# MAPPING OF POTENTIAL LANDSLIDE AREAS IN TERMS OF SLOPE STABILITY

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AUTHORIZATION

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In accordance with the study plan, the draft report on the mapping of potential landslide areas in terms of slope stability is submitted.

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# I. INTRODUCTION

Every year man makes increased demands on the natural resources. These demands may be energy resource acquisition, timber harvesting, recreational developments, or mining activities. As these demands increase, man's influence will greatly affect the equilibrium of the natural environment. If care is not taken, such infringements may induce natural disasters that can interfere with man's activities as well as impact other existing systems. One such hazard is landslides.

In hilly and mountainous terrain of the United States, landslides are often a common occurrence. When a landslide does occur it not only disrupts the activities of man but also has an impact on other natural processes. One such impact is the effect of landslides on sediment production from watersheds. In this case a landslide may act as a direct or an indirect source of sediment. As a direct source, a landslide may enter a stream channel where the landslide material is rapidly transported downstream as a mud flow or mud flood, or is slowly eroded by the stream flow; thus increasing the sediment load. Although the former type of action is extremely destructive, the latter action is more common.

As an indirect source, a landslide can substantially disturb the ground surface making it susceptible to gully and rill erosion that will eventually transport the eroded material into the stream channel. Landslide hazards may be treated in many ways. Generally, after the landslide has occurred, man responds with tremendous expenditures of time, effort, and money to clean up the results. A better method is to determine landslide hazards before their occurrence through the delineation of potential landslide areas. Landslide potential delineation assists the land use planner before proposed activities are initiated in an area and assists the forest engineer in deciding where potential sediment sources may occur.

Landslide potential delineation is defined here as the use of landslide producing factors to demark areas where combinations of such factors indicate a relatively more hazardous landslide situation. Complementary to landslide potential is landslide probability. Factors affecting landslide occurrence are quite variable. Since it is almost impossible to assign every factor a single representative value, the uncertainty in the value selected must be considered. This leads to landslide probability or given imperfect, uncertain knowledge of landslide producing factors, the chance that a combination of factors will occur leading to a landslide. Methods for estimating landslide potential and probability are presented in this report.

## Factors Influencing Landslides

Landslides encompass a variety of types, each having a different form or character. There have been several previous classification systems (e.g., Ladd, 1935; Sharpe, 1938) that attempted to relate landslide form to underlying causes. Varnes (1958) related rate of landslide movement, earth material involved in the slide, and water to develop a system for describing landslide types. Varnes' system is widely used and is adopted in this report.

Cleveland (1971) presented landslide producing factors that could be used on a regional basis for delineating landslides. Simons and Ward (1976) have divided landslide controlling factors into two broad groups:

static factors and dynamic factors. Static factors are those physical quantities that have little variation in real time and include: 1) slope characteristics, 2) geologic characteristics, 3) soil characteristics, and 4) vegetation characteristics. Dynamic factors are variable in real time and include: 1) hydrologic characteristics, 2) man-induced characteristics, and 3) miscellaneous characteristics.

Slope characteristics include inclination and aspect. Slope inclination is a significant factor in determining stability, however, it is not the only factor. Because slope angle is the result of many factors such as erosional processes and strength of the earth materials, it can be used as an indicator of stability. There are certain limits within which landslides often occur. Blanc and Cleveland (1968) suggest a lower limit of 10° in their study, while Radburch and Crowther (1970) suggest 15° as a lower limit. An upper limit may be near 35°, about the angle of repose for most earth materials. Slopes with inclinations less than the lower limit have small forces acting to produce landslides while slopes with inclinations above the upper limit lack a landslide material supply since it is continually being eroded. Slopes between these limits are subject to an ever changing continuum of forces. Slope aspect affects stability through changes in soil moisture and vegetation. Olson (1974) in Colorado and Beaty (1956) and Radburch and Weiler (1963) in California noted that north and east facing slopes usually showed more landslide activity. Usually, north and east facing slopes (in the northern Hemisphere) are wetter than south facing slopes because less solar radiation reaches the ground. Increased vegetative growth tends to affect increases in soil moisture if the vegetation is a beneficial type.

Geologic characteristics that are important to slope stability are rock strength and structure. Rock strength is a result of mineral composition, grain size and shape, porosity and permeability, and the type of binding agent in the rock. In general, fine grained nonporous rocks composed of strong, weather resistant grains and binding agents will be stronger than other types. Rock structure influences slope stability on two scales. On the microscale, structure affects rock strength through cleavage planes, foliations, fractures, or grouping of weak minerals. Similarly on the macroscale, the integrity of rock masses can be decreased by fractures, jointing, bedding planes, or strata of weaker rocks.

Important soil characteristics are those that influence soil shear strength. These include soil type, porosity and permeability, and soil depth. Clay is prevalent in many landslides. Clay chemistry is such that changing environmental conditions can either beneficially or adversely affect the clay structure and thus the soil strength. Changes of strength can, in time, lead to landsliding. Porosity and permeability control the buildup of pore pressure and level of soil moisture, and they also control shear resistance. Soil depth is important since shallow soils are less susceptible to sliding. Fife (1971) found that soils at least one and one-half feet thick were sufficient to cause soil slips when subject to other influences. Swanston (1967, 1969) reported data showing debris avalanches in soils at least one foot thick. This is probably a minimum depth.

Vegetation plays an extremely important role in landslide occurrence. Gray (1970) and the Building Research Advisory Board (1974) indicate that vegetation enhances slope stability by 1) dissipating rainfall energy in the vegetative canopy, 2) lowering soil moisture levels, 3) anchoring surface materials to underlying strata with roots, and 4) binding surface materials together (Figure 1).

Vegetative canopy is composed of trees, brush, grasses, and other small plants. The areal distribution and type of canopy affects the rainfall intensity and the volume of water reaching the ground. Areas with high canopy cover will be less likely to be subject to raindrop impact and rapid saturation; thereby lessening the possibility of mass erosion.

Vegetation can significantly lower soil moisture content through transpiration (Perpich et al., 1965; Hammer and Thompson, 1966). As soil moisture is lowered, water pore pressures and chemical weathering decrease leaving shear strength intact.

According to Rahn (1969), vegetation makes surface materials more resistant to gravitational forces by joining the materials into larger units and anchoring these units to underlying strata. In all cases, the type of vegetation and areal distribution are important measures influencing how effective vegetative cover is in enhancing stability. Plant types that develop deep extensive root systems, deplete soil moisture by transpiration, and possess foliage that dissipates rainfall enhancing slope stability.

There are some deleterious effects from vegetation. Trees can produce a surcharge load on the slope and transmit shear loads during windstorms (Brown and Sheu, 1975). Grasses and other shallow rooted undergrowth can detain water on slopes, allowing more infiltration with

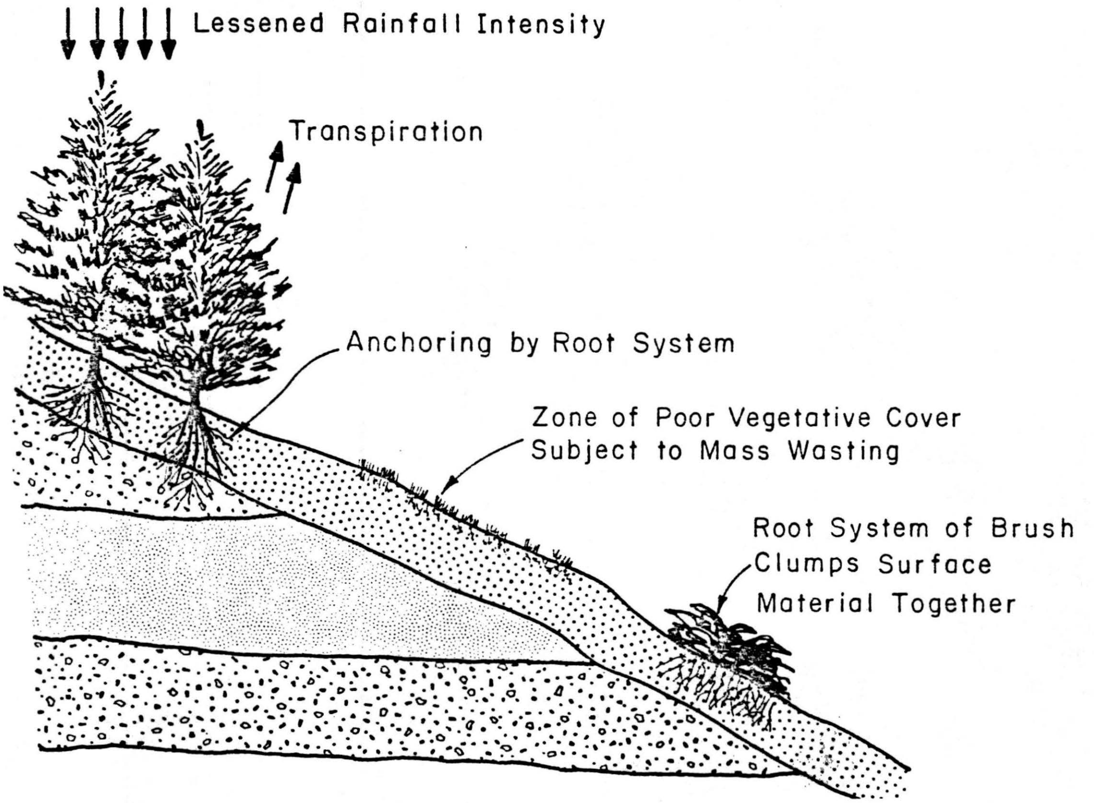



Figure 1. Important effects of vegetation on slope stability (Simons and Ward, 1976).

resultant deleterious effects. Root systems cause discontinuities in soil layers that disrupt the soil structure and provide large infiltration channels (Gaiser, 1952). When vegetation dies or is killed, the decaying root systems make a smaller and smaller contribution to soil stability (Bethlahmy, 1962; Gray, 1970; O'Loughlin, 1974; Brown and Sheu, 1975; Burroughs and Thomas, undated). Despite this, vegetation generally enhances slope stability.

Dynamic factors vary rapidly in real time. These factors fall into three major groupings: hydrologic, man induced, and miscellaneous. Because dynamic factors can vary in time, it is often difficult to quantify the influence a dynamic factor has on slope stability (Thomson, 1971; Vandre, 1975). The relationship between dynamic factors and static factors must be understood in order to ascertain their effects on slope stability (Cleveland, 1971; Simons and Ward, 1976).

Hydrologic factors include precipitation, surface flow, and subsurface flow or soil moisture. Soil moisture and groundwater occurrence are the most important hydrologic factors with regards to slope stability (Simons and Ward, 1976; Nilsen and Turner, 1975).

Soil moisture weathers earth materials, alters strength, and produces pore water pressures. Pore water pressures produced by soil moisture or groundwater can decrease the resistance of the earth materials to sliding. Simultaneously, the increase in the unit weight of the soil usually increases the tendency for the earth materials to slide.

Man-induced factors include those that decrease landslide resistance, increase the failure forces, or a combination of the two (Simons and Ward, 1976). Placement of fill on the head of a slope is a common factor in man-induced landslide occurrences. Oversteeping slopes, removing vegetation, and altering the hydrologic system are also common factors. Landslide literature is filled with case histories of man upsetting the balance between forces (Kiersch, 1964; Wahlstrom and Nichols, 1969; Williams and Armstrong, 1970, Bolt et al., 1975).

Miscellaneous factors include seismic vibration and fires. Seismic vibrations can be caused by blasting, heavy machinery operation, sonic booms, or earthquakes (Conlon, 1966; Seed and Wilson, 1967; Voight, 1973). Seismic vibrations produce horizontal acceleration of slope materials that increase horizontal stresses (Okamoto, 1973). Seismic vibrations can also alter the physical properties of the slope materials by compaction or fragmentation, or the production of liquefaction phenomena (Youd, 1973; Martin et al., 1975).

Generally, landslides resulting from the effects of fires are probably more prevalent than seismic triggered landslides but are not as widely noticed or reported. Fires remove vegetation and alter slope materials. When the rainy season returns, the slope materials are not as resistive to erosion or sliding. This situation can produce numerous landslides and mud flows (Woolley, 1946; De Bano et al., 1967; Cleveland, 1973; Hay, 1975). Landslides subsequent to fires are probably more prevalent than seismic produced landslides since not all landslide regions are subject to seismic disturbance but all are usually subject to fire.

Two types of factors affecting slope stability exist. Static factors are physical quantities relatively constant in real time. Dynamic factors are harder to quantify since they can vary in real time. Because dynamic factors alter static factors, static factors are measured preferentially to dynamic factors. This enables delineation of potential landslide areas on the basis of variables that can be measured and can be altered by dynamic factors.

## Previous Work

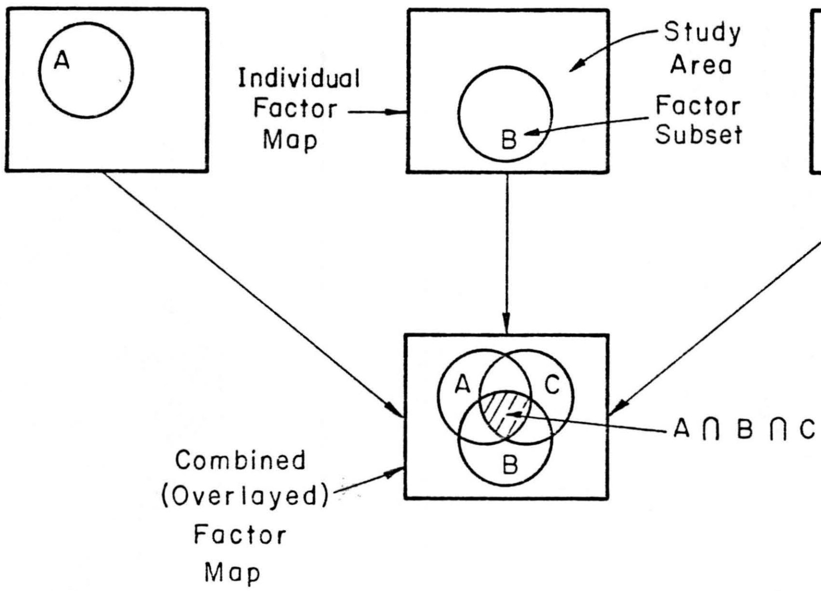
There are many approaches to landslide potential delineation. These approaches include on-ground monitoring, remote sensing techniques, factor overlay methods, statistical models, and geotechnical process models.

On-ground monitoring consists of utilizing installed measuring devices such as strain gages and down hole tilt meters. This type of approach is extremely useful for checking suspected landslide zones but is limited in aerial coverage because of cost of installation and maintenance. Chang (1971) summarized many of these techniques. Takada (1968) and Takenchi (1971) provided two examples of applications of different methods.

Remote sensing coupled with pattern recognition techniques provide a means for surveying large areas. In this approach, remotely sensed data, particularly aerial photography such as black and white, color infrared, and multiban spectral, can be analyzed for features distinctive of landslide hazards (Liang and Belcher, 1958; Poole, 1969, 1972; McKean, 1977). This analysis, a type of the more general pattern recognition, can be quite effective if landslide hazards are manifested in surface characteristics that can be photographed. However, this is not always the situation since landslides often result from deep seated factors not visible on the ground surface.

The most common delineation method currently in use is factor overlay or a combination of landslide producing elements. Krynine and Judd (1957) noted that landslides occur in a regional framework, or that certain factors common to a region contribute to landsliding. Baker and Chieruzzi (1959) expanded this concept to develop a physiographic classification of landslide hazards based on topography, erosional development, and associated rock types. Blanc and Cleveland (1968) were two of the first to attempt delineating landslides by use of selected factors. Evans and Gray (1971) presented a methodology for mud slide risk delineation in Southern Ventura County, California. Cleveland (1971) summarized and presented those factors important in regional landslide prediction. His factors include precipitation, rock strength, vegetation effects, slope, and stream pattern. The approaches described by Nilsen and Brabb (1973) and the Building Research Advisory Board (1974) follow this systematic methodology using landslide factors. In this approach, certain factors related to landslide occurrence are individually delineated. For example, if landslides occur where steep slopes, weak earth materials, and water are all coincident, then these factors should be used as slope stability indicators. Areas where factors coincide can then be classified as a hazard potential. Simons and Ward (1976) summarized this approach as the factor overlay method or set theory approach to hazard delineation as presented in Figure 2. Although not explicitly stated in delineation schemes, this idea is the basis for most techniques.

The factor overlay approach is conceptually correct since it recognizes that landslides are a combination of different factors. However, this approach is subjective and nonsensitive to dynamic inputs. Subjectivity results from a lack of defined guidelines for developing and weighting various factors. Nonsensitivity occurs because static factors are usually considered while dynamic factors, such as groundwater fluctuations, are excluded. Factor overlay can be improved if standardized guidelines are developed, dynamic factors are incorporated, and realistic weighting functions are used. Simons and Ward (1976) presented a numerical approach to the factor overlay technique that may help quantify the relative importance of each factor.




| Potential | Set |
| --- | --- |
| High | $A \cap B \cap C$ |
| Medium | $A \cap B$; $B \cap C$; $A \cap C$; A; B; C |
| Low | $\overline{A \cup B \cup C}$ (i.e. not in A, B, or C) |

$\cap$ - Intersection of Subsets
$\cup$ - Union of Subsets

Figure 2. Set theory approach to landslide potential classification (from Simons and Ward).

Another method of potential delineation is use of empirically developed models. These models, developed through statistical analyses of measurable data, attempt to provide a numerical value related to slope stability. Multiple regression and discriminant function analyses are common techniques for developing such relationships (Jones, Embody and Peterson, 1961; Waltz, 1971). Empirically derived relationships have a major drawback since they require large amounts of data to develop the equations. Such data is usually temporally and spatially static. Temporally static implies the developed relationship is applicable to a limited time span during which data was collected and, therefore, does not represent changing conditions. Spatially static implies the method is applicable to a limited area and transfer to other areas may not be warranted.

A final type of landslide hazard delineation methodology is based on geotechnical models. Geotechnical models are derived from observed natural phenomena and basic laws of physics, and are representative of the physical process being studied. Geotechnical models of slope stability relate the forces acting on a hill slope. One set of forces, predominated by gravity, acts to move earth materials downslope. The other set of forces, predominated by the shear strength of the earth materials, resists the driving gravity forces. When driving forces exceed resisting forces, a landslide occurs. Geotechnical models have been developed and modified to account for primary factors in landslide occurrence such as soil strength, groundwater influences, vegetative effects, and slope inclination. Because geotechnical models represent actual field conditions they can be used to analyze the response of a hill slope to temporally and spatially varying factors. Simplifying assumptions can yield a method for determining the probability of a landslide. Because of the ability to account for several temporally and spatially varying contributing factors in a nonsubjective, physically meaningful manner, geotechnical models are a promising method for landslide potential delineation.

## II. LANDSLIDE HAZARD DELINEATION MODEL

### Model Selection

The analysis presented in this report is applicable to slide and flow types of landslides. Rock masses are a more complex problem because of their dependence on the geometry of failure planes. Data needed for a thorough study of rock masses is often difficult to obtain for most forest engineers.

Various types of slope stability models exist. The two basic types are infinite slope and finite slope models, each with a different set of assumptions (Lambe and Whitman, 1969). Common to both types is the method of formulation into a factor of safety equation. In the factor of safety equation a ratio of resisting to driving forces is formed as

$$FS = \frac{R}{D} \qquad (1)$$

where FS is the factor of safety, R is the resistive forces, and D is the driving forces. Resistive forces are related to soil strength and vegetative parameters while the primary driving force is the downslope weight of the soil mass. If resistance is less than the driving force then the factor of safety is less than one which indicates failure.

