GIS and geotechnical slope stability evaluations for soil map units : Bridger-Teton National Forest, Wyoming
by Donald Walter Fallon

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Soils
Montana State University

Abstract:

Mass wasting has affected nearly 17 percent of National Forest land on the Bridger-Teton National Forest, WY. To properly manage these lands, an adequate slope stability rating system is required to minimize impacts from possible future movements. The purpose of this project was to develop a relative slope stability rating process for the Forest.

This study used a comparison of relative probability of failure ratings derived from geographic information system (GIS) processing and geotechnical engineering analyses as a basis for establishment of broad level relative stability ratings of soil map units. The percent area of a soil map unit which had experienced failure as indicated on existing landslide maps (Case, 1991) provided GIS-derived probability of failures. Probabilistic modeling of the infinite slope equation produced geotechnical engineering probability of failures. Probability of failure values were converted to relative stability ratings for three pilot map units. Examination of the relative stability ratings and map unit composition provided insight which was used to develop a relative stability rating methodology for the remainder of the Forest. The proposed relative slope stability rating methodology was designed to maximize the use of existing data and technologies, while minimizing the time and effort required to develop defensible ratings.

Logistic regression and contingency table analyses of checklist data collected during the soil survey provided additional information and estimates of probability of failures for the three pilot map units. These analyses revealed that while many landslide indicators were significantly related, the best predictors of slope stability were the presence of Cretaceous bedrock, and hummocky topography. A logistic response function provided probabilities of mass movement for soil map units which generally agreed with preliminaiy subjective ratings from the Bridger National Forest, Western Part Soil Survey (USDA Forest Service, 1992). A series of pairwise contingency table tests showed considerable dependency between checklist indicators.

Comparisons of relative stability ratings derived from each process indicated that while ratings were mostly in agreement using different processing techniques, limitations such as heavy conifer cover, and variations in soil compositions at broad analysis levels may hinder the ability for some techniques to accurately predict relative slope stabilities in specific areas.

Results of this project will provide the Bridger-Teton National Forest a framework for updating relative stability ratings throughout the forest. Additionally, the use of GIS products and techniques presented for this study should assist other Forests and geotechnical personnel in deriving broad level slope stabilities using the best available information and technologies.

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Donald Walter Fallon

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Mass wasting has affected nearly 17 percent of National Forest land on the Bridger-Teton National Forest, WY. To properly manage these lands, an adequate slope stability rating system is required to minimize impacts from possible future movements. The purpose of this project was to develop a relative slope stability rating process for the Forest.

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Results of this project will provide the Bridger-Teton National Forest a framework for updating relative stability ratings throughout the forest. Additionally, the use of GIS products and techniques presented for this study should assist other Forests and geotechnical personnel in deriving broad level slope stabilities using the best available information and technologies.

INTRODUCTION

Mass wasting is one of the most active erosion processes in the Bridger-Teton National Forest, Wyoming (Olson and McCaulpin, 1985). Preliminary mapping (Case, 1991) indicates roughly 17 percent of forest lands in the southwestern portion of the Forest have previously been affected by some type of slope movement. Recent soil mapping on the Bridger National Forest, Western Part (Figure 1) provided the foundation for an evaluation of slope stabilities at a broad level. The focus of this project was to examine alternative methods for deriving relative slope stability ratings for soil map units, and use the results to suggest a broad level slope stability methodology for the Forest. A primary use of the developed methodology is to assist land managers in updating the Bridger-Teton National Forest Land and Resource Plan.

Managing lands to minimize impacts from mass wasting requires the ability to assess the likelihood that a slope will fail in the future. Prior research such as Bailey's (1972) relied heavily on recognition and identification of past movements. While Bailey's approach is still valid, technological advances of computer hardware and software have greatly improved geotechnical prediction capabilities. Recent research by Hammond et al. (1992), the USDA Forest Service (1994a), and Wu and Sidle (1995) have incorporated these technological advances. Included in these studies were evaluations of slope stability methodologies at various planning levels. This study relied on geotechnical prediction capabilities, spatial analyses, and landslide indicator processing to determine relative slope stabilities of selected soil map units in the Bridger-Teton National Forest.

Study Area

The area is located on the Bridger-Teton National Forest in western Wyoming (Figure 1). This area is located in the Overthrust Mountain section of the Middle Rocky Mountain Province (USDA Forest Service, 1994b) and consists of arcuate north-south trending anticlines and synclines composed of Mesozoic and Paleozoic limestones, sandstones, siltstones, and shales. These rocks were thrust-faulted eastward along progressively younger west dipping faults.

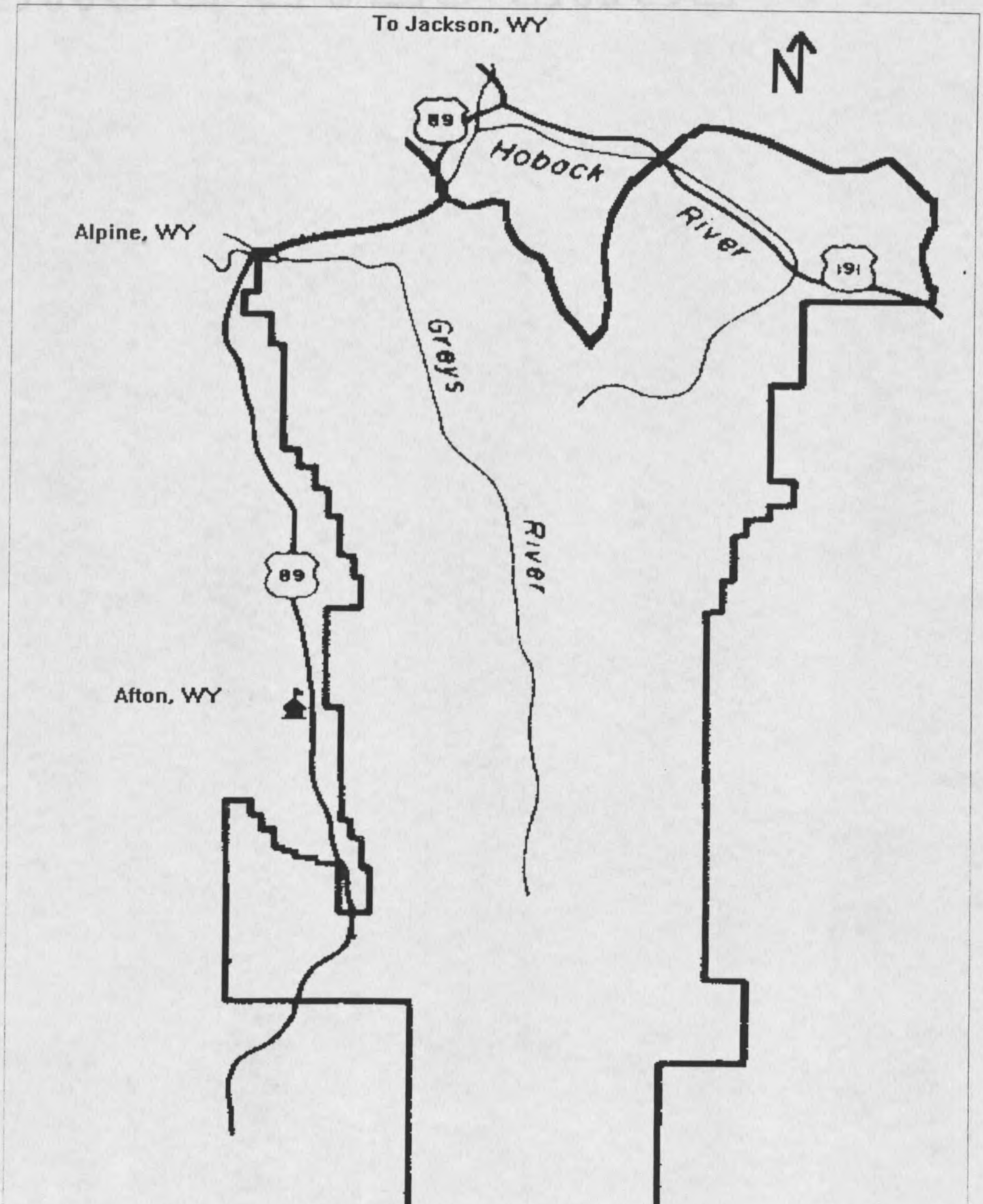


Figure 1. General Location Map: Bridger-West Soil Survey.

The dominant vegetation types of the area are lodgepole pine-subalpine forest and Douglas-fir forest with sagebrush steppe. Elevations range from 6,600 to 11,343 feet (2000 to 3458 m). Annual precipitation ranges from 16 to 40 inches (400 to 1016 mm). Mean annual air temperatures average 35°F to 45° F (2°C to 7° C) (USDA Forest Service, 1994b).

The areal extent of past landslide activity combined with increased recreational activities and resource utilizations have made the area a high priority for assessments of landslide susceptibilities. Campbell (1985) ranks areas of the Northern Rocky Mountains, especially areas of rapid recreational development near Jackson, Wyoming as the eighth most important area in the United States for delineation of susceptibility to mudflows and other landslides. This ranking is based on the areal extent of past events and the frequency with which similar events have occurred in the region. The study area, located just south of Jackson, Wyoming has therefore been nationally recognized to need landslide susceptibility analyses.

Geomorphology

Geomorphologically, the majority of the study area remains as a rugged upland dissected by the Snake, Greys, and Little Greys Rivers. The study area proper did not experience Pleistocene glacial activity. The nearest glacial deposits occur about ten miles north of the study area in the Munger Mountain area (Pierce and Good, 1992). Stream dissection is prominent with few isolated floodplains and a lack of extensive headward erosion. The Snake and Little Greys Rivers crosscut the existing structure and indicate possible superposition from an earlier (Middle Pliocene) basin fill or lake level (Lunceford, 1976). The dominant geomorphic process of the area is mass wasting. Both Holocene and pre-Holocene landslides are present. Recent slides often have visible detachment scarps, and relatively unmodified depositional forms. They often have sag ponds and standing water present. Older (pre-Holocene?) landslides lack easily distinguishable scarps and have modified or subdued depositional features. The majority of old and recent landslides occur on Cretaceous bedrock in dipslope positions. Other landslides occur where associated with oversteepening from drainage dissection or road construction. The last large slide in the area occurred in June of 1992. This slide, located above the Greys River, detached in Twin Creek Limestone along the Absoroka thrust following an extensive precipitation event. The resulting deposit partially dammed the Greys River and had to be altered to prevent possible flooding of the downstream community of Alpine, WY.

Objectives

The purpose of this project was to develop a systematic methodology for assigning relative stability ratings to soil resource map units (map units) through incorporation of existing resource data and advanced technologies. Three pilot map units were rated for relative slope stability based on examination of existing landslide mapping, geotechnical engineering processing, and statistical processing of landslide indicators. An examination of the resulting relative stabilities and process limitations provided a framework for the design of a relative slope stability methodology for use by the Forest.

The relative slope stability rating methodology developed in this project is intended only for use in broad (e.g. 1:24,000) planning level analyses typically included in forest planning, timber or resource allocations, environmental assessments, and transportation planning. The relative stability ratings assigned to soil map units were intended to alert land managers of areas that may be more susceptible to mass wasting. The use of "probability of failure" to estimate slope stabilities allowed direct comparison of probabilistic slope stability modeling with GIS based slope stability assessments. This was possible under the assumption that the percentage of a soil map unit which had experienced mass movements indicates the probability of failure of that map unit (Hammond et al., 1992).

This study examined only the potential for the occurrence of a mass wasting event, not the potential consequences of the event. An assessment process which addresses only the probability of a mass wasting occurrence has been defined as a "hazard" assessment (Hammond et al., 1992). By contrast, a slope stability "risk" analysis has been defined as including the consequences of failure. Brabb (1984) defined landslide risk as " . . . the expected number of lives lost, [and] persons injured, [and the amount of]damage to property, or disruption of economic activity due to a future landslide". As defined, "risk" implies consideration of socio-economic and/or resource values. While two areas may have the same slope stability "hazard" (i.e., probability of failure, or relative stability rating), one of the areas may have a greater associated risk due to a greater potential for impacts on people or resource values. To address risk accurately, land managers and other professionals should be involved in the stability analysis process. This project was aimed at determining slope stability hazard, not risk.

This study was not intended to address all factors such as seismicity and precipitation which contribute to slope stability hazard. These factors have been shown to significantly influence the susceptibility of certain landscapes to mass wasting. The reader is referred to works by DePolo and Slemmons (1990) and Keefer (1984) on seismic hazards, and Cannon and Ellen (1985), Iverson and Major (1987), and Nilsen et al. (1976) on precipitation events.

The methodology proposed in this study was designed to provide the Bridger-Teton National Forest a framework for estimating the relative slope stability of soil map units. Additionally, this study provided an evaluation of the utility and condition of the existing landslide coverage for use in future broad level analyses.

LITERATURE REVIEW

"Practicing forestry in steep, unstable country is one of the most challenging jobs land managers face."
F. Dale Robertson (former Chief USDA Forest Service), 1985

The combination of increased demand for natural resources and the ability to harvest or manage these resources in an environmentally sound manner have made, and will continue to make, slope stability determinations an important part of the land manager's responsibilities. Mass movements may adversely impact site productivity, water quality, fisheries habitat, roads, and structures. Extreme events such as the Lower Gros Ventre slide of 1925 (Teton County, WY) are capable of producing extensive damage and loss of lives. The risk to people from these events has increased as the use of Forest lands has increased. Land managers today must use the best available knowledge and methodology to evaluate the potential for mass movements.

Numerous approaches, including on-ground monitoring, use of remote sensing, factor overlay methods, statistical models, and geotechnical process models using limit equilibrium analysis techniques, have been developed for delineation of potential mass movement areas. Ward et al. (1979) described each of these methods. One of the most common methods of analysis in the 1970s, and still in use today, is the use of factor overlays. Factor overlays examine concurrences of instability factors to indicate areas of high landslide potential. Rib and Liang (1978) presented methods incorporating overlays derived from topographic maps, geologic maps, soil survey reports, and aerial photography to individually delineate factors related to landslide occurrences. Areas where factors coincide were classified into corresponding hazard potentials. Subjectivity in selecting factors to use for indicators of instability and the inability to examine temporal or dynamic changes in these factors, have been listed as limitations in using this approach for slope stability assessments (Ward et al., 1979).

