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Controls on landslide distribution in the Western Cascade Range, Oregon

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ABSTRACT

Slope, aspect, and rock strength were evaluated using a Geographic Information System to examine controls on spatial distribution of landslides in the Blue River watershed, Oregon. A logistic regression was run and only rock strength was found to have a significant influence on landslide occurrence. Land use was also evaluated to determine its effect on landslide hazard. A temporal model of varying landslide hazard due to land use was also developed and run for existing land use data sets for the study area. A GIS map was generated at selected years to show the increase in landslide hazard due to land use. A landscape scale landslide hazard index was generated separately for two adjacent watersheds with different land use histories.

INTRODUCTION

Shallow, rapid landslides are a common erosional mechanism in the steep, forested slopes of the western Cascade Range. They have been shown to be a major source of sediment (Swanson, et al 1987a). Landslides are typically initiated by high rainfall and snowmelt, which act to increase pore pressure.

Many studies have suggested that the spatial distribution of landslides is related to physical factors (Dyrness 1967, Dragovich, et al 1993, McHugh 1986, Marion 1981, Swanson, et al 1987a). According to mechanical theory, steeper slopes should correspond to increased occurrence of landslides (Sidle 1992). Landslides may occur more often on particular aspects than others, as different aspects correspond to different microclimates. Microclimate may also vary with elevation. Geologic conditions, including rock and soil types, may influence the distribution of landslides. Previous studies have also shown that topographic setting may be related to landslide hazard (Swanson 1992).

Land use practices can also affect landslide hazard. Road cuts have long been recognized as a cause of increased landslide frequency (Dyrness 1967, Swanson and Dyrness 1975, Marion 1981). However, forest road engineering has improved drastically in recent decades and has decreased their impact on landslide hazard (Swanson pers com). Forest-cutting can also increase hazard. Root strength is known to be an important factor in preventing landslides (Sidle 1992, Abe 1992), and cutting acts to decrease root strength. There is generally a lag time of about five to ten years after cutting as the roots decompose for landslide hazard to peak. Thereafter slide potential decreases in response to redevelopment of root systems by developing vegetation.

This project can be divided into three phases. (1) The primary objective of the first phase was to evaluate the degree to which slope, aspect, and rock strength influence the frequency of landslide occurrence. The ability to predict landslide hazard using a Geographic Information System (GIS) was also tested through this process. (2) An intrinsic landslide hazard model was constructed based on the physical parameters analyzed in phase one to determine where future landslides are most likely to occur. (3) The objective of the third phase was to determine how land use has affected landslide hazard through time.

STUDY SITE

The 15525 hectare study area lies on the western slope of the Western Cascades, about 80 km east of Eugene, Oregon (figure 1). The study site includes both the Upper Blue River watershed (UBR) and the adjacent H. J. Andrews Experimental Forest (HJA) for which Lookout Creek is the drainage. Average annual precipitation is about 2500 mm. Most of the precipitation falls as rain below 400 m and as snow above 1200 m. The zone between 400 m and 1200 m is known as the transient snow zone and features common rain on snow events (Harr 1981). The forested area is dominated by Douglas fir (Pseudotsuga menziesii) and western hemlock (Tsuga heterophylla).

The Blue River watershed is underlain entirely by rocks of volcanic origin. The oldest rocks are 30 million-year-old hydrothermally altered volcanics that lie at the lower elevations. Middle elevations are underlain by younger ash flow units. The highest elevations are underlain by 3-5 million-year-old unaltered basalt and andesite lava flows (Swanson and James 1975). Fred Swanson (1992) has designated relative rock strengths to the geologic units, with the oldest rocks being the weakest and the youngest having the highest rock strength.

The study site includes two distinct management units, each having its own history of land use. The different development patterns of each unit have played important roles in landslide succesptability. The H. J. Andrews Experimental Forest was cut heavily in the decades of the 1950's and 1960's. Consequently, it suffered numerous landslides in severe storms of this period, including 43 slides from a series of strong storm events in December 1964 and January 1965 (Dyrness 1967). The HJA became part of the International Biological Programme in 1970 and management emphasis shifted to research, which brought about drastic reductions in rates of cutting and road construction. Forest cutting was minimal in UBR through the 1950's, but was heavy from about 1960 to 1990 (Swanson pers com). This unit did not suffer as heavily in the strong storms on 1964, but produced more landslides during a 1986 storm event.

METHODS

Mapping and Observation of Landslides

Mapping of landslides within the study site was first initiated by Dyrness (1967) and later by Swanson and Dyrness (1975) and Marion (1981). Initial identification of landslide sites utilized air photography, followed by field verification. The slope and aspect were recorded, and an estimate of the volume of material released by the slide were made. In many cases the date of the slides were known from post-storm observation. Other landslides were dated initially by using air photographs to establish minimum and maximum ages. The date was then estimated in the field using dendrochronological techniques.

Analysis of Physical and Land-use Parameters

An ARC/INFO® geographic information system was used to analyze the data. A 100 m square grid was applied to the study site and each grid cell was classified as containing landslides or containing no landslides. The two sets of cells were then compared for each physical and land-use parameter.

Slope steepness and aspect parameters were generated from a digital elevation model (DEM) at 1:24000 scale. This process has been shown to produce slope classifications up to 10 degrees below field observations in the study area (Swanson, et al 1992b). Geologic data is based on Swanson and James (1975). Rock strength includes three classifications (weak, intermediate, strong) as described by Swanson (1992a).

For each physical and land use parameter, the total area for each classification that was occupied by landslides was calculated, and chi-square tests were performed. A logistic regression was then executed for the physical factors.

Modeling of Intrinsic Landslide Hazard

A landslide hazard model was constructed for the study site based on the results of the analysis of physical and controls. For each factor found to have a significant control on landslide frequency, values were designated for each class based on the degree of difference in landslide frequency found in the analysis.

Effect of land use on landslide hazard through time

A function was developed for forest cuts and roads to model the relative increase in landslide hazard relative to the intrinsic, physically-based (assuming a forested, unroaded watershed condition) hazard through time (figure 2). A separate curve was developed for roads built before and after 1970, as improved engineering appears to have lessened the effect of roads on landslide hazard (Swanson pers com). The function was applied to each clear cut and road segment. The change in landslide hazard was calculated for each cut and road at five year intervals from 1950 to 2015. The model is based on data up to 1993 and assumes no additional road or forest cutting from that point on.

A landscape scale landslide hazard index was calculated separately for the UBR and HJA. At each five year interval, the increased landslide hazard for each cut and road segment was multiplied by its area. The (assumed road-affected) area for roads was calculated by multiplying their lengths by a 25 m buffer. The sum of all landslide hazard-area was calculated at each interval for both watersheds.

A GIS map was constructed to represent the effect of land use on landslide hazard for selected years. The increased landslide hazard value for each cut and road was applied to the map for each represented year. Where roads and cuts overlapped their increased landslide hazard values were added.

RESULTS

When a 100 m square (1 hectare) grid was applied to the site, 205 out of 15525 grid cells contained landslides.

Slope

The greatest percentage of landslides occurred on class 5 slopes, (40 to 50 degrees). However, there was no clear trend of landslide distribution with respect to slope (Figure 3). The chi-square value for slope was 7.915 and the p-value was 0.244, indicating that slope was not a significant control on landslide occurrence.

Geology

Landslides occupied a higher percentage of land classified as having weak rocks, followed by intermediate rock strength, and strong (figure 4). Landslides occupied 4% of grid cells containing weak rocks, 1% of cells with intermediate rocks, and 0.5% of cells with strong rocks. The chi-square value for geology was 71.75 and the p-value was 2.2×10^{-16}, indicating rock strength was a significant control on landslide occurrence (at $p=0.05$).