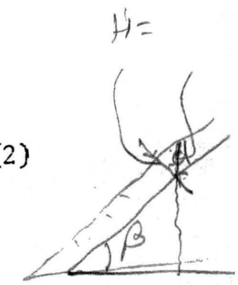
Finite slope models are used to analyze slopes of finite length and known geometry, such as slump landslides with curvilinear failure planes. Analysis of finite slopes relies on methods such as the ordinary method of slices or the Bishop method of slices (Lambe and Whitman, 1969). Methods of slices are needed since the geometry of

The model used in this report represents the consolidation and refinement of ideas presented by Swanson, et al. (1973), O'Loughlin (1974), Brown and Sheu (1975), and Simons, Ward, and Li (1976). These developments were further refined by Ward (1976) into the model's present form.

Model Formulation

The infinite slope factor of safety model used in this study for estimating landslide potential is

$$FS = \frac{\dfrac{2(Cs + Cr)}{\gamma_w H \sin 2\beta} + \left[\dfrac{qo}{\gamma_w H} + \left(\dfrac{\gamma_{sat}}{\gamma_w} - 1\right) M + \dfrac{\gamma}{\gamma_w}(1-M)\right] \dfrac{\tan \phi}{\tan \beta}}{\dfrac{qo}{\gamma_w H} + \left(\dfrac{\gamma_{sat}}{\gamma_w}\right) M + \dfrac{\gamma}{\gamma_w}(1-M)} \qquad (2)$$




where $C_s$ is soil cohesion, expressed as a pressure; $C_r$ is effective root cohesion, expressed as a pressure; $\gamma_w$ is unit weight of water; $H$ is a soil depth measure equal to $\frac{d}{\cos\beta}$ ; $d$ is soil depth; $\beta$ is slope inclination; $q_o$ is tree surcharge expressed as a pressure; $\gamma_{sat}$ is saturated unit weight of soil; $M$ is relative groundwater height; $\gamma$ is unit weight of the soil; and $\phi$ is angle of interval friction for the soil. A complete derivation of this model is presented in Appendix A. Equation 2 defines the landslide potential of a slope in terms of a factor of safety value. For relative rankings of hazards, limits of factor of safety values can be established. Relative error in factor of safety values can be approximately 20 to 30 percent (Ward, 1976). This range agrees with Feld (1965) and

Singh (1971). A realistic set of relative hazard levels is:

1) high potential where $FS < 1.2$,
2) medium potential where $1.2 \leq FS \leq 1.7$, and
3) low potential where $FS > 1.7$.

These values are used in this study although other limits could be selected.

Equations used for determining landslide probability are derived from Equation 2. The average factor of safety, $\overline{FS}$, is

$$\overline{FS} = L_1 \ (\overline{Cs} + \overline{Cr}) + L_2 \ (\overline{\tan \phi}) \qquad (3)$$

The variance or standard deviation squared of the factor of safety, Var[FS], is formulated as

$$\begin{aligned} Var[FS] = & \ L_1^2 \ \{Var\ [Cs] + (\overline{Cs})^2 + 2(\overline{Cs})(\overline{Cr}) + Var[Cr] + (\overline{Cr})^2\} \\ & + L_2^2 \ (Var[\tan \phi] + (\overline{\tan \phi})^2) + 2L_1L_2(\overline{\tan \phi})(\overline{Cs} + \overline{Cr}) \\ & - (\overline{FS})^2 \qquad (4) \end{aligned}$$

In Equations 3 and 4, $\overline{Cs}$, $\overline{Cr}$, and $\overline{\tan \phi}$ are average values and Var[ · ] is the variance of the variable inside the brackets. The constants $L_1$ and $L_2$ are

$$L_1 = \frac{2}{\gamma_w H \sin 2\beta \ [\frac{qo}{\gamma_w H} + \frac{\gamma_{sat}}{\gamma_w} M + \frac{\gamma}{\gamma_w} (1-M)]} \qquad (5)$$

and

$$L_2 = \frac{[\frac{qo}{\gamma_w H} + \left(\frac{\gamma_{sat}}{\gamma_w} - 1\right) M + \frac{\gamma}{\gamma_w} (1-M)]}{[\frac{qo}{\gamma_w H} + \left(\frac{\gamma_{sat}}{\gamma_w}\right) M + \frac{\gamma}{\gamma_w} (1-M)] \tan\beta} \tag{6}$$

where the other variables were previously defined. A complete derivation is presented in Appendix A. The mean and variance computed from Equation 3 and 4 can be used to estimate failure probability. This is written as

$$P[FS \leq 1] = p \tag{7}$$

where $p$ is the probability of failure and $P[FS \leq 1]$ is the cumulative probability that FS is less or equal to one. A reasonable distribution of failure probabilities is a normal or Gaussian distribution. Making this choice allows computation of the failure of probability. First, a non-dimensional variate, U, is computed as

$$U = \frac{1 - \overline{FS}}{(\text{Var}\ [FS])^{1/2}} \tag{8}$$

The value of $U$ is used to compute another variable, p, the cumulative failure, as

$$p = 0.4|U| \quad \text{if } |U| \leq 0.13 \tag{9}$$

or

$$p = -0.01314 + 0.49494|U| - 0.15804|U|^2 + 0.01661|U|^3$$
$$\text{if } |U| > 0.13 \tag{10}$$

Equations 9 and 10 are approximations with errors less than one percent.

From U and B the failure probability is found as

$$P[FS \leq 1] = 0.5 + p \quad \text{if} \quad U > 0 \tag{11}$$

$$P[FS \leq 1] = 0.5 - p \quad \text{if} \quad U < 0 \tag{12}$$

$$P[FS \leq 1] = 0.5 \quad \text{if} \quad U = 0 \tag{13}$$

Similar to potential rankings, probabilities can be grouped into three hazard classes:

1) high probability when $P[FS \leq 1] > 60\%$,

2) medium probability when $30\% \leq P[FS \leq 1] \leq 60\%$, and

3) low probability when $P[FS \leq 1] < 30\%$.

These limits are abritrary and can be modified.

The means and variances of Cs, Cr, and $\tan \phi$ must be known or estimated in order to find the failure probability. Usually this type of information is not available to the forest engineer without extensive testing. Ward (1976) and Ward, Li, and Simons (1978) suggest that the input variables be assumed as uniformly distributed random values. With this assumption the mean of a random number is found as

$$\overline{X} = \frac{X_a + X_b}{2} \tag{14}$$

and the variance as

$$\text{Var}[X] = \frac{(X_b - X_a)^2}{12} \tag{15}$$

where $X_a$ and $X_b$ are the lower and upper limits on the variable X. Ward, Li, and Simons (1978) used Monte Carlo generation techniques to demonstrate that in their example the assumption of a uniform distribution provided a more conservative estimate (over estimate) of failure probability. Another appealing aspect of the uniform distribution assumption is that a range of values can be chosen as input. Ward (1976) presented a set of ranges for Cs, $\phi$, and Cr based on the Uniform Soil Classification and vegetative characteristics (Tables 1, 2, and 3). These values are just guidelines and are subject to modification by the user. Tree root cohesion representing the tensile and shear resistance of the roots may vary significantly. Although the table indicates values up to 250 psf, Burroughs and Thomas (undated) present tree root strengths of 2856 psf for Douglas fir growing in Tyee sandstone basins. This value is extremely high, much higher than the cohesion of most soils (Ward, 1976) and is also higher than values presented by O'Loughlin (1974). It should be noted that tree roots are only effective if the failure surface passes through them. In deep seated slides, the failure surface is often below the roots. In instances of planar type landslides, the roots are effective only if they connect the soil mass to the underlying stable strata. Although considered as a beneficial influence to slope stability, tree roots will only enhance stability under certain conditions.

Table 1. Estimates of Cs values based on Unified Soil Classification System (tentative values).

| Unified Soil Classification | Range in Cs Values (psf) |
|---|---|
| GW | - - - |
| GP | - - - |
| GM | 0 - 50 |
| GC | 0 - 100 |
| SW | - - - |
| SP | - - - |
| SM | 0 - 50 |
| SC | 0 - 100 |
| ML | 0 - 100 |
| CL | 0 - 400 |
| OL | 0 - 200 |
| MH | 0 - 200 |
| CH | 0 - 500 |
| OH | 0 - 400 |
| PT | - - - |

Table 2. Selection of $\phi$ values based on Unified Soil Classification System (extracted from Moore, 1969).

| Unified Soil Classification | Range of $\phi$ Values (°) |
|---|---|
| GW | 38.3 |
| GP | 36.5 |
| GM | 33.8 |
| GC | 31.0 |
| SW | 37.6-39.0 |
| SP | 35.8-37.2 |
| SM | 30.6-36.1 |
| SC | 27.9-33.8 |
| ML | 30.1-33.4 |
| CL | 26.6-30.1 |
| OL | - - - |
| MH | 22.9-27.5 |
| CH | 14.6-23.8 |
| OH | - - - |
| PT | - - - |

Table 3. Estimates of Cr values based on vegetation characteristics (tentative).

| Vegetation Characteristics | Range of Cr Values (psf) |
|---|---|
| Well developed forest stands, forest area >75% of total area | 40-125 (extreme at 250) |
| Forest-brush mixtures forest area 50-75% of total | 20-80 |
| Brush-forest-grass mixtures forest area 25-50% of total | 0-60 |
| Grass-brush mixtures forest area < 25% of total | 0-40 |
| Grass | 0 |

## Model Sensitivity

An important aspect of any mathematical model is its sensitivity to the various input variables. Often a user desires to know how accurately an input must be measured or similarly if an input, such as stand density, changes by a certain percentage, how it will affect the model's output. Ward (1976) used partial differentation of the factor of safety equation to demonstrate model response to changes in each of the input variables. Table 4 summarizes those results.

Table 4. Change in FS produced by increasing value of input variable.

| Input Variable | Change in FS Value* |
|---|---|
| Cs | + |
| Cr | + |
| $\phi$ | + |
| qo | +, 0, - |
| $\beta$ | - |
| H | -, 0 |
| M | - |
| $\gamma$ | +, 0, - |
| $\gamma_{sat}$ | +, 0, - |

* + = increase, - = decrease, 0 = change

As Table 4 indicates, under certain conditions an increase in the value of certain input variables can produce positive, negative, or no change in the FS value. These types of relationships occur for $\gamma$, $\gamma_{sat}$, qo, and H. The soil depth measure, H, usually has a negative influence on FS except for a dry cohesionless slope where FS is equal to the ratio $\frac{\tan\phi}{\tan\beta}$. It can be demonstrated mathematically that increasing the "loading" terms of $\gamma$, $\gamma_{sat}$, and qo may have a beneficial effect on slope stability under certain conditions. Mathematically, this would occur when

$$Cs + Cr < \gamma_w Hw \tan\phi \cos^2\beta \qquad (16)$$

When conditions exist that satisfy this inequality, uniform loading of a slope should theoretically increase stability. This result indicates that in some cases forests also aid stability by adding a uniform load to the soil. Although Table 4 indicates the direction of change that may be produced by altering input variables, it does not provide an indication of the relative importance of each variable. A method for doing this is through numerical computation of the FS values, then graphical display of the result. This approach is conducted in four steps.

First, a realistic range of values is selected for each input variable. Second, a base FS value is computed using the median values for each variable. Third, the value for one input at a time is varied across the range of values, and a new FS value is computed for each altered input. Fourth, the results are plotted as a relative percentage shown in Figure 3. Figure 3, for a selected set

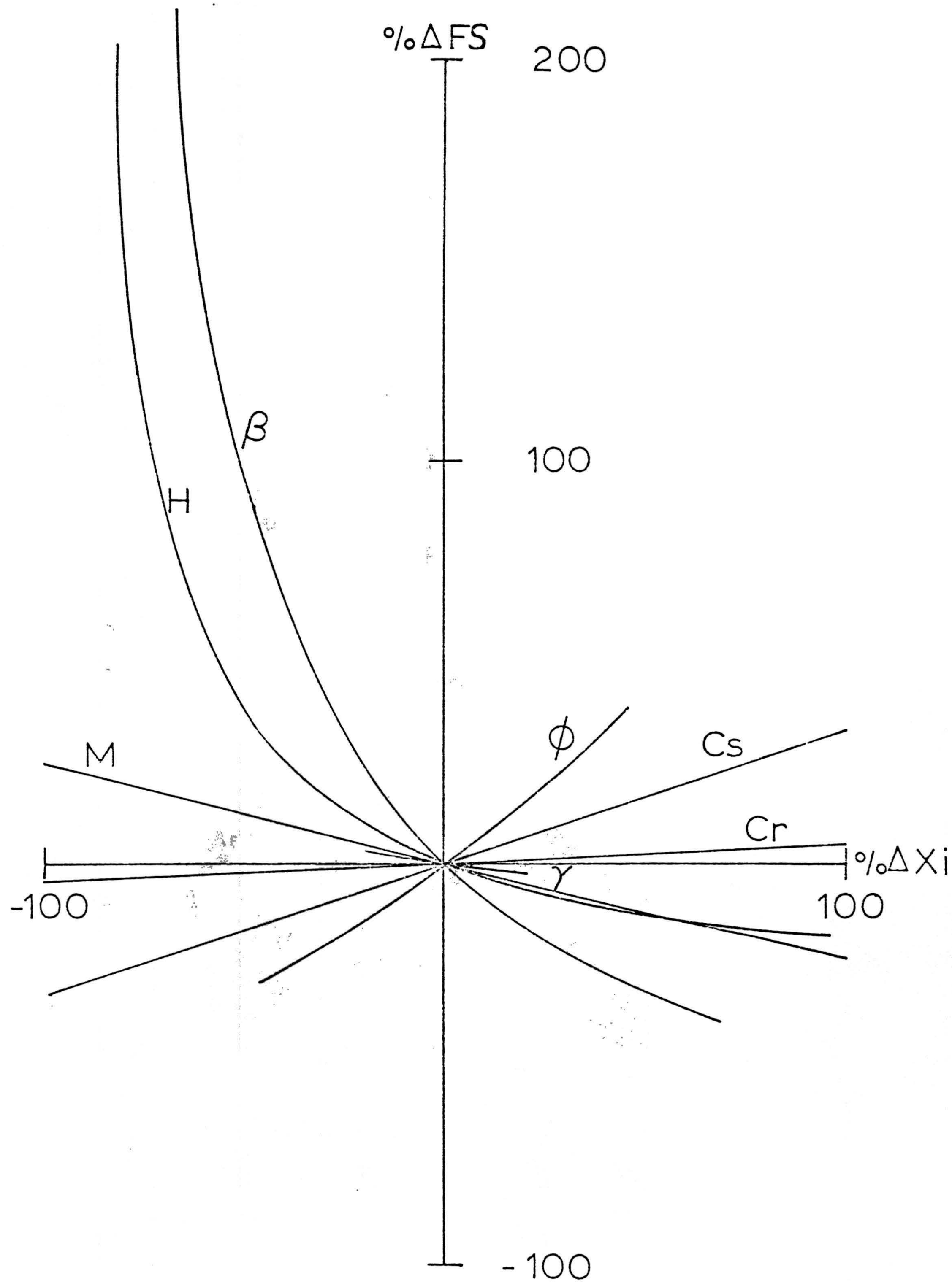



Figure 3. Percent change in FS versus percent change in variable.

of conditions, shows that some inputs have a linear effect on FS values while others, notably H and $\beta$, have strongly nonlinear effects. Graphs such as Figure 3 are useful in that they show the relative importance of each variable compared to the others. Although Figure 3 is for a selected set of values, computations for other input sets show the same relative shapes. Sometimes Cs and Cr reverse their relative importance and qo, not shown here, becomes slightly more important. In most cases $\gamma$ has only a slight affect, as do $\gamma_{sat}$ and qo. These three variables have smaller effects for reasons as explained before but also because they are included in the numerator (resisting force) and denominator (driving force) of Equation 1. This type of analysis becomes important when applying the model to each new area, since it indicates which input variables may be the most important to measure and what changes in a slope may most affect slope stability.

## III. COMPUTER MAPPING OF WATERSHED LANDSLIDE HAZARDS

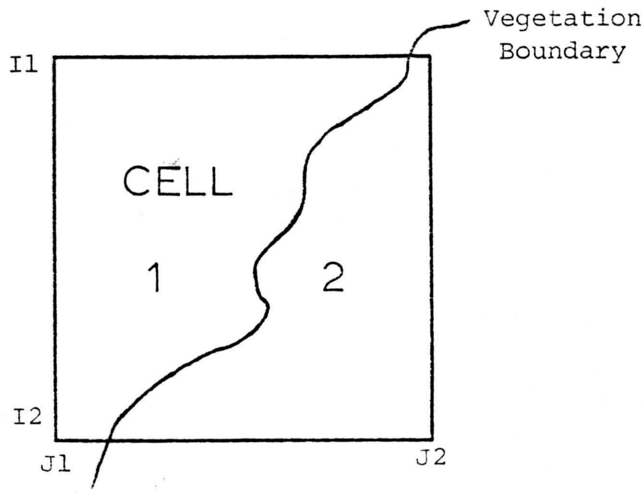
### General

The landslide potential and probability model together with a realistic range of input values allows the land manager to analyze slope stability. Such an approach is adequate for small areas but for large areas these models must be computer based in order to process large quantities of input data and to simulate short- and long-term changes in the area being studied. Another desirable feature of computer based system response models is the ability to process and utilize information from remote sensing sources.

The emphasis on use of computer based models to analyze physical systems has received special attention in the last several years. Turner and Coffman (1973) made use of computer based information to demonstrate land-use classification algorithms. Although presented as a review of how computer mapping can become a powerful tool, the authors clearly demonstrated some basic applications. A landslide potential delineation application was presented that utilized logical overlay techniques. Potentially hazardous areas were delineated by the computer and displayed by a printed output. The output utilized different intensities of computer print to shade hazardous areas on the output map. No suggestion was made that the algorithm used provided an accurate delineation. Tom et al. (1974) utilized remotely sensed data to predict growth patterns in the Denver, Colorado area by use of a computer based algorithm and a Markovian state matrix. Results were displayed on computer output. Tom and Getter (1975) developed a wildfire mapping algorithm that utilized slope and aspect information. Coincident with this effort was the development of a watershed response model by Li (1974). Subsequent study led to a watershed segmentation model (Simons and Li, 1975). Simons and Li suggested using a grid system that conforms to the watershed boundary to subdivide the watershed into response units. These response units, usually squares or rectangles, are also called cells. The cell size should depend on the accuracy required for the output data. In the case of landslide potential delineation this size will depend on the size of the area to be mapped, quality of input data, use of the output, and whether or not the mapping is to reflect effects of land-use changes.

Watershed Segmentation

The segmentation model (WASEG) that is used to prepare input to the landslide potential delineation model was developed by Simons and Li (1975). The method of data input is fairly general. A cell size is selected and the grid corresponding to this size is overlayed on the raw data maps (Figure 4). Some raw data maps are composed entirely of code numbers keyed to characteristics related to that code. For example, if the raw data are vegetation types, a code number 1 may indicate a type that possesses high root strength while type number 2 may indicate vegetation of low root strength. The codes then allow assignation of values to the respective variables, in this case Cr. The code data is input at the grid line intersections or nodes. This procedure is followed for vegetation and soil. Other types of data such as elevation data or canopy density, a measure of relative amount of vegetation, are input as raw numbers and not coded. With the data input and stored, the segmentation model then computes several useful quantities. The elevation data is used to compute the slope inclination and aspect of the cell. The aspect indicates the direction the cell




Vegetation(I1,J1)=Vegetation(I2,J1)=1
Vegetation(I1,J2)=Vegetation(I2,J2)=2

Figure 4. Input format to segmentation model.

slopes or the direction of landslide movement if there is a landslide in the cell. The watershed segmentation program organizes data on a cell by cell basis for the watershed. For example, the vegetation code (like the soil code) for the cell shown in Figure 4 would be 1221 reading counterclockwise from the lower left corner. The average slope of the cell would be a single value similar to the average canopy cover density. These coded and averaged values are then output to a mass storage device (permanent file) where they are accessed by the landslide hazard mapping program. More details on program WASEG can be obtained from Simons and Li (1975).