The use of geotechnical models for slope stability analyses has become more popular with improved computer technology. Computer technology has allowed complex calculations to be completed more efficiently. Geotechnical models rely on the characterization of factors controlling slope stability. Characterizations have been measured or estimated using basic laws of physics, reported literature values, remote sensing techniques, and field sampling. The ability to account for temporal and spatial variations of contributing factors has been indicated as one of the primary strengths of this approach (Ward et al., 1979). The USDA Forest Service (1994a) produced a three volume set of manuals based on geotechnical engineering principles that direct the slope stability assessor through analyses at three different levels. Techniques discussed in these manuals have been used by government personnel, and in the private sector of the United States, Canada, and Europe to evaluate the potential for mass movements.

Mass movements have been defined and classified differently over the last forty years. Varnes (1958) defined the term "landslide" as the downward and outward movement of slope-forming materials such as natural rocks, soils, artificial fills, or combinations of these materials. He later discarded this nomenclature in favor of the term "slope movement" (Varnes, 1978). Due to the familiarity and inclusiveness of the former definition, the term "landslide" as used herein refers to the former definition as an all-inclusive term for almost all varieties of mass movements including falls, topples, slides, lateral spreads, flows, and complex movements.

The Three-Level Concept

The USDA Forest Service (1994a) described a three-level concept for examination of landslide susceptibilities (Figure 2). The concept allows slope stability specialists to predict how land management activity will affect Forest land stability at different scales. Each consecutive level involves a more detailed examination of landslide potential. The three-level approach involves increasing degrees of complexity, scale, and accuracy at successive levels. Prellwitz (1985) was the first to document the three-level concept.

Level I, the broadest level, is used primarily for resource level allocations and forest planning purposes. Stability assessments at this level are usually derived from available information at a scale of 1:24,000 or smaller. Analysis techniques are generally simplified and able to handle multiple modes of failure. Tools used for level I analyses include topographic maps, slope maps, aerial photographs, previous landslide inventories, and information on general soil types and depths, and field reconnaissance.

Level II stability assessments are targeted toward the project planning phase of management. Results from this level are more accurate than are those from level I due to the increased detail and quantity of

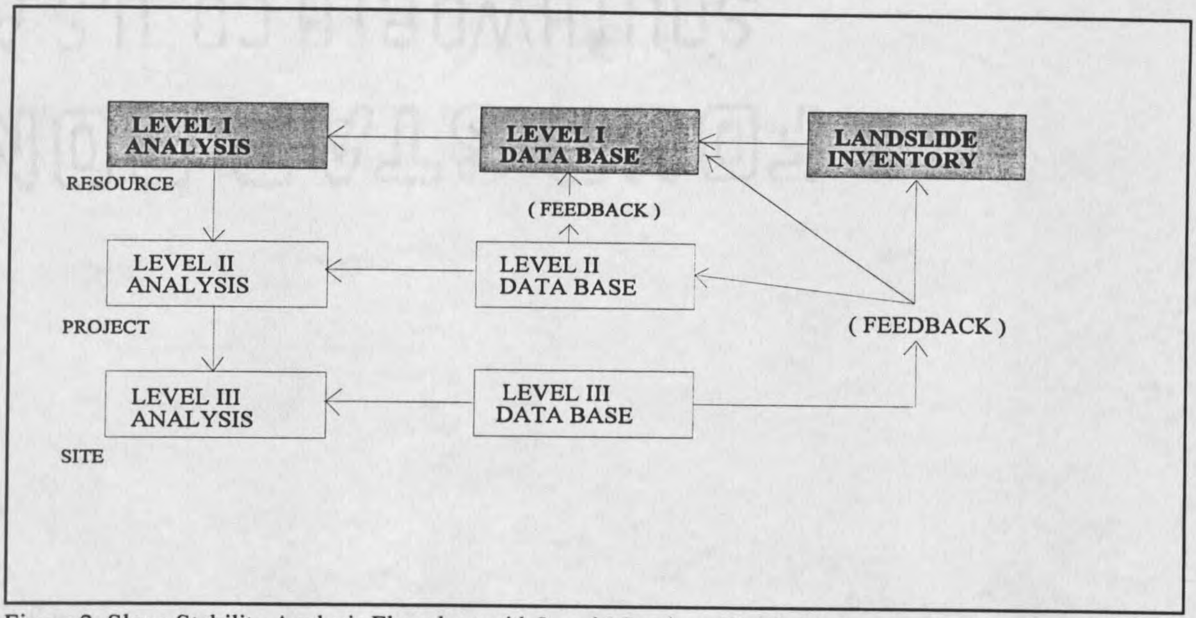


Figure 2. Slope Stability Analysis Flowchart with Level I Portions Highlighted.
(from USDA Forest Service, 1994a).

information that is collected. Tools used for this level include all level I tools plus field-developed cross-sections and more detailed soil property investigations. Level II assessments are generally at a scale of 1:600 to 1:13,600.

Level III assessments are at the most intensive and complex level. A Level III analysis is aimed at site stabilization and remedial measures of specific locations. This analysis level more closely examines the specific conditions of the soil, groundwater, and geology at sites before and after a proposed management activity such as road construction or timber harvest. Scales of assessments are generally 1:120 to 1:600.

At each of these levels, the input data required must match the desired accuracy level. The three-level concept aids the stability assessor in choosing and devising an evaluation approach which is commensurate with the purpose of the analysis.

Two Methodological Approaches to Slope Stability Evaluations

Schroeder (1985) stated that there have been two general approaches used in examining areas for slope stability. The inductive approach to slope stability is based largely on judgement derived from observations and logical reasoning, while the deductive approach to slope stability is based primarily on predictions derived from acquisition and analyses of quantified information. Both approaches are required to utilize the often sparse data and develop a defensible analysis.

The inductive approach to slope stability analysis relies on professional experience and logical reasoning based on field observations and mapping. This approach is most often used by geologists and engineering geologists. The inductive approach has been historically used for level I stability analyses. This approach typically involves examination of past landslides to determine the conditions which produced mass movement. These examinations then form the basis for evaluations of the likelihood that landslide processes will occur in similar settings in the future.

The deductive approach to slope stability assessments is largely theoretical or analytical, being based on the acquisition of quantified information resulting in quantifiable predictions. This approach uses case studies, theory, and acquired data to examine and define slope stabilities. It has historically been used for larger scale (level II or level III) analyses. Recent advances in probabilistic analyses have enabled engineers, geologists, and soil scientists to better predict slope stability and account for uncertainties in evaluations. These advances have led to increased usage of the deductive method for slope stability analyses at broader (level I) scales. The major drawback to the deductive approach is the sometimes misleading credibility implied by the precision of the numerical answers (Schroeder, 1985).

Schroeder (1985), and Schroeder and Swanston (1987) suggested that due to the limitations encountered in using either approach exclusively, an integrated approach is needed to best evaluate slope stabilities. The integrated approach provides an opportunity to maximize the often sparse knowledge required to adequately assess slope stabilities of an area. For this study, GIS processing and landslide indicator analyses used mostly inductive reasoning. Engineering analysis relied primarily on deductive reasoning.

Use of GIS in Slope Stability Analysis

Geographic information systems (GIS) have been used to facilitate soil survey mapping for more than ten years. The Natural Resource Conservation Service (formerly Soil Conservation Service), the Bureau of Land Management, and the Forest Service have used and evaluated digital elevation model (DEM) derived products since 1982 (Klingebiel et al., 1988). Advances in technology and availability have resulted in computer workstations in many Forest Service offices. More recently, these workstations have used satellite imagery and DEM derived products to supplement existing tools for inventory processing (Fallon et al., 1994; Wirth et al., 1996).

The availability of inventory data in a GIS format facilitates incorporation of GIS technology into slope stability analyses. Carrara et al. (1991) used GIS techniques and discriminate analysis to evaluate landslide hazard and risk for slope units in Italy. They used GIS technology to build a geographical data base which facilitated a multivariate approach to landslide hazard distributions. Gao (1993) used GIS to focus on terrain control of the spatial distribution of landslide paths. He used an overlay approach to evaluate the statistical significance of four topographic variables to the spatial distribution of landslide paths. Hammond et al. (1992) and USDA Forest Service (1994a) suggest using DEM data to derive input distributions of slope gradient to be used with the infinite slope equation. No details were given by either source as to the methods required to incorporate the technologies. Wu and Sidle (1995) used a GIS-based slope stability model incorporating the infinite slope model in a contour-line based topographic analysis to evaluate slope stability of an area in the Oregon Coast. This study used GIS for a number of operations, including the use of DEM-derived slope distributions, as input into the factor of safety and probability of failure calculations.

Factor of Safety Determinations

Several different models are used to deductively determine stability of soil slopes based on limit equilibrium analyses of strength parameters, environmental effects, and underlying assumptions (e.g., Bishop, Morgenstern-Price, Spencer, and Janbu). The factor of safety has been defined by Morgenstern (1992) as "that factor by which the shear strength parameters may be reduced in order to bring the slope into a state of limiting equilibrium along a given surface." Duncan (1992) has viewed the factor of safety as "the factor by which the shear strength of the soil would have to be divided to bring the slope into a state of barely stable equilibrium." Expressed algebraically, the factor of safety has been defined by many authors as:

$$FS = R/D \qquad \text{(Ward et al., 1979)}$$

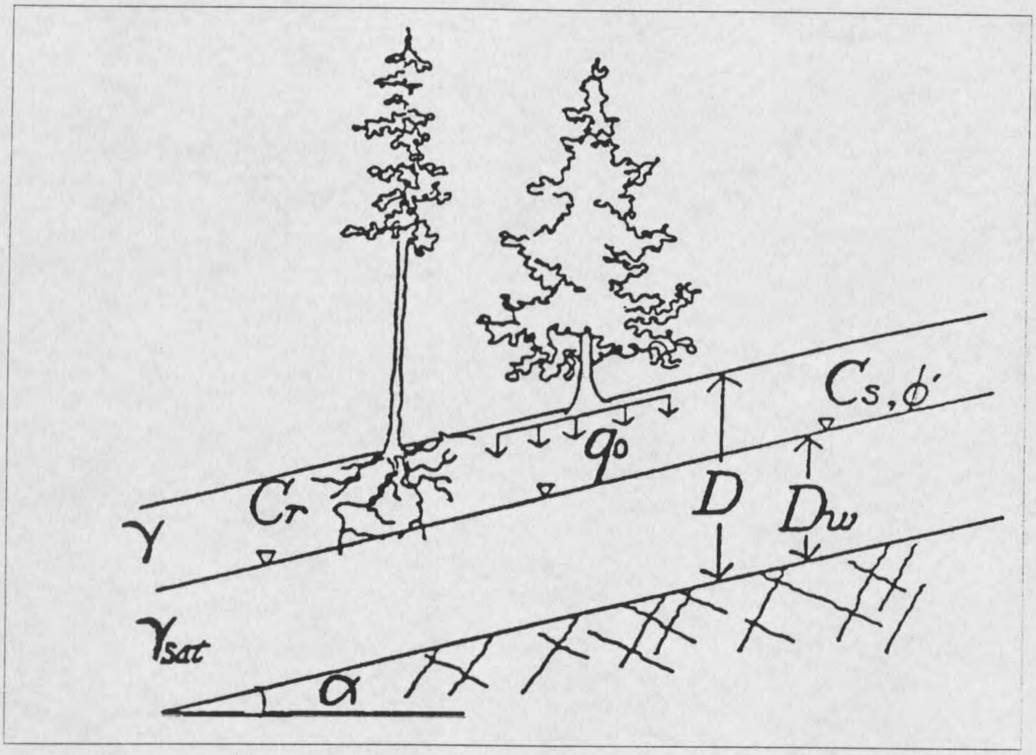
where; FS = Factor of Safety; R = Resistive Forces; and D = Driving Forces

The resisting forces are related to soil and root strengths while the driving forces are the downward weight of the soil mass and surcharge created by overlying vegetation. Groundwater affects both resisting and driving forces. Deterministically, factors of safety less than one (resisting forces less than driving forces) indicate that movement will occur.

The infinite slope equation is the simplest method for determining the factor of safety for a slope (Figure 3). The model is primarily applicable to planar failures that have shallow soil depths and long failure surfaces. The model has also been used to examine the failure potential of movement types such as translational slides, debris flows and rotational failures. Schroeder (1985) indicated that landslides in forested terrain nearly all initiate with a translational or rotational slide. Ward et al. (1979) found that due to its ability to relate the same resisting and driving forces, the infinite slope model allows for failure potential estimates for landslide types other than translational, such as rotational slumps. Hammond et al. (1992) stated that the infinite slope model has been used for planning purposes to adequately analyze the most common failure types found in the mountainous west (debris flows and debris avalanches of a soil mantle overriding a drainage barrier). The ability for the infinite slope equation to easily and adequately evaluate the failure mechanisms existing in the study area makes it ideal for a level I analysis.

The infinite slope equation along with graphical depictions of its associated variables is shown in Figure 3. The graphical depiction demonstrates two important assumptions of the infinite slope model; both the failure surface and groundwater surface are assumed to be parallel to the ground surface. For colluvial soils on undissected and smooth surfaces overlying bedrock, these assumptions are generally valid.

Infinite slope equation assumptions which are not depicted in Figure 3 relate to how the model treats the soil mass and failure plane. The infinite slope equation considers the soil mass overlying the failure plane to be one layer. Horizonation changes in soil properties and groundwater relationships must be manually incorporated into the model. This is usually done through applying weighted averages to soil properties above the failure plane. The failure plane as pertains to the infinite slope equation, is only considered in two dimensions. Forces acting on the plane from the sides are not included in the analysis. Hammond et al. (1992) reported that when the width of failures exceeds twenty-five to thirty feet, the forces acting along the surface of the failure plane are significantly more important than forces acting along the side of the mass.



$$FS = \frac{C_r + C'_s + \cos^2 \alpha [q_0 + \gamma(D - D_w) + (\gamma_{sat} - \gamma_w)D_w] \tan \phi'}{\sin \alpha \cos \alpha [q_0 + \gamma(D - D_w) + \gamma_{sat} D_w]}$$

where FS = factor of safety
α = slope of ground surface, degrees
D = total soil thickness, ft
D_w = saturated soil thickness, ft
C_r = tree root strength expressed as cohesion, psf
q_0 = tree surcharge, psf
C'_s = soil cohesion, psf
ϕ' = effective internal angle of friction, degrees
γ = moist soil unit weight, pcf
γ_{sat} = saturated soil unit weight, pcf
γ_w = water unit weight, pcf

Figure 3. The Infinite Slope Equation and Variables Used in LISA (from Hammond et al., 1992).