Aspect

Landslides seemed to occur more often on slopes with northern aspects (figure 5), however the trend is not well developed. The chi-square value for aspect was 10.176 and the p-value was 0.179, indicating that aspect was not a statistically significant control on landslide occurrence.

Logistic regression for slope, geology, and aspect

The results of the logistic regression (Table I) confirmed that rock strength was the only significant physical control on landslide occurrence.

Land use

Landslides occurred on 3% of grid cells that contained roads and 0.5% of grid cells containing no roads (figure 6). Two percent of grid cells with clearcuts contained slides and 1% of grid cells with no clearcuts contained slides. The chi-square value for roads was 104.982 and the p-value was 0.000001. The chi-square value for forest cuts was 16.097 and the p-value was 6.01×10^{-5}. Both forest cuts and roads were significant controls on landslide occurrence.

Intrinsic landslide hazard model

Because rock strength was the only physical parameter found to have a significant control on landslide occurrence, it is the only factor to base an intrinsic landslide hazard model on. Therefore this model would look exactly like the rock strength map (figure 7) with weak rocks having the greatest landslide hazard.

Effect of land use on landslide hazard through time

The landscape scale landslide hazard index (figure 8) represents the relative increase in landslide hazard due to land use through time. UBR and HJA are represented by separate curves because of their unique land use histories. A GIS map of the effect of land use on landslide hazard for the years 1965, 1975, 1985, 1995, and 2005 (figure 9) represents snapshots of increased landslide hazard at those particular years.

DISCUSSION

Physical controls on spatial distribution of landslides

The results show that rock strength is the only significant control on landslide occurrence. While past studies have indicated that slope and aspect are important factors, in this study they were not significant. The most likely explanation is the matter of scale. The results do not show that slope is not a factor in landslide occurrence, but only that slope at a scale of 100 square meters is not a significant factor. The same is true for aspect. However, rock strength should be consistent within a 100 meter grid cell.

While the results seem to indicate that slope is not a significant control on landslide occurrence, this contradicts many previous studies as well as common sense. In fact, Dyrness (1967) found strong influences of slope using a limited set of HJA landslides (and different methods of analysis). Obviously, more landslides are going to occur on steeper slopes than on gentle slopes (up to about 40°). There are many possible reasons for this seemingly unusual result. The method of analysis must be considered, since slope was generated from a digital elevation model by the GIS. Therefore the slope designations that were studied may not precisely represent the slopes found in the field, especially in tall forested areas. Also, slope was calculated for 100 m grid cells. It would seem that this grid cell size is small enough to avoid the problems of generalizing associated with large grain size data, however it has not been tested.

Their may have also been a higher number of landslides on shallow slopes in the study area because of a unique relationship between slope and geomorphic conditions. A high percentage of land with gentle-slopes in the study area lie in lower elevations which are also transected by a well-developed stream network. A high incidence of stream-side landslides have occurred in this area (Swanson pers com). This relationship may also be affecting the results.

In a similar study by Dragovich and others (1993) increased slope was shown to correlate to increased landslide occurrence. However, field observed slopes for landslides were compared to GIS-generated slope distribution, whereas in this study the slopes of landslide sites were generated by GIS. The method used in the Dragovich study would probably result in a significant correlation if applied to this study area also. While this method may be useful in evaluating slope as a control on landslide occurrence, it does not test the usefulness of slope in predicting future landslides using GIS analysis.

The results indicate that physical controls on landslide occurrence may be more complex than was assumed for the purposes of this study. There may be other physical controls that play an important role, such as geomorphic setting, hydrological features, and geologic structure. It is likely that one or more of these factors is/are not randomly distributed with respect to slope (and possibly aspect). The influence of these factors could be affecting the slope data.

Effect of land use on landslide hazard

The two curves for the HJA and UBR for the landscape scale landslide hazard index reflect their different land use histories. HJA was primarily developed in the fifties and sixties, whereas UBR was developed primarily in the seventies and eighties. This is reflected by the much higher hazard index for the HJA in the earlier decades and the reverse situation in later decades.

The susceptibility for the two management units during two years of severe storm events, 1964 and 1986, reflects the relative amount of slides suffered by each unit during those events. In 1964, HJA had a greater hazard index, and suffered many more slides. In 1986, UBR was more susceptible and also suffered more slides.

CONCLUSIONS

The method of analysis used for this study did not show a significant correlation to the spatial distribution of landslides for slope and aspect. Because rock strength was shown to be the only significant control on landslide occurrence, a landslide hazard map based on physical influences can only be based on rock strength.

Since other studies have shown that slope should correlate to landslide occurrence, the result indicates that their is a problem in using GIS-generated slope data as a predictive tool. There is a need for further study of the relationship between physical factors and landslides. Methods of using slope and aspect with the GIS need to be refined.

The effect of land use on landslide occurrence was highly significant. The landscape scale landslide hazard index (figure 8) and the GIS 'snapshot' map (figure 9) represent this effect. The rates used to calculate the impact of forest cuts and roads (figure 2) need to be tested and refined. There are many possible methods to quantitatively develop a rate of change in landslide hazard for land use.

The somewhat unexpected results of this project most likely reflect the limitations of using GIS-generated data for predictive models. The problems with the model can mostly likely be overcome through further development. The GIS is a powerful tool for producing predictive models, however models need to be tested on existing data prior to being used as predictive tools. It is crucial when testing a model to ensure that existing data and predicted data are collected with the most similar methods that are possible.

ACKNOWLEDGMENTS

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Table I: Logistic Regression Results

```
                            The LOGISTIC Procedure

 Data Set: WORK.NEW
 Response Variable: LANDSLID
 Response Levels: 2
 Number of Observations: 197
 Weight Variable: COUNT
 Sum of Weights: 18504
 Link Function: Logit


                              Response Profile

                  Ordered                                Total
                    Value  LANDSLID     Count           Weight

                        1         0       127        18299.000
                        2         1        70          205.000


                  Testing Global Null Hypothesis: BETA=0

                               Intercept
                  Intercept       and
Criterion           Only       Covariates    Chi-Square for Covariates

AIC               2255.841      2183.017            .
SC                2259.124      2202.717            .
-2 LOG L          2253.841      2171.017        82.823 with 5 DF (p=0.0001)
Score                 .             .          117.987 with 5 DF (p=0.0001)


                 Analysis of Maximum Likelihood Estimates

              Parameter Standard     Wald        Pr >     Standardized     Odds
Variable DF   Estimate    Error   Chi-Square Chi-Square     Estimate      Ratio

INTERCPT 1      5.1934    0.2533   420.3554     0.0001           .           .
SCOS     1    0.000959  0.00419      0.0523     0.8191      0.089545     1.001
SSIN     1     0.00288  0.00433      0.4427     0.5058      0.264982     1.003
SLOPE    1     0.00696  0.00718      0.9396     0.3324      0.363013     1.007
I1       1     -2.2126   0.2484     79.3421     0.0001     -2.785928     0.109
I2       1     -0.8586   0.2172     15.6224     0.0001     -2.196230     0.424


      Association of Predicted Probabilities and Observed Responses

               Concordant = 50.1%          Somers' D = 0.141
               Discordant = 36.0%          Gamma     = 0.164
               Tied       = 13.9%          Tau-a     = 0.065
               (8890 pairs)                c         = 0.571
```