Landslide Hazard Mapping

Output from program WASEG is used as input to the landslide hazard mapping program LSMAP (LandSlide MAPping). The basic program is presented in Appendix B. In the basic version LSMAP requires input from program WASEG and the user. A more advanced version incorporates WASEG, LSMAP, gray map printing routines, and other analyses features into a complete method for delineating landslide hazards as well as numerous other watershed characteristics. This more complex model is not presented here because the gray map printing routines are specific to Colorado State University's CYBER computers, and inclusion and full documentation of the entire complex program is beyond the scope of this report. The complete model, once thoroughly checked and upgraded, will be presented at a later date.

Program LSMAP views the watershed on a cell by cell basis. Choice of cell size is left to the user. In the program, output information from WASEG is decoded before use or directly incorporated into computations. Other required input is related to characteristics for the different soil and vegetation types, typical soil unit weight, typical soil porosity, and the relative groundwater level, M. Although M must presently be input, it is anticipated that the landslide potential mapping program will eventually be linked with a realistic long-term water balance model so a more dynamic view of landslide hazard fluctuation may be obtained. Only relative hazards under slected groundwater conditions can be provided at this time to aid the land manager in planning activities. Soil and root strength values as well as soil depths are averaged for each cell. Therefore, the factor of safety is based on the averaged values for each cell and not on the average of the factors of safety at each node point.

The landslide hazard mapping model presented here can provide a rapid means of assessing the impacts of various land use changes on slope stability. Such an application using actual field data is presented in the following section.

# IV. APPLICATION OF MODEL

## Site Selection

A heavily forested, landslide prone watershed was selected for application of the landslide hazard delineation model. This watershed, number 2 (Figure 5), is located in the H. J. Andrews Experimental Forest. about 50 miles east of Eugene, Oregon on the western edge of the Cascade Range.

Watershed 2, located in the southwest corner of the Experimental Forest, has an area of about 149 acres. Elevations range from 1730 to about 3500 feet above mean sea level. Slopes in the area are often in excess of 80 percent. Two companion watersheds, numbers 1 and 3 were not modeled because of man-induced landslides resulting from road construction or because of a lack of adequate data (Fredricksen, 1965, 1970).

The vegetation of the watershed is typical of the area. The canopy is primarily Douglas-fir in the 125-year age class (second-growth), 450-year age class (old-growth), or a combination of the two age classes (Hawk and Dyrness, undated). In some locations, however, Western Red cedar and Hemlock are also present. In contrast, Watershed 1 was completely clear cut between the fall of 1962 and the fall of 1966 using skyline logging. Watershed 2 remains as a control watershed with no logging activity. The geology of the watersheds has been described by Swanson and James (1975) as being characterized by lava flows, welded and unwelded tuffs and pyroclastic flows, and water worked volcanic sediments. Almost all of the landslide activity is confined to the altered volcaniclastic rocks with little activity occurring in the lava

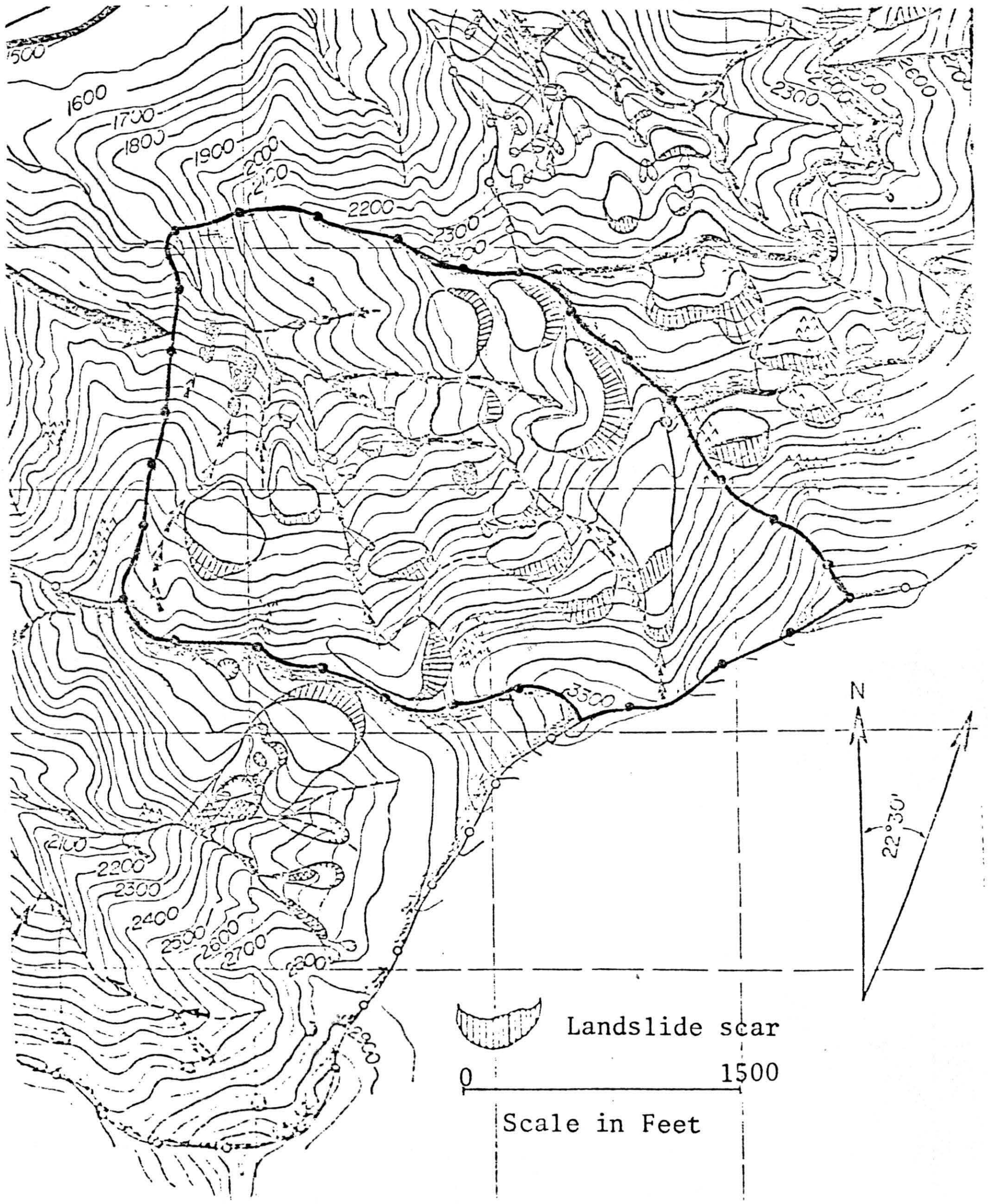



Figure 5. Topographic map of Watershed 2 showing landslide scars and deposits.

flows (Swanson and Dyrness, 1975). Soils in this area are weathered from the underlying volcanic rocks and have been described by Dyrness (1969), Paeth et al. (1971), and Hawk and Dyrness (undated). The soils can be roughly grouped into five broad classes as shown in Table 5.

Table 5. Soil classes for Watershed 2.

| Class | Description |
| --- | --- |
| 1 | Rock outcrop |
| 2 | Andesite series |
| 3 | Budworm, Limberlost (slope < 20 percent), Andesite (slope < 20 percent) |
| 4 | Limberlost, Flunky |
| 5 | Frissell |

Five groups were used to account for subtle but important variations in soil depth and relative stability that produced unrealistic results when three original groupings were used.

The estimated Unified Soil Classifications for the soils shown in Table 5 were ML, CL, and CH. These assumed classifications were used for initial estimates of soil strength parameters as outlined by Ward (1976). The distribution of these soil classes is shown in Figure 6 which indicates that group 2 and 3 soils predominate the watershed.

Watershed 2 was left as a control watershed and is characterized by abundant canopy, understory, and ground cover vegetation. A vegetation grouping was conducted on Watershed 2. Because the canopy is well developed, it is assumed the root system is also well developed. Therefore, the classification of vegetation as to characteristic root strength is based on a combination of the canopy cover densities of the overstory

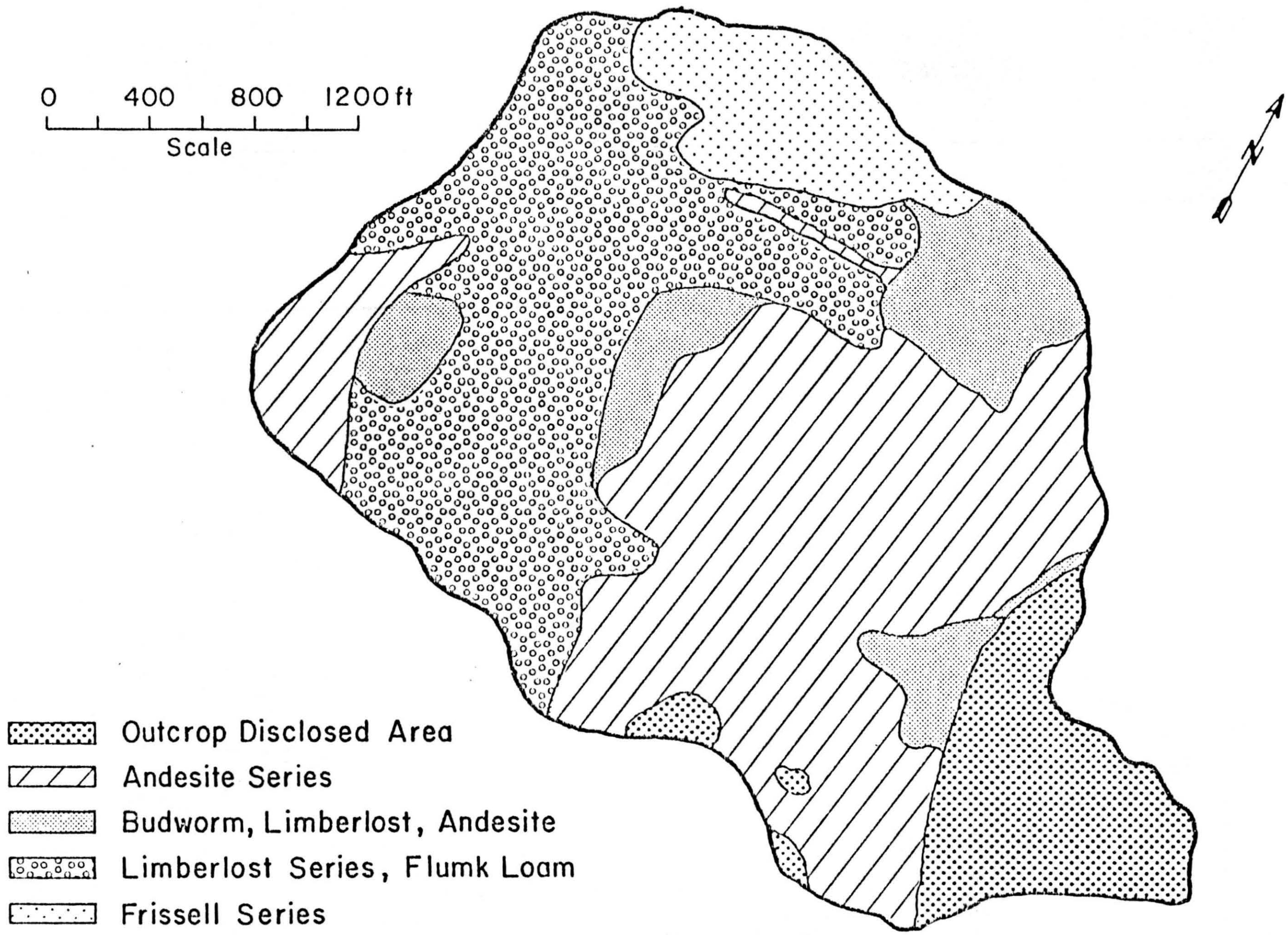



Figure 6. Soil classification map of Watershed 2 (after Hawk and Dyrness, undated).

and understory growth. If the understory growth consists principally of Douglas-fir or Western hemlock, the canopy cover density is computed as

$$\% \text{ Cover density} = \% \text{ overstory density} + \% \text{ understory density} - \frac{(\% \text{ overstory density} \times \text{understory density})}{100} \quad (17)$$

If the understory is composed principally of vine maple, rhododendran, or sword fern communities then the cover density is

$$\% \text{ Cover density} = \% \text{ overstory density} \quad (18)$$

This approach allows for differentiation between areas with predominately timber growth versus those with mixed timber and brush growth. The resultant cover percentages provide a method of classification as shown in Table 6.

Table 6. Vegetation classification based on cover density.

| Group | % Cover |
|---|---|
| 1 | $\geq$ 75% |
| 2 | 50-75% |
| 3 | 25-50% |
| 4 | 5-25% |
| 5 | 0-5% |

Most of Watershed 2 was characterized by vegetation groups 1, 2, and 3 as shown in Figure 7.

Runoff from the watershed is controlled by groundwater discharge. Precipitation in the area averages near 90 inches per year with about 90 percent of the total occurring as rainfall from October to April.

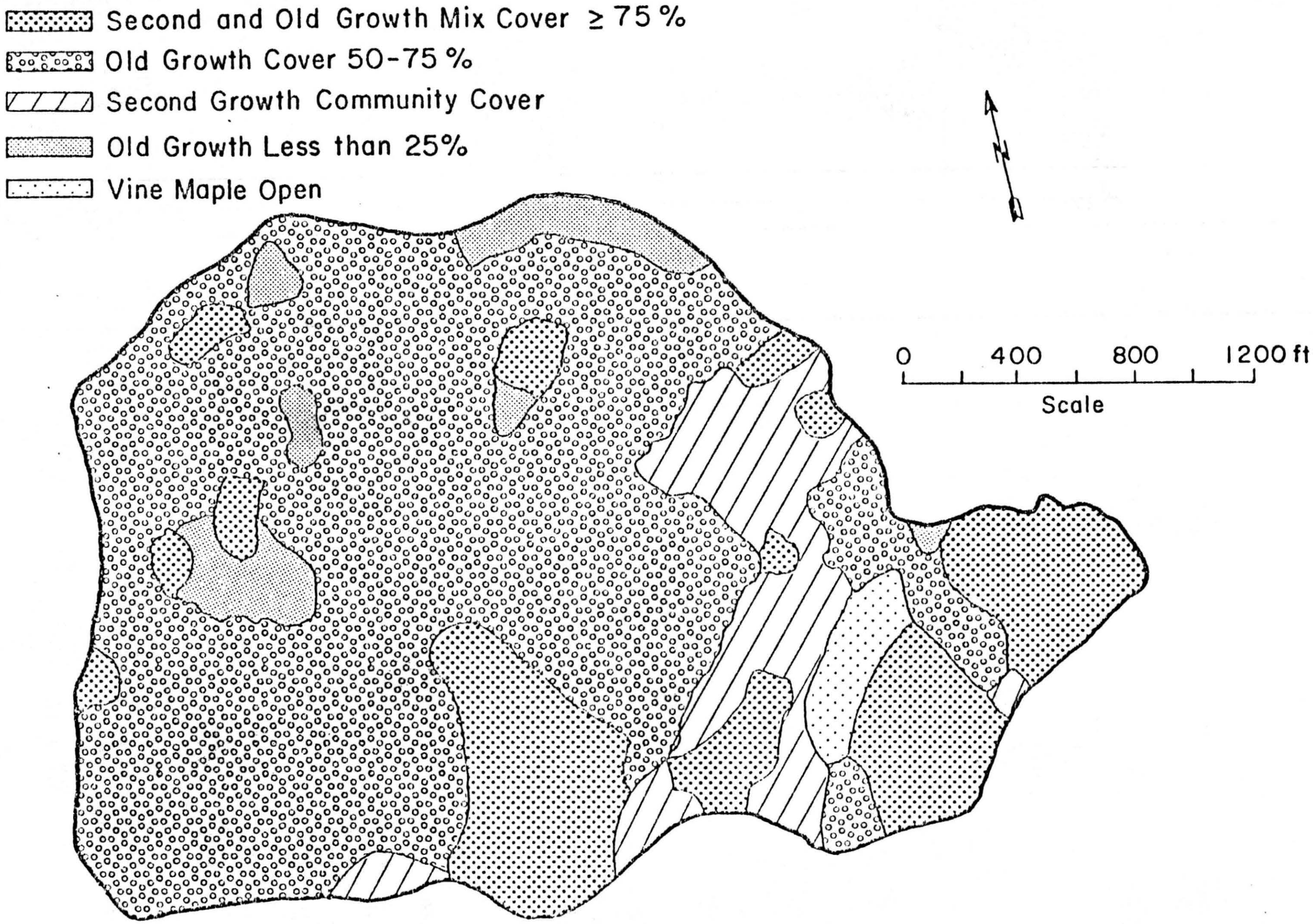



Figure 7. Vegetation classification map of Watershed 2 (after Hawk and Dyrness, undated).

Storms may last several days producing rainfall of several inches. Rainfall intensities are usually low and soil infiltration rates high so that overland flow seldom occurs. Streamflow is fed primarily by saturated and unsaturated groundwater flow. Because of the importance of groundwater in slope stability, it was recognized that fluctuations in the groundwater table during a storm were important. Unfortunately, an acceptable, easy to use groundwater model was not available for use at this time. Therefore, only selected levels were utilized for comparison.

Watershed Segmentation

Watershed 2 was segmented using program WASEG. Figure 8 shows the watershed with the superimposed grid system. Figure 9 shows an enlargement of a microfilm plot of the grid system and computed flow or aspect directions for the watershed. Code values were input for the five soil classes and vegetation types along with elevations and cover densities.

Figures 10 and 11 show computer printed base maps for the cell by cell soil and vegetation codes. Each cell is represented by a set of four code numbers in these plots. Similarly, gray map plots for slope and canopy cover density are presented in Figures 12 and 13.

Basic input data from WASEG were decoded and processed in LSMAP. Other input data required were soil and vegetative characteristics. These values were chosen from previously presented tables or were supplied by U.S. Forest Service personnel and available literature.

