

SITE CONDITIONS RELATED TO EROSION ON LOGGING ROADS

By

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SYNOPSIS

Data collected from 299 road segments in northwestern California were used to develop and test a procedure for estimating and managing road-related erosion. Site conditions and the design of each segment were described by 30 variables. Equations developed using 149 of the road segments were tested on the other 150. The best multiple regression equation explained only 37% of the variance in the logarithm of road-related erosion. A discriminant analysis correctly classified 74% of the test data set. Road segments it predicted to be hazardous produced 82% of the measured erosion in the test data set. Analysis of the variables in the discriminant function indicates that the effect of terrain slope nearly overwhelms the effects of all other variables in determining the posterior probability of instability. Discriminate analysis also provides a means by which a forest manager can explore the expected effect that different strategies will have on erosion and on the resources spent on mitigation measures.

INTRODUCTION

Forest roads have been identified as an important source of erosion associated with forest management activities in the western United States. Rothacher and Glazebrook (1968) found that "roads were, involved in 60% of all major storm damage reports." The relative amounts of erosion associated with forest roads and timber harvest areas has ranged from areas occupied by roads being more than 133 times more erodible than harvest areas (Morrison, 1975) to as low as only 3 times more erodible (Greswell et al, 1979).

The relative importance of road-related erosion appears to be inversely related to the overall susceptibility of an area to mass erosion. In the Cascade Mountains of central Oregon, roads produced 10.7 times more landslides than did timber harvest areas on the unstable volcaniclastic terrane, but on the more stable lava-flow terrane all landslides were associated with roads (Swanson and Dyrness, 1975). In northwestern California steepplands (steeper than 30% and adjacent to streams), slides associated with roads accounted for 12% of the slide volume, but on non-steepplands, roads accounted for 85% of the slide volume (Furbish, 1981). These findings are not surprising because road cuts and fills can artificially create unstable slope configurations on sites that would otherwise be stable, whereas, harvesting disturbances are much less likely to make such a decisive change in stability.

Much attention has been directed to erosion on roads because their erosion rates per unit area are typically higher than those in timber harvest areas. Such an emphasis may be appropriate when managers attempt to identify important sources of erosion or when they allocate resources to prevent erosion. Roads may

lose much of their importance as sources of erosion, however, when estimating the over-all erosion from areas which are being managed for wood production. When a commercial forest area is completely under management, the erosion coming from roads and from harvest areas is estimated to be about equal (Swanson and Dyrness, 1975, McCashion and Rice, 1983, Amaranthus et al, in press). Roads occupy such a small proportion of the total area under management (typically 4-8%) that their contribution to total erosion is balanced by the lower erosion rate on the much larger harvest area.

This paper reports a study to develop an equation by which forest managers can estimate the expected amount of road-related erosion that might result from a particular standard of road on a particular site. Although our analyses only dealt with road-related erosion, we presumed that site conditions associated with a high risk of road-related erosion were indicative of a high risk of the road being damaged by erosion events started off of the road.

STUDY AREA

The roads investigated in this study were in the Coast Range and Klamath Mountains of northwestern California. Study sites were from 10 to 60 km inland from the coast and extended from 40° to 41°30' north latitude. For this study, the geologic parent materials of the area were grouped into six broad types: Acid Igneous, Ultramafic, Metamorphic, Soft Sedimentary, Hard Sedimentary, and the Franciscan Formation. Over half of the sites were found on either hard sedimentary rocks of the Cretaceous and Jurassic periods or on the Franciscan Formation, which is a highly sheared and complex unit consisting mainly of massive