Figure 1. Study area

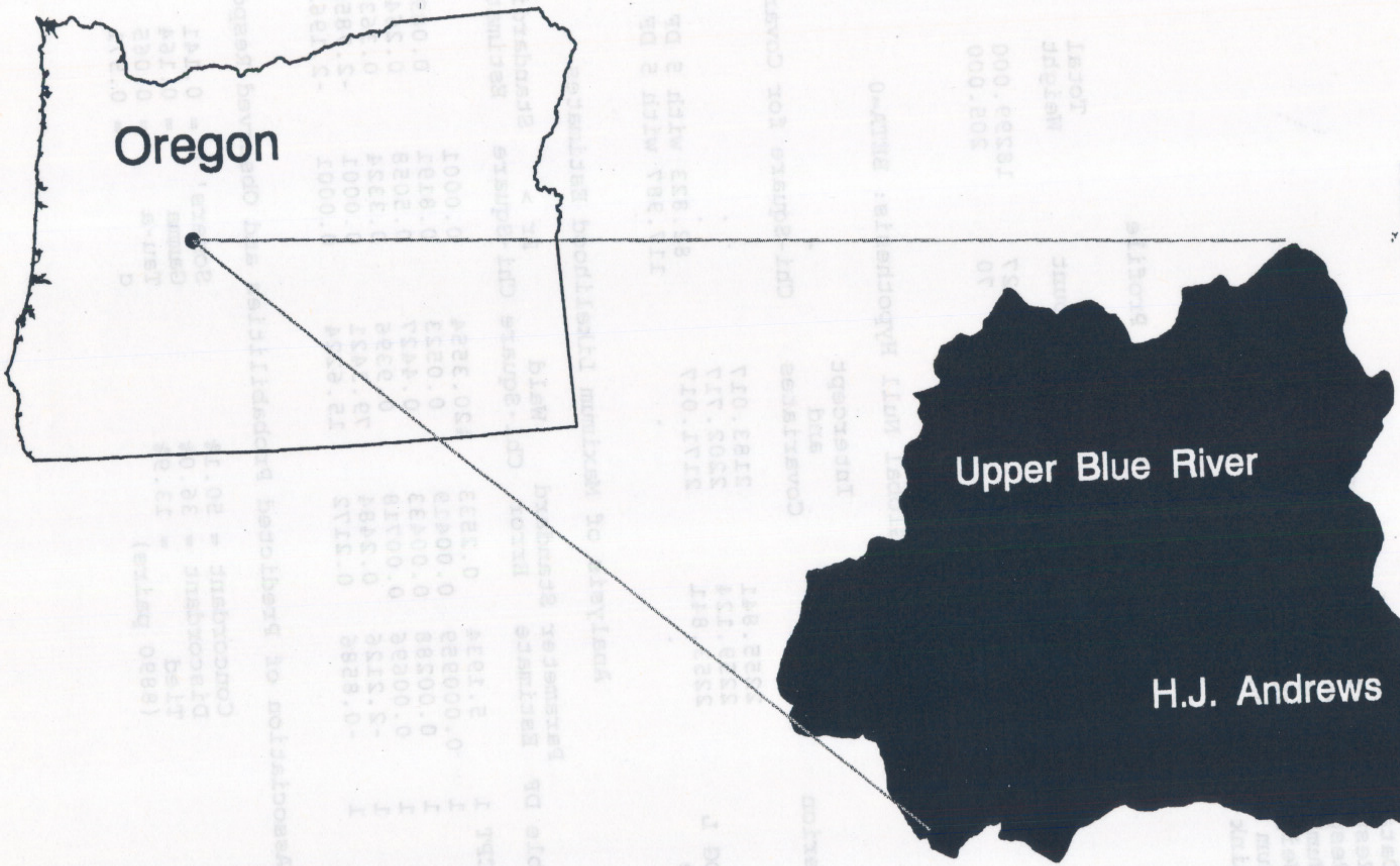


Figure 2

Effect of land use on landslide hazard through time

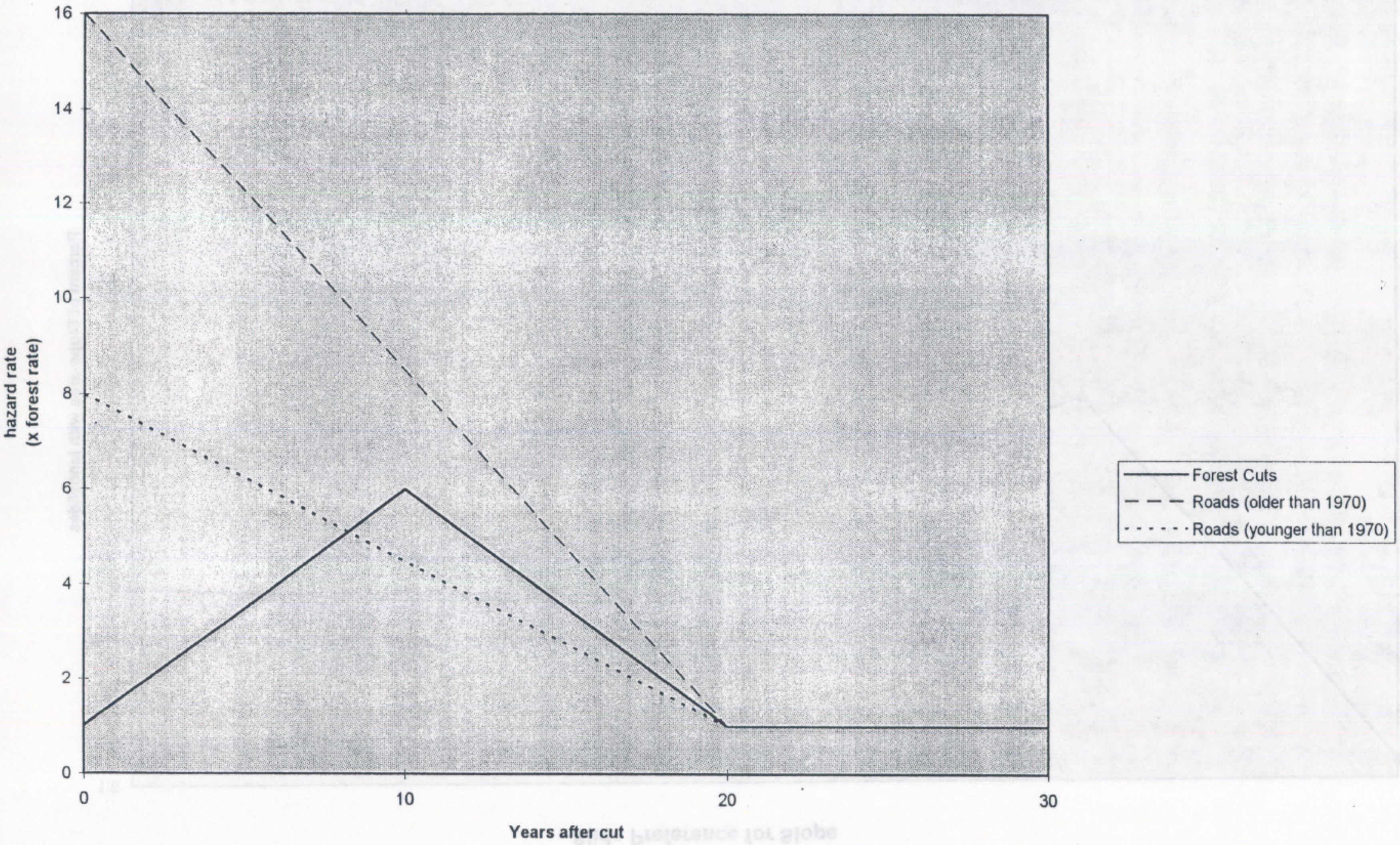


Figure 3

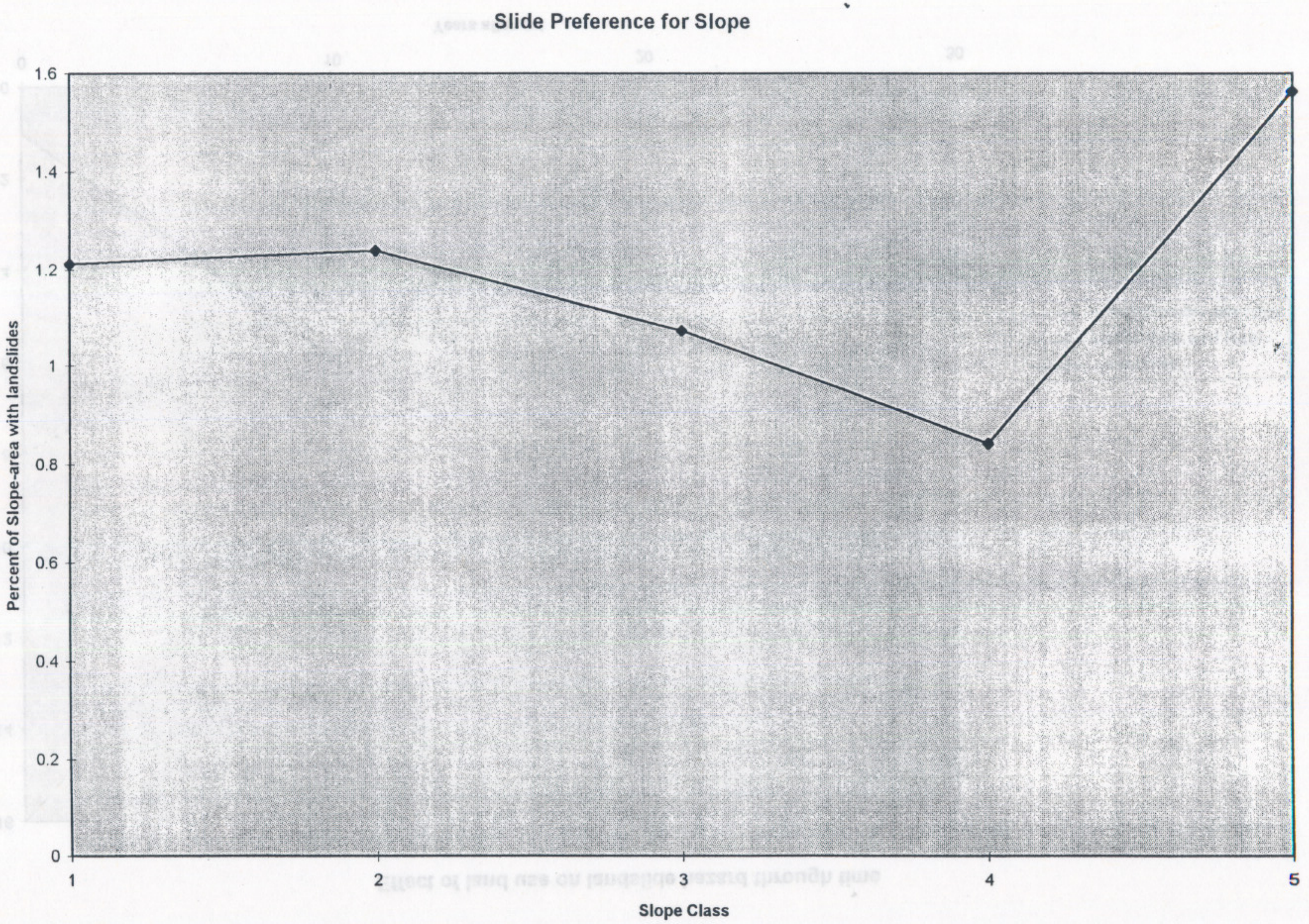