Once the model was supplied with the necessary data, preliminary computations were made to pinpoint any adjustments that may be needed

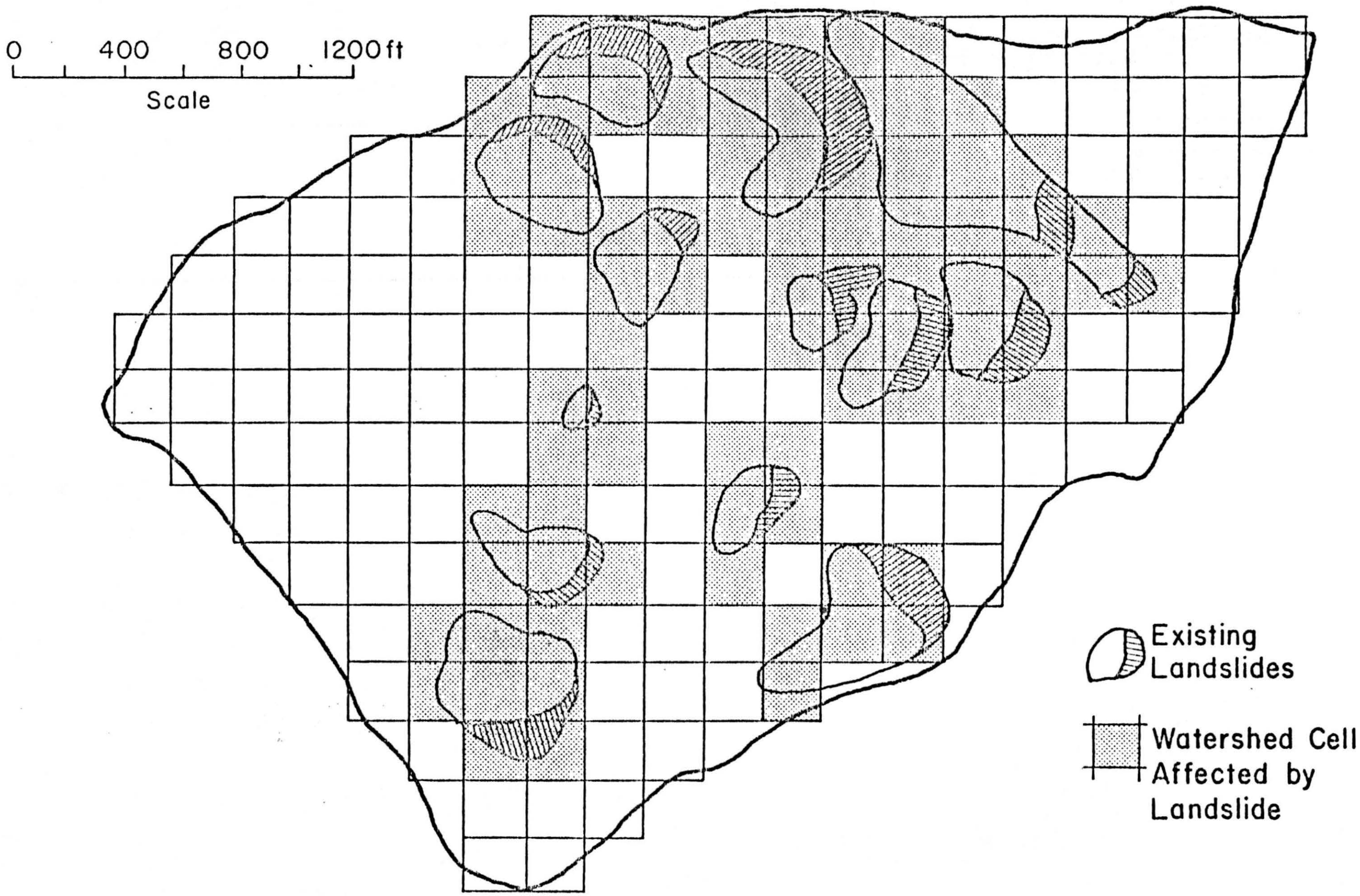



Figure 8. Watershed Number 2: Existing landslides and watershed cell system.

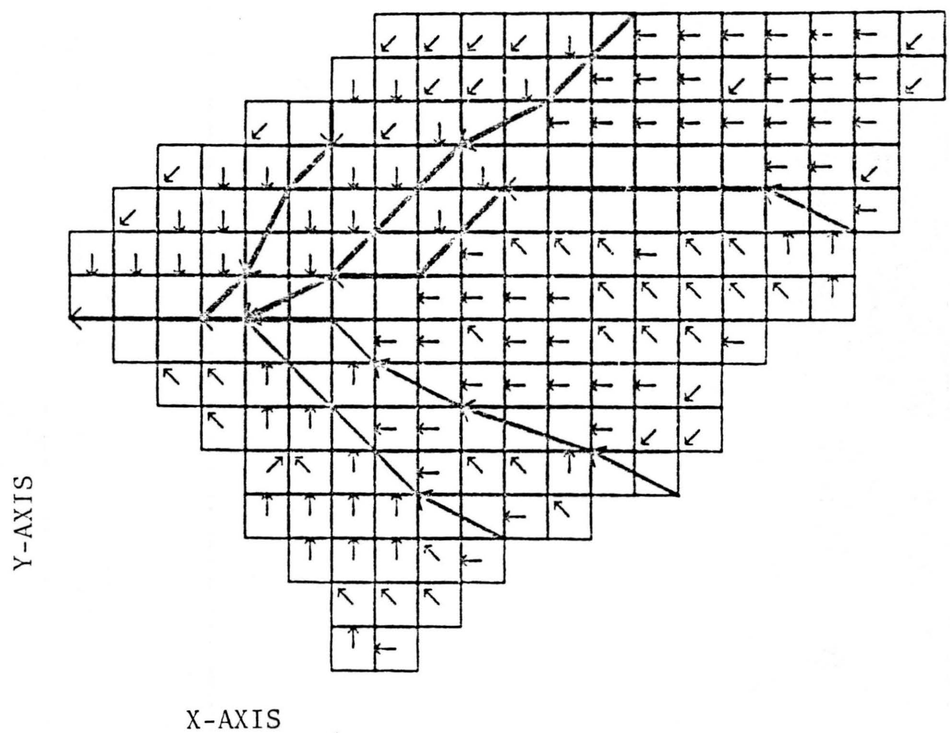



Figure 9. Microfilm plots of segmented Watershed 2 showing aspect or flow directions.

*****BASE MAP FOR SOIL TYPE*****

H. J. ANDREWS EXPERIMENTAL FOREST, OREGON          WATERSHED 2

RELATIVE GROUNDWATER DEPTH     1.000          MAP SCALE   1  TO  4800

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | 3333 | 3233 | 2223 | 2222 | 2222 | 8222 | 2232 | 2113 | 1111 | 1111 | 1111 | 1111 | 1111 |
| | | | | | | | | 3333 | 3233 | 2223 | 2222 | 2222 | 8222 | 2232 | 2113 | 1111 | 1111 | 1111 | 1111 | 1111 |
| | | | | | | | | 3333 | 3233 | 2223 | 2222 | 2222 | 8222 | 2232 | 2113 | 1111 | 1111 | 1111 | 1111 | 1111 |
| | | | | | | | | 3333 | 3233 | 2223 | 2222 | 2222 | 8222 | 2232 | 2113 | 1111 | 1111 | 1111 | 1111 | 1111 |
| 2 | | | | | | | 3333 | 3333 | 3333 | 3223 | 2222 | 8222 | 2222 | 2332 | 3133 | 1113 | 1111 | 1111 | 1111 | 1111 |
| | | | | | | | 3333 | 3333 | 3333 | 3223 | 2222 | 8222 | 2222 | 2332 | 3133 | 1113 | 1111 | 1111 | 1111 | 1111 |
| | | | | | | | 3333 | 3333 | 3333 | 3223 | 2222 | 8222 | 2222 | 2332 | 3133 | 1113 | 1111 | 1111 | 1111 | 1111 |
| | | | | | | | 3333 | 3333 | 3333 | 3223 | 2222 | 8222 | 2222 | 2332 | 3133 | 1113 | 1111 | 1111 | 1111 | 1111 |
| 3 | | | | | 5555 | 5335 | 3333 | 3333 | 3323 | 8322 | 8222 | 2222 | 2222 | 2332 | 3333 | 3133 | 1113 | 1111 | 1111 | |
| | | | | | 5555 | 5335 | 3333 | 3333 | 3323 | 8322 | 8222 | 2222 | 2222 | 2332 | 3333 | 3133 | 1113 | 1111 | 1111 | |
| | | | | | 5555 | 5335 | 3333 | 3333 | 3323 | 8222 | 8222 | 2222 | 2222 | 2332 | 3333 | 3133 | 1113 | 1111 | 1111 | |
| | | | | | 5555 | 5335 | 3333 | 3333 | 3323 | 8222 | 8222 | 2222 | 2222 | 2332 | 3333 | 3133 | 1113 | 1111 | 1111 | |
| 4 | | | 5555 | 5555 | 5555 | 8535 | 3342 | 3324 | 8322 | 2222 | 2222 | 2222 | 2222 | 2332 | 3333 | 3333 | 3123 | 1122 | 1112 | |
| | | | 5555 | 5555 | 5555 | 8535 | 3342 | 3324 | 8322 | 2222 | 2222 | 2222 | 2222 | 2332 | 3333 | 3333 | 3123 | 1122 | 1112 | |
| | | | 5555 | 5555 | 5555 | 8325 | 3342 | 3324 | 8222 | 2222 | 2222 | 2222 | 2222 | 2332 | 3333 | 3333 | 3123 | 1122 | 1112 | |
| | | | 5555 | 5555 | 5555 | 8325 | 3342 | 3324 | 8222 | 2222 | 2222 | 2222 | 2222 | 2332 | 3333 | 3333 | 3123 | 1122 | 1112 | |
| 5 | | 5555 | 5555 | 5555 | 8555 | 5244 | 2444 | 8424 | 2222 | 8222 | 2221 | 2222 | 2222 | 2322 | 3322 | 3322 | 9322 | 9222 | 2142 | |
| | | 5555 | 5555 | 5555 | 8555 | 5244 | 2444 | 8424 | 2222 | 8222 | 2221 | 2222 | 2222 | 2322 | 3322 | 3322 | 9322 | 9222 | 2142 | |
| | | 5555 | 5555 | 5555 | 8545 | 5244 | 2444 | 8224 | 2222 | 8212 | 2221 | 2222 | 2222 | 2322 | 3322 | 3322 | 9322 | 9222 | 2142 | |
| | | 5555 | 5555 | 5555 | 8545 | 5244 | 2444 | 8224 | 2222 | 8212 | 2221 | 2222 | 2222 | 2322 | 3322 | 3322 | 9322 | 9222 | 2142 | |
| 6 | 5555 | 5555 | 5555 | 5545 | 8544 | 4444 | 8444 | 4223 | 8222 | 2112 | 1221 | 2222 | 2222 | 2222 | 2222 | 2212 | 2211 | 2211 | | |
| | 5555 | 5555 | 5555 | 5545 | 8544 | 4444 | 8444 | 4223 | 8222 | 2112 | 1221 | 2222 | 2222 | 2222 | 2222 | 2212 | 2211 | 2211 | | |
| | 5555 | 5555 | 5555 | 5545 | 8444 | 4444 | 8434 | 4223 | 8222 | 2112 | 1221 | 2222 | 2222 | 2222 | 2222 | 2212 | 2211 | 2211 | | |
| | 5555 | 5555 | 5555 | 5545 | 8444 | 4444 | 8434 | 4223 | 8222 | 2112 | 1221 | 2222 | 2222 | 2222 | 2222 | 2212 | 2211 | 2211 | | |
| 7 | 5544 | 5544 | 5544 | 8544 | 8444 | 8444 | 4344 | 3234 | 2223 | 2112 | 1221 | 2222 | 2222 | 2222 | 2212 | 2141 | 1144 | 1114 | | |
| | 5544 | 5544 | 5544 | 8544 | 8444 | 8444 | 4344 | 3234 | 2223 | 2112 | 1221 | 2222 | 2222 | 2222 | 2212 | 2141 | 1144 | 1114 | | |
| | 5544 | 5544 | 5544 | 8444 | 8444 | 8444 | 4344 | 3234 | 2223 | 2112 | 1221 | 2222 | 2222 | 2222 | 2212 | 2141 | 1144 | 1114 | | |
| | 5544 | 5544 | 5544 | 8444 | 8444 | 8444 | 4344 | 3234 | 2223 | 2112 | 1221 | 2222 | 2222 | 2222 | 2212 | 2141 | 1144 | 1114 | | |
| 8 | | 4444 | 4444 | 4444 | 4444 | 4444 | 9444 | 4344 | 3234 | 2123 | 1232 | 2223 | 2212 | 2211 | 2111 | 1411 | | | | |
| | | 4444 | 4444 | 4444 | 4444 | 4444 | 9444 | 4344 | 3234 | 2123 | 1232 | 2223 | 2212 | 2211 | 2111 | 1411 | | | | |
| | | 4444 | 4444 | 4444 | 4444 | 4444 | 9444 | 4344 | 3234 | 2123 | 1232 | 2223 | 2212 | 2211 | 2111 | 1411 | | | | |
| | | 4444 | 4444 | 4444 | 4444 | 4444 | 9444 | 4344 | 3234 | 2123 | 1232 | 2223 | 2212 | 2211 | 2111 | 1411 | | | | |
| 9 | | | 4444 | 4444 | 4444 | 9444 | 4434 | 9444 | 9434 | 3244 | 2344 | 3224 | 2122 | 1122 | 1142 | | | | | |
| | | | 4444 | 4444 | 4444 | 9444 | 4434 | 9444 | 9434 | 3244 | 2344 | 3224 | 2122 | 1122 | 1142 | | | | | |
| | | | 4444 | 4444 | 4444 | 9444 | 4434 | 9443 | 9444 | 3244 | 2344 | 3224 | 2122 | 1122 | 1142 | | | | | |
| | | | 4444 | 4444 | 4444 | 9444 | 4434 | 9443 | 9444 | 3244 | 2344 | 3224 | 2122 | 1122 | 1142 | | | | | |
| 10 | | | | 4444 | 4444 | 4434 | 9434 | 3444 | 4444 | 9444 | 9444 | 9424 | 2234 | 2233 | 2443 | | | | | |
| | | | | 4444 | 4444 | 4434 | 9434 | 3444 | 4444 | 9444 | 9444 | 9424 | 2234 | 2233 | 2443 | | | | | |
| | | | | 4444 | 4444 | 4434 | 9443 | 3444 | 4444 | 9444 | 9444 | 9444 | 2234 | 2233 | 2443 | | | | | |
| | | | | 4444 | 4444 | 4434 | 9443 | 3444 | 4444 | 9444 | 9444 | 9444 | 2234 | 2233 | 2443 | | | | | |
| 11 | | | | | 4424 | 4332 | 3433 | 9444 | 4444 | 4444 | 4444 | 4434 | 9433 | 9333 | | | | | | |
| | | | | | 4424 | 4332 | 3433 | 9444 | 4444 | 4444 | 4444 | 4434 | 9433 | 9333 | | | | | | |
| | | | | | 4424 | 4332 | 3433 | 9443 | 4444 | 4444 | 4444 | 4434 | 9433 | 9333 | | | | | | |
| | | | | | 4424 | 4332 | 3433 | 9443 | 4444 | 4444 | 4444 | 4434 | 9433 | 9333 | | | | | | |
| 12 | | | | | 4224 | 2332 | 3333 | 3443 | 9444 | 9444 | 4434 | 4333 | | | | | | | | |
| | | | | | 4224 | 2332 | 3333 | 3443 | 9444 | 9444 | 4434 | 4333 | | | | | | | | |
| | | | | | 4224 | 2332 | 3333 | 3443 | 9444 | 9444 | 4434 | 4333 | | | | | | | | |
| | | | | | 4224 | 2332 | 3333 | 3443 | 9444 | 9444 | 4434 | 4333 | | | | | | | | |
| 13 | | | | | | 2324 | 3322 | 3442 | 4444 | 4444 | | | | | | | | | | |
| | | | | | | 2324 | 3322 | 3442 | 4444 | 4444 | | | | | | | | | | |
| | | | | | | 2324 | 3322 | 3442 | 4444 | 4444 | | | | | | | | | | |
| | | | | | | 2324 | 3322 | 3442 | 4444 | 4444 | | | | | | | | | | |
| 14 | | | | | | | 2222 | 2422 | 4442 | | | | | | | | | | | |
| | | | | | | | 2222 | 2422 | 4442 | | | | | | | | | | | |
| | | | | | | | 2222 | 2422 | 4442 | | | | | | | | | | | |
| | | | | | | | 2222 | 2422 | 4442 | | | | | | | | | | | |
| 15 | | | | | | | 2222 | 2222 | | | | | | | | | | | | |
| | | | | | | | 2222 | 2222 | | | | | | | | | | | | |
| | | | | | | | 2222 | 2222 | | | | | | | | | | | | |
| | | | | | | | 2222 | 2222 | | | | | | | | | | | | |

Figure 10. Soil base map for Watershed 2 (Each cell consists of four code numbers. Numbers 8 and 9 indicate half cells).

H. J. ANDREWS EXPERIMENTAL FOREST, OREGON WATERSHED 2

RELATIVE GROUNDWATER DEPTH 1.000 MAP SCALE 1 TO 4800

SYMBOL SET USED FOR THIS GRAY MAP INDICATES:

| | |
|---|---|
| GREATER OR EQUAL TO 0.80 | W |
| GREATER OR EQUAL TO 0.70 AND LESS THAN 0.80 | N |
| GREATER OR EQUAL TO 0.60 AND LESS THAN 0.70 | U |
| GREATER OR EQUAL TO 0.50 AND LESS THAN 0.60 | I |
| GREATER OR EQUAL TO 0.40 AND LESS THAN 0.50 | = |
| GREATER OR EQUAL TO 0.30 AND LESS THAN 0.40 | + |
| GREATER OR EQUAL TO 0.20 AND LESS THAN 0.30 | - |
| LESS THAN 0.20 | . |

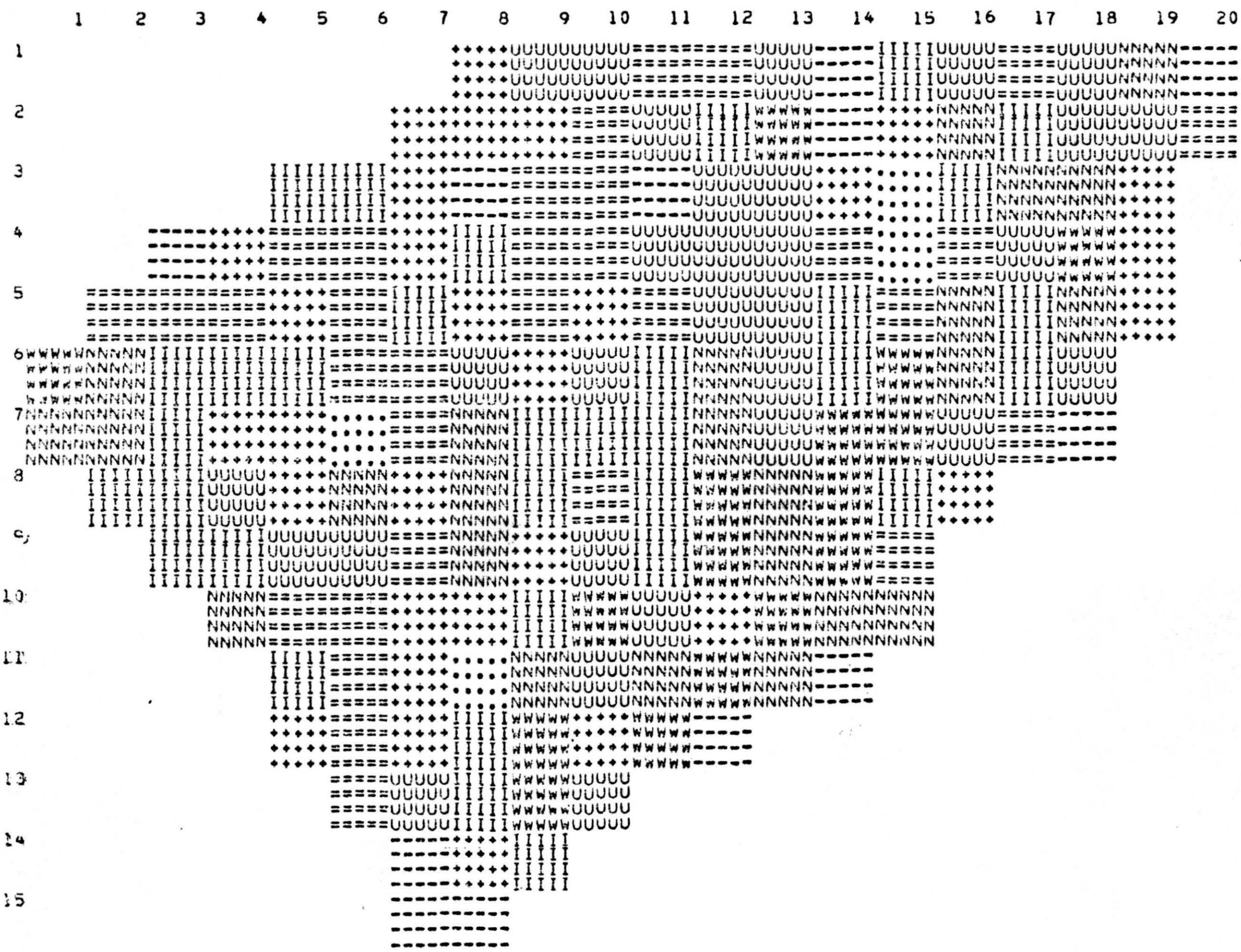


Figure 12. Gray map of Watershed 2 showing slope classes.