The Level I Stability Analysis (LISA) computer program was developed by Hammond et al. (1992) to assist in broad area stability analyses. This program calculates factors of safety and probabilities of failure using a probabilistic processing of the infinite slope equation from a given set of input criteria. The authors allow for uncertainty in criteria input and variability of *in situ* conditions to be incorporated through Monte Carlo simulation techniques. Uncertainty is incorporated by choosing the range and type of input distribution commensurate with the quality and quantity of data, and the spatial heterogeneities of the soil map unit. The simulation involves a large number of repeated iterations (typically 1000) of the infinite slope model based on random seeding. The results of these iterations produce a factor of safety distribution whose values determine a probability of failure.

For managers considering implications of a possible mass movement, the probability of failure concept may be expressed as "the portion of a land area in, or potentially in, a failed state during the period appropriate to the analysis" (Hammond et al., 1992). Intuitively, this assumption is valid. However, due to the length of time required to monitor landsliding, formal testing is prohibitive. This analogy not only makes communication of failure potential to manager more forthright, but provides the basis for comparison of landslide mapping using inductive reasoning with deductive calculations of failure potential.

LISA calculates a probability of failure by dividing the number of iterations resulting in a factor of safety of less than or equal to one by the total number of iterations. The probability of failure may be expressed graphically as the area under the factor of safety frequency distribution curve with values less than or equal to one (Figure 4).

The capabilities of the LISA program have been duplicated through incorporation of statistical analysis software. @RISK software (Palisades Corp., 1992) statistically processes the infinite slope algorithm in a manner that simulates the LISA model. @RISK is a spreadsheet add-in that uses either Monte Carlo or Latin Hypercube stochastic simulation. Spreadsheets originally developed by René Renteria (Geotechnical Engineer, USDA Intermountain Regional Office), and later modified to account for groundwater ratios by Rich Kennedy (Assistant Forest Engineer, Bridger-Teton National Forest), allowed input and probability analyses to be completed just as they would with the LISA program. Besides adding Latin Hypercube risk analysis capabilities, the @RISK program allows for correlation of inputs and automated sensitivity analyses. All features and discussions of LISA in this study are applicable to the @RISK analysis program and spreadsheets.

Risk analysis software which incorporates Monte Carlo simulation techniques provides a method to account for uncertainties which exist in the values of geotechnical parameters. These uncertainties may be attributed to scatter in the data or systematic errors attributed to inadequate or biased sampling (Christian et al., 1992). Data scatter occurs because of spatial variability in the soil profile and random measurement errors. For level I analyses, the spatial variability may be quite large as map units are designed to cover large acreages. Systematic errors occur because of inadequate sampling or bias in measurement procedures. Uncertainties from systematic errors may also be quite large for level I analyses due to soil property estimation procedures and the selection of nonrepresentative sites during stratified sampling.

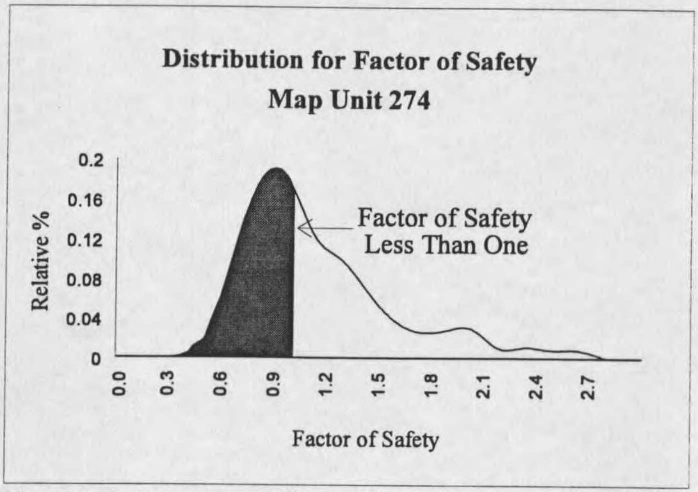


Figure 4. Relationships of Probability of Failure and Factor of Safety.

Treatment and recognition of uncertainties and variability in a probabilistic analysis differ from those used in a deterministic analysis. A deterministic analysis incorporates uncertainties and variability into the analysis through the choice of conservative single values. In deterministic analyses, factors of safety less than one indicate failure. In a probabilistic analysis, uncertainties are accounted for during the selection of the shape and range of input distributions. Because the selection of distribution types and ranges is rather subjective, Roberds (1991) suggested that one of the most popular methods for developing defensible parametric distributions is through the use of informal solicitation of expert opinion. While this technique has some limitations such as conservative and cognitive biases, credibility of probability of failure estimates is greatly increased.

Indicator Checklists

Landslide indicator checklists provided subjective or "soft" data on the environmental conditions of selected sites in soil map units. For this study, more than 220 checklists were completed on the Bridger-West soil survey area. For each checklist, more than 50 factors relating to geology, groundwater, site conditions, and soil movement indicators were initially collected at each site. Such checklists have been used to facilitate analyses of slope stability data for more than 30 years. Hansen (1984) cited one of the first uses of a checklist system in Czechoslovakia in the early 1960s. Since then, such other authors as Carrara et al. (1977), Kienholz (1978), and Cooke and Doornkamp (1990) have used checklists as a primary means of instability data collection. Montagne (1976) used indicators to analyze slope stability for a land capability reconnaissance in Montana. Thomas (1985), and Rib and Liang (1978) also used easily attainable indicators to evaluate slope stability. Carrara et al. (1977) used multivariate analysis to process their checklists. Lee and Juang (1992) used fuzzy sets to process indicator data in Taiwan. Each of these sources used some type of checklist of stability indicators to collect and analyze slope stability. Cooke and Doornkamp (1990) indicated that there is no set method for using checklist indicators in a stability analysis. Each method has limitations.

Multivariate analysis and regression analysis techniques used to predict slope stabilities from measured values require large amounts of data to develop the equations. The collected data are for a single point in time. No future dynamic changes in any of the factors are accounted for in the analysis. Furthermore, the equations are applicable primarily to the area in which the data were collected, and may not be applicable elsewhere. These limitations generally preclude the use of these techniques for level I slope stability analyses.

MATERIALS AND METHODS

When undertaking a slope stability analysis, one must determine the scale, accuracy, and intended purpose of evaluation. These determinations provide a framework for choosing a stability analysis technique that is matched to the complexity of the problem. An approach must be used which incorporates both inductive and deductive reasoning. If geotechnical processes are to be used, the proper model and processing techniques need to be determined. In all phases, data availability, processing time, and desired and achievable accuracies must be addressed. With due consideration of each phase, the final assessment will be more defensible.

For this study, a dichotomous approach was used to derive relative slope stabilities. Inductive methods were used to process GIS products of spatial data. Conversely, deductive methods were used during geotechnical analyses. Some steps in the analyses, such as slope processing, used both approaches.

GIS Processing

Incorporation of spatial analysis into slope stability rating processes through the use of a GIS system has received increased attention. With the approaching availability of GIS technology to all Forest Service offices, the need for methodological documentation of GIS processing techniques will increase. Resource specialists will be required to run analyses and maintain data integrity. Therefore, in this study, procedures for using GIS technologies have been thoroughly documented and are intended to provide the reader with the ability to duplicate and expand on the proposed methodologies.

GIS procedures were incorporated into three aspects of the analysis: 1) documentation of the areal distribution and extent of previous landslide activity; 2) determination of percent slope measurements of map units; and 3) location and extent of soil survey data and stratification. A combination of raster (grid) based processing and vector (polygon) based processing was used. Slope and DEM data were treated as raster data, while soil map unit and landslide processing were vector-based.

Landslide Coverage Processing

Case (1991) compiled existing information about landslides throughout the Bridger-Teton National Forest as part of the statewide Wyoming Geological Survey landslide inventory program. Draft landslide maps

(1:24,000 scale) were created using existing data and 1:15,840 scale color aerial photography. These maps were digitized at a scale of 1:24,000 for incorporation into the Forest data base. The digitized maps were imported as a polygon coverage for analysis in this project. Examination of the landslide polygon coverage revealed numerous errors which required additional GIS processing.

Correction of errors associated with the use of the draft landslide coverage required several additional processing steps. Documentation of these additional processing steps provided an indication of the time and effort required to convert the draft landslide coverage into a useful format for further slope stability analyses. Six sources of error were revealed which required additional processing: 1) inaccurate polygon boundaries due to digitizing from an unstable base; 2) adjacent quadrangles lacking proper edge-matching; 3) one missing quadrangle; 4) lack of polygon attributes in the coverage; 5) missing or misplaced polygons; and 6) digitized arcs from nonthematic sources (quadrangle boundaries).

Processing of the initial landslide coverage (Table 1) was based on edits performed with a GIS workstation using ARC/INFO version 6.0 (ESRI, 1992). The purpose of this processing was to correct only those errors which were present in the study area. The landslide coverage process consisted of coverage preparation, preliminary edits, and final edits.

Preparation of the initial landslide coverage was completed to reduce file size and GIS processing time. Quadrangle boundaries from the Forest cartographic features file (CFF) were selected and reduced to include only those 7.5 minute quadrangles where the Bridger-West soil mapping had occurred. The outer boundaries of these quadrangles were used to clip the initial landslide coverage to the desired study area. The clipped landslide coverage was then used for preliminary edits.

Preliminary edits allowed the coverage to be plotted for final editing. This process included four steps: 1) digitizing a missing quadrangle into the initial landslide coverage; 2) removing all quadrangle boundaries from the landslide coverage; 3) correcting edge-matching of adjacent quadrangles; and 4) correcting topology by snapping and manipulating arc placements. Completion of preliminary edits produced a coverage suitable for plotting and final editing.

Plots of landslide quadrangles were edited using aerial photographs (1:15,840) and light table overlays with draft landslide maps (Case, 1991). Corrections were digitized back into the initial coverage with a

Table 1. Landslide Coverage Processing

Process	Steps	Tools
Preparation of Coverage	1. Clip 7.5 minute topographic quadrangle boundaries of Forest to those of the Bridger-West Soil Survey	Workstation
	2. Clip landslide coverage with Bridger-West Soil Survey quadrangle boundaries	Workstation
Preliminary Edits	1. Digitize missing quadrangle into landslide coverage	Digitizing Tablet
	2. Remove quadrangle boundaries from landslide coverage	Workstation
	3. Edge match adjacent landslide quadrangles	Workstation
	4. Correct topology by snapping and manually manipulating arc placements	Workstation
Final Edits	1. Plot landslide quadrangles on stable base vellum	Plotter
	2. Use original draft maps and aerial photos to adjust linework	Light Table
	3. Digitize changes back into preliminary landslide coverage	Digitizing Tablet
	4. Add movement type attributes to all landslide delineations	Workstation
	5. Remove all relatively unstable polygons (alluvial fans and alluvial terraces)	Workstation
	6. Clean corrected landslide coverage	Workstation

digitizing tablet. Movement type attributes were added as items to the coverage polygon attribute table. The processing was completed by selecting only polygons which appeared to have resulted from mass movements. Alluvial fans and alluvial terraces were removed from the landslide coverage. The final landslide coverage provided the acreage of past landslides and an estimation of the percentage of a map unit which had previously experienced landslides (i.e., estimated probability of failure).

Percent Slope Processing

Digital elevation models (DEMs) were used to calculate the percent slope of ground surfaces in selected soil map units. The calculated slope distributions were used to create input for the ground slope parameter of infinite slope modeling. Transformation of DEM elevations to GIS slope lattices of map units required four steps (Figure 5): 1) import DEM elevations into GIS lattice; 2) clip the Forest-wide DEM lattice to a smaller area of the Bridger-West Soil Survey area; 3) filter elevations to correct problems in older DEM data; and 4) derive percent slope values for ground surfaces within pilot soil map unit boundaries.

DEMs at a thirty-meter resolution were obtained for the entire Forest from the Bridger-Teton National Forest data base and imported into the GIS (ARC/INFO) as an elevation lattice. Accuracies of the DEMs varied from ±7.5 meters to ± 15 meters. The Forest-wide DEM lattice was clipped by outer quadrangle boundaries of areas mapped during the Bridger-West Soil Survey. This provided a smaller set of elevations for use in subsequent processes.

A 7x7 deconvolution filter was applied to correct inherent problems associated with DEM stereoplotting. These problems exist on older photogrammatically derived DEM products (Ron Carlisle, Photogrammerty Analyst, USDA Geometronics Service Center, Salt Lake City, UT., personal communication). The filter was designed to spatially average elevation values. The 7x7 deconvolution filter passed a kernel of coefficients (Table 2) over each pixel and calculated new elevation values based on the sum of the original elevation values divided by the sum of the coefficients. This filter type is known as a low-pass filter. The filtering process was completed using ERDAS IMAGINE, version 7.5 (ERDAS, 1991) image processing software.

Three methods of converting survey area elevation data to soil map unit slope lattices (Figure 6) were used to validate percent slope assignments and select the most efficient processing method. These methods varied in their processing order or slope calculation algorithms. The resulting slope lattices from each process were compared in linked viewers on the GIS workstation. A slope calculation process was selected for creation of slope distributions of each soil map units. The selected slope calculation process was selected from two which appeared to adequately calculate slope values throughout the entire soil map unit.