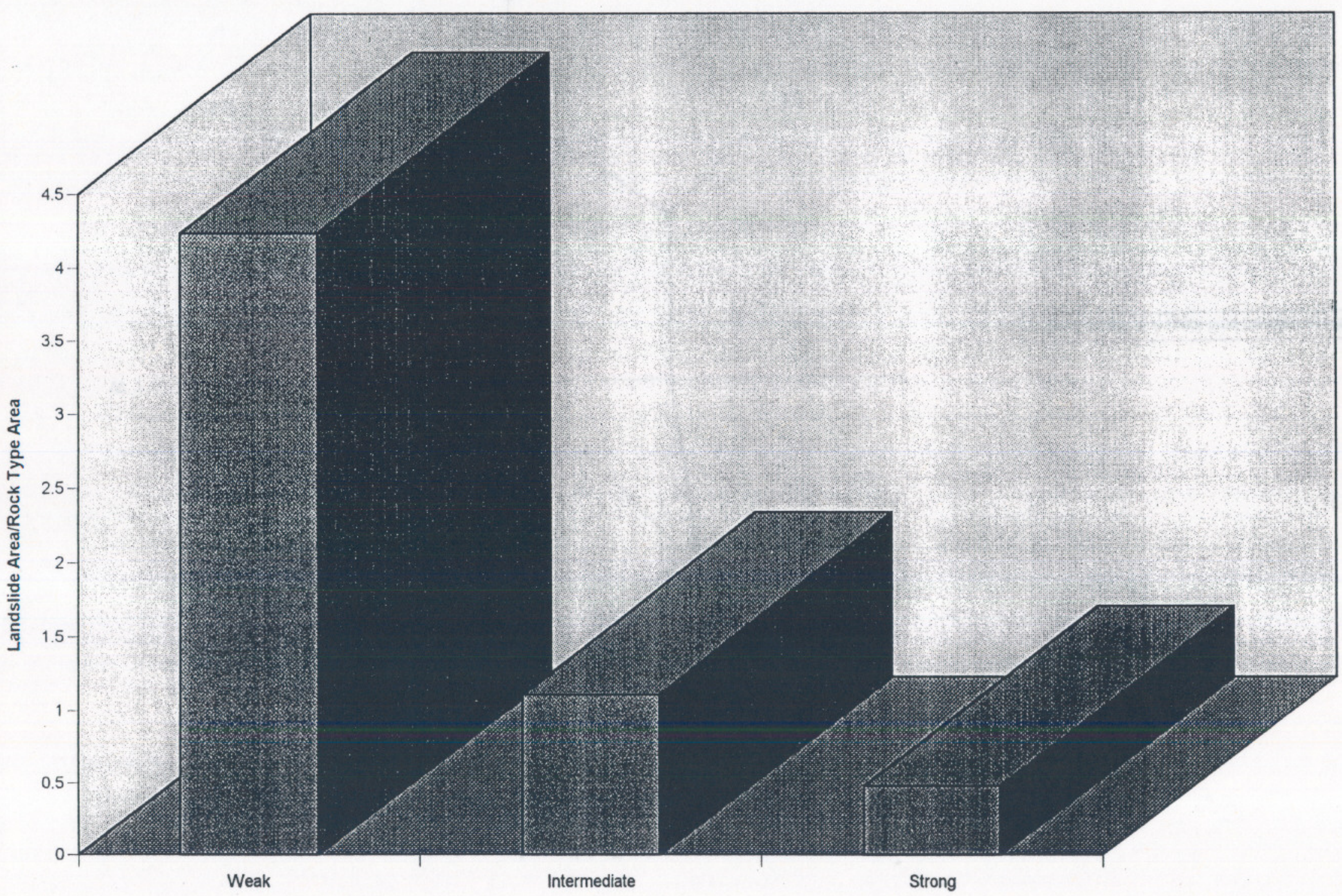

Slide Preference for Slope
Percent of Slope-area with landslides
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
2
3
4
5
Slope Class