H. J. ANDREWS EXPERIMENTAL FOREST, OREGON — WATERSHED 2

RELATIVE GROUNDWATER DEPTH 1.000 — MAP SCALE 1 TO 4800

SYMBOL SET USED FOR THIS GRAY MAP INDICATES:

| | |
|---|---|
| GREATER OR EQUAL TO 0.75 | W |
| GREATER OR EQUAL TO 0.70 AND LESS THAN 0.75 | N |
| GREATER OR EQUAL TO 0.65 AND LESS THAN 0.70 | U |
| GREATER OR EQUAL TO 0.60 AND LESS THAN 0.65 | I |
| GREATER OR EQUAL TO 0.55 AND LESS THAN 0.60 | = |
| GREATER OR EQUAL TO 0.50 AND LESS THAN 0.55 | + |
| GREATER OR EQUAL TO 0.45 AND LESS THAN 0.50 | - |
| LESS THAN 0.45 | . |

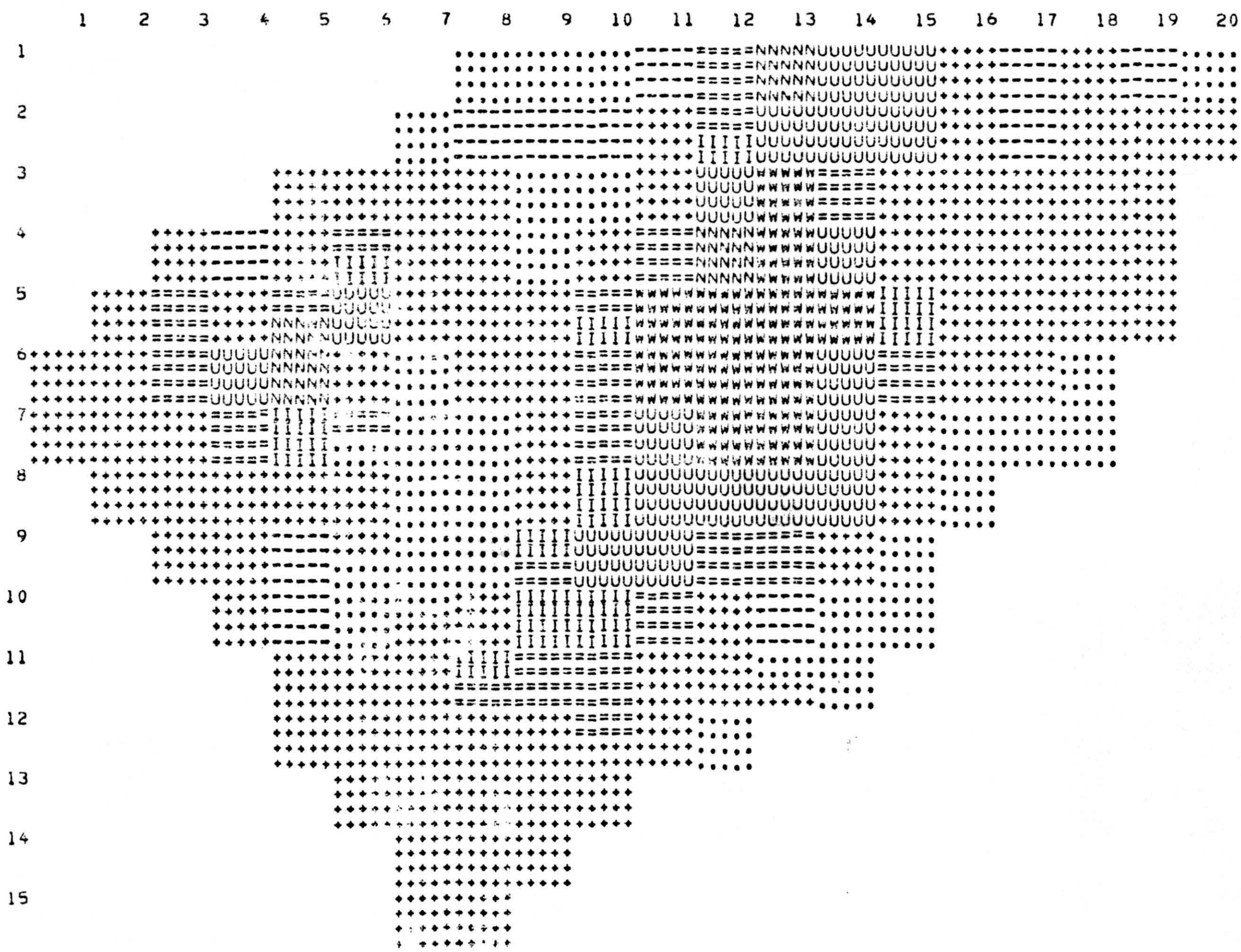



Figure 13. Gray map of Watershed 2 showing canopy cover density classes.

in the data. These initial runs immediately indicated a data organization problem. Therefore, the number of soil classes was increased to better reflect the important soil characteristics. However, the initial runs indicated that failure potential was high in the cells where landslides had occurred. In Watershed 2, 78.5 cells (0.5 cells for a cell near a stream channel) out of a total of 181 cells in the segmented watershed were denoted as having mappable landslide scars and deposits (Figure 8). These cells were used as a guide to model performance and adjustment. It was assumed that such cells are hazard cells. If the model predicted a potential landslide hazard in these cells then it is accepted as a correct result. Overestimation or underestimation of the number of hazardous cells indicates that a) some hazardous cells may have characteristics undetected on this mapping scale and are mapped as being non-hazardous, b) cells mapped as hazardous but not containing landslides may not yet have failed, or c) the model is incorrect for other reasons such as erroneous data. Comparison of the number of correct classifications with incorrect classifications for initial runs indicated the physical process model did reflect the correct slope stability conditions.

The model was adjusted through soil and root strength parameters to better match the observed data. Two criteria were established to help in this adjustment. First, under typical soil moisture conditions no cell should fail. Second, under saturated conditions all the landslide cells should fail. Although failure may occur in all the landslide cells before saturated conditions are reached, there is no data to indicate at what saturation failure did occur. Using these two criteria, the input values were adjusted over realistic ranges. These values plus others not used in model adjustment are listed in Table 7.

Table 7. Input values for LSMAP.

Soil porosity = 0.60
Dry unit weight of soil = 66.1 pounds per cubic foot
Saturated unit weight of soil = 103.6 pounds per cubic foot
Vegetative surcharge = 50 pounds per square foot

| Soil Class | Cohesion Range, Pounds per Square Foot | Friction Angle Range, Degrees | Typical Depth, Feet |
|---|---|---|---|
| 1 | 1000-2000 | 35-40 | 3 |
| 2 | 20-50 | 5-20 | 8 |
| 3 | 0-5 | 2-5 | 10 |
| 4 | 150-200 | 25-28 | 5 |
| 5 | 350-400 | 30-33 | 4 |

| Vegetation Class | Root Strength Range, Pounds per Square Foot |
|---|---|
| 1 | 290-360 |
| 2 | 220-260 |
| 3 | 5-25 |
| 4 | 100-125 |
| 5 | 15-65 |

Low values of cohesion and friction angle for soils classes 2 and 3 were used to insure that the model indicated failure for these soils. Higher values for the other three soil classes reflect the relative stability associated with those groupings. Similar considerations were used when trying to select proper ranges of root strengths. No formal methodology was used for arriving at the adjusted values in Table 7. The values do, however, reflect the relative stability of groups they represent.

Comparison of Model with Observed Landslides

The adjusted model indicated a total of 81.5 hazardous cells, 69 of which corresponded with the assumed hazardous cells, an 87.9 percent match. A total of 9.5 cells were classed as safer than they were assumed to be and 12.5 were classed as more hazardous. This is an encouraging comparison as it indicates that the model represents the physical processes controlling landslide occurrence.

The adjusted model was then used to demonstrate its usefulness in studying dynamic changes in the watershed. The first application is the change in landslide hazard under varying groundwater conditions. Figure 14 and 15 shows the potentially hazardous landslide areas and their estimated failure probabilities for a relative groundwater level of 0.0. Even under these conditions there are numerous areas where the potential is quite high because of the overwhelming driving forces brought about by the steep terrain. Figures 16 and 17 for $M = 0.5$ and Figures 18 and 19 for $M = 1.0$ show that, as expected, rising groundwater levels increase landslide hazards. If a real time groundwater level model were available, daily or seasonal fluctuations in landslide hazards could be determined. Use of the model in determining relative hazards in terms of groundwater levels is important in planning watershed activities. Based on model results, scheduling of activities may be better determined to coincide with lower landslide hazards. Roadways may also be better planned to avoid consistently hazardous areas or to provide stability enhancement where indicated.

Timbering is another dynamic watershed activity that can be assessed with the model. Figure 20 shows the landslide potential for a 50 percent clearing of the canopy cover. Comparison of Figure 20

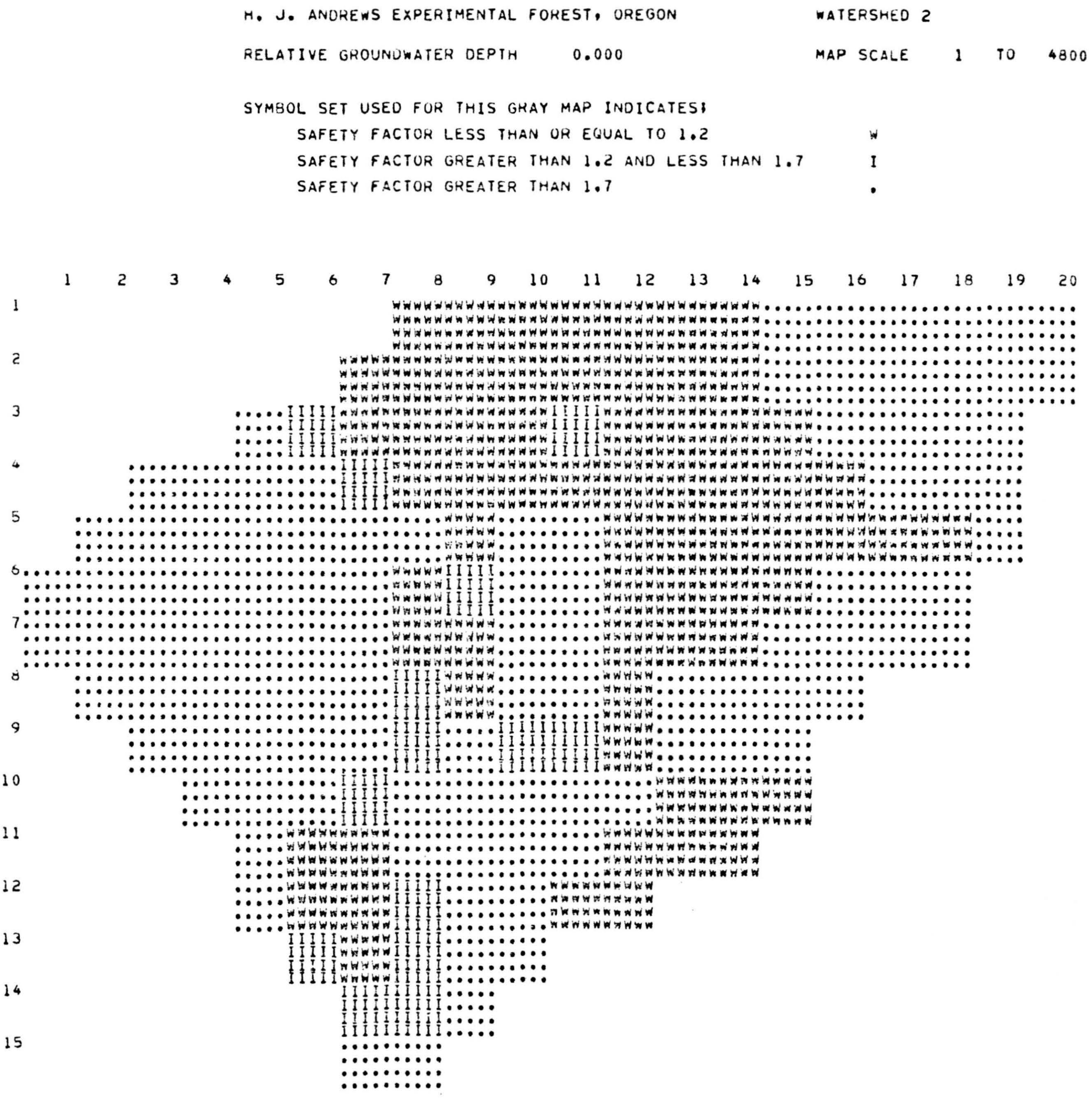



Figure 14. Gray map of potentially hazardous landslide areas for Watershed 2 with relative groundwater level of 0.0.

H. J. ANDREWS EXPERIMENTAL FOREST, OREGON WATERSHED 2

RELATIVE GROUNDWATER DEPTH 0.000 MAP SCALE 1 TO 4800

SYMBOL SET USED FOR THIS GRAY MAP INDICATES:

| | |
|---|---|
| PROBABILITY OF SLIDING HIGHER THAN 60 PERCENT | W |
| PROBABILITY HIGHER THAN 30 PERCENT AND LESS OR EQUAL TO 60 PERCENT | I |
| PROBABILITY OF SLIDING LESS THAN 30 PERCENT | . |

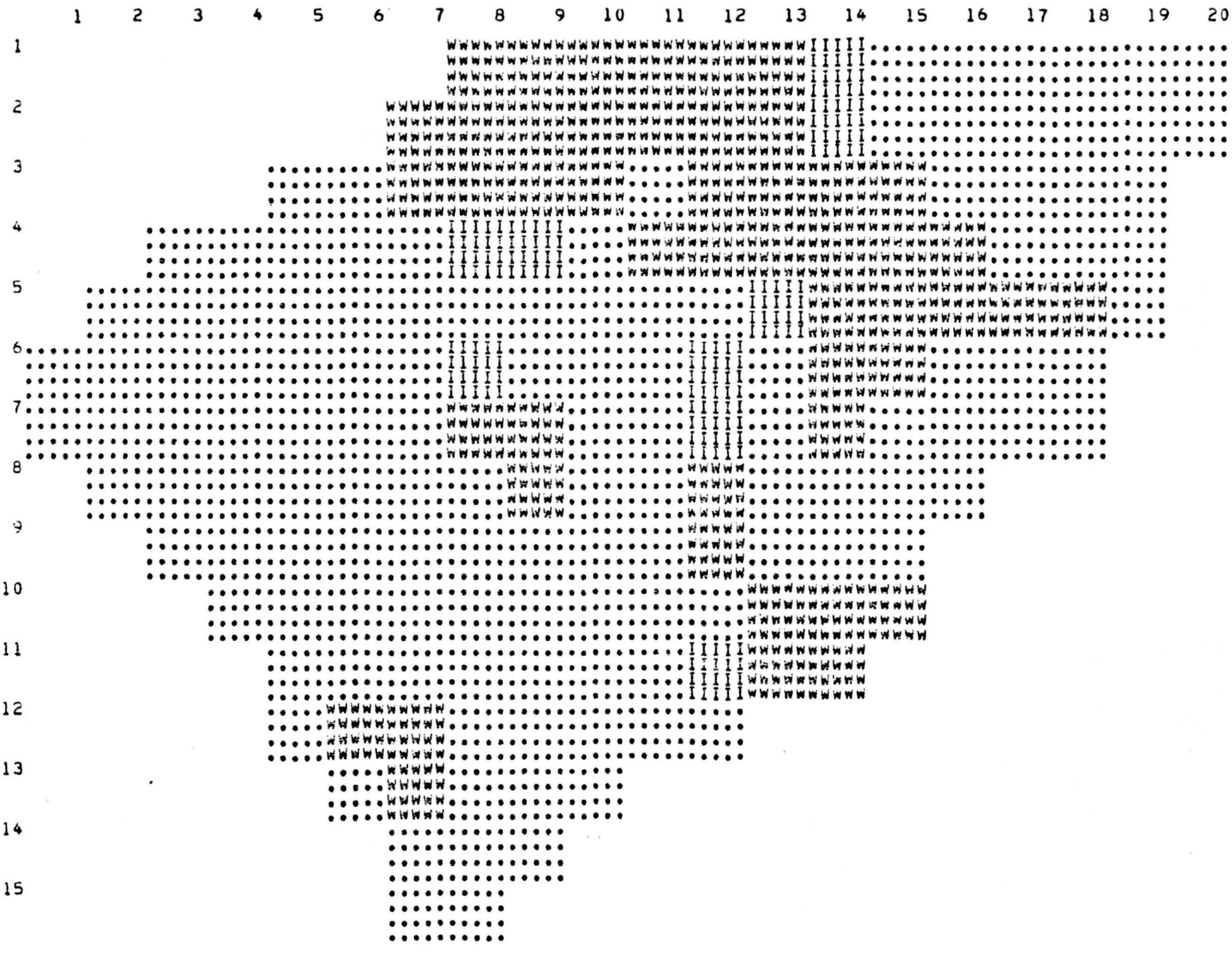



Figure 15. Gray map of estimated failure probabilities of landslide areas for Watershed 2 with relative groundwater level of 0.0.

