground cover provided by the crowns of the dominant vegetation within a 0.405 ha circular plot, expressed as a percent; HORSTM is the horizontal distance in meters from the stream to the centroid of the slide or to the stable site; and, DRAREA is the tributary surface drainage area above the slide scarp or stable sampling pint in square meters (Fig. 2).

The variables in the equation seem plausible. SLOPE indexes the magnitude of the force of gravity promoting failure. DOM is more complicated. Its coefficient indicates that sites supporting heavier timber are more prone to failure after logging. Possible causal factors include: (a) The timber may be indexing high moisture conditions and greater probability of high pore water pressures that may promote slope failure; (b) slopes with heavier forest covers may depend more upon the structural support of tree roots to maintain their stability; and, (c) they may depend more on transpiration to dispose of excess soil water than slopes with lighter stands. HORSTM indexes the prevalence of slides at the head of "zeroth order" basins (Tsukamoto and others 1982). Such sites have been identified (Diet rich and Dunne 1978) as the critical interface between gradual, and more or less continuous, processes of weathering, creep, and surficial erosion and episodic mass wasting processes. DRAREA seems to be indexing the same conditions as HORSTM because small drainage areas are indicative of instability. It may be, however, that small drainage areas also index the possibility of subsurface delivery of water from the slope on the other side of the ridge.

In each of the study areas, only slides unrelated to roads, landings, or stream-channel undercutting were included in the analysis. These restrictions were imposed so that we might study a relatively homogeneous population of slides resulting from logging and unaffected by other disturbing influences. Stable sites were characterized by data collected from the nodes of a randomly oriented square grid (61 m x 61 m). On the English Peak Batholith, the grid was randomly located with the restriction that no point fall on a slide. On the two test batholiths, the first grid orientation was accepted and points falling on slides ignored. We collected data from approximately the same number of stable sites as there were slide sites on each of he batholiths.

The first statistical test of the data was a Chi-square (χ^2) goodness of fit test addressing he question of whether the distributions of discriminant scores in the two test areas can be considered as coming from the same population of discriminant score as those collected on the English Peak Batholith. The discriminant scores for all stable and unstable sites were computed for all batholiths. A probability distribution of scores was then generated by weighting stable and unstable scores by the proportion of the area in each of the batholiths that was either stable or unstable The weighting was necessary because all slide sites were measured but the stable areas were only lightly sampled in the data collection. On both test

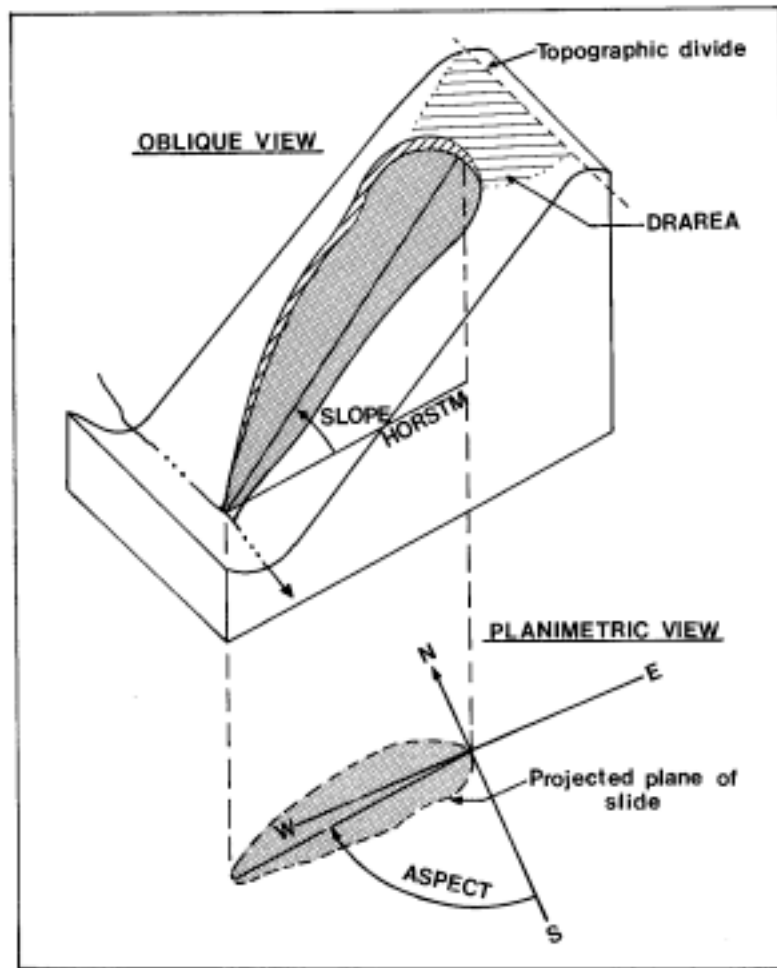


FIGURE 2. Oblique and planimetric views of a debris slide showing the location of variables used in equation (1).