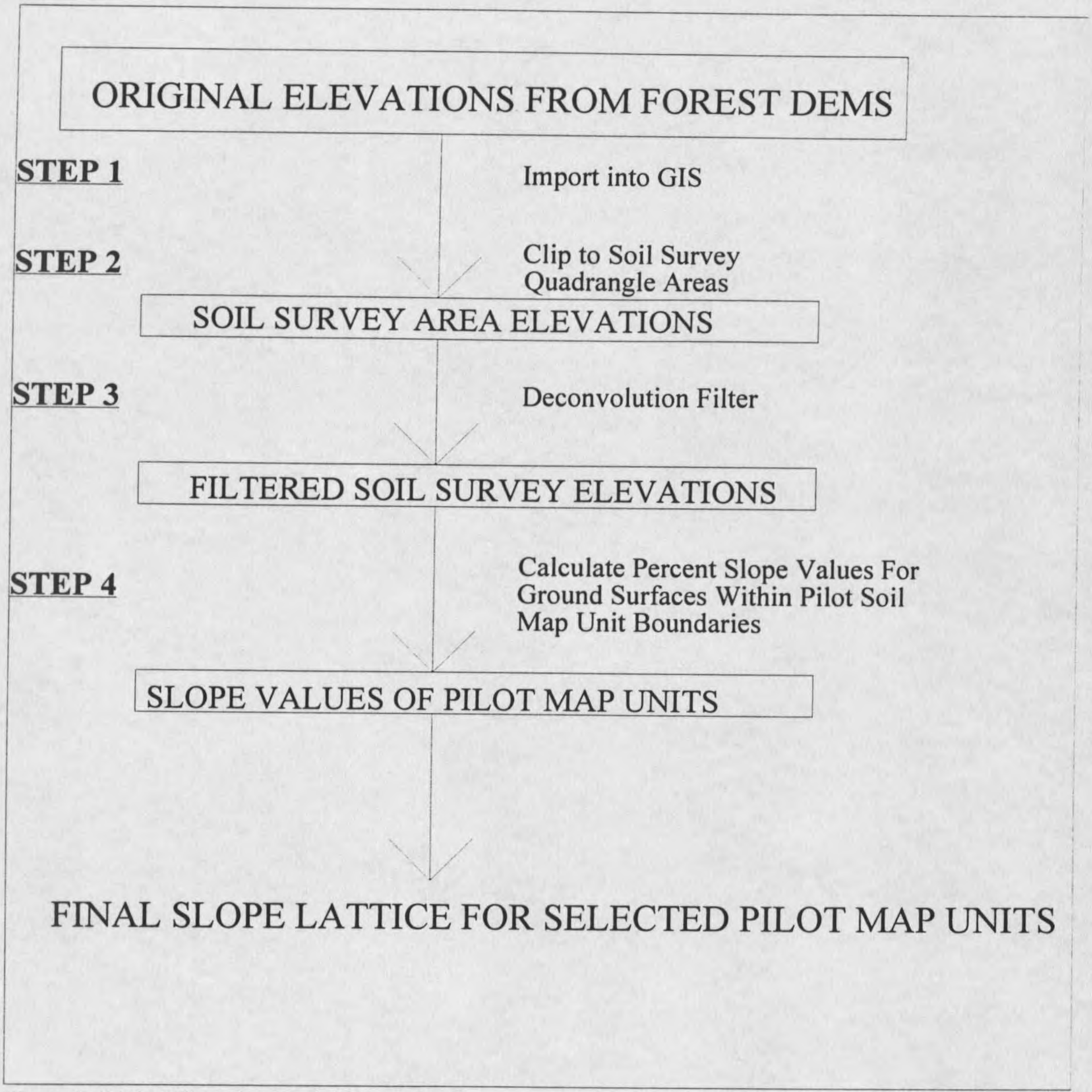


Figure 5. Digital Elevation Model Processing.

The final slope products were slope class lattices with 1 percent slope increments for each soil map unit. Histograms of slope distributions for each selected map unit were plotted in ARC/INFO for examination. The slope lattices' attribute tables were used to derive slope input into the LISA model.

Table 2. 7x7 Deconvolution Kernel

0	0	1	1	1	0	0
0	1	1	1	1	1	0
1	1	2	2	2	1	1
1	1	2	2	2	1	1
1	1	2	2	2	1	1
0	1	1	1	1	1	0
0	0	1	1	1	0	0

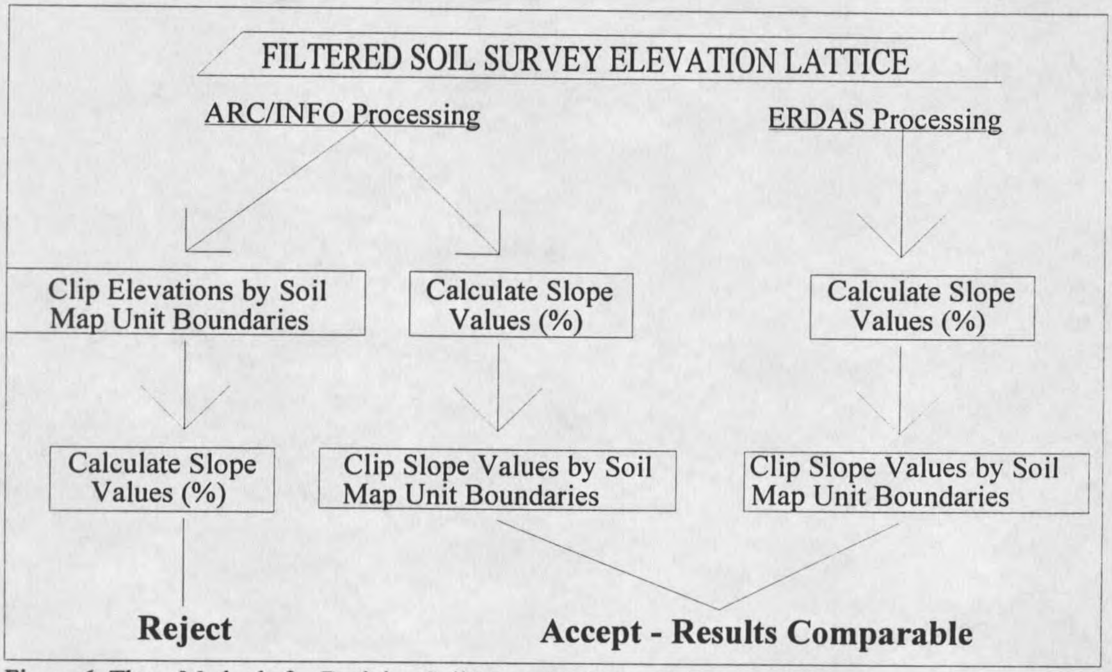


Figure 6. Three Methods for Deriving Soil Map Unit Slope Values.

Soil Resource Inventory Processing

Soil maps completed during the Bridger-West Soil Survey (USDA Forest Service, 1992) were used to select and delineate the areal extent of the study area and the selected individual map units. Hammond et al.

(1992) suggest that for preliminary (ie., level I) analyses, soil resource inventory polygons may be used due to the availability of polygon (map unit) information. Schroeder and Swanston (1987) found that soil bodies provided a useful landscape stratification for resource allocation level slope stability analyses. Soil maps document landscape stratifications called soil map units (map units). Each map unit consisted of multiple polygons representing repeating similarities of landform, parent material, climate, and geomorphic processes.

Map units were selected for analysis based on the availability of data, their spatial distribution, and their susceptibility to landslides. Initially, four map units were selected to be processed. This was later reduced to three map units because of inadequate landslide checklist data for one of the initial map units. Information about the soils and landforms in each map unit was collected during the mapping process to provide map unit characterization. This data were either generalized for the whole map unit after field work, or tied to site-specific sites where data points were established and soil profiles described. Soils from all selected map units were mapped as complexes. Complexes consist of two or more dissimilar components occurring in a regularly repeating pattern which cannot be mapped separately at a scale of 1:24,000 (USDA Soil Survey Division Staff, 1993). Collectively, much of the available soil resource inventory data for the selected map units and components was incorporated into this study. Map unit descriptions provided general information on parent material, elevation range, and vegetation. Point data provided the initial values for many of the infinite slope input parameters.

Soil map units were mapped on 1:40,000 black and white aerial photography during the Bridger-West Soil Survey. Mapping followed conventions used for typical soil surveys and met National Cooperative Soil Survey (NCSS) standards. The soil map unit boundaries were digitized into ARC/INFO format at a scale of 1:24,000 as a polygon coverage. A reduction in scale was required due to anticipated use and management of the data (Randy Davis, Bridger-Teton National Forest Soil Scientist, personal communication).

As this coverage was still in draft form, some edits were required before further processing. Soil survey field sheets were used to assist edge matching and attributing where necessary. County boundaries were deleted, and acreage calculated for each polygon. Adjacency requirements were checked by dissolving inadvertent boundaries between like map units.Small polygons (less than .01 acre) were checked and removed as necessary to alleviate slivers created during processing. Areas containing selected soil map units were clipped by topographic quadrangle boundaries for display. Selected polygon map unit boundaries were used to clip the finalized landslide coverage and slope lattices.

A point coverage of sample sites within selected soil map units was created to pinpoint data locations. Where soil investigation sites had been located with a global positioning system (GPS), Universal Transverse Mercator (UTM) coordinates were imported into a data base. The remaining sites were transferred from aerial photography to orthophotographic quadrangles and digitized into the GIS system using a digitizing tablet.

Factor of Safety and Probability of Failure Determinations

Factor of safety and probability of failure determinations using the infinite slope model required characterization of several soil-vegetation-hydrology parameters. These parameters reflect conditions which relate to the geometry, shear strengths, unit weights, and water pressures of soils occurring in soil map units. Table 3 shows the factors that LISA and @RISK use for input into the probabilistic slope stability analysis, along with possible input distribution types. Probabilistic analysis allows each parameter to be estimated using any of a variety of distribution types. Selection of distribution types allows uncertainties and heterogeneities to be incorporated into the analysis. In this study, selected distribution types for each parameter generally followed recommendations provided by Hammond et al. (1992) and the USDA Forest Service (1994a) for level I analyses. A solicitation of expert opinions was used to increase the credibility of the selected distributions of input variables. All distributions were examined by the Bridger-Teton National Forest Assistant Forest Engineer for an assessment of the likely value and uncertainty associated with each input distribution.

The sensitivity of the factor of safety and probability of failure varies for each parameter of the infinite slope equation. Figure 7 illustrates the sensitivity of the infinite slope equation to some of the more significant parameters as measured by the change in factor of safety (%) for a soil depth of ten feet. Abbreviations follow those given in Figure 3. Figure 7 illustrates that for deep soils, the infinite slope equation is generally most sensitive to changes in groundwater ratio, and is somewhat insensitive to changes in cohesion (root and soil), and friction angles. Sensitivity to dry unit weight, moisture content, and tree surcharge were so insignificant that they were not plotted on the figure.

Table 3. Infinite Slope Equation Input Variables and Possible Distribution Types

Input Variable	Possible distribution Types
Depth of Soil (D), ft.	Beta
Ground Slope (α), %	Bivariate Normal
Tree Surcharge, psf	Constant
Root Cohesion (C_r), psf	Lognormal
Friction Angle (Φ), °	Normal
Soil Cohesion (C_s), psf	Relative Frequency Histogram
Dry Unit Weight (γ_d), pcf	Triangular
Moisture Content, %	Uniform
Specific Gravity (S_g)	
Groundwater Ratio (D_w*/D)	

* Depth of Water (thickness of saturated zone)

Figure 7 depicts sensitivities for a selected set of input values for a relatively deep soil. The more sensitive that the factor of safety is to a given parameter, the steeper the slope of the line or curve. For more shallow soils, the infinite slope equation becomes much more sensitive to cohesion (root and soil), and less sensitive to friction angle and groundwater-soil depth ratio. Because root and soil cohesion are additive in the numerator (resisting force) of the infinite slope equation, the sensitivity of factor of safety to each is the same. Cohesive strength is generally more important to the overall factor of safety under low normal stress loads (ie., shallower soils). On deeper soils, friction angle generally becomes more important due to greater amounts of normal stress exerted on the soil. If the groundwater ratio is held constant, the factor of safety decreases with increasing depth.

Soil Depth

The depth of a soil, as defined by the infinite slope model, is the depth of the soil to potential failure planes (Hammond et al., 1992). Generally, this depth represents the depth of unconsolidated material overlying competent bedrock. However, any location in the soil where positive pore pressure may develop can be used as a soil depth. For instance, a porous unconsolidated soil surface horizon overlying a dense water inhibiting soil subsurface horizon may create a saturated layer where positive pore pressure develops. This may result in a zone of weakness through the saturated layer where failure planes would preferentially occur. Soil depths for selected map units were estimated from examination of 1:15,840 scale color aerial photography. Indicators such

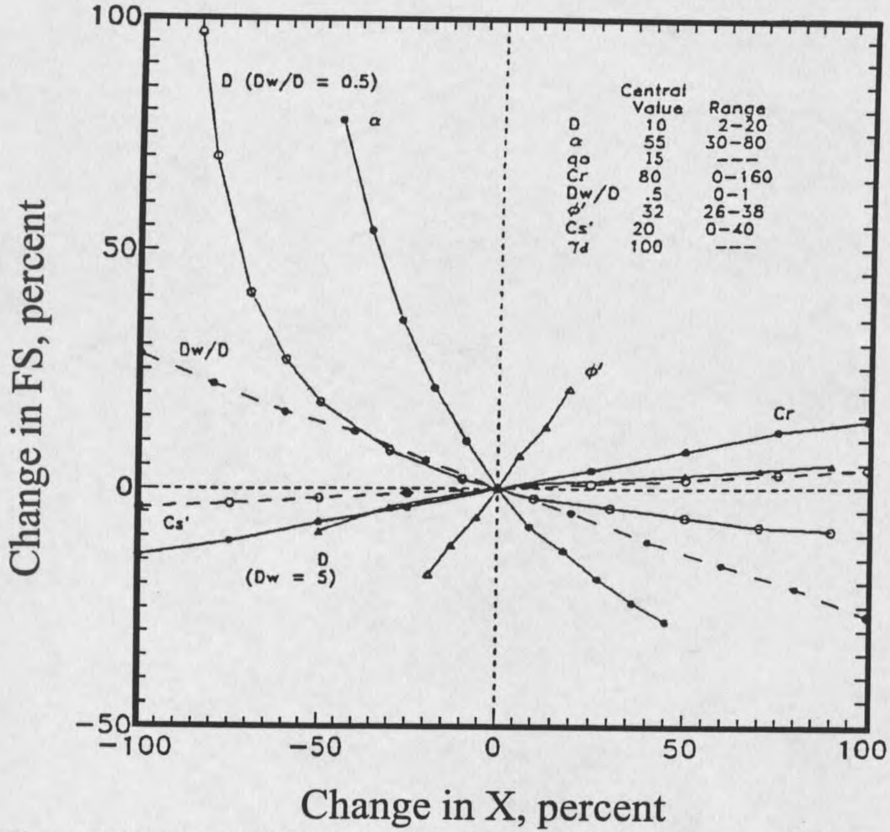


Figure 7. Example Sensitivity Plot for the Infinite Slope Equation with Central Soil Depth Equal to 10 Feet (from Hammond et al., 1992).

as attitude of bedrock outcrops, landslide deposit volumes, and vegetation provided clues of soil depths. These depths were characterized for input into the infinite slope equation as triangular distributions.

To avoid unrealistic combinations of soil depth and ground slope, a correlation was established between these two input parameters. Young (1972) discussed the common observation that soil thickness decreases with increased slope angles. The strength of the correlation depends on many local influences and factors affecting weathering rates and transport of materials. Alexander (1995) found for arid regions of Central Nevada and more humid regions in the Klamath Mountains, California that soil depth was significantly related to slope classes. He attributed differences in soil slope/depth class relations to differences in slope forming processes of the two regions. Among the factors found influencing soil slope/depth class relations were vegetation and litter cover, soil transport mechanisms, and chemical denudation rates.

An exact correlation between soil depth and percent slope in this study area was not attempted. A rank correlation was used to maintain realistic values of soil slope/depth combinations. The rank correlation was established between the two parameters using a correlation matrix present in the @Risk simulation program. Correlation coefficients were used to depict the strength of the relationship between soil depth and percent slope. Sensitivity analysis of the correlation coefficients chosen for the @RISK simulation revealed that only minor changes in the overall factor of safety and probability of failure occurred using coefficients ranging from -0.10 to -1.0 (Table 4). In this study, correlation coefficients ranging from -0.5 to -0.7 were used.