H. J. ANDREWS EXPERIMENTAL FOREST, OREGON WATERSHED 2

RELATIVE GROUNDWATER DEPTH .500 MAP SCALE 1 TO 4800

SYMBOL SET USED FOR THIS GRAY MAP INDICATES:

| | |
|---|---|
| SAFETY FACTOR LESS THAN OR EQUAL TO 1.2 | W |
| SAFETY FACTOR GREATER THAN 1.2 AND LESS THAN 1.7 | I |
| SAFETY FACTOR GREATER THAN 1.7 | . |

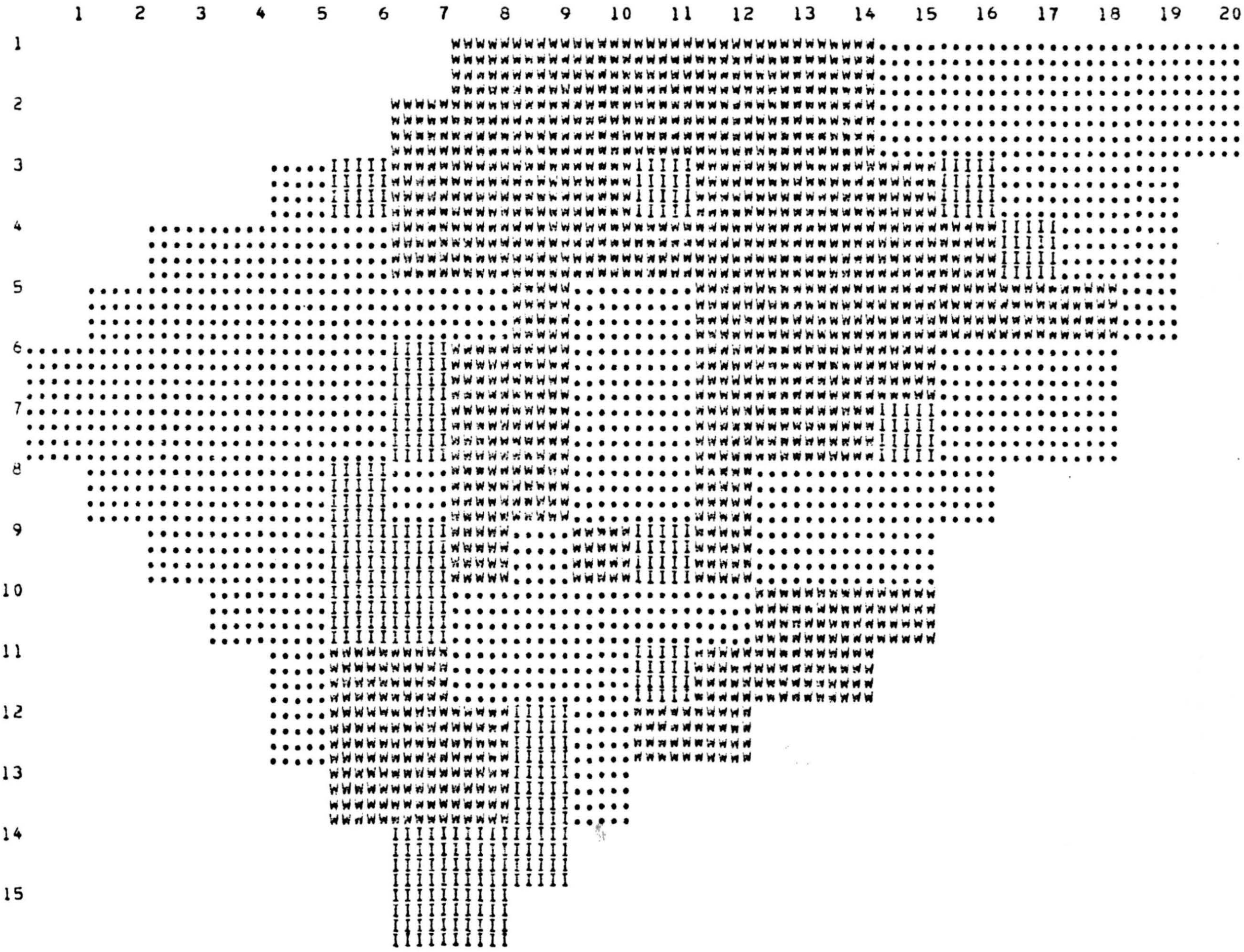


Figure 16. Gray map of potentially hazardous landslide areas for Watershed 2 with relative groundwater level of 0.5.

H. J. ANDREWS EXPERIMENTAL FOREST, OREGON WATERSHED 2

RELATIVE GROUNDWATER DEPTH .500 MAP SCALE 1 TO 4800

SYMBOL SET USED FOR THIS GRAY MAP INDICATES:

| | |
|---|---|
| PROBABILITY OF SLIDING HIGHER THAN 60 PERCENT | W |
| PROBABILITY HIGHER THAN 30 PERCENT AND LESS OR EQUAL TO 60 PERCENT | I |
| PROBABILITY OF SLIDING LESS THAN 30 PERCENT | . |

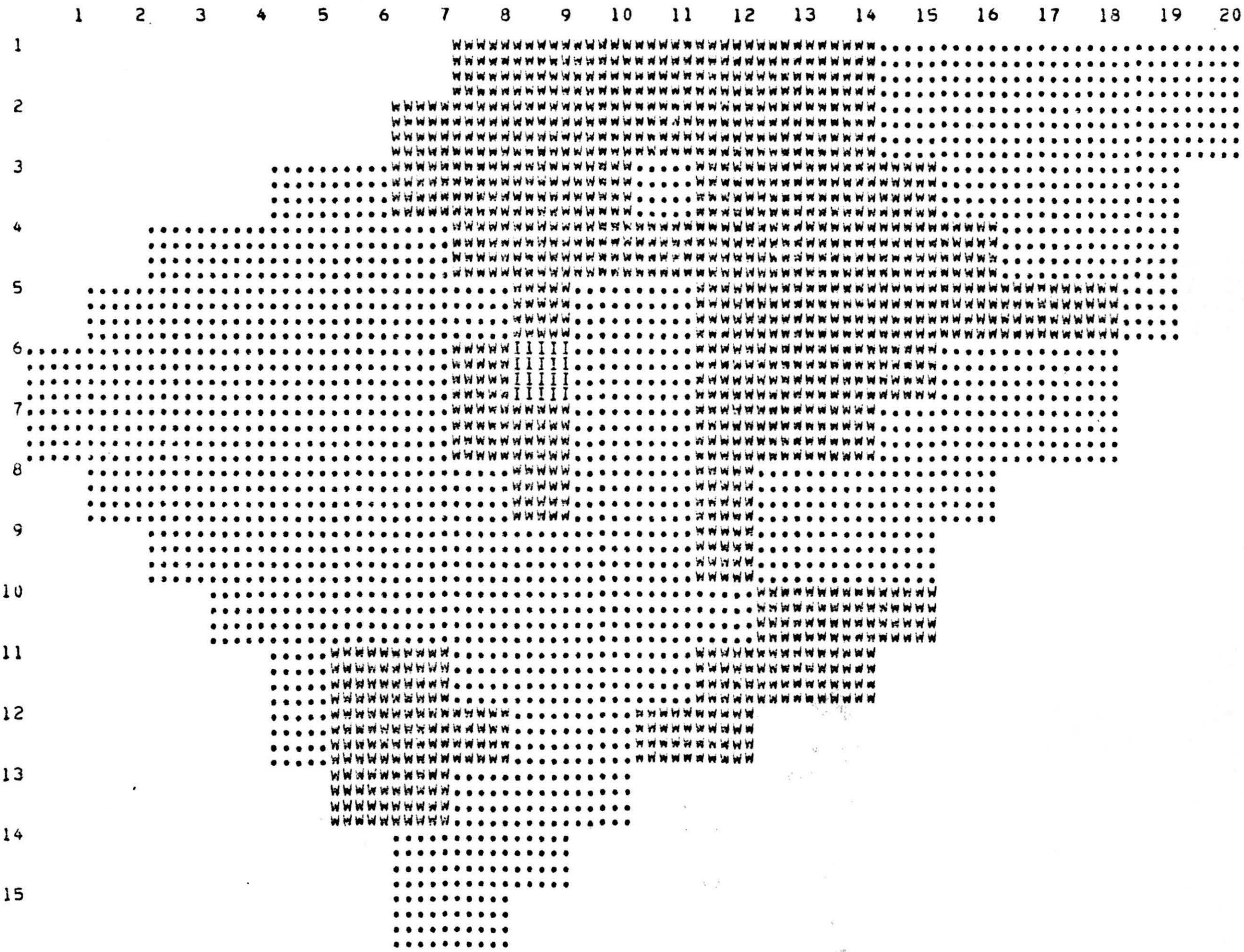



Figure 17. Gray map of estimated failure probabilities of landslide areas for Watershed 2 with relative groundwater level of 0.5.

H. J. ANDREWS EXPERIMENTAL FOREST, OREGON — WATERSHED 2

RELATIVE GROUNDWATER DEPTH 1.000 — MAP SCALE 1 TO 4800

SYMBOL SET USED FOR THIS GRAY MAP INDICATES:

- SAFETY FACTOR LESS THAN OR EQUAL TO 1.2 — W
- SAFETY FACTOR GREATER THAN 1.2 AND LESS THAN 1.7 — I
- SAFETY FACTOR GREATER THAN 1.7 — .

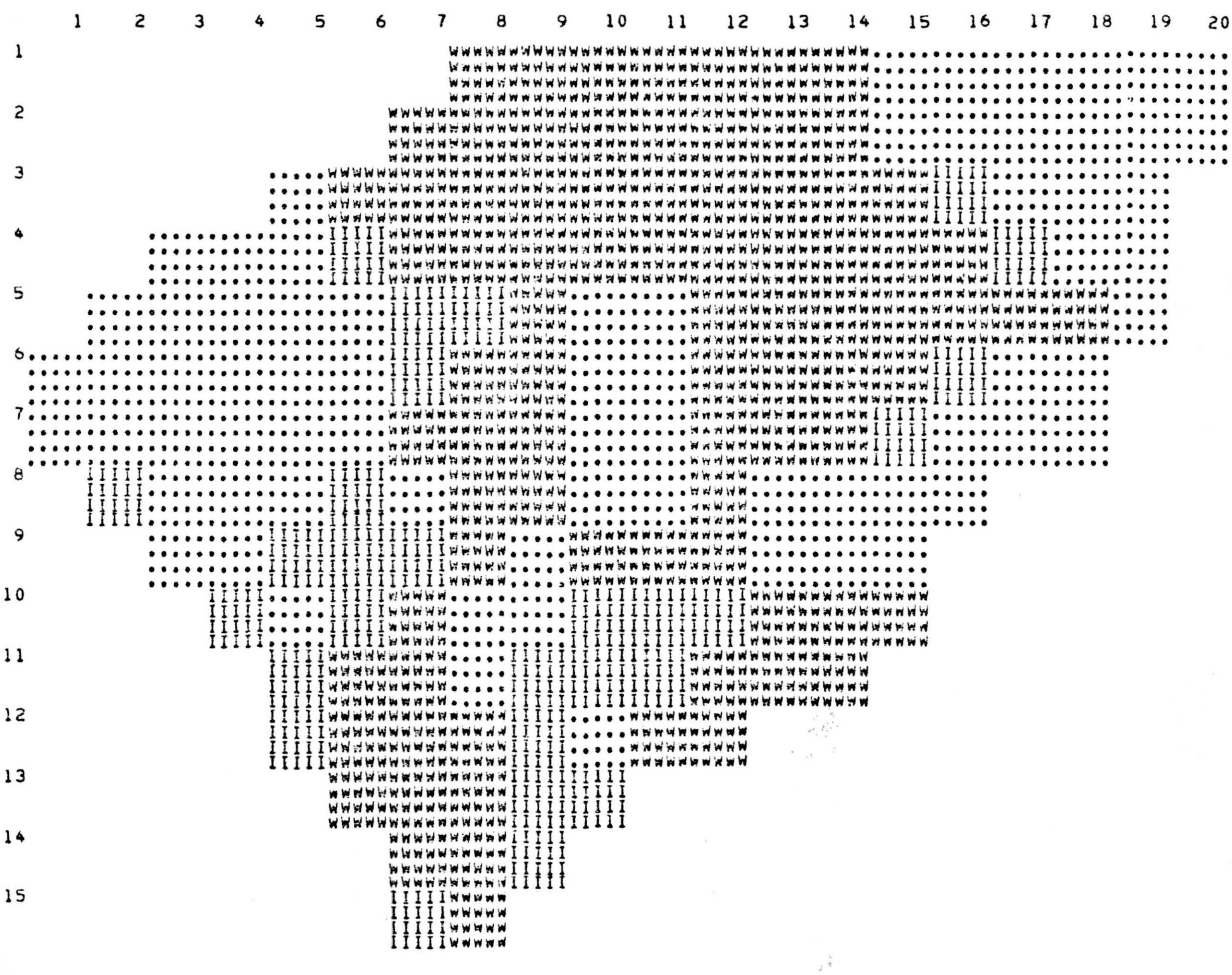


Figure 18. Gray map of potentially hazardous landslide areas for Watershed 2 with relative groundwater level of 1.0.

H. J. ANDREWS EXPERIMENTAL FOREST, OREGON WATERSHED 2

RELATIVE GROUNDWATER DEPTH 1.000 MAP SCALE 1 TO 4800

SYMBOL SET USED FOR THIS GRAY MAP INDICATES:

PROBABILITY OF SLIDING HIGHER THAN 60 PERCENT W

PROBABILITY HIGHER THAN 30 PERCENT AND LESS OR EQUAL TO 60 PERCENT I

PROBABILITY OF SLIDING LESS THAN 30 PERCENT .

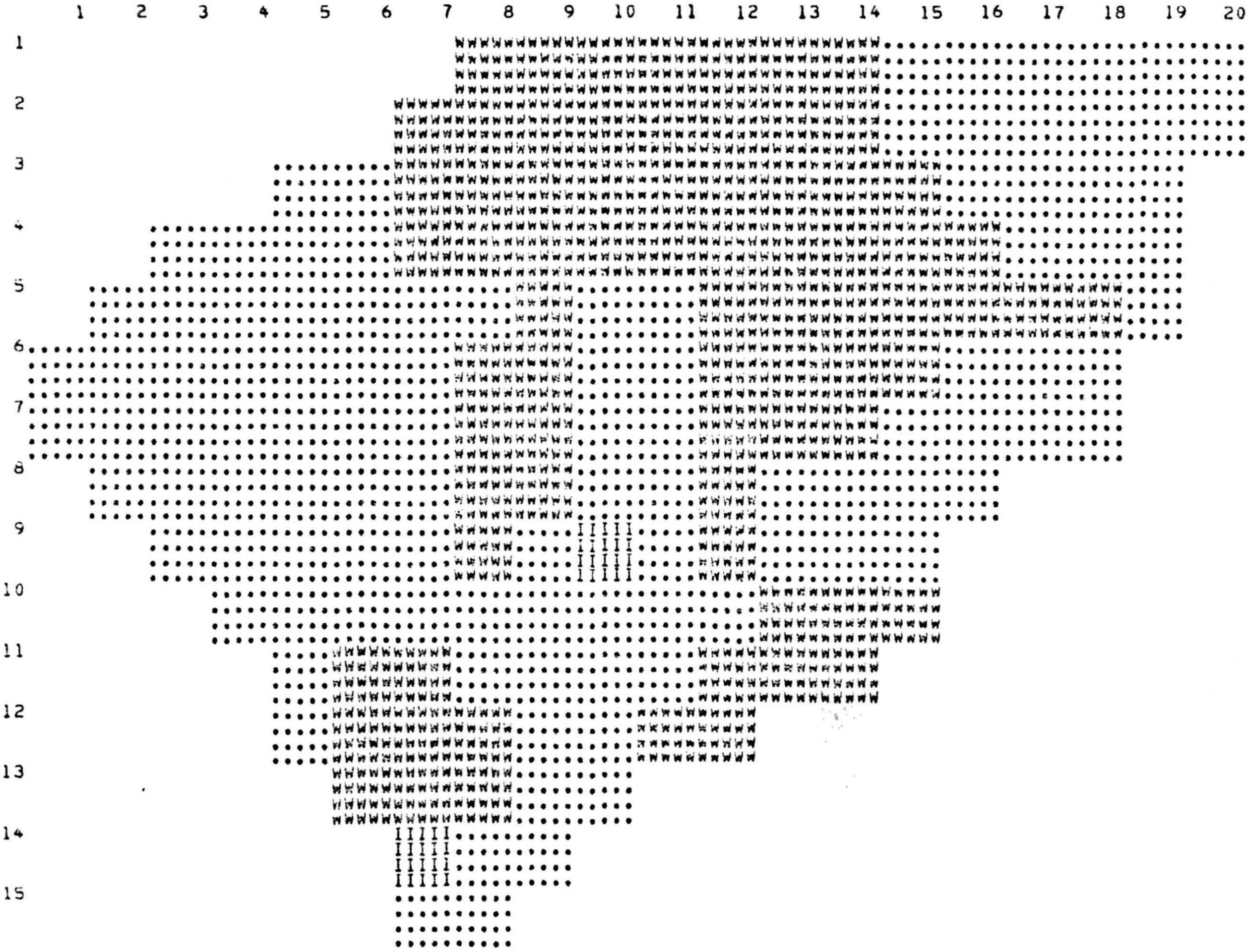


Figure 19. Gray map of estimated failure probabilities of landslide areas for Watershed 2 with relative groundwater level of 1.0.

H. J. ANDREWS EXPERIMENTAL FOREST, OREGON WATERSHED 2

RELATIVE GROUNDWATER DEPTH .500 MAP SCALE 1 TO 4800

SYMBOL SET USED FOR THIS GRAY MAP INDICATES:

SAFETY FACTOR LESS THAN OR EQUAL TO 1.2 W

SAFETY FACTOR GREATER THAN 1.2 AND LESS THAN 1.7 I

SAFETY FACTOR GREATER THAN 1.7 .

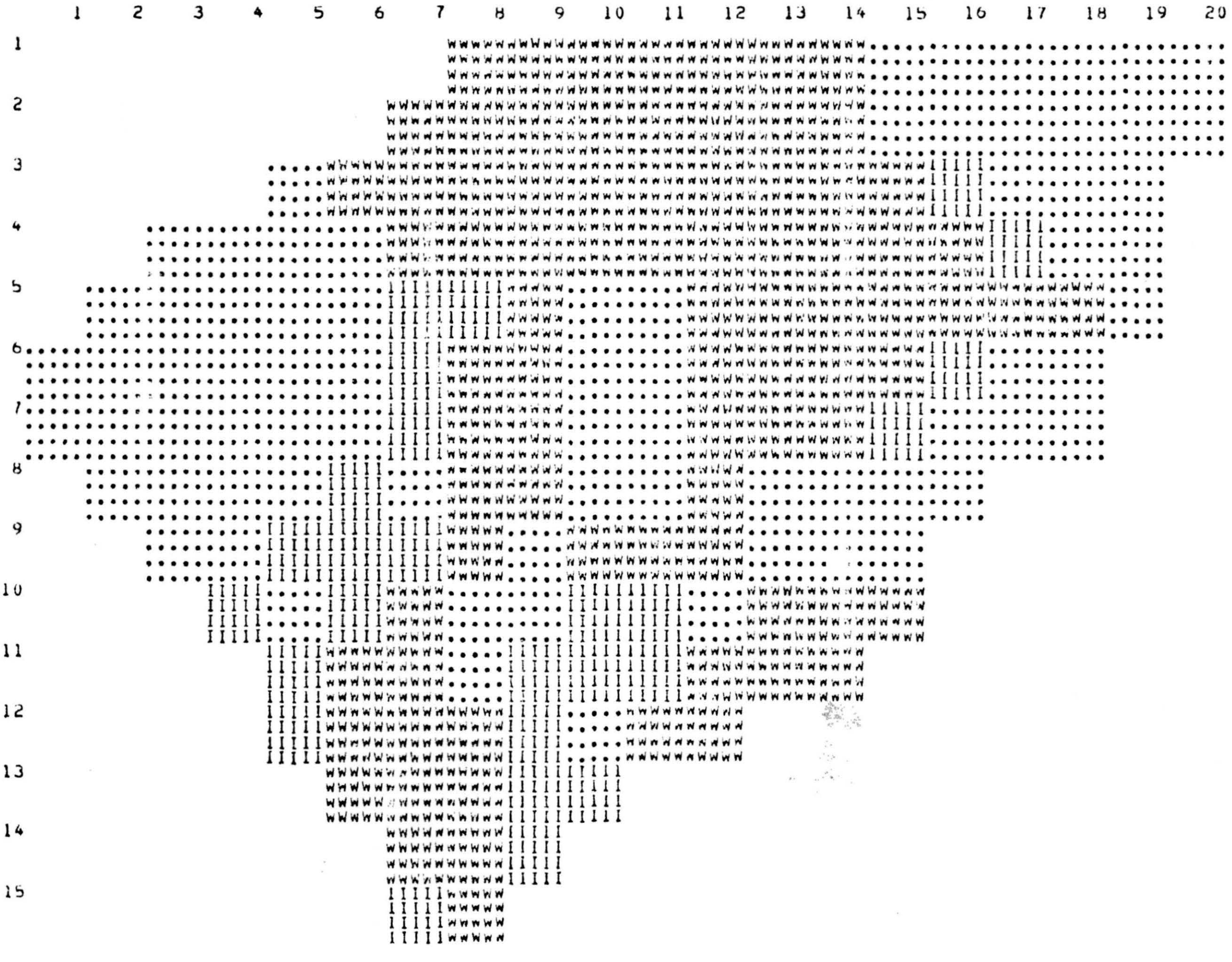



Figure 20. Gray map of potentially hazardous landslide areas for a 50 percent clearing of canopy cover with relative groundwater level of 0.5.

with Figure 16 shows adverse effect on slope stability produced by vegetation removal. Similarly, if the watershed is clear cut, as shown in Figure 21, even more instability is produced. However, an instantaneous drop in root strength is assumed, which is incorrect. A more realistic approximation would be a decay of strength with time. The end result, however, is represented by Figures 20 and 21. Again, the model has provided a method for assessing the impact of one type of timbering activity on the watershed.