batholiths we accepted the hypothesis that their discriminant scores came from the same population as those from the English Peak Batholith. The probability of our observed χ^2 due to chance alone was 0.31 for the Ashland Batholith and 0.49 for the White Rock Batholith.

In our second, and more crucial test, we used BMD-P4F to compare the correct and incorrect classifications in each of the test areas in a three-way contingency table (Dixon and Brown 1981). The test addressed the questions of whether equation (1) yielded accurate predictions and consistent patterns of correct and incorrect predictions on the test batholiths. The test revealed a highly significant association between predicted and observed values even though there was also a highly significant association between prediction accuracy and batholiths. Inspection of the data (Table 2) confirmed that the prediction equation was not accurately classifying the Ashland sites. Only 25 percent of the slide sites were correctly identified. This result was not unanticipated. While collecting the data we observed that the relationship between stability and the drainage area variable was reversed in the Ashland Batholith. The drainage areas of the slide sites, rather than being smaller, were four times larger than the drainage areas of the stable

TABLE 2. Observed and predicted conditions and percent correct classifications in three batholiths as determined from equations (1), (2), and (3).

Equation and batholith	Observed condition	Predicted condition		Correct classifications percent
		Stable	Unstable	
Equation (1)				
English Peak	Stable	57	9	86
	Slide	<u>5</u>	<u>63</u>	<u>93</u>
	Total	<u>62</u>	<u>72</u>	<u>90</u>
Ashland	Stable	18	7	72
	Slide	<u>15</u>	<u>5</u>	<u>25</u>
	Total	<u>33</u>	<u>12</u>	<u>51</u>
White Rock	Stable	34	10	77
	Slide	<u>13</u>	<u>30</u>	<u>70</u>
	Total	<u>47</u>	<u>40</u>	<u>74</u>
Equation (2)				
English Peak	Stable	53	13	80
	Slide	<u>6</u>	<u>62</u>	<u>91</u>
	Total	<u>59</u>	<u>75</u>	<u>86</u>
Ashland	Stable	17	8	68
	Slide	<u>3</u>	<u>17</u>	<u>85</u>
	Total	<u>20</u>	<u>25</u>	<u>76</u>
White Rock	Stable	28	16	64
	Slide	<u>6</u>	<u>37</u>	<u>86</u>
	Total	<u>34</u>	<u>53</u>	<u>75</u>
Equation (3)				
English Peak	Stable	52	14	79
	Slide	<u>5</u>	<u>63</u>	<u>93</u>
	Total	<u>57</u>	<u>77</u>	<u>86</u>
Ashland	Stable	17	8	68
	Slide	<u>4</u>	<u>16</u>	<u>80</u>
	Total	<u>21</u>	<u>24</u>	<u>73</u>
White Rock	Stable	34	10	77
	Slide	<u>3</u>	<u>40</u>	<u>93</u>
	Total	37	50	85

sites. Because DRAREA was the least significant variable in the discriminant function, we eliminated it and recomputed the discriminant function, still using English Peak Batholith data

$$X = 17.08 - 5.67 \log(\text{SLOPE}) - 3.21 \log(\text{DOM}) - 1.19 \log(\text{HORSTM}). \quad (2)$$

The new three-variable discriminant function greatly improved prediction on the Ashland Batholith. There was no longer a significant association between prediction accuracy and batholith. Overall, 65 percent of the stable sites on the two batholiths were correctly identified and 86 percent of the unstable sites were correctly identified, yielding an overall accuracy of 75 percent (Table 2). The χ^2 goodness of fit test now indicated that the distribution of discriminant scores in

the White Rock Batholith was significantly shifted toward smaller values than was the distribution of scores in the other two batholiths, indicating less stability.