Figure 4



Percent Occurance by Rock Strength

Figure 5

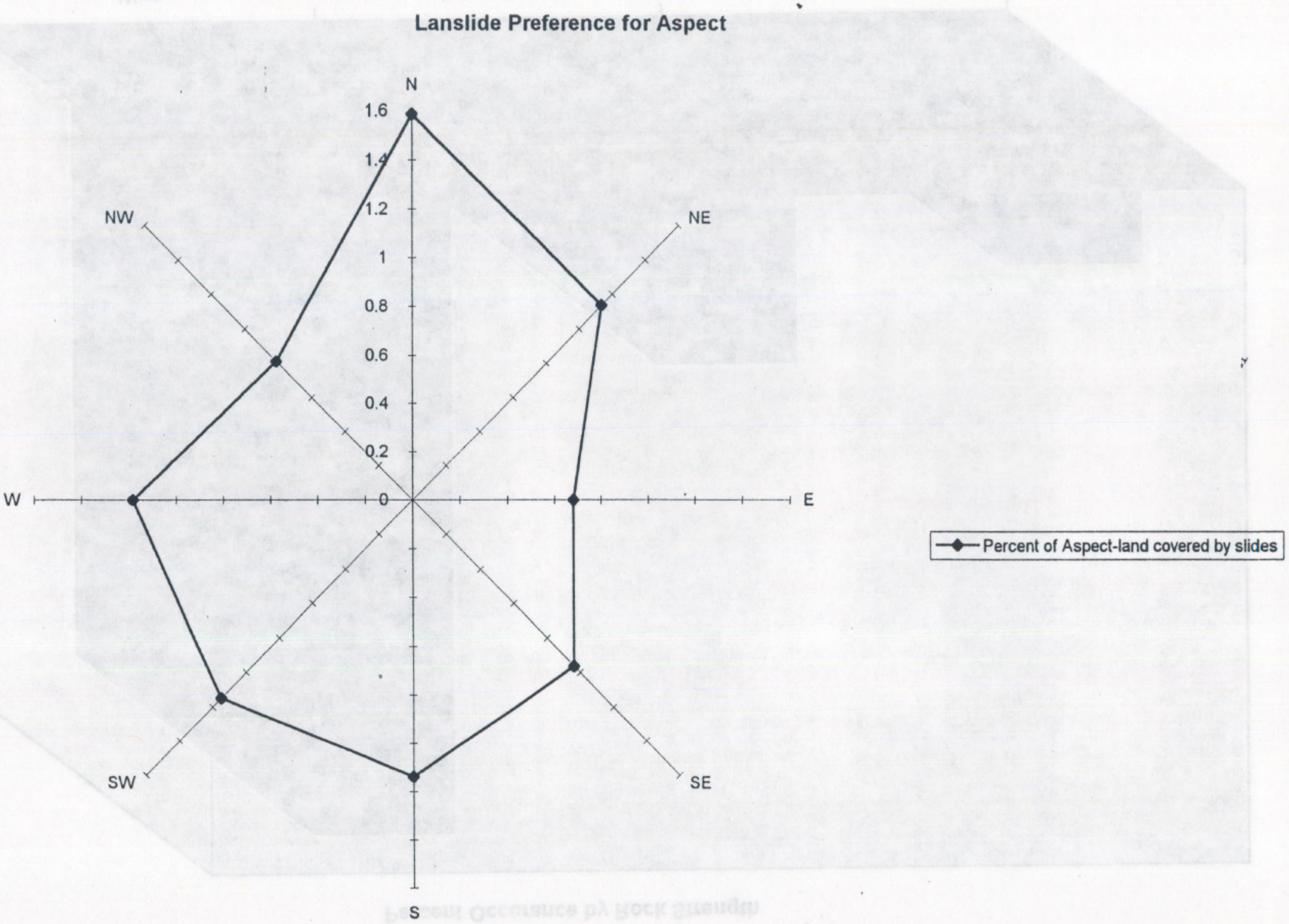
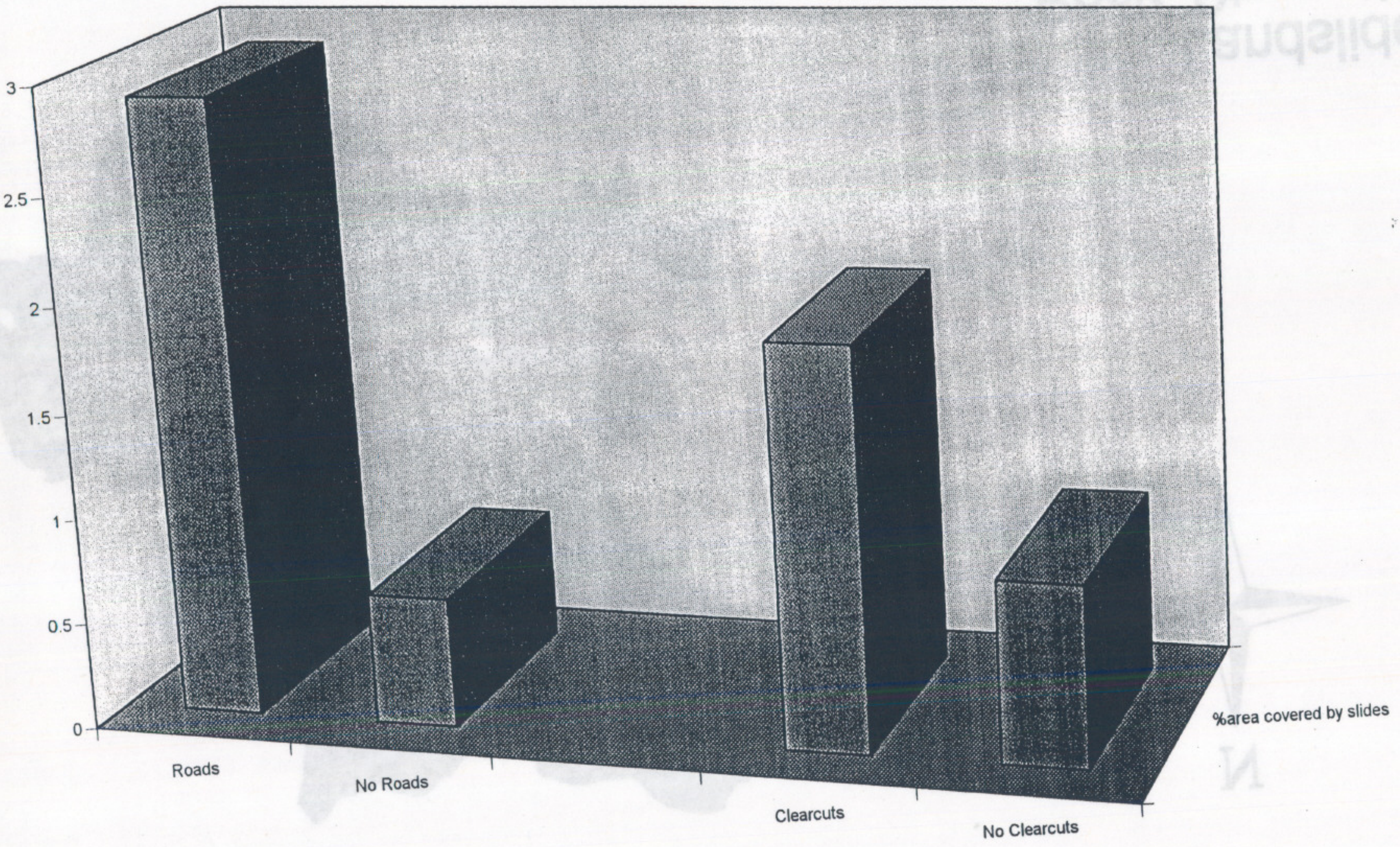