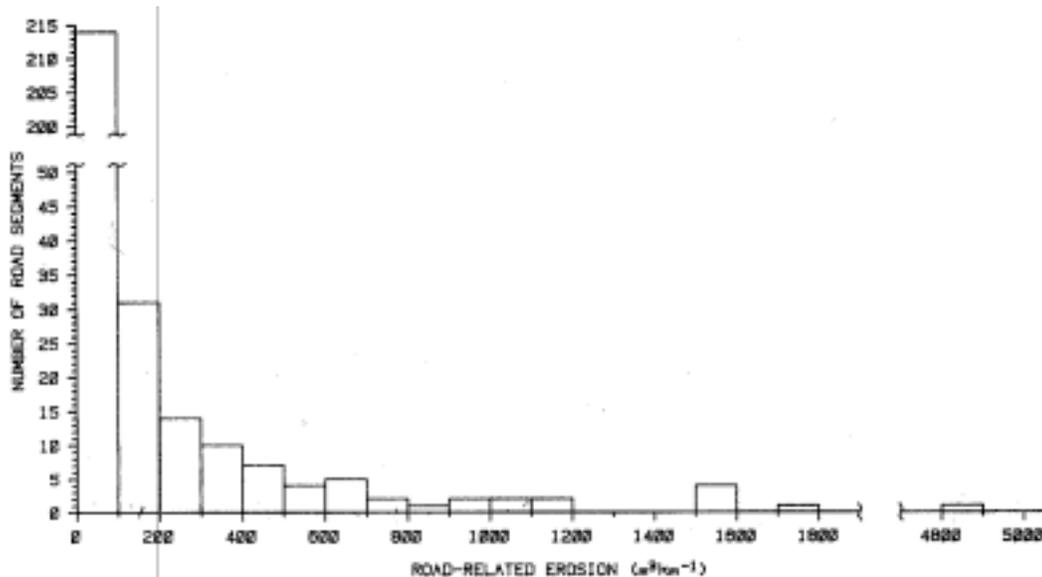


Figure 1 Frequency of road segments yielding various amounts of road-related erosion.

greywacke and interbedded shales. Slopes average 24°, and range from 0° to over 45°. Elevation ranges from sea level to 1920m, averaging 843m. Annual precipitation in the area averages 200cm, ranging between 100cm and 300cm. Snow is a significant part of the precipitation only for the 25% of the study sites above 1200m elevation.

Study sites were selected by using a stratified sampling design to insure that the data spanned the ranges of important site variables and their interactions. Stratified sampling was also used to destroy naturally occurring associations between important site variables. The four strata were road standard, topographic slope, geologic parent material, and precipitation intensity.

Our stratification of the data seems to have been successful. The coefficient of determination of the regression of the logarithm of slope on the other stratification variables was 0.17. The coefficient of determination of the regression of the common logarithm of the 25-year/24-hour precipitation intensity on the other stratification variables was 0.18. The squared canonical correlations (Hotelling, 1936) of the road standard and geologic variables with the remaining variables were 0.13 and 0.28, respectively.

FIELD METHODS

The roads we studied were constructed primarily for use by trucks transporting logs. They averaged 11.5 years old. Available running surface averaged 5m wide, ranging from 3m to 9m. About 67% of the roads were surfaced with crushed rock, 15% were unsurfaced, and 17% were

paved with asphalt. The average road gradient was 4°, but some short segments were as steep as 9°.

Each study site consisted of a 1.61-km road segment. The site conditions describing the road were the averages of those measured at the ends of the road segment and at 0.32-km intervals along the road. Within the study road segment all erosional features appearing to have displaced more than 15 m³ of soil were measured individually. Smaller erosional features were estimated by a detailed survey of a randomly chosen 0.32-km segment of the road. Soil properties for the road were based on samples taken from this segment.

STATISTICAL ANALYSIS

We measured conditions on 299 road segments. A logarithmic transformation was used for the dependent variable and all of the continuous independent variables. This transformation was adopted because a plot of road-related erosion appeared to be approximately log-normally distributed (Figure 1) and because other similar studies in the area (Rice and Datzman, 1981, Rice and Pillsbury, 1982, Furbish and Rice, 1983) had found logarithmic models superior to models using untransformed data.

We then randomly divided the road segments. The first group, containing 149 segments, was used to develop our prediction equations. Data from the second group of 150 road segments was set aside to be used in testing the results of our analyses. Preliminary screening of the proposed 30 independent variables resulted in the rejection of two: soil depth and degree of fracturing because they were nearly constant.

The constancy of the degree of fracturing probably reflect true conditions, but we believe that our soil depth data are not correct. For the statistical analyses, categorical variable, such as geologic parent material, were coded by using +1 for the presence of each of the conditions and 0 if one of its companion conditions was present. This raised the number of statistical variables to 38.

The first screening of the 38 independent variables used a stepwise multiple regression program (Dixon and Jennrich, 1981). Next, the 22 variables showing the most promise were analyzed by using an all possible subsets regression (Norick and Sharpnack, 1977). The results were disappointing. The best regression equation, using Mallows' Cp (Daniel and Wood, 1971) as a criterion, had a coefficient of determination of only 0.37. In it, erosion was a function of slope position, slope, precipitation intensity, vegetative cover, cut bank height, and vegetation on the cut bank (APPENDIX).