Table 4. Correlation Coefficient Sensitivity for Map Units 274 and 315

Stability Indicator by Map Unit	Correlation Coefficient										
Map Unit 274	0	-.1	-.2	-.3	-.4	-.5	-.6	-.7	-.8	-.9	-1.0
Factor of Safety (mean value)	1.49	1.70	1.70	1.72	1.72	1.72	1.72	1.73	1.72	1.72	1.73
Probability of Failure (%)	24.77	24.26	24.29	24.29	24.75	24.57	25.07	24.05	24.47	25.10	25.53
Map Unit 315	0	-.1	-.2	-.3	-.4	-.5	-.6	-.7	-.8	-.9	-1.0
Factor of Safety (mean value)	2.40	2.71	2.70	2.69	2.69	2.69	2.69	2.69	2.69	2.68	2.69
Probability of Failure (%)	7.16	8.77	8.97	8.99	8.35	7.99	8.00	8.19	8.51	9.26	8.55

The relative insensitivity to the magnitude of the soil slope/depth correlation using @RISK may be due to the type of correlation (Spearman's rank) used to model the relationship. The Spearman's rank correlation coefficient is calculated using ranks of values, not actual values themselves. The rank values for each variable were paired with the rank values of the other variable using the @Risk correlation function. The simulation selected a pair of random numbers to be used in selecting sampling values from the correlated distributions for each iteration of the simulation (Palisade Corp., 1992). The magnitude of the correlation coefficient (between -.10 and -1.0) did not significantly affect the rank order of selected pairs over the given ranges of the input distributions. The effects on factor of safety and probability of failure were minimal within the chosen range of correlation coefficients. The most significant differences in output were noticed between the use of either no correlation coefficent or a coefficient in the indicated range. The sensitivity regarding correlation indicated that as long as any correlation coefficient was used within the range of -.10 to -1.0, the relationships between soil slope and soil depth were similarly modeled.

Ground Slope

Slope gradients (measured as percent slope) for the selected map units were derived from computer processing of the digital elevation models (DEMs). Percent slope values for each thirty-by-thirty meter DEM cell were grouped into ten equal-width classes for each soil map unit. The relative frequencies of each slope class were directly input into the LISA model (@Risk model) as a histogram (Figure 8). The number of classes allowed by LISA (ten) was always smaller than that calculated using the equation given in Hammond et al. (1992) for estimating the appropriate number of classes given a known number of data values. This resulted in a slight smoothing and loss of distribution detail, yet was deemed insignificant given the broad nature of the overall analysis.

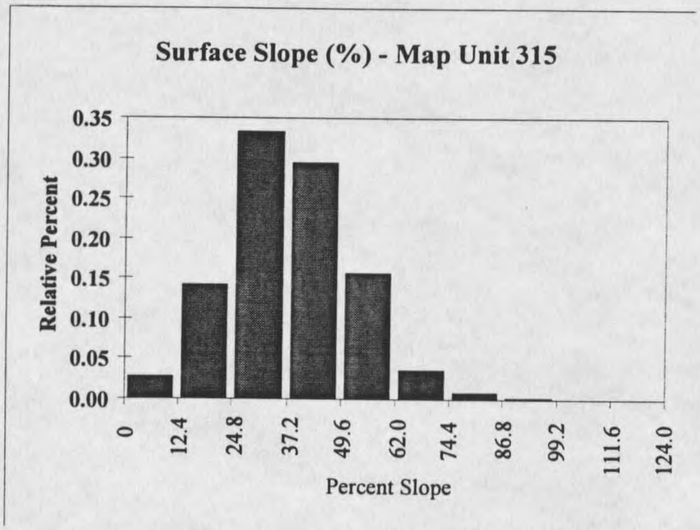


Figure 8. Surface Slope (%) Input Histogram Distribution Type.

Tree Surcharge

Tree surcharge is the effect of additional weight applied to a slope by overlying vegetation. Tree surcharge increases the driving forces (stress normal to the surface) within the soil. Coppin and Richards (1990) state that the effect of tree surcharge on a slope may vary depending on factors such as slope geometry, slope position, and soil properties. In some cases, it may actually increase the strength of the soil by increasing the frictional resistance. The factor of safety as determined by the infinite slope equation is fairly insensitive to tree surcharge (Hammond et al., 1992). Tree surcharge values were omitted for all but the most heavily forested map unit because of this insensitivity coupled with estimation inaccuracies associated with heterogeneities in species, plant heights, and density of timber stands,. For map unit 315, a value for tree surcharge was taken from the literature (USDA Forest Service, 1994a).

Root Cohesion

The presence of vegetation results in an overall increase in the strength of a soil body. Roots serve to bind the soil mass together and to other objects with higher tensile strength. The resulting increase in shear strength of the soil body may be viewed as supplemental cohesion- "root cohesion". The density, size, surface roughness, inclination, tensile strength, distribution, and location of roots in relation to the possible failure plane are all factors which influence the magnitude of root cohesion for a particular site. Root systems of tree species may also act as anchors to deeper, more competent material, and buttresses to upslope soil material. The effects of roots on the soil are particularly significant at shallow depths where root concentrations are highest, and reinforcement effects the greatest (Gray, 1992). Estimations of the contribution to soil shear strength from root cohesion are difficult to make. Wu (1995) indicated that even for the same species, actual tensile strengths of roots will vary depending on their geographic setting. He suggested using reported literature values as rough approximations of root cohesion. Hammond et al. (1992) stated that "Additional research is necessary to increase our understanding of soil-root interaction during slope failure and to estimate defensible values for root strength to use in stability analyses."

For this analysis, root cohesion was assumed to be insignificant for all soils except those where relatively homogeneous stands of conifers were present. For these heavily timbered areas, estimates of root cohesion were selected from the literature for species which most closely resembled those in the study area. A range was established from these values. The range was then adjusted downward to account for the absence of root abundance at deeper failure plane depths. Since in all heavily forested map unit components the soils were deep (>60"), the factor of safety was relatively insensitive to values used for root cohesion.

Friction Angle

The angle of internal friction (friction angle) is defined in this study in terms of effective stress. The friction angle results from the interlocking effects of soil particles and frictional resistance. The friction angle has been defined as "the angle defining the relationship of shear strength to shear stress" (Ritter, 1982; p. 139).

Friction angle distributions of each representative soil were determined by using values reported in the literature and values derived from representative soil data. For cohesionless soil map unit components, values were taken from the literature, and ranges for each soil horizon were established according to their respective Unified Soil Classification System (USCS) textures. A triangular distribution was selected by using the ranges of the horizon values and the weighted average value of all horizons. Where dry unit weights were anomalously high due to large percentages of coarse fragments, these values were either discarded, or adjusted downward to coincide with reported values. For cohesive soils, friction angle ranges were determined by using the plasticity index (PI) reported on the USDA-Form 5. The equation used for these calculations states:

$$\sin \phi'_p = 0.808 - 0.229 \log_{10} \mathrm{PI} \qquad \text{(Hammond et al., 1992)}$$

where ϕ'_p is the peak friction angle for normally consolidated clay
and PI is the Plasticity Index in percentage

Soil Cohesion

Effective soil cohesion is the shear strength of a soil at zero normal force. Cohesion is unaffected by normal stress. Input distributions for soil cohesion were omitted for all cohesionless soils. Hammond et al. (1992) stated that no true cohesion is present in nonplastic silts, sands, and gravels. The authors indicated small amounts of cohesion (20 to 60 psf) reported from back-analysis were likely a result of capillary suction, or were from differences between the infinite slope model assumptions and actual failure mechanisms. Tom Koler (Research Engineering Geologist, USDA Forest Service, Intermountain Research Station, personnel communications) has stated that resent evidence suggests that matric suction is critical to slope stabilities.

It was assumed that cohesive soils had not experienced overconsolidation in the study area. Sources of overconsolidation are very unlikely since no glaciation occurred in the area either during Holocene, or Pleistocene time. Overconsolidation due to removal of previous overburden may be possible in some areas, but the probability of previously thick overburden deposits is small due to the highly dissected and generally steep nature of the topography. Fluctuations in pore water pressures which change the effective stress may have occurred in isolated locations. However, the landslide indicators showed no presence of saturated or fluctuating groundwater tables near the surface at any sites in the three map units. Therefore, all cohesive soils in the study area were assumed to possess only normal consolidation.

Effective cohesion for normally consolidated soils has been generally reported to be minimal (0 to 100 psf) (Hammond et al., 1992). This range was used in the form of a uniform distribution type for all cohesive soils in the selected map units. No effort was made to correlate friction angle and soil cohesion.

Dry Unit Weight

The dry unit weight of a soil is the oven dried soil mass divided by the total soil volume (including water and air). This is analogous to the weight per unit volume at oven dryness on a whole-soil basis (USDA Natural Resources Conservation Service, 1995). For each map unit, initial dry unit weight values were determined for each of the major components. This was done by converting each horizon's moist bulk densities (oven dried bulk densities) reported on the USDA-Form 5 from a fine fraction (<2mm) basis to a whole-soil basis using the equation:

$$Db_{dws} = \frac{100}{(Wt_{>2mm}/SG_{>2mm}) + ((100 - Wt_{>2mm})/Db_{d<2mm})}$$

(USDA Natural Resource Conservation Service, 1995)

where; Db_{dws} = Bulk density at oven dryness on a whole-soil basis (g/cc)
$Db_{d<2mm}$ = Bulk Density at oven dryness on a <2mm basis (g/cc)
$Wt_{>2mm}$ = Weight percentage of the >2mm fraction
$SG_{>2mm}$ = Specific Gravity of the whole soil (g/cc)

After values were converted to a pounds per cubic foot basis, a triangular distribution of dry unit weights was selected for input into the infinite slope model. Input distributions used the maximum and minimum values of all horizons, with a weighted average for modal values. Where dry unit weights were anomalously high in denser horizons due to a large amount of coarse fragments, the distributions were recalculated above the dense horizons. Adjustments to dry unit weight for dense horizons were made under the assumption that high densities render these horizons relatively stable in comparison with less dense overriding horizons. Therefore, the failure planes would preferentially occur in the overlying material.

The final input distributions were compared with tables reported in the literature (Hammond et al., 1992) (USDA Forest Service, 1994a) for each soil type. Distributions were adjusted to include uncertainty and heterogeneity estimates. Model errors introduced from imprecise estimates appeared negligible due to the infinite slope equation's relative insensitivity to dry unit weight values. The adjusted input distributions were used for direct input into the infinite slope equation and to assist in determining initial values for friction angles and soil cohesion. Because the estimated dry unit weights were used to help derive friction angle and soil cohesion values, proper estimations were critical.

Moisture Content

The moisture content of the soil is used by LISA and the @RISK model to determine the moist soil weight of the soil above the groundwater table. Moisture contents for each map unit were estimated by examination of soil properties such as available water holding capacities, permeabilities, clay content, liquid limit, and plasticity index. The liquid limit provided a maximum value to the estimated range of moisture content. A uniform distribution was formed based on the soil's remaining properties. Hammond et al. (1992) recommended a uniform distribution type due to the relative insensitivity of the LISA model to this factor.

Specific Gravity

The specific gravity of soil particles is the mass of the dried soil divided by the volume of the dried soil. Hillel (1982; p. 9) defined specific gravity as "the ratio of the density of the soil material to that of water at 4 degrees C and at atmospheric pressure." For most mineral soils the specific gravity is generally accepted to range from 2.6-2.7 g/cc. The USDA Natural Resource Conservation Service (1995) suggested using a specific gravity of 2.65 g/cc (165 pcf) for both the fine fraction (<2mm) and the whole soil. This value was entered as a constant for all factor of safety calculations.

Groundwater

The infinite slope equation which was used by LISA and @RISK during this study characterized groundwater depths in relation to depths of the host soil. The expression *Dw/D* (the ratio of groundwater depth to soil depth) provided a method of estimating groundwater depth for varying soil depths. General ranges for the groundwater ratio were initially determined through examination of aerial photography (1:15,840) for evidence of shallow water depths. Evidence included the presence of hydrophytic vegetation, and topographic relations of aspect, dissection, drainage, slope gradient, and slope shape. Summaries of wetness indicators from the landslide checklists were used to confirm or adjust the general ranges for more site specific groundwater relations. Soil textures, available water holding capacities, and permeabilities from each representative soil were used to capture the subsurface soil properties affecting groundwater distributions. Where fine textures were present (i.e., clays, clay loams, and silty clays) the groundwater ratio was increased to account for better water holding capacities of the fine soil pores.

Landslide Checklist Processing

A checklist of landslide indicators was developed to capture landslide factors related to slope instability at each soil investigation site. Checklist items were chosen from the literature as those which may be significant to instability in the study area (Table 5). These factors represent indicators used by soil scientists to subjectively determine the relative slope stability of a soil investigation site. The checklist items were measured as a success or failure (presence or absence) of known instability indicators. The checklists were completed at most 1991 soil survey investigation sites and for transects along the Little Greys River. More than 220 checklists were collected in 25 soil map units.

The checklists included 51 factors which have been reported to be related to increased landslide activity. Forty-three of the initial 51 landslide factors were selected for statistical processing. The remaining factors were discarded for three reasons: the data were used elsewhere in the survey (slope gradient classes); instability with reference to other checklist items (scarpslope vs. dipslope), or noncontributing data (zero occurrence) to landslide prediction.

An examination of statistical independence of factors was done through the use of a 2x2 contingency table analysis (McKenzie et al., 1995). Results from this test were useful in determining which checklist factors were related. Knowledge of independence was used in determining which of the many indicators could be eliminated (due to dependency) from incorporation into future soil survey investigation processes.