Lanslide Preference for Aspect
N
NE
E
SE
S
SW
W
NW
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Percent of Aspect-land covered by slides

Figure 6

Land-use Effects on Landslide Occurance



Geology Classes

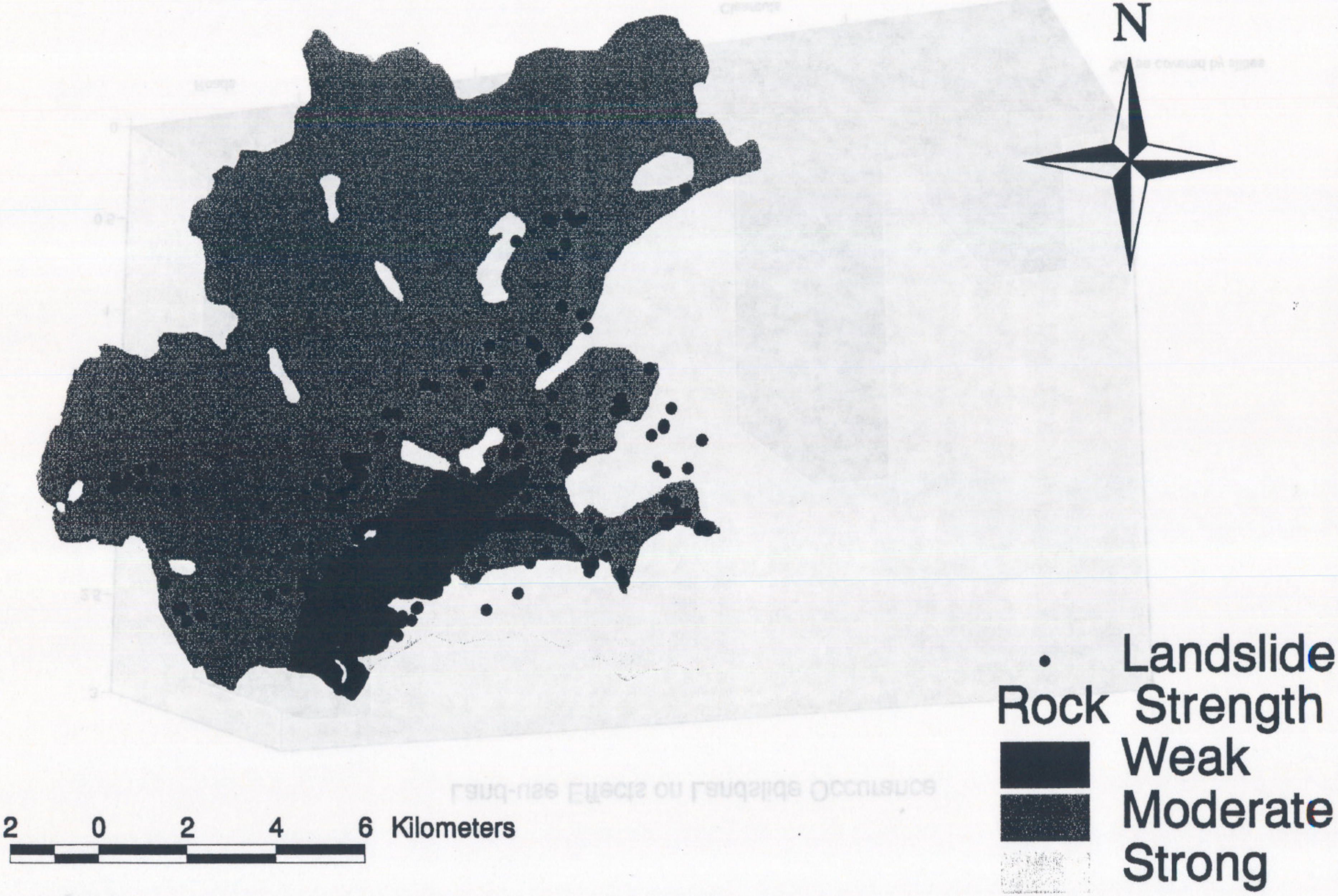
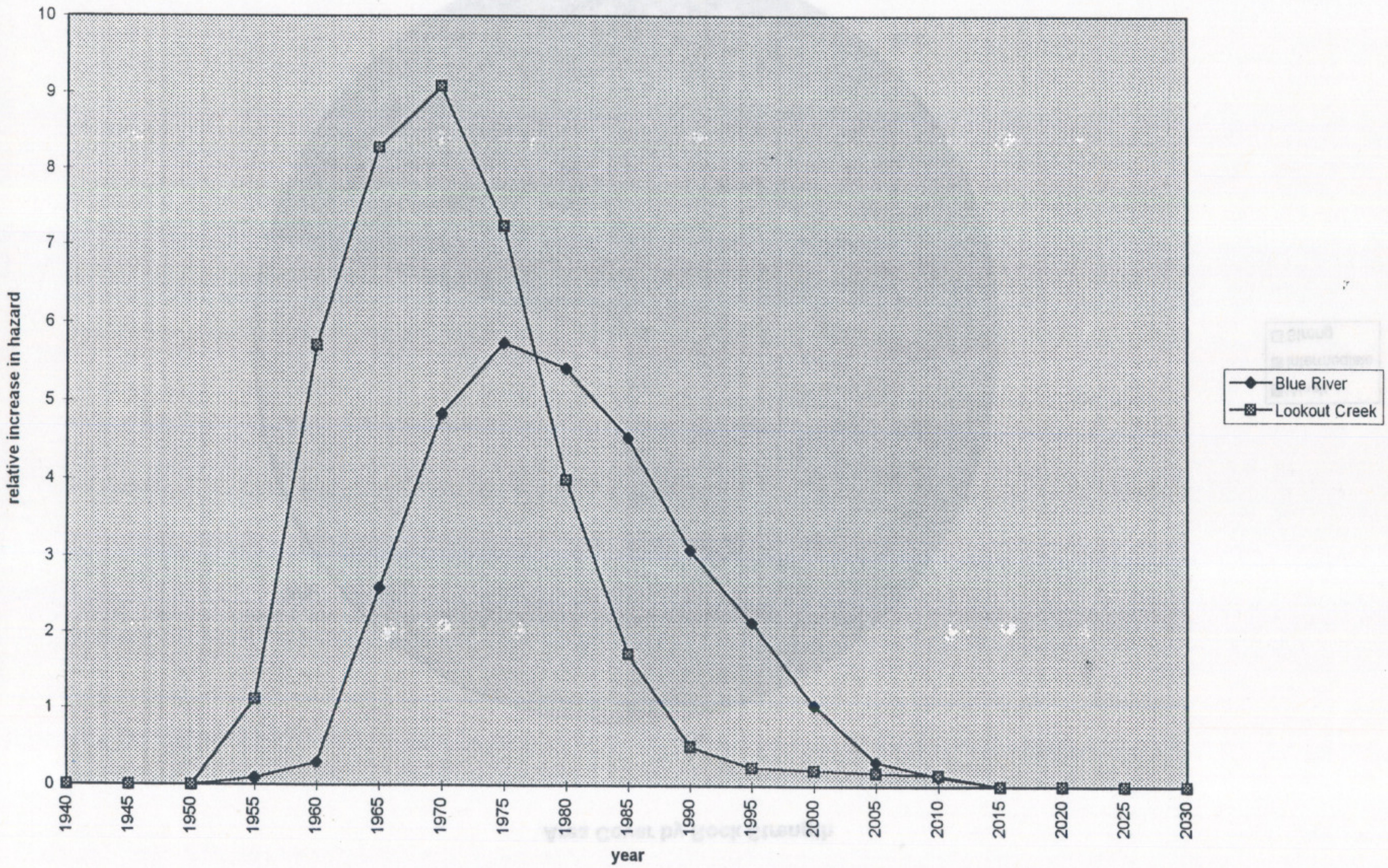
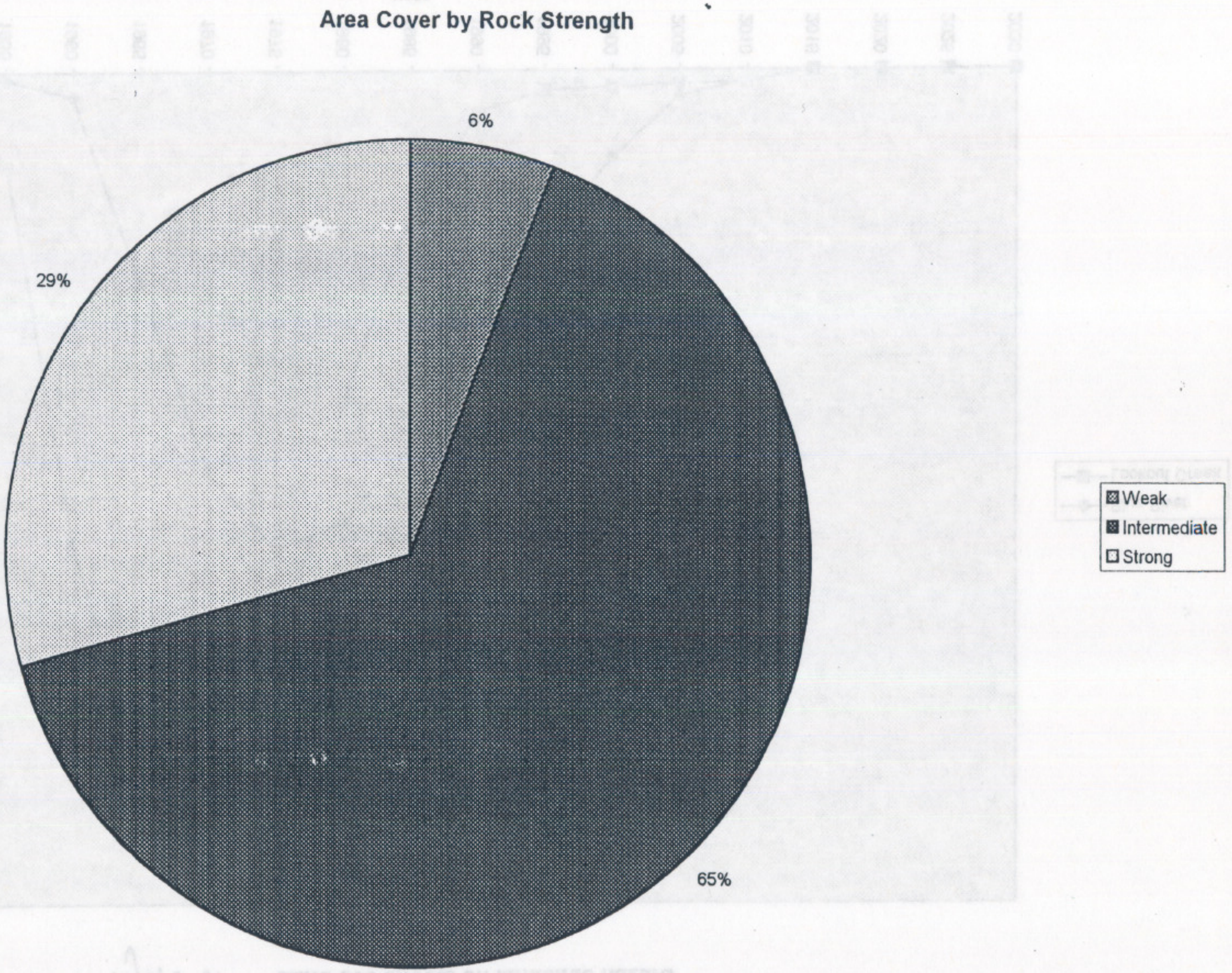