Our experience was not unlike that of Furbish (1981). When he tested an equation developed in the Hurdy-Gurdy and Jones Creek watersheds on a random sample of sites from the Six Rivers National Forest in northern California, he found that the least significant variable in his equation (aspect) was useless as a predictor of stability. Apparently, in his study and ours, attempts to improve the prediction capabilities of the discriminant functions led to inclusion of a variable the utility of which was purely an artifact of the developmental data set and which inadequately expressed the processes it supposedly represented.

As a final step in our analysis, we recomputed equation (2) using all of the data

$$X = 16.59 - 5.54 \log(\text{SLOPE}) - 3.69 \log(\text{DOM}) - 0.42 \log(\text{HORSTM}). \quad (3)$$

We thought it likely that an equation based on all of the data would perform more accurately if used in still other areas. In comparison with equation (1), equation (3) performed almost as well on the English Peak Batholith, somewhat better with the White Rock Batholith, and was a considerable improvement on the Ashland Batholith (Table 2). Equation (3) correctly identified 76 percent of the stable sites and 91 percent of the unstable sites, for an overall accuracy of 83 percent. It is the performance of this equation that is discussed in the remainder of the paper.

PREDICTING SLIDES IN OTHER AREAS

Equation (3) was developed from samples that included approximately equal numbers of slide and stable sites. We thought this sampling scheme could give the best information characterizing the differences between stable and unstable sites. On the batholiths sampled, however, the occurrence of stable and unstable sites have a ratio of approximately 99:1. If equation (3) is to be applied to the evaluation of any new area, that proportion must be factored into our predictions. This we accomplished by using Bayes' theorem.

According to Bayes' theorem, the posterior probability (P) of a slide occurring, given a particular discriminant value (x), is determined by

$$P(\text{slide} | x) = \frac{P(x | U)\pi_u}{P(x | U)\pi_u + P(x | S)\pi_s} \quad (4)$$

in which π_u is the prior probability of an unstable site as determined by the proportion of the study area in slides; $\pi_s = 1 - \pi_u$ is the prior probability of a stable site; x is the computed value of discriminant function from equation (3); U is the probability distribution of x 's for the unstable sites in the developmental data; S is the probability distribution of x 's for the stable sites in the developmental data.

Bayes' theorem yields rather disconcerting results (Fig. 3). We find that the average discriminant score (-0.86) of the slide sites on the three batholiths is related to a posterior probability of only 0.05. The smallest computed value of the discriminant function carried only a 0.33 posterior probability of failure. These low probabilities reflect the fact that only a tiny fraction of the terrain fails at any one time. Because of natural variability among the stable sites, and their prevalence, many will appear to be as unstable (i.e., have similar discriminant scores and posterior probabilities) as potential slide sites. Although the unstable sites may have a low probability of failure, the posterior probability (0.003) associated with the average discriminant score (0.84) of the stable sites is much lower. A site having a discriminant score equal to the mean of the scores of the unstable sites, therefore, is estimated to be nearly 17 times more likely to experience a slide after clearcutting than the average stable site.