An important aspect of the model as demonstrated above is that of estimating landslide probability. Joint use of the potential and probability maps can provide the land use manager with another means for making decisions on watershed activities. The probability map is valuable in analyzing the potential map.

H. J. ANDREWS EXPERIMENTAL FOREST, OREGON — WATERSHED 2

RELATIVE GROUNDWATER DEPTH .500 — MAP SCALE 1 TO 4800

SYMBOL SET USED FOR THIS GRAY MAP INDICATES:

| | |
|---|---|
| SAFETY FACTOR LESS THAN OR EQUAL TO 1.2 | W |
| SAFETY FACTOR GREATER THAN 1.2 AND LESS THAN 1.7 | I |
| SAFETY FACTOR GREATER THAN 1.7 | . |

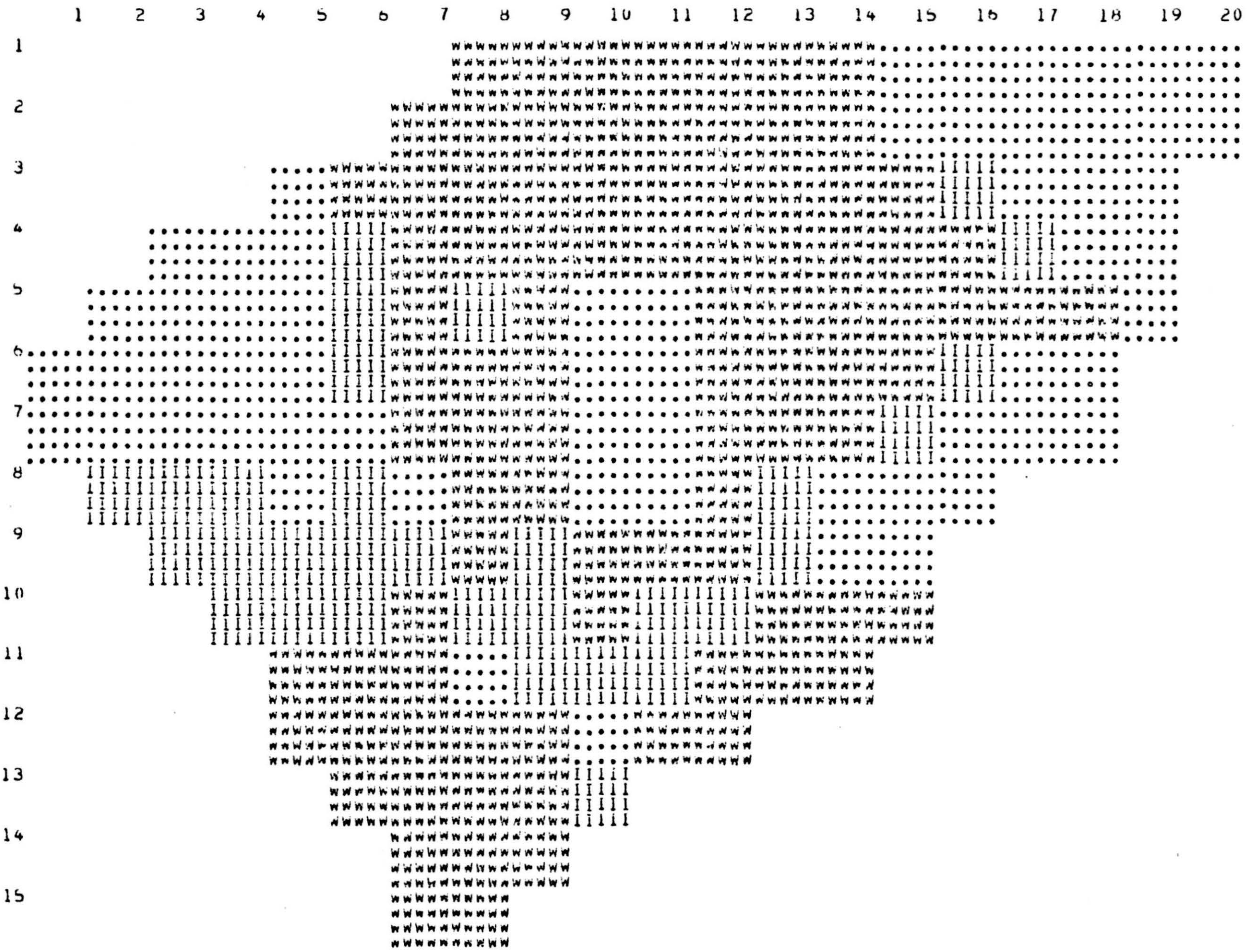


Figure 21. Gray map of potentially hazardous landslide areas for clear cut watershed with relative groundwater level of 0.5.

# V. SUMMARY AND CONCLUSIONS

A physically based mathematical model was developed that estimates landslide potential. Because uncertainty exists in the input variables, a probability of failure reflecting this situation is also computed. The model was applied to a forested watershed in Oregon. Results indicate the model provides a realistic approach for determining landslide hazards. A limitation of this method is encountered in providing actual input data for soil parameters and vegetative strength. Although these values are often hard to obtain, realistic estimates can provide a relative classification of landslide hazards in the watershed. Examples demonstrated the use of the model in delineating hazards under varying groundwater and timbering activities. The landslide hazard delineation model can provide an effective methodology for assessing the relative stability of a watershed under various dynamic conditions.

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# APPENDIX A

## Derivation of Model Equations

Derivation of the equations of static equilibrium for an infinite slope are relatively easy to compute (Lambe and Whitman, 1969; O'Loughlin, 1974; or Brown and Sheu, 1975). The derivation presented here is similar in form to those presented by the above authors but with changes in the formulation and simplification of the basic model. An idealized infinite slope is shown in Figure A-1 that consists of a single soil type with isotropic properties resting on a bedrock interface. This is a situation similar to residual soil slopes found in forested watersheds and most hilly or mountainous terrain. Symbols in Figure A-1 will be used in the Factor of Safety model (F.S.).

The shear strength of a soil can be represented by the Coulomb equation of

$$\tau = \bar{c} + \bar{\sigma} \tan \bar{\phi} \tag{A-1}$$

where $\tau$ is shear strength, $\bar{c}$ is effective* cohesion intercept, $\bar{\sigma}$ is effective normal stress, and $\bar{\phi}$ is effective angle of internal friction. Equation 2 is applicable to situations under consideration here, drained soil strength conditions, and represents resisting forces contributed by the soil mass. Components of $\bar{c}$ and $\bar{\phi}$ (hereafter, the overbar will be dropped) are intrinsic soil strength characteristics of soil and represent interaction of soil factors.

Inspection of Figure A-1 aids evaluation of $\bar{\sigma}$. Normal stress on plane A' - B' at some position Z in the soil mass can be easily

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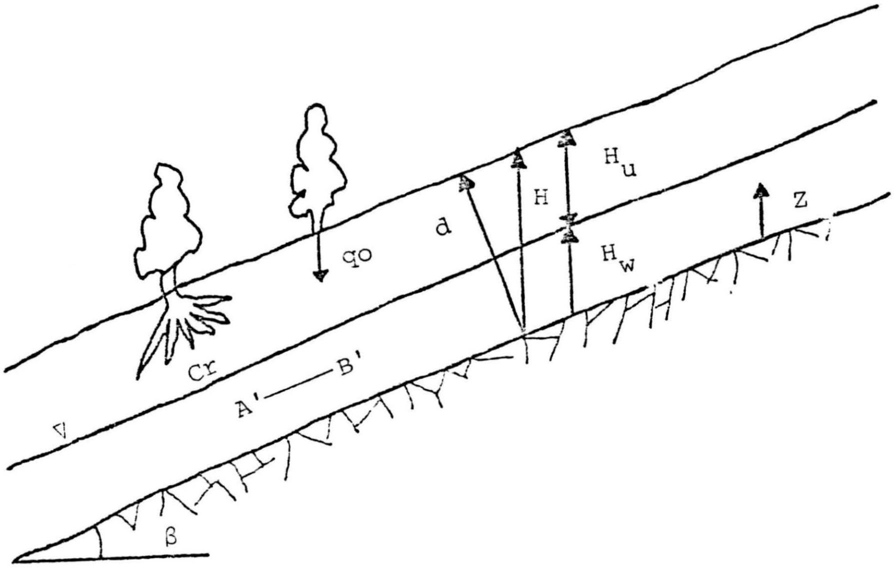
*effective refers to measurements that have taken into account pore water pressure effects.




β = slope inclination

Cr = Root cohesion

d = actual soil depth = $H\cos\beta$

$\gamma$ = unit weight of soil

$\gamma_{sat}$ = saturated unit weight of soil

H = height of soil mantle above bedrock surface

$H_w$ = height of water table above bedrock surface

$H_u = H - H_w$

qo = tree surcharge

Z = elevation coordinate

Figure A-1. Idealized infinite slope.

solved if the plane is assumed to be parallel to soil and bedrock surfaces and lies between $z = 0$ and $Z = H_w$. The total normal stress, r, on this plane can be written as

$$\sigma = \sum_{i=1}^{n} \gamma_i \, \Delta z_i \qquad \text{(A-2)}$$

In this case $n = 2$ for the saturated and unsaturated soils but can be expanded to a multi-layer case. However, in many soils assumption of a single soil type is often representative (Lumb, 1970). The geometry and important factors presented in Figure A-1 can be used to evaluate $\sigma$. The normal stress on plane A' - B' is composed of stresses from soil weight and tree surcharge. Soil weight per area component is $H_a \cos \beta \, \gamma$ for the soil above water table level and $(H_w - Z) \cos \beta \, \gamma sat$ for soil below water table. Normal force per area supplied by tree surcharge is $q_o \cos \beta$. Assuming a unit square area allows the normal stress to be written as

$$\sigma = [q_o \cos \beta + (H_w - Z) \cos \beta \, \gamma sat + H_u \cos \beta \, \gamma] \cos \beta \qquad \text{(A-3)}$$

In Equation A-3 the area that normal force acts on is taken as $\cos \beta$ times a unit area. Since $H_u = H - H_w$, Equation A-3 can be converted to

$$\sigma = H \cos^2 \beta \, [q_o/H + \gamma sat \, (M - Z^*) + \gamma \, (1 - M)] \qquad \text{(A-4)}$$

where $M = \frac{H_w}{H}$ is relative to groundwater height and $Z^* = \frac{Z}{H}$ is relative position from bedrock surface. Because groundwater is present the buoyancy effect of pore water pressures must be accounted for in Equation A-3. From the effective stress concept the relationship between total and effective normal stress in soil mass components is

$$\sigma = \overline{\sigma} - u \qquad \text{(A-5)}$$

where u is the pore water pressure. Hydrostatic pressure can be formulated as

$$u = H(M-Z^*)\ (\cos^2\beta)\gamma \qquad \text{(A-6)}$$

Combining Equations A-4, A-5 and A-6 yields, after simplification,

$$\bar{\sigma} = H\cos^2\beta\ [q_o/H + (\gamma_{sat} - \gamma_w)\ (M-Z^*) + \gamma(1-M)] \qquad \text{(A-7)}$$

The shear resistance equation now becomes

$$\tau = c + H\cos^2\beta\ [q_o/H + (\gamma_{sat} - \gamma_w)\ (M-Z^*) + \gamma(1-M)]\ \tan\phi \qquad \text{(A-8)}$$

The cohesion term, c, in Equation A-1 has two components in forested watersheds, soil cohesion, and tree root cohesion. Gray (1970) described several ways that vegetation enhances slope stability. One of these is anchoring soil to underlying strata. Endo and Tsuruta (1968) and O'Loughlin (1974) showed that this anchoring can be represented in the F.S. equation as a cohesion term, Cr. The cohesion term, C, can now be replaced by terms for soil cohesion, Cs, and root cohesion, Cr.

A similar analysis can be made for shear stresses induced on the plane. Shear stress is composed of loads resulting from weight of soil mass, tree surcharge, and wind shear in trees that is imparted to the soil mass. Seismic loading is not considered but can be added. Because air flow ususally conforms to ground or tree top surface, wind shear will be directed parallel to the failure plane. Downslope components of tree and soil loadings are used with one exception. If groundwater flow is assumed parallel to the failure plane then pore water pressure does not enter shear force computation. Shear stress can now be represented as

$$\tau' = H\sin\beta\cos\beta\ [\frac{q_o}{H} + \frac{T_{sw}}{HS_{in}\beta\cos\beta} + \gamma_{sat}(M-Z^*) + \gamma(1-M)] \quad \text{(A-9)}$$

Resisting forces are equivalent to shear strength as formulated in Equation A-8. Driving forces are equivalent to shear stress as formulated in Equation A-9. If $T_r$ is overall shear resistance and $T_d$ is overall shear stress than the Factor of Safety equation can be written as

$$FS = \frac{T_r}{T_d} \quad \text{(A-10)}$$

where FS is the Factor of Safety. Substituting shear strength and shear stress Equations A-8 and A-9 into Equation A-10 yields a Factor of Safety equation of

$$FS = \frac{Cs+Cr+H\cos^2\beta\{(\frac{qo}{H}) + (\gamma_{sat} - \gamma_w)\ (M-Z^*) + \gamma(1-M)\}\tan\phi}{H\{(\frac{qo}{H}) + (Tsw/H\sin\beta\cos\beta)+\gamma_{sat}(M-Z^*)+\gamma(1-M)\}\sin\beta\cos\beta} \quad \text{(A-11)}$$

The parameters in Equation A-11 can be placed into nondimensional groups. Multiplying by $\frac{1}{\gamma_w H\cos^2\tan\beta}$, noting that $\sin\beta\cos\beta = \frac{1}{2}\sin2\beta$, and multiplying by $\frac{\gamma_w}{\gamma_w}$ produces the Factor of Safety model as

$$FS = \frac{\frac{2(Cs+Cr)}{\gamma_w H\sin2\beta} + [\frac{qo}{\gamma WH} + (\frac{\gamma_{sat}}{\gamma_w} - 1)(M-Z^*) + \frac{\gamma}{\gamma_w}(1-M)]\ \frac{\tan\phi}{\tan\beta}}{\frac{qo}{\gamma_w H} + \frac{2Tsw}{\gamma_w H\sin2\beta} + (\frac{\gamma_{sat}}{\gamma_w})\ (M-Z^*) + \frac{\gamma}{\gamma_w}(1-M)} \quad \text{(A-12)}$$

As Equation A-12 shows, the basic model contains variables for four factors present in a forested area. Representing soil factors are $\gamma$, $\gamma sat$, Cs, and $\phi$, all determined by soil type, H, a measure of soil depth. Topography is included as $\beta$, slope inclination. Vegetative factors are qo, Cr, and Tsw. Finally, a dynamic factor for relative groundwater level is included as M. This basic equation is used to derive a more simplified form. Using sensitivity and order of magnitude, analysis techniques, Ward (1976) demonstrated that the Factor of Safety equation (A-12) could be reduced to an accurate, simpler form. Ward determined that certain variables were relatively unimportant and others could be assumed as constants. Relative depth Z* was set at zero for the worst case. Wind shear, Tsw, was found to be insignificant in magnitude, and soil mass and tree loading terms had little effect on equation sensitivity. Ward did find that soil and tree loading could have either positive or negative effects on slope stability depending on other factors.

Derivation of Statistical Parameter Equations

Soil and root strength parameters have the highest variability or uncertainty. Other parameters such as soil depth, slope angle, unit weight of soil, and groundwater depth can be readily estimated and set at some conservative value. If groundwater level M is assumed as steady state and H, B, and $\gamma$ are known then the factor of safety equation can be simplified to

$$FS = L_1(Cs) + L_1(Cr) + L_2(\tan\phi) \qquad \text{(A-13)}$$

where

$$L_1 = \frac{2}{\gamma_w H \sin 2\beta \left(\frac{qo}{\gamma_w H}\right) + \left(\frac{\gamma_{sat}}{\gamma_w}\right)M + \left(\frac{\gamma}{\gamma_w}\right)(1-M)} \qquad \text{(A-14)}$$

and

$$L_2 = \frac{\left[\left(\frac{qo}{\gamma_w H}\right) + \left(\frac{\gamma_{sat}}{\gamma_w} - 1\right)M + \left(\frac{\gamma}{\gamma_w}\right)(1-M)\right]}{\left(\frac{qo}{\gamma_w H}\right) + \left(\frac{\gamma_{sat}}{\gamma_w} - 1\right)M + \frac{\gamma}{\gamma_w}(1-M)} \qquad \text{(A-15)}$$

If Equation A-13 is rewritten in terms of random variables it becomes

$$S = L_1X + L_2Y + L_3Z \qquad \text{(A-16)}$$

where S, X, Y, and Z are random variables. The expected value or mean of a linear equation such as A-16 is (Benjamin and Corrall, 1970)

$$E[S] = L_1\ E[X] + L_2E[Y] + L_2E[Z] \qquad \text{(A-17)}$$

If the strength parameters are considered independent (Lumb, 1970; Holtz and Krizek, 1971) the variance or standard deviation squared becomes

$$Var[S] = E[(S - E[S])^2] \qquad \text{(A-18)}$$

or

$$Var[S] = E[S^2 - 2E[S]S + E^2[S]] \qquad \text{(A-19)}$$

Following the form of Equation A-17, Equation A-19 becomes

$$Var[S] = E[S^2] - 2E[S] \cdot E[S] + E^2[S] \qquad \text{(A-20)}$$

because

$$E[E[S]] = E[S].$$

Equation 20 reduces to

$$Var[S] = E[S^2] - E^2[S] \qquad \text{(A-21)}$$

The term $S^2$ is

$$S^2 = L_1^{\ 2}\ [X^2 + 2XY + Y^2] + L_1L_22Z[X + Y] + L_2^{\ 2}Z^2 \qquad \text{(A-22)}$$

Substitution of Equation A-22 into A-21 yields

$$VAR[S] = L_1^{\ 2}\ [E[X^2] + 2E[X]E[Y] + E[Y^2]]$$
$$+ 2L_1L_2E[Z]\ [E[X] + E[Y]] + L_2^{\ 2}\ E[Z^2] - E^2[S] \qquad \text{(A-23)}$$

Following the form of Equation A-21, the substitution for $E[X^2]$ can be made as

$$E[X^2] = Var[X] + E^2[X] \qquad \text{(A-24)}$$

Similar substitutions are made for Y and Z yielding

$$
\begin{aligned}
Var[S] = {} & L_1^{\,2}[Var[X] + E^2[X] + 2E[X]E[Y] + Var[Y] + E^2[Y]] \\
& + 2L_1L_2E[Z]\ [[E[X] + E[Y]] + L_2^{\,2}\ [Var[Z] + E^2[Z]] \\
& - E^2[S] \qquad \text{(A-24)}
\end{aligned}
$$