The selected indicators were also processed using a stepwise multiple logistic regression model-SAS/INSIGHT (SAS Institute, 1993) to determine which factors were most significantly related to the presence or absence of landslides. Results from the logistic regression were used to determine relative slope stability

Table 5. Checklist of Landslide Indicators by Major Grouping

Grouping	Landslide Indicator
Wetness	Seeps and Springs
	Hydrophytic Vegetation
	Permeable over Impermeable Bedrock
	Water Inhibiting Layer (Aquiclude)
	Gleyed Colors or Mottles
	Standing Water
	Sag Ponds
	Piping of Water from Roadcut or Structure
	Wet or Moist Soil Pit Bottom
Position	Threshold Basin Location
	Fault Zone
	Hanging Wall of Thrust
	Concave Slope
	Dipslope
	Oversteepened Slope
Movement	Hummocky Surface
	Tension Cracks
	Terracettes
	Colluvial Filled Bedrock Depressions (CBDs)
	U-Shape or Downhill Depressions
	Pistol-Butting of Trees
	Jacksawed or "Crazy" Trees
Bedrock	Incompetent Bedrock (Shale or Mudstone)
	Jointed or Fractured Bedrock
	Interlayered Bedrock
	Interbedded Bedrock
	Cretaceous Bedrock
Soil Property	Shallow Soils (<20")
	Shallow and Moderately Deep Soils (<40") with Sandy Textures (S, LS, SL)
	Deep Soils with Silty Textures (SiL, SiCL, SiC)
	Inclined Peds in Profile
	A-C Horizonation
Surface	Thick "O" Horizon (>2")
	Bare Ground > 75%
	Bare Ground > 25%
	Natural Meadows
	Dark "A" Horizon (Soil Color Hue/Value < 3/3)
	Abundant Macropores at Surface (Roots and Animals)
Strength	Roadcuts in Area
	Shallow and Moderately Deep Soils (<40") Lacking Deep Roots (Root Depth <Bedrock)
	Few Small Roots in "A" Horizon (Very Fine, Fine, and Medium)
	Lack of Large Tree Roots
	Recent Logged Area (<10Yrs.)
Landslide	Previous Landslide Activity

ratings for the25 soil map units where landslide checklists were completed.

Independence of Checklist Indicators

Of the original 51 indicators, one (previous landslide activity) was selected as a response variable while 43 were selected as explanatory variables. The explanatory variables were divided into seven groupings (Table 5). Groupings were designed to represent dominant features related to slope instability (wetness, position, movement, bedrock, soil properties, surface features, and strength). Indicator factors within groupings were tested against each other pairwise using a contingency table test. This test relies on a chi-square (χ^2) distribution to determine whether two variables are statistically independent, or that a relationship exists between them.

The χ^2 distribution is a measure of the deviation of a sample distribution from its expected distribution among two or more factors. Where relationships existed between variables at a significance level of $P<0.10$, the surviving indicator was chosen to produce the fewest number of surviving indicators. This process was completed for each of the seven groupings, resulting in a reduction of indicators from 43 to 13.

The surviving variables from each grouping were subsequently tested against each other using the same 2x2 contingency table test to determine interrelationships between groups. This allowed the 13 surviving variables to be further reduced to three variables. These three variables were each tested against the presence of previous landslide activity to determine which were most significant. While less formal than the logistic regression analysis, this test still provided an indication of which indicators best predicted landslide occurrence.

Logistic Regression

The binary (presence/absence) nature of the indicator variables necessitated a nonlinear method of regression analysis. Problems such as nonnormal errors, unequal variances, and constraints of the predicted responses to occur between zero and one ruled out typical linear regressions using a least-squares approach. The logistic model was chosen to handle these limitations. Numerous authors including Mendenhall and Sincich (1986), Webster and Oliver (1990), and Neter et al. (1989) suggested a logistic transformation to best handle binary data. The logistic model was originally developed for use in cases where the response variable is typically measured by the success or failure of an experiment (Mendenhall and Sincich, 1986). Logistic transformations stretch out data which fall close to zero or one to best approximate a normal curve. The logistic response function is expressed as:

$$E(y) = \exp(\beta_0 + \beta_1x_1 + \beta_2x_2 + ... + \beta_kx_k) / 1 + \exp(\beta_0 + \beta_1x_1 + \beta_2x_2 + ... + \beta_kx_k)$$

where: $E(y)$ is the mean response (the probability that $y = 1$)

A logistic regression analysis used the logistic response function to describe the nature of the relationship between the dependent variable (previous landslide activity) and the independent variables (43 checklist indicators). This knowledge was used to determine the relative stability of a map unit by predicting the occurrences of landslides. The fitting of the response function was completed through the use of SAS/INSIGHT (SAS Institute, 1993) at the USDA Forestry Sciences Laboratory in Logan, Utah.

The fitted logistic response function was used to evaluate relative map unit stabilities for the 25 map units where landslide indicator data was collected. The probabilities of landslide occurrence for map units were determined by applying the fitted logistic response function to each sample site in a map unit. Descriptive statistics of the landslide probability distributions of a map unit were used to partition the range of map unit probabilities into four discrete relative slope stability classes: stable, marginally stable, marginally unstable, and unstable.

Relative slope stability classes of map units were ranked by observing the mean, median, and quartile distributions of expected landslide occurrences within soil map units. These ranks were analyzed and subjectively divided into the four stability classes. Stability classes were based on only the 25 map units where landslide indicator data were collected, not on all the map units which exist on the Bridger-West Soil Survey area. However, the results did provide a broad comparison with those initially designated during the soil survey.

RESULTS AND DISCUSSION

Slope stability ratings for three pilot soil map units were calculated as probabilities of failure using existing landslide coverages and infinite slope probability assessments. Landslide indicator processing provided relative slope stabilities for an additional 21 soil map units for comparison with preliminary ratings. The comparison of the relative stability ratings for the three pilot map units allowed for a better understanding of the soil map units and the slope stability derivation processes.

GIS Coverages and Processes

Slope stability ratings derived from GIS processing were calculated as the percentage of a map unit which has experienced mass movements in the past. If it is assumed that all areas that are in, or potentially in, a failed state have experienced movement previously, this percentage estimates the probability of failure for that unit (Hammond et al., 1992).

GIS processing provided more than just an inductive slope stability analysis of pilot map units in this study. GIS processing methods also provided the best available ground slope estimates for use during infinite slope modeling. Sensitivity analyses indicated that the percent slope factor is the most highly correlated factor used in the infinite slope equation. This suggests it is also the most important factor influencing landsliding in this study. Additionally, the use of GIS provided a platform for spatial analyses and display of the terrain involved in the study. Factor overlays depicting the relationships between map units and existing landslides were used to derive some of the underlying relationships between soil properties, groundwater, and landslides by providing observations from which distributions could be estimated (Appendix A).

Existing Landslide Mapping and Coverages

Existing landslide delineations digitized at a 1:24,000 scale were based on mapping completed by the Geological Survey of Wyoming (Case, 1991) as part of a statewide geological hazard mapping program. Warrington (1991) indicated that there were up to three separate checks made to verify mapping accuracy for the Bridger-Teton National Forest lands. Despite these checks, some significant sources of errors were discovered. Corrections for these errors were incorporated into the GIS processing of the digitized coverage of the draft landslide maps. An understanding of problems associated with the landslide coverage should allow a manager to determine the utility of this product for level I type analyses.

The use of unstable paper copies for the base maps was recommended to the Forest by Warrington (1991). He advised that a disclaimer be added to the coverage describing the limitations imposed from this process. The effects of digitizing from an unstable base were apparent upon examination of the coverages. Most pronounced were errors introduced from inaccurate tic mark registrations. While the areal extent of polygons was generally accurate, placement in reference to known quadrangle boundaries was not accurate.

The process of placing the landslide coverage into separate quadrangle tiles was likely intended to facilitate digitizing and file management. However, this process disallowed easy edge-matching between adjacent quadrangles and introduced nonthematic data into the coverage. Some of the edge matching problems were due to inaccurate digitizing by the contractor, and some were present on the original draft maps.

An initial examination of nodes, pseudo nodes, and errors associated with polygons on the coverage revealed that numerous polygons did not possess proper topology. These errors were not solely due to edge-matching problems, but occurred within each of the quadrangle boundaries. The source of these errors is unknown. Error correction was completed for selected quadrangles by on-screen manipulations and manual digitizing with a digitizing tablet.

Landslide polygon attributes were missing on the initial landslide coverage. Draft labels included up to six types of movements on a single landslide. While the draft labels captured complex movement types, the labeling convention was not amenable to data base design. Due to the labeling convention used on the draft maps, several items in the coverage polygon attribute table were created. This method was useful for this study, but may not prove sufficient for use on a Forest-wide basis. As polygons were most often labeled as a complex of movements types, some categorization of dominant movement types (i.e., flows, slides, falls) may need to be applied.

The process of GIS editing of a large number of landslide quadrangles across the entire Forest may be prohibitively time consuming and expensive for the Forest to incorporate for Forest planning purposes. Some of the automated transformations could be completed rather quickly, but manual manipulations would still be required to produce an error free coverage. The present state of the existing landslide coverage was determined to be adequate for many Forest purposes such as initial examinations of project level or transportation planning purposes. However, use of the coverage to quantify acreages of existing landsliding would require processing using the above techniques, or redigitizing from a stable base after more thorough checks of the initial drafting were completed.

Determination of estimated probability of failures for soil map units was relatively quick and forthright once the landslide coverages were corrected for errors. The use of this process in level I slope stability analysis provides a quick and inexpensive method to supplement geotechnical processing techniques.

Soil Survey Mapping and Coverages

Soil Survey mapping on the Bridger-West portion of the Forest was completed in 1992. This mapping provided the landscape stratifications used as the base for this slope stability analysis. Three soil map units were selected from the survey mapping for this pilot study. These map units were selected based on initial stability ratings (marginally unstable and marginally stable), locations, and the amount of collected landslide checklist data. Table 6 illustrates the soil and vegetation composition for these map units. Appendix A provides complete descriptions from the Bridger-West Soil Survey (USDA Forest Service, 1992) as well as maps depicting the extent of landslides and map unit polygons. The selected map units were among many which were digitized for Forest use. The soil map unit coverage was used as a base to clip and calculate percent slope grids and existing landslide polygons. This coverage was high quality and no significant errors were identified.

Digital Elevation Models and Percent Slope Processing

Elevations for the study area were derived from digital elevation model (DEM) data imported from tape into the GIS workstation in a raster format. Three methods were used to calculate percent ground slope from this data. It was found that regardless of whether ARC/INFO or ERDAS was used, that calculating slope values prior to clipping by map unit boundaries resulted in greater accuracies around boundary edges. For this study, ARC/INFO slope processing was used. Where elevations were clipped by map unit boundaries prior to slope calculations, anomalously low values were present within two to three pixels of the boundary. If used, the inaccurate slope lattice would skew the slope gradient distribution to lower slope values. Low percent slope

Table 6. Pilot Map Unit Compositions

Map Unit Number	Map Unit Name	Major Soil Components	USDA Classification	Percent of Map Unit	Habitat Type
274	Midfork - Targhee Families complex, 30 to 70 percent slopes	Midfork	Typic Cryoborolls, Loamy - Skeletal, mixed	45	Mountain Big Sagebrush / Mountain Snowberry / Mountain Brome
		Targhee	Typic Cryochrepts, Loamy - Skeletal, mixed	40	Subalpine Fir / White Spirea
315	Targhee Family - Mollic Paleboralfs, cobbly subsoil complex, 30 to 60 percent slopes	Targhee	Typic Cryochrepts, Loamy - Skeletal, mixed	50	Subalpine Fir / Common Snowberry
		Mollic Paleboralfs, cobbly subsoil	Mollic Paleboralfs, Clayey - Skeletal, mixed	35	Subalpine Fir / Pinegrass
433	Beaverdam - Cowdrey Families complex, 0 to 30 percent slopes	Beaverdam	Argic Cryoborolls, Fine, montmorillonitic	50	Mountain Big Sagebrush / Mountain Snowberry / Bluebunch Wheatgrass
		Cowdrey	Typic Cryoboralfs, Fine, montmorillonitic (moderately deep)	35	Mountain Big Sagebrush / Mountain Snowberry / Bluebunch Wheatgrass

values could yield lower probability of failures and higher relative stability ratings of a map unit.

Application of a 7x7 deconvolution filter corrected problems associated with older vintage DEMs. The application of this filter should not have adversely affected derived slope values as the output values are all within the general range of the input values. Hammer et al. (1995) found that application of a low pass filter increased the percentage of the area that was accurately classified into slope classes.

Slope values derived from DEMs may not reflect actual landscape conditions. Small or localized irregularities in gradient may not be accounted for at thirty meter resolutions. Distances used to calculate slopes at this resolution (30 to 42.4 meters) are too long to capture minute slope changes. Usually these minute changes are localized and may be overlooked for a level I analysis.

Relative Stabilities of Selected Map Units

Level I stability ratings are designed to inform the land managers of land areas which have the potential for landsliding. The relative rating scale allows land managers to more efficiently use the derived ratings for land managements decisions. The use of probability of failure estimates has increased the understandability of engineering-based analysis, and enabled calculations derived from infinite slope based probability analyses to be directly compared with GIS based probability of failures.

The assignment of relative stability classes based on probability of failure estimates has not been well documented. Most engineering analyses have traditionally based relative stabilities on factor of safety calculations (Schroeder and Swanston, 1987). Using this approach, factors of safety less than 1.5 were generally considered unstable. Comparisons of central tendencies of factors of safety have been used to equate probability of failure to factor of safety (Schroeder, 1985). However, the benefit of the probability of failure approach is based on the area of the factor of safety distribution curve which is less than or equal to one. This relationship is largely lost for distributions where only central tendency measures of factors of safety are used. For this study, relative stability ratings were selected from a working group analysis of slope stabilities on the Gifford Pinchot National Forest (USDA Forest Service, 1994a). More work is required to design relative stability ratings based on probabilities of failure which are consistent and represent the whole population of slopes with factors of safety less than one.

GIS Determinations

Slope stabilities were calculated inductively from GIS by comparing the total acreage of a map unit with the total acreage of landslides within that unit. Expressed as a ratio of landslides per unit area, this percentage approximates the probability of failure for the map unit. Where landslides crossed map unit boundaries, only the portion of the landslide within the boundaries was used for acreage calculations. Table 7 shows initial Bridger-West Soil Survey slope stability ratings, acreages of landslides and soil map units, and calculated probability of failures for the three selected map units. An estimate of the probability of failure was calculated from GIS processing of soil maps (USDA Forest Service, 1992) and landslide maps (Case, 1991) using the equation:

Approximate Probability of Failure (%) = (Landslide Acres / Total Acres) * 100

The use of a percentage to express probability of failure means that even if two different soil map units have the same landslide acreages, their probability of failures may vary. Since map unit 315 is nearly four times as large as map unit 433, its estimated probability of failure is greater (marginally unstable) than map unit 433 (marginally stable) even though their respective landslide acreages are rather similar (Table 7).

Table 7. Probability of Failure Ratings for Three Map Units Derived from GIS Processing

Map Unit Number	Initial Stability Rating [1]	Landslide Acres [2]	Total Acres [3]	Probability of Failure (Percent)
274	Marginally Unstable	1047.06	5324.02	19.67
315	Marginally Unstable	720.32	11768.00	6.12
433	Marginally Stable	535.73	2904.09	18.45

[1] From USDA Forest Service (1992) draft, (based on subjective judgement)
[2] From GIS processing of Case (1991) draft maps
[3] From GIS processing of USDA Forest Service (1992) draft maps.