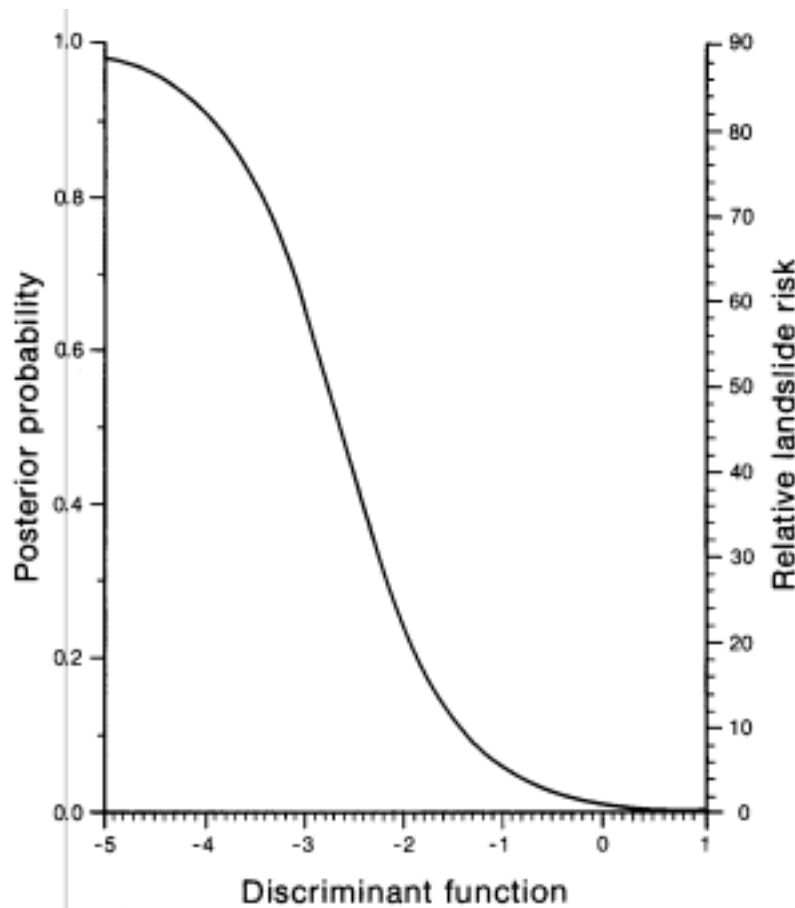


FIGURE 3. The probability that landslides will occur after clearcut logging of granitic terrain as estimated by equations (3) and (4).

RISK ANALYSIS

To predict the probability of a slide after clearcutting is the first step in deciding how to log slide-prone area. Four possible results of each stability prediction are A^* -correctly identifying a stable site; B^* -incorrectly identifying a stable site as unstable; C^* -incorrectly identifying an unstable site as stable; and D^* -correctly identifying an unstable site.

The manager must decide upon the penalties and benefits associated with the consequences of various correct and incorrect site classifications. By fixing payoffs for each of these consequences, the manager can establish a value system that can be used to decide how to manage timber on slide-prone sites. The overall payoff of a particular cutting rule can be estimated by

$$Y = aA + bB + cC + dD \quad (5)$$

in which Y is a number that integrates the penalties and benefits derived from the various correct and incorrect predictions and a, b, c, d are coefficients selected to weight the consequence of conditions A^*, B^*, C^*, D^* . A, B, C , and D are the corresponding proportions of correct or incorrect predictions. The payoff coefficients a, b, c, d may be monetary values if the analyst is fortunate enough to have such estimates. If not, they may merely be subjective weights attached to each

consequence. Even in this situation, we think that use of such quantities will lead to improved decisions because of the discipline imposed by an explicit value system. An explicit system also permits evaluating the effect of incremental changes in the decision criterion.

Before equation (5) can be solved, it is necessary to estimate A , B , C , and D . Their values, however, will depend on what posterior probability level is considered as the dividing line between sites that can be managed normally and those carrying an unacceptably high risk of slope failure after logging. If P is the posterior probability considered as dividing stable from unstable sites, the integrated payoff is calculated as

$$Y = aP_sC_s + b(1 - P_u)C_u + c(1 - P_s)C_s + dP_uC_u \quad (6)$$

in which Y is the integrated payoff resulting from the use of the criterion P ; C_s is the proportion of the area under investigation that is classified as stable using the criterion P ; C_u is the proportion of the area under investigation that is classified as unstable using the criterion P ; P_s is the proportion of C_s that is correctly classified. P_s is estimated to be 1 minus the posterior probability of a slide corresponding to the average discriminant score of the sample points falling in C_s , and P_u is the proportion of C_u that is correctly classified as unstable. P_u is estimated to be the posterior probability of a slide corresponding to the mean of the discriminant scores of the points falling in C_u .

Once the values of the coefficients a , b , c , d in equation (6) have been decided upon, trial values of Y can be computed for different values of P until the maximum value of Y is approximated. The landslide risk probability corresponding with that value of Y is the criterion that will result in the maximum net benefits for the assumed value system. We used data from the three batholiths to explore the application of equation (6). We created a data set of 500 observations by sampling randomly (with replacement), taking 5 percent of our observations from unstable site data and 95 percent from stable site data.