We next turned to a linear discriminant analysis (Fisher, 1936). It seemed to us that it would be useful to identify those road segments most likely to produce large amounts of erosion. We divided our data in half: one half had road segments with more erosion than $25 \text{ m}^3 \text{ km}^{-1}$ -- these were designated "unstable"; the other half had road segments with less erosion than $25 \text{ m}^3 \text{ km}^{-1}$ -- these were designated "stable". The results of the discriminant analysis were encouraging. An equation based on slope position on slope, road standard cut height and the vegetative condition of the cut (Table I) correctly

Table I Linear discriminant function resulting from analysis of variables measured on the 149 road segments in the developmental data set.

Y =	(the canonical variate)
0.259	(a constant)
-0.297	(if LOW)
-0.706	(if MID)
0.353	(if UPPER)
0.650	(if RIDGE)
-0.777	(if CUTBARE)
0.197	(if CUTGRASS)
0.580	(if CUTWOOD)
-0.218	(if SEASON)
0.485	(if AW2ND)
-0.267	(if MAIN)
-1.168	log(SLOPE)
-1.676	log(CUTHT)

classified 74.5% of the developmental data set (Table II-A). When this equation was used to classify the road segments in the test data set, the classification accuracy was 74.0% (Table II-B). A chi-square test showed the classification accuracy with the test data set to be highly significantly different from chance (50%).

Table II Classification of 1.61-km road segments by linear discriminant function (Table I).

Actual Condition	Predicted Stable ^a	Predicted Unstable ^b	Correctly Classified (%)
A - Developmental data			
Stable ^a	55	20	73.3
Unstable ^b	18	56	75.7
Total	73	76	74.5
B - Test data			
Stable ^a	57	16	78.1
Unstable ^b	23	54	70.1
Total	80	70	74.0
a/	Road segments yielding less than $25 \text{ m}^3 \text{ km}^{-1}$ erosion.		
b/	Road segments yielding more than $25 \text{ m}^3 \text{ km}^{-1}$ erosion.		

DISCUSSION

The weak correlation between road-related erosion and the independent site and road design variables in the regression may result from road-related erosion not being due to a single process, but being the sum of several erosional processes (Table III). The relationship between site variables and erosion is not constant for all processes. Differences in slope, for example, primarily affect the occurrence of slides when the slope exceeds the

Table III Road-related erosion in northwestern California.

Type of Erosion ^a	Frequency km^{-1}	Volume $\text{m}^3 \text{ km}^{-1}$	Volume $\text{m}^3 \text{ ha}^{-1}$
Slide	0.111	39.0	49.0
Slump	0.142	51.3	64.5
Debris Flow	0.004	3.3	4.2
Earth Flow	0.006	3.8	4.8
Rock Fall	0.004	0.5	0.6
Gully ^b	0.009	7.6	9.6
Rills	-	1.9	2.4
Surface	-	80.3	101.0
Sloughing ^c			
Total	0.276	187.6	235.9

^a Mass wasting types as defined by Varnes (1958).

^b About one-half the gully erosion not tallied as individual events.

^c Surface sloughing is almost planar retreat of cut and fill slopes because of dry ravel, minor rills, and small mass movements.

Source: McCashion and Rice 1983

angle of internal friction of the soil. Erosion by rills and gullies is affected by all slopes. Surface vegetation and litter, which will reduce surface erosion, may lead to mass erosion by promoting infiltration. The effects of other variables are, no doubt, also poorly expressed by a regression model.

How can a linear discriminant function help the forest manager reduce road-related erosion? It is not as useful as a regression equation for estimating erosion. Rather, it answers a simpler question: Which road segments are likely to produce the bulk of the erosion caused by a road? For example, in the test data set, the 70 road segments predicted to be unstable (Table II-B) produced 82% of the total measured erosion (Table IV). Had effective mitigating measures been taken on these roads, their erosional impact might have been substantially reduced.

Table IV Total road-related erosion measured on test road segments according to predicted and actual condition.

Actual Condition	Predicted Stable ^a	Condition Unstable ^b	Total
	-----m ³ -----		
Stable ^a	239	51	290
Unstable ^b	4,306	21,039	25,345
Total	4,545	21,090	25,635

a/ Road segments yielding less than 25 m³km⁻¹ erosion.
b/ Road segments yielding more than 25 m³km⁻¹ erosion.