Examination of the probabilities of failure show that map unit 315 is the most stable, while map units 274 and 433 have significantly higher and approximately equal slope stability ratings. The Bridger-West Soil Survey ratings were derived from subjective assessments of soil map units by field soil scientists.

Geotechnical Engineering Analysis Determinations

Probability of failure values for map units were most dependent on ground slope (slope gradient) and soil depth input parameters. Sensitivity analyses of input parameters for all three map units (274, 315, and 433) indicated that these two variables had consistently higher correlations with factor of safety than did any other variable. Figure 9 illustrates this for map unit 315. The diagram was created from @RISK analysis of each parameters' correlation with the probability of failure resulting from Monte Carlo simulation analysis. The soils of this map unit represent both cohesive and noncohesive textures. For pure cohesive soils, soil cohesion becomes more important than friction angle. For noncohesive soils, friction angle is generally the dominant contributing factor.

The importance of the percent surface slope (Figure 9) to the factor of safety illustrates the utility of incorporation of DEM-derived slope distributions into the analysis. DEMs provided a quick, cost-effective method for determinations of slope values across entire soil map units. Traditional methods such as aerial photograph interpretations, contour line measurements, or actual field sampling requires much more time and effort to derive representative slope distributions. Additionally, these techniques are subject to systematic measurement errors and uncertainties associated with manual measurements. Application of GIS technology to derive surface slope angles minimized systematic errors and uncertainties through computer automation.

One limitation to the use of DEM derived slope distributions was the inability to separate the map unit slope distributions into distributions reflecting slope values for individual components of a map unit. This limitation was not due to limitations in the derived slope values. Rather, it reflects problems associated with mapping at smaller level 1 scales. The ability to separate slope distributions by map unit components would require mapping at tighter scales more appropriate to a level II type analysis.

The inability to separate slope distributions by component led to the necessity of combining soil and groundwater estimates for input into the infinite slope equation. This resulted in broader input distributions of soil parameters in the LISA model. The factor of safety's sensitivity to changes in soil and groundwater factors was much less than its sensitivity to percent slope changes (Figure 9). Figure 9 was created using the @Risk program to derive correlation coefficients between input values for each parameter and the resulting factor of safety. The single most important input factor which was affected by the combination of soil and groundwater estimates was soil depth. Where soil depths were similar between components, there was little change in the probability of failures. However, where a map unit consisted of two soil components of different depth classes, the breadth of soil depth input values generally produced probability of failures which were more stable.

Soil map unit 433 consists of both moderately deep (<40") and deep (>60") fine textured soils (Appendix A). Examination of the sensitivity analysis based on a triangular soil depth input distribution (1.6 ft, 4.0 ft, 7.0 ft) indicated that soil depth in this range is highly correlated with factor of safety (.509). Therefore, the combination of soil depth ranges of the two components resulted in increased factors of safety, and decreased probabilities of failure. Where soil map unit components fall into distinctly different depth classes, the combination of ranges will significantly affect the resulting probability of failures for that map unit. Special care should be taken by the slope stability investigator where this situation occurs.

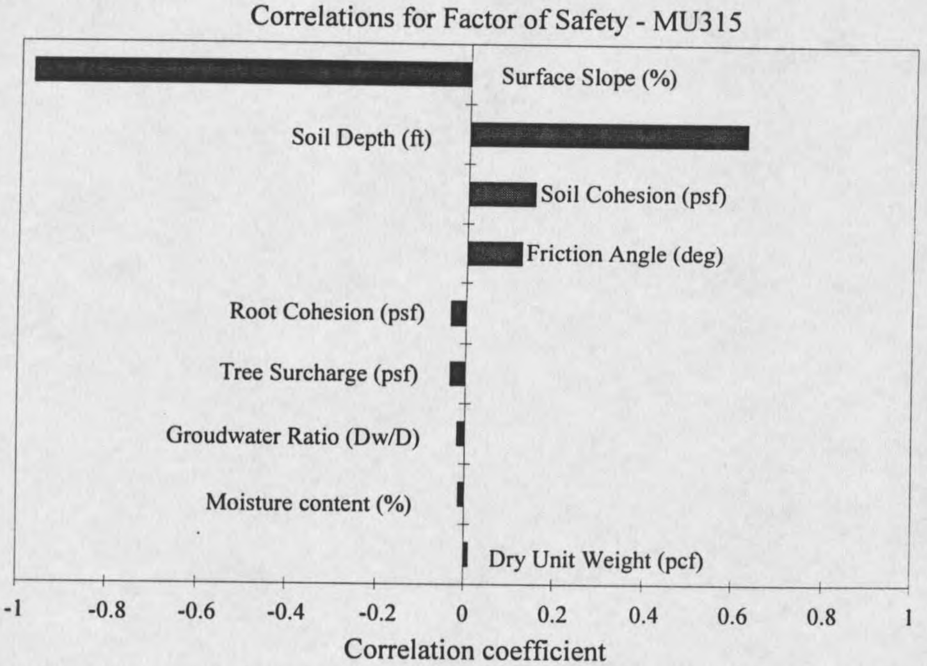


Figure 9. Sensitivity Analysis of Map Unit 315 Input Parameters.

The effect on combinations of soil properties for the rest of the input factors had less of an impact on probability of failure determinations than the soil depth property. Because ground water ratio depends on soil depth, this factor was also affected. The correlation between groundwater ratio and factor of safety is much lower for each of the three map units than it is between soil depth and factor of safety. Groundwater correlation values around -0.05 to -0.10 were indicated through sensitivity analysis for the three pilot units. Such factors as soil cohesion, friction angles, dry unit weight, were so insensitive to the factor of safety that effects from combining textures were relatively insignificant. The combination of soil properties had no direct effect on root cohesion or tree surcharge.

The single most important factor for determination of probabilities of failure using the infinite slope equation is the percent slope of the slope surface. The use of DEM-derived slope distributions provided the best possible values for this factor at a level I scale. Probability of failure ratings resulting from the use of DEM-derived slope distributions along with best estimates of the remaining infinite slope parameters, provided a good basis for assigning relative stability ratings to the pilot soil map units.

Relative slope stability ratings determined by the geotechnical engineering approach were assigned based on ranges provided in Hammond et al. (1992) as determined on the Gifford Pinchot National Forest. Table 8 lists the relationship between probabilities of failure as referenced by Hammond et al. (1992) and those used during this study.

Table 8. Criteria Used in Establishment of Relative Slope Stability Ratings

Probabilities of Failure	Gifford Pinchot National Forest[1]	This Study
0% - 2.9%	Very Low	Stable
3.0% - 7.9%	Low	Stable
8.0% - 15.9%	Moderate	Marginally Stable
16% - 24.9%	High	Marginally Unstable
> 25%	Very High	Unstable

[1] From Hammond et al., 1992

The relationship between probabilities of failure and relative slope stability ratings is nebulous. There are no consistent criteria for establishment of relative stability ratings from probability of failure ratings. While some National Forests such as the Gifford Pinchot National Forest have used five relative stability classes, others such as the Bridger-Teton National Forest have used four classes. For this study, the relationship between relative stability classes and probabilities of failure was based solely on the ratings provided in the above reference. No other references were found which directly address this subject. Application of the assigned classes to both GIS and LISA (@RISK) derived probability of failures provided realistic values for the landscapes of the study area.

Landslide Indicator Determinations

The primary function of collecting landslide indicator data during this study was to evaluate the usefulness of the data toward future slope stability evaluations and to provide a comparison with preliminary stability ratings developed during the Bridger-West Soil Survey. The landslide indicator checklist provided a systematic method for collection of data which typically are subjectively evaluated by soil scientists during a soil survey. Systematic collection of these data is not a standard procedure during soil surveys. Therefore, the use of these data to derive relative stability ratings for level I type analyses is limited. The statistical processing of checklist data through contingency table and logistic regression provided valuable insight into landslide factors relating to slope stability.

Contingency Table Determinations

Checklists of landslide indicators completed during field sampling for selected map units were used to examine the interdependency of landslide indicators and their relation to the presence of previous landslide activity. Two indicators (Cretaceous bedrock and hanging wall of thrust) which survived a series of contingency table tests were shown to be significantly related to the presence of previous landslide activity.

Contingency table test results indicated that a significant number of landslide indicator data were not independent. Dependency existed within and among subjective groupings. Table 9 lists the total number of relationships where independencies could not be concluded from 2x2 contingency tests within groups and among groups at $P<0.10$. This dependency allowed the total number of landslide indicators to be reduced from 45 to three. The three selected indicators represent independent distribution segments of the sampling population. These segments were related not only to the selected variable, but also to all variables which were dependent with it. Results indicate that population distributions could be characterized by three surviving landslide indicators: hanging wall of thrust, Cretaceous bedrock, and natural meadows.

The three surviving variables were tested for relationships with previous landslide activity to determine which were related to the presence of landslides. Two of the three indicators showed a relationship to previous landslide activity at $P< 0.01$. The most significant relationship was for Cretaceous bedrock (p-value = .0000). Hanging wall of thrust was also highly related (p-value = .0052). Natural meadows were shown independent of previous landslide activity (p-value = .1997) at a $P< 0.10$ significance level. The results of the test for independence of the three surviving variables with previous landslide activity were very close to the results of the logistic regression analysis.

Logistic Regression Determinations

The presence of Cretaceous bedrock and hummocky topography were most significantly related to the presence of previous landslides in the logistic regression model. The logistic model depicted the nature of the binary distributions of the indicators. The model used 43 initial landslide indicators as explanatory variables to predict landslide activity. Relative stability ratings derived from the regression were similar to stability

Table 9. Relationships Among Landslide Indicators from 2x2 Contingency Table Analyses

Initial Group Processing			Final Processing	
Initial Groupings	Pairwise Relationships[1]	Selected Indicators	Pairwise Relationships[1]	Selected Indicators
Wetness	4	Sag Ponds Piping of Water Gleyed or Mottled Colors	35	Hanging Wall of Thrust Cretaceous Bedrock Natural Meadows
Position	3	Concave Slope Hanging Wall of Thrust		
Movement	7	Hummocky Surface		
Bedrock	1	Cretaceous Bedrock		
Soil Property	3	Shallow Soils Inclined Peds in Profile		
Surface	10	Natural Meadows Bare Ground > 25%		
Strength	0	Few Small Roots in "A" Horizon Lack of Large Tree Roots		

[1] The total numbers of pairwise relationships where independencies could not be concluded at $P < 0.10$.

ratings initially determined in the Bridger-West Soil Survey. The final logistic response function was determined to be:

$$E_{LS} = \frac{\exp(-2.8923 + 2.8125*\text{Humm} + 2.8379*\text{Kbr})}{1 + \exp(-2.8923 + 2.8125*\text{Humm} + 2.8379*\text{Kbr})}$$

where: E_{LS} = Expected value (probability) of landslide occurrence.
Humm = Hummocky surface indicator.
Kbr = Cretaceous bedrock indicator.

The function successfully predicted the presence or absence of landslides approximately 83% of the time when expected probabilities were rounded to zero or one, and 69% of the time without rounding. Application of the logistic response function to each of the 25 map units (226 sites) where indicator data were collected determined a distribution of expected landslides per map unit. Descriptive statistics of expected landslide occurrence were used to derive map unit relative stability ratings for each map unit (Table 10).

Relative stability ratings initially assigned by the Bridger-West Soil Survey and those derived through logistic regression generally concurred (Table 11). Of the 25 map units where checklists were collected, 14 were assigned the same ranking, while eight others were within one rating class. The best correlation was for

Table 10. Relative Stability Ratings and Descriptive Statistics of Expected Landslide Occurrences for Soil Map Units Selected from Logistic Regression Analysis

Stability Rating	Map Unit	n*	Mean	Median	Quartile 1	Quartile 3
Stable	102	14	0.30240	0.05250	0.05250	0.48640
	140	4	0.05254	0.05254	0.05254	0.05254
	201	12	0.05254	0.05254	0.05254	0.05254
	211	3	0.05254	0.05254	0.05254	0.05254
	221	2	0.05254	0.05254		
	312	4	0.15900	0.05300	0.05300	0.37300
	313	4	0.05254	0.05254	0.05254	0.05254
	346	3	0.05254	0.05254	0.05254	0.05254
	411	7	0.12480	0.05250	0.05250	0.16100
Marginally Stable	331	5	0.30900	0.48000	0.05300	0.48000
	403	13	0.52290	0.48640	0.48640	0.48640
Marginally Unstable	244	24	0.78910	0.94040	0.48640	0.94040
	274	17	0.67500	0.94040	0.48320	0.94040
	315	17	0.80690	0.94040	0.48640	0.94040
	404	18	0.73860	0.94040	0.48640	0.94040
	413	7	0.68100	0.48640	0.48640	0.94040
	414	7	0.49200	0.48600	0.05300	0.94000
Unstable	224	28	0.89150	0.94040	0.94040	0.94040
	234	9	0.94037	0.94037	0.94037	0.94037
	243	2	0.94037	0.94037		
	305	5	0.84960	0.94040	0.71340	0.94040
	333	1	0.94037	0.94037		
	334	3	0.94037	0.94037	0.94037	0.94037
	433	8	0.82690	0.94040	0.59990	0.94040

* number of sites

stable units, while ratings disagreed more often for marginal classes. In all 23 of 25 relative stability ratings were within one class of those assigned by the Bridger-West Soil Survey. This general agreement does not imply that the ratings are correct, merely that they were derived using similar criteria.

The Bridger-West Soil Survey ratings were subjectively derived by soil scientists using field experience, and aerial photography. These ratings represented the scientists' best opinions of stability of each map unit. Landslide indicator checklist factors were designed to be used in the field as a tool to document the criteria which soil scientists used during subjective evaluations. The accuracy of this method requires comparison with other methods such as GIS-derived and LISA-derived slope stability ratings.