We assumed that a , b , c , d had the values 1, -1, -5, 25 respectively, as proposed by Pillsbury (1976). His rationale for those values was: "A weight of + 1 was used as a bench mark from which to establish the relative weight of conditions A , B , C , D . A prediction of condition B is an error. This means a loss of revenue since timber resources available for harvest will not be utilized. Although undesirable this is not a serious error. A prediction of C is a serious error since logging on unstable slopes is permitted. This condition is the type of error already committed in the Little North Fork. Mass movement by landsliding will result in physical damage to roads and culverts. Sedimentation may affect downstream users and fish populations for years. A prediction of condition D is the most difficult and was a major objective in this research. It allows the manager to design timber sales aware of the impact of logging and road construction on soil loss, site deterioration, and downstream problems. A decision not to log means a loss of timber revenue and second growth potential. A successful prediction of condition D was considered five times more important than the incorrect classification of C ." The choice of a value system, however, will change with each situation, depending on the relative importance of the timber and its competing resources. By repeated trials, the optimum probability was determined to be about 0.06 (Table 3). The use of this criterion can be expected to yield the greatest payoff for the assumed value system and database. In this instance, the payoff function seems relatively insensitive to changes in the failure criterion. This results from the fact that the highest posterior probability in our data was 0.33. Had the range in posterior probabilities been greater, the range in the payoff function would have increased also.

TABLE 3. Estimates of an integrated payoff function (equation (6)) using the system of benefits and penalties proposed by Pillsbury (1976).

Probability of failure chosen as criterion	Integrated payoff function	Proportion of area classified stable	Proportion of C_s assumed stable	Proportion of area classified unstable	Proportion of C_u assumed unstable
P	Y	C	P_s	C_u	P_u
0.01	0.740	0.696	0.997	0.304	0.045
.02	.961	.840	.995	.160	.074
.03	1.017	.890	.994	.110	.094
.04	1.052	.930	.993	.070	.129
.05	1.055	.936	.992	.064	.136
.06	1.061	.960	.991	.040	.185
.07	1.061	.962	.991	.038	.192
.08	1.060	.964	.991	.036	.198
.09	1.057	.968	.990	.032	.212
.10	1.055	.970	.990	.030	.220

LIMITATION OF ANALYSIS PROCEDURE

A discriminant function for landslide prediction contains an explicit and several implicit assumptions. The explicit assumption is that the discriminant scores from a new test area come from the same population of discriminant scores as those that were contained in the developmental data. Implicit in this assumption is the assumption that the variables included in the discriminant function, *and all the variables excluded from the function*, have the same relative importance as they had in the developmental data set. Our experience when using equation (1) on the Ashland Batholith illustrates the errors resulting from violating this implicit assumption.

It is also implicitly assumed that timber harvest will have the same environmental effect in the area being appraised as in the area that produced the developmental data. This assumption may be risky. One study hypothesized that "Operator performance may be as great a source of variation in logging-related erosion as are site characteristics" (Rice and Datzman 1981).

The last major implicit assumption is that the area being analyzed will experience the same storms after logging as did the area that produced the developmental data. The similarity of severities (S) of the slide producing storms in each of the areas investigated (Fig. 1) suggests that this is likely to happen. Estimates of the return periods of the slide producing storms ranged from as low as 5 years at Tiller, Oregon, near the White Rock Batholith, to 25 years for the storm causing slides on the English Peak Batholith. A 1-day rainfall at Caine's (1980) landslide threshold has a return period of about 4 years in northwestern California (Goodridge 1972). If the period during which logged slopes are vulnerable to landslides is 15 years (Ziemer 1981), then the probability of having a storm that exceeds Caine's landslide threshold during that period is about 0.99. The probability of experiencing at least one storm that has a return period of 25 years or more during a 15-year period is 0.46. It appears almost a certainty, therefore, that some postlogging landslides will occur and about an even chance that severe sliding will be experienced.

If the analyst has meteorological information for the area being analyzed it may be possible to estimate more accurately the appropriate probability criterion. This can be done by comparing the probability of exceeding Caine's threshold in the area under investigation with the storm probability in the area that produced the

discriminant function. The posterior probability criterion then can be adjusted either up or down, as indicated. On the other hand, it may be difficult to estimate the effect of qualitative differences in how the logging is carried out or the effect of excluded variables. Uncertainty about prediction will always be greater than indicated by calculations.

CONCLUSIONS

A discriminant function can be a useful tool for estimating landslide risk after clearcut logging.

A simple equation based on slope, crown cover, and distance to a stream showed a greater reliability than an equation that included drainage area, when each was applied to new data not used in the development of the equation.

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