The classification of a road segment in the test data set as accomplished by computing its posterior probability (Figure 2); that is, the probability that it belonged to the unstable group, given its set of values for the variables in the discriminant function (Table I). A road was predicted to be unstable if it had a probability greater than 0.50 of belonging to the unstable half of the population of road segments. But penalties are associated with any criterion. Sixteen of the 70 road segments predicted to be unstable (Table II-B) produced almost no erosion (Table IV). Resources spent to reduce erosion on these road segments would be wasted. On the other hand, the 23 roads incorrectly predicted to be stable produced 17% of the total erosion. A forest manager might consider this quantity to be too much erosion. The uncontrolled erosion could be reduced by lowering the criterion probability. If roads having posterior probabilities of more than 0.3 of belonging to the unstable group were considered unstable and subjected to effective mitigation measures, erosion might be reduced to 3% of the amount to be expected if no mitigation were attempted. But, at the cost of undertaking unnecessary mitigation measures on the 24% of the road segments now misclassified as unstable.

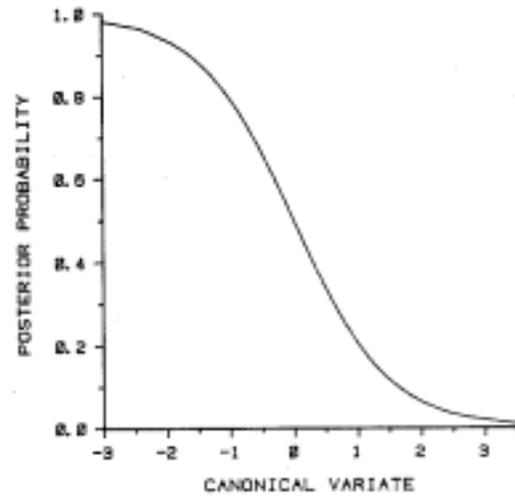


Figure 2 Probability that a road segment will produce more than 25m³km⁻¹ erosion, given the value of its discriminant function.

In practice the trade-offs need not be so severe. A manager could use the probability of instability to identify road segments requiring closer scrutiny. After a technical specialist had evaluated them, many of the erroneous classifications might be corrected.

In addition to serving as a predictive tool, a discriminant function can be used interpretively. When used in this fashion, it is assumed that the variables in the equation are, in fact, expressing the relationships indicated by their names. With that assumption, what does our discriminant function (Table I) suggest about conditions leading to high risk of road-related erosion? The effect of slope can be estimated by the product of its range and its coefficient in the discriminant function. That product is 4.73, which nearly spans the range of values of the canonical variate (Figure 2). Therefore, even if all of the other variables in the discriminant function took on values associated with stability, a steep slope could still lead to a high posterior probability of instability.

Cut height is the variable having the second greatest influence on the canonical variate. The product of its range and coefficient is 2.99. Because cut height results from the interaction of road width and slope, the importance of this variable further emphasizes the importance of slope. Slope position and vegetation on the cut slope are the next most important variables. And because they are categorical, their influence on the canonical variate is estimated from the range in coefficients for their various categories. Slope position and cut slope vegetation each can affect a change of 1.36 in the canonical variate.

Road standard is the least influential variable, affecting a change of only 0.75 in the canonical variate. The effect that changes in the canonical variate would be expected to have on the posterior probability depends on where the other variables in the discriminant function place the canonical variate (Figure 2). In the middle of its range, a change of 1.00 in the canonical variate is associated with a change of about 0.30 in the posterior probability.

A discriminant analysis can also help the forest manager decide on the appropriate criterion probability (Rice and Pillsbury, 1982). If relative values can be assigned to each type of correct and incorrect classification, the data from a proposed road alignment can be used to estimate the criterion that will maximize the benefits expressed by the user's value system.

At first glance the discriminant function (Table I) appears to indicate that most of the risk of road-related erosion is determined by elements of road design over which the road designer has control. Only terrain slope is beyond the designer's control. Upon closer inspection, however, it becomes evident that the designer's options may be more limited. The position to lower standard roads on the slope may be dictated by slope morphology and the system being used to bring logs to the road. Road standard is largely determined by the expected type and volume of traffic. Cut height is an interaction between road standard and slope. An the vegetation on the cut slope is constrained by microclimate and the fertility and physical properties of the material into which the road is cut.

Road design variables may be correlated with site variables (and presumably determined by them). The coefficient of determination between slope the only site descriptor) and the other variables in the discriminant function (Table I) was 0.67. This finding supports our earlier conclusion (McCashion and Rice, 1983) that the choice of a road alignment is crucial in determining subsequent erosion.

CONCLUSIONS

Site condition -- particularly terrain slope -- where a road is located greatly influence subsequent road-related erosion. Road design variables are constrained by management considerations and site conditions so that the road designer has relatively few options when attempting to void road-related erosion.

A multiple regression equation was not effective in predicting road-related erosion. Its coefficient of determination was only 0.37. We attribute the poor performance of the regression mainly to the fact that the model was necessarily simplistic.