# APPENDIX B

```
      PROGRAM LSMAP(INPUT,OUTPUT,PUNCH,TAPE5=INPUT,TAPE6=OUTPUT,TAPE8=PU
     1NCH,TAPE4)
C                LSMAP IS THE MAIN CALLING PROGRAM FOR THE
C       FACTOR OF SAFETY PROGRAM AND THE LANDSLIDE PROBABILITY
C       SUBROUTINE PROGRAM
C       LABELLED COMMON FOR FACTOR OF SAFETY COMPONENT
      COMMON/FSDAT1/RTS1(10),RTS2(10),CS1(10),CS2(10),SD1(10)
      COMMON/FSDAT2/PHI1(10),PHI2(10),CSA1,CSA2,SDA,PHIA1,PHIA2
      COMMON/FSDAT3/QO,SAT,HMW,FSC(2000),PFSC(2000),PORO
       COMMON/FSDAT4/CK1,CK2,CK3,CL1,CL2,FSS
      COMMON/FSDAT5/CSA,RTSA,PHIA,RTSA1,RTSA2,FCLS1,FCLS2,PCLS1,PCLS2
      COMMON/CONTROL/NFSW,NFSP,IFSPU,TITLE(20),KCS,NST,NVT
C       LABELLED COMMON FOR THE INFORMATION FROM WASEG
      COMMON/SEGIN/SLOPE(2000),CANOP(2000),JVEGE(2000),JSOIL(2000)
C       LIST OF FACTOR OF SAFETY EQUATION VARIABLES
C       RTS=ROOT STRENGTH
C       SDA=SOIL DEPTH
C       CS=SOIL COHESION
C       PHI=ANGLE OF INTERNAL FRICTION OF THE SOIL
C       BETA=SLOPE ANGLE
C       HMW=RELATIVE HEIGHT OF GROUNDWATER TABLE
C       GAMS=SPECIFIC WEIGHT OF THE SOIL
C      PORO=AVERAGE POROSITY OF THE SOIL
C      I= CELL INDEX
C     INPUT VARIABLES
C
C     FCLS1     LOWER LIMIT ON ASSIGNING LANDSLIDE CLASS
C     FCLS2     UPPER LIMIT ON ASSIGNING LANDSLIDE CLASS
C     PCLS1     LOWER LIMIT PROBABILITY
C     PCLS2     UPPER LIMIT PROBABILITY
C
C     PRINT CONTROLS
C                            PRINT OUT
C     NFSW    GT.0           FACTOR OF SAFETY MAPPING FOR EACH RESPONSE CELL
C     NFSW    LE.0           NOTHING FOR EACH CELL
C     NFSP    GT.0           HAZARD RANKED FACTOR OF SAFETY AND PROBABILITIES
C     NFSP    LE.0           FACTOR SAFETY VALUES,FAILURE PROBABILITIES IN PERCENT
C
C     IFSPU   GT.0           PUNCHED CARDS ARE GENERATED
C
C       INPUT TITLE OF WATERSHED
      CALL DATAIN
C       INPUT LAND USE OR OTHER CELL DATA CHANGES AS NEEDED
      CALL DATCHG
C       THIS CALL BRINGS IN THE COEFFICIENT CALCULATION SUBROUTINE
      CALL FSCO
      KE=KCS
      DO 111 I=1,KE
      CALL AVERAG(I)
      CALL FSEQN(I,FS1,PFAIL)
      FV1=FS1
      FV2=PFAIL
      IF(NFSP.GT.0) CALL FSPCLS(FV1,FV2,FS1,PFAIL)
      FSC(I)=FS1
      PFSC(I)=PFAIL
  111 CONTINUE
C       PRINT TITLES
      WRITE (6,126) TITLE
  126 FORMAT(40X,20A4/)
      CALL PROUT
      STOP
      END
```

```
      SUBROUTINE DATAIN
      COMMON/FSDAT1/RTS1(10),RTS2(10),CS1(10),CS2(10),SD1(10)
      COMMON/FSDAT2/PHI1(10),PHI2(10),CSA1,CSA2,SDA,PHIA1,PHIA2
      COMMON/FSDAT3/QO,SAT,HMW,FSC(2000),PFSC(2000),PORO
       COMMON/FSDAT4/CK1,CK2,CK3,CL1,CL2,FSS
      COMMON/FSDAT5/CSA,RTSA,PHIA,RTSA1,RTSA2,FCLS1,FCLS2,PCLS1,PCLS2
      COMMON/SEGIN/SLOPE(2000),CANOP(2000),JVEGE(2000),JSOIL(2000)
      COMMON/CONTROL/NFSW,NFSP,IFSPU,TITLE,KCS,NST,NVT
C     THIS SUBROUTINE INPUTS DATA FROM USER
C     PROGRAM WASEG AND FROM THE
      READ (5,120) TITLE
  120 FORMAT(20A4)
C      INPUT DATA OUTPUT CONTROL
      READ(5,116) NFSW,NFSP,FCLS1,FCLS2,PCLS1,PCLS2,IFSPU
  116 FORMAT(2I5,4F5.0,I5)
C      INPUT NUMBER OF RESPOSE UNITS (IDENTIFIED AS
C      OVERLAND FLOW UNITS IN WASEG), NOT CHANNEL UNITS AND NUMBER
C      OF SOIL AND VEGETATION TYPES
C      ALSO INPUT CODE IF READING FROM TAPE
C      WHICH CONTAINS CHANNEL UNITS
      READ(5,131) KCS,NST,NVT,NSREAD
  131 FORMAT(4I10)
C      INPUT TOTAL NUMBER OF UNITS INCLUDING
C      CHANNEL UNITS IF REQUESTED
      IF(NSREAD.GT.0) READ(5,777) NS
  777 FORMAT(I10)
C      INPUT DATA FROM WASEG
      READ(4)  (SLOPE(I),I=1,NS)
      READ(4)  (JSOIL(I),I=1,NS)
      READ(4)  (JVEGE(I),I=1,NS)
      READ(4)  (CANOP(I),I=1,NS)
C      INPUT GROUNDWATER LEVELS
      READ(5,118) HMW
  118 FORMAT(F5.0)
C      INPUT DATA FOR FACTOR OF SAFETY CONSTANTS
      READ(5,132) SAT,QO,PORO
  132 FORMAT(5F5.0)
C      READ VEGETATIVE AND SOIL PROPERTIES
      READ(5,115)  ((RTS1(IT),RTS2(IT)),IT=1,NVT)
      READ(5,115)  ((CS1(ISS),CS2(ISS)),ISS=1,NST)
      READ(5,115)  ((PHI1(ISS),PHI2(ISS)),ISS=1,NST)
  115 FORMAT((10X,5(2F7.0)))
      READ(5,119)  (SD1(ISS),ISS=1,NST)
  119 FORMAT (10X,10F7.0)
      RETURN
      END

      SUBROUTINE DATCHG
      COMMON/FSDAT1/RTS1(10),RTS2(10),CS1(10),CS2(10),SD1(10)
      COMMON/FSDAT2/PHI1(10),PHI2(10),CSA1,CSA2,SDA,PHIA1,PHIA2
      COMMON/FSDAT3/QO,SAT,HMW,FSC(2000),PFSC(2000),PORO
       COMMON/FSDAT4/CK1,CK2,CK3,CL1,CL2,FSS
      COMMON/FSDAT5/CSA,RTSA,PHIA,RTSA1,RTSA2,FCLS1,FCLS2,PCLS1,PCLS2
      COMMON/SEGIN/SLOPE(2000),CANOP(2000),JVEGE(2000),JSOIL(2000)
C      THIS SUBROUTINE IS USED TO TRANSFER DATA
C      INTO LSMAP WITHOUT RECREATING A NEW DATA FILE FROM WASEG
C      THIS IS USEFUL IF CERTAIN LAND USE CHANGES ARE CONSIDERED
C      INPUT ANY CHANGES OF CELL DATA SUCH AS CHANGES
C      IN VEGETATION, SLOPE, OR SOIL PROPERTIES.
      RETURN
      END

      SUBROUTINE FSCO
C      THIS SUBROUTINE CALCULATES CONSTANTS FOR THE FACTOR OF SAFETY
C      EQUATION
      COMMON/FSDAT3/QO,SAT,HMW,FSC(2000),PFSC(2000),PORO
       COMMON/FSDAT4/CK1,CK2,CK3,CL1,CL2,FSS
      VOIDRAT=PORO/(1-PORO)
      CK1=QO/62.4
      CK2=(2.65+VOIDRAT)/(1+VOIDRAT)
      CK3= (2.65+SAT*VOIDRAT)/(1+VOIDRAT)
      RETURN
      END
```

```
      SUBROUTINE AVERAG(I)
      COMMON/FSDA11/RTS1(10),RTS2(10),CS1(10),CS2(10),SD1(10)
      COMMON/FSDA12/PHI1(10),PHI2(10),CSA1,CSA2,SDA,PHIA1,PHIA2
      COMMON/FSDA15/CSA,RTSA,PHIA,RTSA1,RTSA2,FCLS1,FCLS2,PCLS1,PCLS2
      COMMON/SEGIN/SLOPE(2000),CANOP(2000),JVEGE(2000),JSOIL(2000)
      COMMON/CONTROL/NFSW,NFSP,IFSPU,TITLE,KCS,NST,NVT
      DIMENSION ID(4)
C     THIS SUBROUTINE AVERAGES THE SOIL AND VEGETATIVE PROPERTIES
C     FOR THE CELL
      M=JVEGE(I)
      CALL IDEN(M,4,1,ID)
      R1=0.0
      R2=0.0
      DO 112 J=1,4
      K=ID(J)
      IF(K.LT.1.OR.K.GT.NVT) PRINT 141, I,J,K
  141 FORMAT(5X*ERROR IN VEGETATION INPUT AT CELL*I5*CODE*I2,I2)
C      AVERAGE THE LOW AND HIGH RANGE VALUES FOR THE
C     FACTOR OF SAFETY INPUT DATA
      R1=R1+RTS1(K)
      R2=R2+RTS2(K)
  112 CONTINUE
      RTSA1=R1/4
      RTSA2=R2/4
      RTSA1=RTSA1*CANOP(I)
      RTSA2=RTSA2*CANOP(I)
      M=JSOIL(I)
      CALL IDEN(M,4,1,ID)
      C1=0.0
      C2=0.0
      S1=0.0
      P1=0.0
      P2=0.0
      IF(K.LT.1.OR.K.GT.NST)PRINT 142, I,ID
  142 FORMAT(5X,*ERROR IN SOIL INPUT AT CELL*I5*CODE*4I2)
      DO 113 J=1,4
      K=ID(J)
      C1=C1+CS1(K)
      C2=C2+CS2(K)
      S1=S1+SD1(K)
      P1=P1+PHI1(K)
      P2=P2+PHI2(K)
  113 CONTINUE
      CSA1=C1/4
      CSA2=C2/4
      SDA=S1/4
      PHIA1=P1/4
      PHIA2=P2/4
      RETURN
      END

      SUBROUTINE IDEN(M,LS,NS,ID)
C     THIS SUBROUTINE IDENTIFY A STRING OF SIGNALS
C     M=STRING OF INTEGER DIGIT
C     LS=LENGTH OF STRING (NO. OF SIGNAL)
C     NS=LENGTH OF SIGNAL (NO. OF DIGIT WHICH CONSTRUCTS A SIGNAL)
      DIMENSION ID(4)
      DO 1 K=1,LS
      NE=NS*(LS-K)
      ID(K)=M/10**NE
      M=M-ID(K)*10**NE
    1 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE FSEQN(I,FSI,PFAIL)
       THIS ROUTINE COMPUTES AN AVERAGE FACTOR OF SAFETY FOR THE CELL
       BY USING AN INFINITE SLOPE APPROXIMATION APPROACH
      COMMON/FSDAT2/PHI1,PHI2,CSA1,CSA2,SDA,PHIA1,PHIA2
      COMMON/FSDAT3/QO,SAT,HMW,FSC(2000),PFSC(2000),PORO
       COMMON/FSDAT4/CK1,CK2,CK3,CL1,CL2,FSS
      COMMON/FSDAT5/CSA,RTSA,PHIA,RTSA1,RTSA2,FCLS1,FCLS2,PCLS1,PCLS2
      COMMON/SEGIN/SLOPE(2000),CANOP(2000),JVEGE(2000),JSOIL(2000)
      REAL M
      M=HMW
      RADS=57.29577951
      PHIA1=PHIA1/RADS
      PHIA2=PHIA2/RADS
      PHIA=(PHIA1+PHIA2)/2
      BETA=ATAN(SLOPE(I))
      IF(BETA.LE.0.0) GO TO 333
      SDA=SDA/COS(BETA)
      A1=2*BETA
      CSA=(CSA1+CSA2)/2
      RTSA=(RTSA1+RTSA2)/2.
      A=2*((CSA+RTSA)/(62.4*SDA*SIN(A1)))
      E=TAN(PHIA)/TAN(BETA)
      DF=(CK1/SDA+CK2*M+CK3*(1-M))
      CL1=2.0/(62.4*SDA*SIN(A1)*DF)
      CL2=(DF-M)/(DF*TAN(BETA))
      FSS=CL1*(CSA+RTSA)+CL2*(TAN(PHIA))
      CALL FSPROB (PFS)
      PFAIL=PFS*100.
      GO TO 555
  333 FSS=99.9
  555 FSI=FSS
      RETURN
      END


      SUBROUTINE FSPROB(PFS)
C      THIS SUBROUTINE DETERMINES THE FAILURE PROBABLILITY
C      FOR THE CELL USING A NORMAL DISTRIBUTION DETERMINED BY A
C      POLYNOMIAL EQUATION
      COMMON/FSDAT2/PHI1(10),PHI2(10),CSA1,CSA2,SDA,PHIA1,PHIA2
       COMMON/FSDAT4/CK1,CK2,CK3,CL1,CL2,FSS
      COMMON/FSDAT5/CSA,RTSA,PHIA,RTSA1,RTSA2,FCLS1,FCLS2,PCLS1,PCLS2
      ES=FSS
      EX=CSA
      EY=RTSA
      EZ=TAN(PHIA)
      VX=((CSA2-CSA1)**2)/12
      VY=((RTSA2-RTSA1)**2.)/12
      VZ=((TAN(PHIA2)-TAN(PHIA1))**2)/12
      V1=VX+EX*EX+2.*EX*EY+VY+EY*EY
      V2=VZ+EZ*EZ
      V3=EX+EY
      ES=CL1*EX+CL1*EY+CL2*EZ
      VS=CL1*CL1*V1+CL2*CL2*V2+2.*CL1*CL2*EZ*V3-ES*ES
      U=(1.0-ES)/SQRT(VS)
      A=ABS(U)
      IF(A.LE.0.13) Z=A*0.4
      IF(A.GT.0.13) Z=-0.01314+0.49494*A-0.15804*A*A+0.01661*A*A*A
      IF(U.GT.0.0) PFSN=0.5+Z
      IF(U.LT.0.0) PFSN=0.5-Z
      IF(U.EQ.0.0) PFSN=0.5
      FS1=CL1*(RTSA1+CSA1)+CL2*(TAN(PHIA1))
      IF(FS1.GT.1.0)  PFSN=0.0
      FS2=CL1*(RTSA2+CSA2)+CL2*(TAN(PHIA2))
      IF(FS2.LE.1.0) PFSN=1.00
      PFS=PFSN
      RETURN
      END
```

```
      SUBROUTINE FSPCLS(FV1,FV2,FSI,PFAIL)
C       THIS SUBROUTINE CLASSIFIES THE FACTOR OF SAFETY
C       AND FAILURE PROBABILITIES INTO 3 GROUPS WITH
C       1 BEING THE BEST AND 3 BEING THE WORST.
C       CLASSIFICATIONS ARE SET BY CHOICE
      COMMON/FSDAT5/CSA,RTSA,PHIA,RTSA1,RTSA2,FCLS1,FCLS2,PCLS1,PCLS2
C       CLASSIFY THE FACTOR OF SAFETYS
      FSI=3.0
      IF(FV1.GT.FCLS1.AND.FV1.LT.FCLS2) FSI=2.0
      IF(FV1.GE.FCLS2)FSI=1.0
      IF(FV1.GT.90.) FSI=99.9
C       CLASSIFY THE FAILURE PROBABILITIES
      PFAIL=3.0
      IF(FV2.GT.PCLS1.AND.FV2.LE.PCLS2) PFAIL=2.0
      IF(FV2.LE.PCLS1) PFAIL=1.0
      RETURN
      END

      SUBROUTINE PROUT
      COMMON/FSDAT1/RTS1(10),RTS2(10),CS1(10),CS2(10),SD1(10)
      COMMON/FSDAT2/PHI1(10),PHI2(10),CSA1,CSA2,SDA,PHIA1,PHIA2
      COMMON/FSDAT3/GO.SAT,HMW,FSC(2000),PFSC(2000),PORO
       COMMON/FSDAT4/CK1,CK2,CK3,CL1,CL2,FSS
      COMMON/FSDAT5/CSA,RTSA,PHIA,RTSA1,RTSA2,FCLS1,FCLS2,PCLS1,PCLS2
      COMMON/SEGIN/SLOPE(2000),CANOP(2000),JVEGE(2000),JSOIL(2000)
      COMMON/CONTROL/NFSW,NFSP,IFSPU,TITLE,KCS,NST,NVT
C     THIS SUBROUTINE PRINTS THE COMPUTED FACTORS OF SAFETIES AND
C     PROBABILITIES OR THEIR HAZARD CLASSES
      IF(NFSW.LE.0) WRITE (6,137)
  137 FORMAT(10X*NO DATA PRINT REQUESTED     OTHER OUTPUTS AS FOLLOWS*/)
      IF(NFSW.GT.0) WRITE(6,122)
  122 FORMAT(30X*FACTOR OF SAFETY MAPPING FOR EACH RESPONSE CELL*/)
      IF(NFSP.LE.0) WRITE(6,123)
  123 FORMAT(35X*FACTOR OF SAFETY VALUES, DIMENSIONLESS*/35X*FAILURE PRO
     1BABILITIES IN PERCENT*/)
      IF(NFSP.GT.0) WRITE(6,124)
  124 FORMAT(35X*FACTORS OF SAFETY AND FAILURE PROBABILITIES BOTH HAZARD
     1 RANKED*/35X*            1=LOWEST HAZARD   2=MEDIUM   3=HIGHEST HAZA
     2RD*/)
C       PUNCH DATA IF REQUESTED
      IF(IFSPU.GT.0) WRITE(6,136)
  136 FORMAT(10X*OUTPUT PUNCHED ON DATA CARDS*)
      IF(NFSW.LE.0) GO TO 90
C       PRINT FACTORS OF SAFETY VALUES AND FAILURE PROBABILITIES
      WRITE(6,117)
  117 FORMAT (/30X*CELL NUMBER*5X*FACTOR OF SAFETY*5X*FAILURE PROBABILIT
     Y*/)
      KSKIP=0
      KE=KCS
      DO 95 I=1,KE
      WRITE(6,114) I,FSC(I),PFSC(I)
  114 FORMAT(31X,I5,14X,F6.2,16X,F9.2)
      KSKIP=KSKIP+1
      IF(KSKIP.GE.5) WRITE(6,139)
  139 FORMAT(/)
      IF(KSKIP.GE.5) KSKIP=0
   95 CONTINUE
   90 CONTINUE
      IF(IFSPU.GT.0) WRITE(8,125)((FSC(I),PFSC(I)),I=1,KE)
  125 FORMAT(5(2F8.2))
      RETURN
      END
```