Figure 8. **Land use effects on landslide hazard**



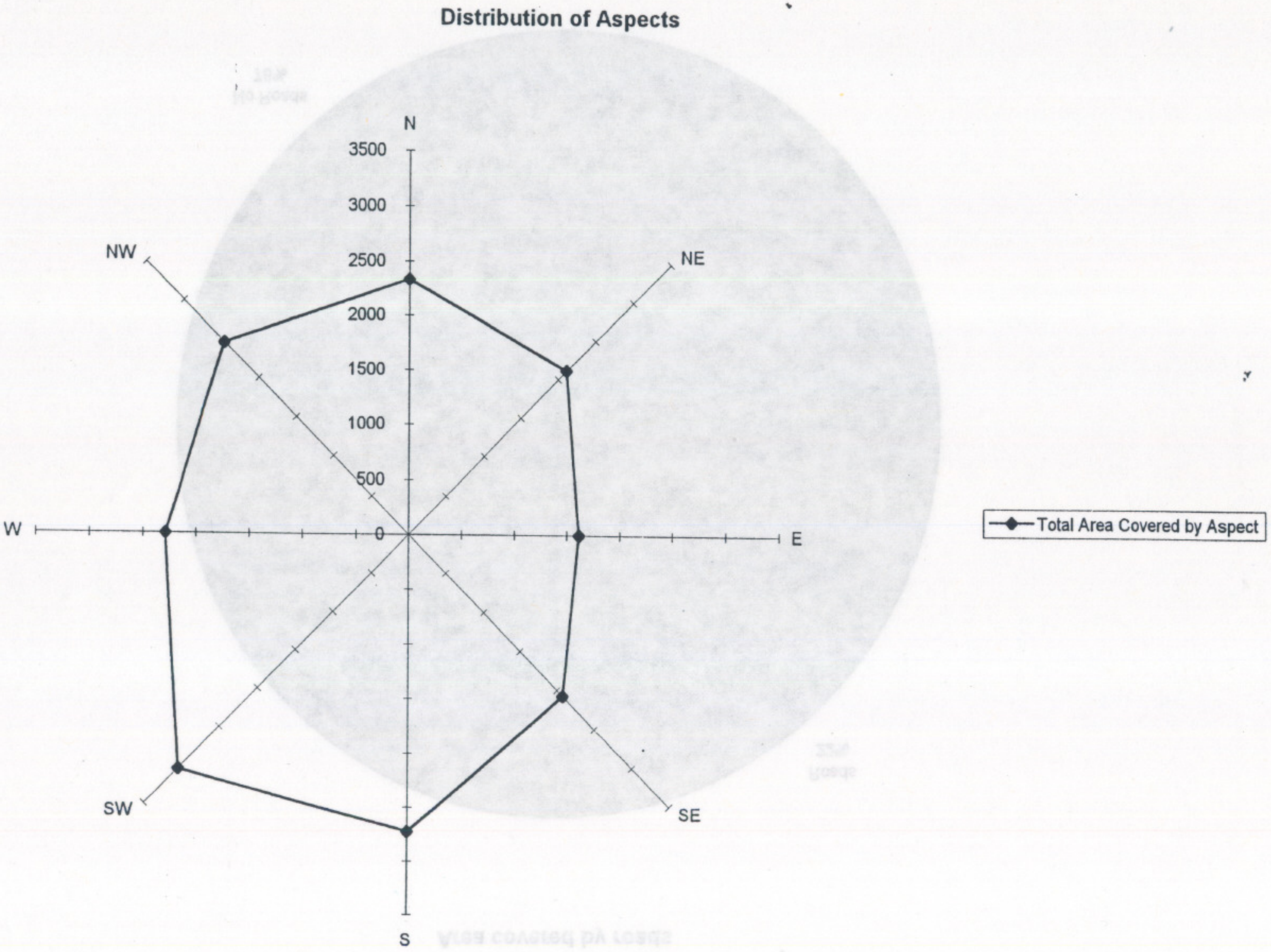
Appendix 2

GEOPTS Chart 2



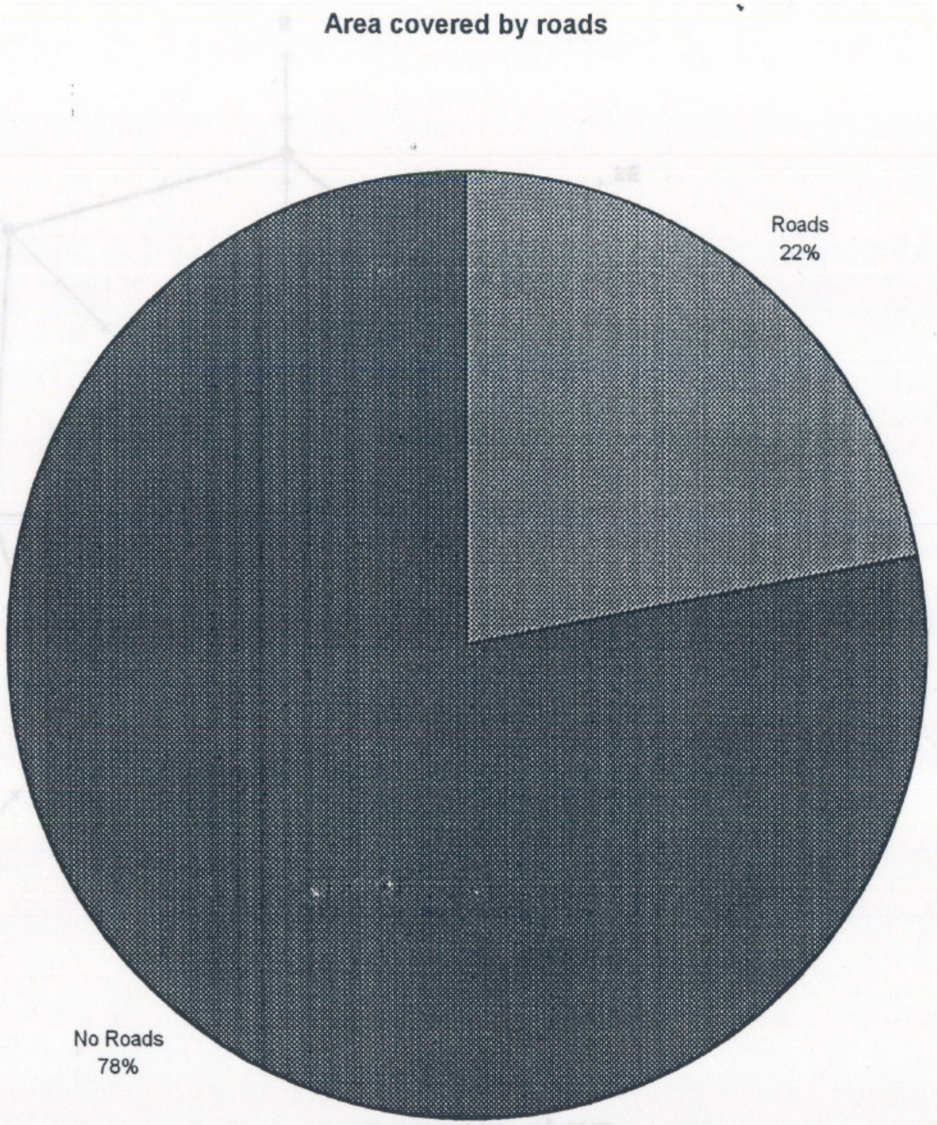
Appendix 3

ASPECTPT Chart 2



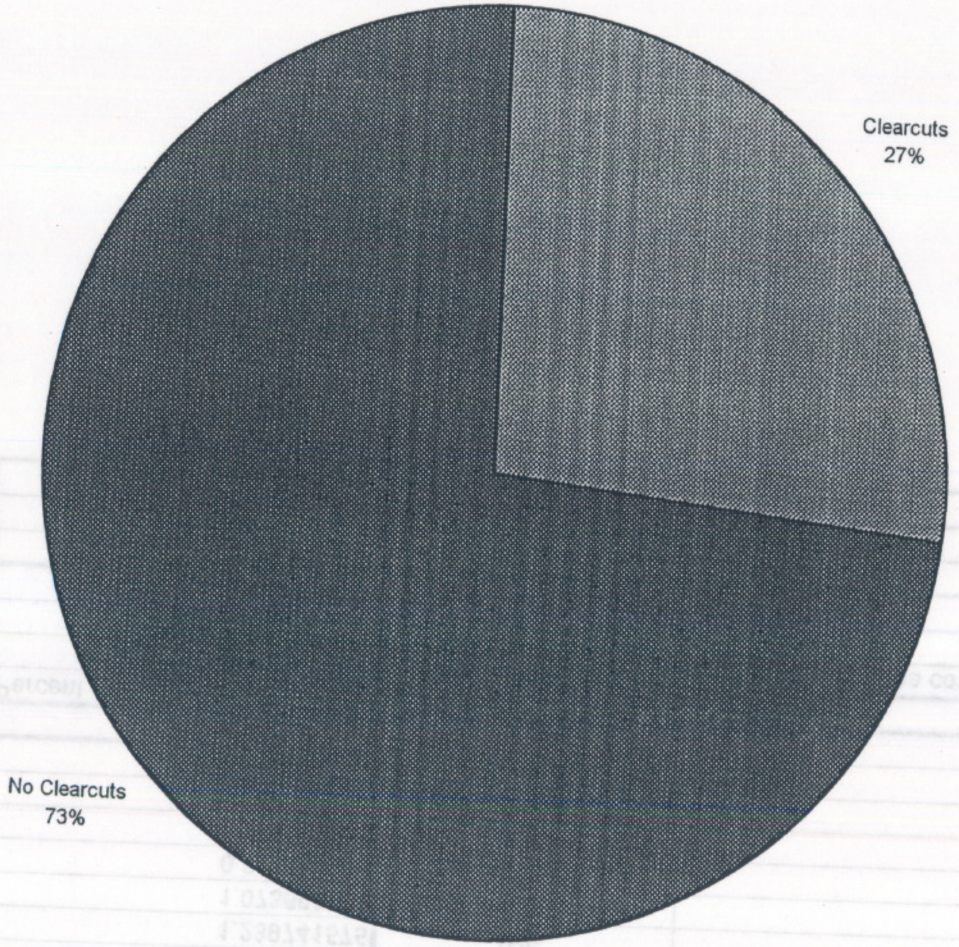
appendix 4

ROADPTS Chart 1



Appendix 5

Area covered by clearcuts



Appendix 6

Results

Relative Slope	Percent of slope-area with slides
1	1.211801897
2	1.239741575
3	1.073665374
4	0.843127236
5	1.5625
6	0
7	0

Rock Strength	Percent of geo-area with slides
Weak	4.231830727
Intermediate	1.108056319
Strong	0.478380865

Aspect	Percent of Aspect-land covered by slides
N	1.587982833
NE	1.138519924
E	0.681959082
SE	0.963391137
S	1.138032305
SW	1.14791735
W	1.183172656
NW	0.81366965

Land Use	Percent of use-area covered by slides
Roads	2.892865899
No Roads	0.602242835

Clearcuts	1.857460125
No Clearcuts	0.832596522