A linear discriminant analysis appears to be a promising statistical aid to road design. In this study it correctly identified as hazardous those road segments producing 82% of the measured erosion. Discriminant analysis can be used to display for the manager's consideration the proportion of unstable road segments that

might be identified by using a particular criterion, the expected proportion of unstable road segments that might go undetected, and the proportion of stable road segments which might be treated unnecessarily.

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APPENDIX Dependent and independent variables used in regression and discriminant analyses.

DEPENDENT VARIABLE

ROADCOZD - Erosion presumed to have been caused by the road ($m^3 km^{-1}$).

INDEPENDENT VARIABLES

Road Variable

Position on slope

LOW - Valley bottom and lower 1/3 of the slope.
 MID The middle 1/3 of the slope.
 UPPER - To upper 1/3 of the slope.
 RIDGE - The ridge (Dummy variable designated by coding the above three variables as -1).

Road surface material

LITE - Road surfaced with 5 cm or less of gravel.
 HEAVY - Road surfaced with more than 5 cm of gravel.
 PAVED - Road surface sealed with a permanent hard material.
 NONE - Road surface consists of existing natural material (dummy variable).

Road standard

SEASON - Roads used in dry season only, 3-4 m wide surfaced with natural soil or thin rock, may or may not have permanent drainage structures.
 AW2ND - An all-weather secondary road suitable for year-round use, 3.5-5 m driveable width, surfaced with gravel or crushed rock of moderate depth, and drainage structures adequate for a 25-year storm.
 MAIN - Permanent all-weather roads used as main collectors of traffic with a driveable surface of about 9 m. They receive regular maintenance, are heavily surfaced with gravel or pavement, and have drainage structures to accommodate a 25-year storm (dummy variable).

Vegetation on cut surface

CUTBARE - Cut surface essentially devoid of vegetation.
 CUTWOOD - Cut surface revegetated with woody vegetation.
 CUTGRASS - Cut surface revegetated with herbaceous vegetation (dummy variable).

Vegetation on fill surface

FILLBARE - Fill surface essentially devoid of vegetation.

FILLWOOD - Fill surface revegetated with woody vegetation.
 FILLGRASS - Fill surface revegetated with herbaceous vegetation (dummy variable).

GRADE - The average road gradient (%).
 CUTHT - Road cut height (m).
 FILLHT - Height of road fills (m).
 WIDTH - Width of road operating surface (m).
 YRSLOG - Time since the area adjacent to the road was logged (yrs).
 PROPLOG - Proportion of the area adjacent to the road which had been logged.
 FILLVOL - Volume of fill ($m^3 km^{-1}$).
 CUTVOL - Volume of cut excavation ($m^3 km^{-1}$).
 TOTEXC - FILLVOL + CUTVOL (not used in $m^3 km^{-1}$).
 ROADAGE - Age of the road at the time of measurement (yrs).

Site Variables

SLOPE - Average terrain slope (tangent).
 ASPECT - Coded 1-8 in rough approximation to microclimate (Rice and Datzman, 1981).
 ELEV - Mean road elevation (m).
 COVER - The proportion of ground covered by the crowns of the dominant vegetation (%).
 25YR24HR - The maximum amount of precipitation in 24 hours resulting from a storm having a 25-year return period (Miller et al, 1973)(cm).
 MAP - Mean annual precipitation (Rantz, 1968)(cm).
 SAND - Proportion of soil composed of particles between 2 and 2×10^{-2} mm in diameter
 CLAY - Proportion of soil composed of particles smaller than 2×10^{-3} mm in diameter (%)
 SILT - Proportion of soil composed of particles between 2×10^{-2} and 2×10^{-3} mm in diameter (%)
 PCTGT2MM - Proportion of soil composed of particles greater than 2 mm in diameter (%).
 FAULTS - Distance to nearest mapped geologic fault (km) (faults more distant than 8 km coded as 8 km).

Shape of Slope

CONCAVE - Average slope configuration normal to contours is concave.
 CONVEX - Average slope configuration normal to contours is convex.
 UNIF - Uniform slope (Dummy variable).

Geologic parent material

GR - Acid igneous rocks, mainly granitics.
 UM - Ultramafic rocks.
 MM - Metamorphic rocks, including meta-sedimentary rocks.
 SS - Soft sedimentary rocks, mainly of Cenozoic era.
 HS - Hard sedimentary rocks, mainly of Cretaceous and Jurassic periods.
 FR - The Franciscan Formation, a highly sheared and complex unit consisting mainly of massive graywacke and interbedded shales. (Dummy variable).