Results from the contingency table analysis and the logistic regression analysis indicate that while most of the landslide indicators examined during this study were dependent, the significant indicators (Cretaceous bedrock and hummocky topography) corresponded well with initial determinations derived from

Table 11. Relative Stabilities and Logistic Regression Analysis of Landslide Indicators from the Bridger-West Soil Survey

Map Unit	Bridger-West	Landslide Indicators (this study)
102	Stable	Stable
121	Stable	*
140	Stable	Stable
201	Stable	Stable
211	Stable	Stable
221	Stable	Marginally Stable
224	Unstable	Marginally Unstable
234	Unstable	Unstable
243	Unstable	Marginally Unstable
244	Marginally Unstable	Marginally Unstable
274[1]	Marginally Unstable	Marginally Unstable
305	Unstable	Marginally Unstable
312	Stable	Stable
313	Stable	Stable
315[1]	Marginally Unstable	Marginally Unstable
331	Marginally Stable	Marginally Stable
333	Unstable	Stable
334	Unstable	Unstable
346	Stable	Stable
403	Marginally Stable	Marginally Stable
404	Marginally Unstable	Unstable
411	Stable	Stable
413	Marginally Unstable	Marginally Unstable
414	Marginally Unstable	Marginally Stable
433[1]	Unstable	Unstable

* Not Rated - Insufficient Data

[1] Pilot Map Units the subjective ratings assigned during field work of the Bridger-West Soil Survey area.

the subjective ratings assigned during field work of the Bridger-West Soil Survey area. Ratings derived for the three pilot map units provided a relative stability rating to compare with the GIS-derived and geotechnical engineering-derived ratings.

Relative Stability Ratings for Pilot Map Units

Relative stability ratings derived from different processes were not in agreement for every pilot map unit examined during this study. This lack of agreement illustrates the subjectivity of slope stability evaluations and problems which exist when slope stabilities are derived from a single method. Each method has underlying assumptions and uncertainties associated with it. Examination of results from this study illustrated some of the limitations inherent in each method. Transects by the author of each of the pilot map units provided insight into the nature of landsliding and some of the controlling factors which would not typically be available at a level I scale.

Relative slope stability ratings for three pilot soil map units (274, 315, and 433) were derived in this study using three separate processes. Additionally, initial relative stabilities were collected from the Bridger-West Soil Survey (USDA Forest Service, 1992). For each soil map unit, the relative slope stabilities derived from each processing method did not consistently agree (Table 12). Due to the lack of agreement among the ratings for some of the individual map units, a closer look at the results and assumptions incorporated into each process was required.

Table 12. Relative Stability Summaries for Pilot Soil Map Units

Map Unit	GIS Processing	LISA Processing	Checklist Processing	Initial Ratings[1]
274	Marginally Unstable	Unstable	Marginally Unstable	Marginally Unstable
315	Stable	Stable	Marginally Unstable	Marginally Unstable
433	Marginally Unstable	Stable	Unstable	Marginally Stable

[1] From USDA Forest Service, 1992.

Soil Map Unit 274

The relative stability ratings assigned to this map unit were fairly consistent. Ratings of "marginally unstable" were derived for all methods except infinite slope modeling. The proximity of the LISA-derived probability of failure for this map unit is very close (0.2 percent) to the boundary between "marginally unstable" and "unstable" relative stability classes. This proximity is within a reasonable margin of error given the subjective nature of the relative stability rating system. General agreement of relative stability ratings from alternate approaches implied that the derived ratings were more accurate for this map unit than for any other examined for this study. Concurrence of slope stability ratings suggested that problems associated with each stability processing method were minimized for this map unit. An examination of the environmental characteristics of this map unit illustrated landslide conditions which are generally conducive to accurate slope stability estimations.

Map unit 274 has been mapped to occur primarily on oversteepened, south facing backslopes of sandstones and siltstones of the Cretaceous Gannet Group. Soils are deep and noncohesive across the 5,300 acres of the map unit. Soil moisture contents are generally low with high depths to groundwater. The map unit is vegetated by both sagebrush rangeland and sparse to moderately dense conifers. These environmental factors allowed accurate processing from each of the slope stability methods.

The consensus of the relative stability techniques to produce a general rating of marginally unstable indicated this as the ultimate rating for the map unit. It is suggested that for landscapes dominated by rangeland or grassland vegetation with similar soil component properties, the concurrence of LISA and GIS processing of landslide acreages is sufficient to adequately characterize the associated relative slope stabilities.

Factors Influencing GIS Determinations. GIS-derived slope stability ratings were facilitated by a dominance of open rangelands and sparse to moderately forested slopes. The open nature of the map unit allowed more accurate delineations of existing landslides through the use of aerial photography. The primary benefit of this open nature was the ability to examine a large portion of the actual ground surface through the use of aerial photography. Densely forested slopes were generally located at lower elevations (with flatter slopes) with more densely forested areas along smaller north facing scarpslopes of the area. The probability of landsliding occurring in these areas would be smaller than for upslope dipslope positions. The dominantly south aspect also provided fewer slopes affected by shade and poor lighting conditions which hinder aerial photography interpretations.

Factors Influencing LISA Modeling. The dominance of generally south aspects and open terrain assisted in estimations used for input into the infinite slope method of slope stability determination. South aspects of this unit were relatively steep and bedrock controlled. South aspects resulted in generally low moisture contents due to increased solar radiation. Where groundwater is present, it likely travels through the moderately permeable non-cohesive soils to greater depths, most likely to bedrock. Water that reaches these depths may then form a phreatic surface parallel to the ground surface. Most landslides were either multiple blockslides or multiple debris flows and rockslides (Case, 1991) with failure planes apparently parallel to the surface. The behavior of groundwater and landslides were assumed to generally conform with the infinite slope assumptions that these features occur parallel to the ground surface (Ward et al., 1979).

Soil textures were relatively homogeneous between components and throughout the soil profiles. Unified Soil Classification (USCS) textures were all noncohesive with similar friction angles and lacked true soil cohesion. Permeabilities were similar in all horizons of both of the representative soils (from USDA Form-5). In general, the soil components of this map unit allowed relatively straightforward determinations of appropriate LISA (and @RISK) input distributions. High dry unit weights due to very gravelly substrata of the Midfork component may have slightly elevated probability of failure ratings using the infinite slope method.

The accuracy of relative stability ratings derived through infinite slope modeling for map unit 274 was improved by good visibility of the ground surface and conformity of slopes and landsliding to assumptions of the infinite slope equation. The use of LISA (and @RISK) to accurately depict relative slope stability in similar settings would be appropriate.

Factors Influencing Landslide Checklist Determinations. The relative stability derived from landslide indicator checklist processing for map unit 274 was based on a fairly large number of samples (n=17) taken in a variety of map unit polygons. This broad sampling distribution resulted in smaller systematic errors associated with sampling design. As with other processing techniques, the generally open nature of the vegetative layer assisted in the identification of slope stability features. For this technique, the uniformity of parent material (Cretaceous bedrock) and visibility of hummocky topography provided estimates of expected landslide frequency in the logistic regression analysis which were in agreement with estimates derived using the other techniques.

Soil Map Unit 315

The relative stability of this map unit was rated as either stable, or marginally unstable according to which technique was used for rating derivation. GIS and LISA processing indicated a "stable" rating, while checklist processing and subjective Bridger-West Soil Survey ratings indicated the stability as "marginally unstable". The reason for these differences was primarily due to the scale at which information was collected.

Field work during soil survey and landslide transecting revealed the presence of numerous small undetected landslides beneath the dense conifer cover. Tools such as topographic maps, slope maps, aerial photographs, landslide inventories, and general soil types and depths, which are typically used for level I stability analyses would not detect the presence of these concealed landslides. If additional transects in other polygons revealed similar undetected landslides, the initial level I slope stability rating would need to be shifted from "stable" to a more unstable class. Additional level II or level III analyses could be used to provide feedback which could be incorporated into revisions of the level I relative stability ratings.

Factors Influencing GIS Determinations. The steep, densely forested, north facing map unit made accurate landslide delineations difficult. While some movements such as very large landslides, rockslides, and debris flows were generally detectable, numerous smaller movements were not. The combination of dense conifer cover and north aspect shading on aerial photographs were not conducive to accurate landslide delineations for this map unit.

Factors Influencing LISA Modeling. The presence of a dense conifer cover over most of this unit would also have affected estimates of some of the factors required for infinite slope modeling. Depth of soil and groundwater ratio estimates were the most important input parameters which relied heavily on aerial photography for selection of input distributions. While these factors appear relatively insignificant in a sensitivity analysis (Figure 9), increases in the distribution ranges by a reasonable amount resulted in a shift of relative stability rating from "stable" to " marginally stable" for the map unit. The inability to characterize soil depths and groundwater due to dense conifer cover reduced the confidence of the relative slope stability rating for this map unit using the infinite slope method.

Factors Influencing Landslide Checklist Determinations. While this map unit had a relatively large number of samples (n=17), most of these samples were(n=8) were out of one polygon where transects were completed. This clustering of samples in a single polygon may have resulted in increased systematic errors from nonrepresentative characterization of significant landslide checklist parameters. A more representative sample of the nearly 40 polygons of this map unit would result in more accurate characterization of the landslide checklist parameters.

Soil Map Unit 433

Soil map unit 433 is a spatially small map unit (2,900 acres) delineated on ridgetops and upper backslopes. The map unit supported a rangeland vegetation of sagebrush, snowberry, and grasses. Slopes were generally straight or convex. Soils were cohesive and montmorillonitic.. Relative slope stability ratings for this unit covered the complete range of stability classes from "stable" to "unstable".

The relative stability method which appears to best represent the nature of the slopes in map unit 433 is the GIS processing method. A rating of "marginally unstable" or "unstable" would have to be selected based on subjective judgement or further sampling. One possible explanation for the "stable" rating provided from the infinite slope modeling method is that only saturated conditions were examined. Where fine textures and shallower soil depths may produce saturation, the use of a total stress analysis may yield more appropriate stabilities.

Factors Influencing GIS Determinations. GIS should have provided an adequate characterization of the relative slope stabilities of this unit. The surface of the ground was easily visible on aerial photography because of the dominant rangeland vegetation types. A large portion of the probability of failure (extent of landsliding) in this unit was due to the delineation of a large segment (about 50 acres) of a polygon in the Pine Creek quadrangle which was mostly located in the adjacent map unit. This landslide polygon appeared from aerial photography to be a result of headward erosion of Pine Creek. The northwest aspect and morphology of the slide area also suggested that much of the movement was due to complete saturation during snowmelt. If this polygon were neglected in determination of the stability rating according to GIS, the resulting probability of failure would be right on the boundary between "marginally unstable" and "unstable".

Factors Influencing LISA Modeling. The major drawback of applying the LISA (and @RISK) analysis to soil map unit 433 was the inability to accurately model the soil depth (depth to failure). The two soil components of this map unit differed in depth ranges from moderately deep (Cowdrey) and deep (Beaverdam) (Appendix B). While the textures, friction angles, dry unit weights, and soil cohesion values were all identical, the effects of a wide range of soil depths on groundwater ratios, soil moisture content, and ultimately probability of failure had a significant influence.

Root cohesion was not used in this map unit due to the lack of conifer cover. At shallow depths however, even root cohesion associated with shrub cover may be significant. Mike Remboldt (Assistant Forest Engineer, Payette National Forest, personal communication, 1996) reported a surprising contribution of root strength from understory. He reported that even moderately burned slopes retained significant stability due to unburned shrubland species on slope gradients greater than 70 percent. For the Cowdrey component of this map unit, the relative shallow depths (<40 inches) would have made the infinite slope equation much more sensitive to any incorporation of root strength.

Parametric values of LISA input variables were constructed under the assumption of drained conditions. For the Cowdrey component of the map unit, this assumption may be invalid. Because of the slow (poor) permeabilities of the fine textures associated with the Cowdrey soil and the relatively shallow depths (<40 inches) the soils may have had the ability to maintain a high soil moisture content for long periods (days to weeks). If undrained conditions were met, the soils may have lost all of their cohesion with a significant reduction in friction angle requiring a total stress analysis for probability of failure determinations. While a total stress analysis was not completed for this study, it represents one possible explanation for the "stable" infinite slope processing rating and the much more unstable ratings (marginally unstable) of GIS and landslide indicator processing.

Factors Influencing Landslide Checklist Determinations. For this map unit, the landslide indicator processing was biased through sampling design. Of the eight sites used for the analysis, five were collected during a transect on a single dipslope of the unit. To achieve a more accurate slope stability rating through this method, additional polygons would need to be sampled.

Suggested Methodology for Deriving Relative Slope Stabilities

Analyses of the three pilot map units in this study provided insight which was used to derive a preliminary relative slope stability rating methodology for incorporation into level I stability analyses for the Bridger-Teton National Forest. The methodology minimizes analysis time while maximizing the use of Bridger-West Soil Survey information and recent improvements in Forest GIS and remote sensing capabilities. The methodology uses a series of decisions to determine the best approach to derivation of slope stability ratings for each soil map uni. Relative stability ratings determined using this process represent preliminary ratings. As additional soils, climate, and slope stability information become available, incorporation of additional processes such as expected maximum precipitation events, precipitation models, or seismic hazard may be added as determined necessary.

The proposed relative slope stability rating methodology relies on determination of the GIS and LISA estimates for probability of failures. A key (Table 13) is used to lead the slope stability assessor through a series of decisions regarding the nature of the map unit. The key is based on results derived during this study concerning GIS and LISA based relative slope stability determinations. Progression through the key will lead the assessor to an estimated probability of failure for a soil map unit. The key is designed to seek congruence of LISA and GIS derived probability of failure estimates. The final estimated probability of failure may then be used to derive a relative slope stability rating using Table 8.

Densely forested slopes make recognition of landslides and infinite slope input parameters difficult. Where map units are dominated by conifer cover, probability of failure estimates using GIS and LISA processing are subject to increased uncertainties. The first decision in determining relative stability ratings for soil map units is to decide if the map unit is dominantly coniferous. For the Bridger-West Soil Survey (1992), the connotative legend may be used for this determination, as all dominantly coniferous map units are labeled as three hundred series (ie., 301, 315, 366). For other areas of the Forest, the use of supervised or unsupervised classification of LANDSAT thematic mapping imagery, and/or aerial photography may be used to determine if a map unit is coniferous. For dominantly coniferous map units, the confidence in LISA and GIS derived probability of failure estimates may be less than for map units which are not densely forested.

The second step in assessing map units for slope stability examines the individual components of a map unit to determine if their associated soil properties are similar. Of particular concern during this step are the depths, textures, permeabilities, water holding capacities, and bulk densities of each component. Where soil component properties differ significantly, a grouping of properties must be made. Whether grouped or not, the component soil properties are used as input to derive LISA probability of failure values for comparison with GIS derived probability of failure values.

Where LISA derived probability of failure values agree with GIS derived probability of failure values, the matching value may be used in Table 8 to determine a relative slope stability rating for the map unit. Where LISA and GIS values do not agree, the process is repeated after refinement of either the LISA input distributions, or the GIS landslide delineations. Where congruence between the probability of failures is not achievable, subjective judgement or additional data must be used to determine the estimated probability of failure.

Table 13. Key for Level I Probability of Failure Determinations

Key for Determination of Level I Probability of Failures

1. Map unit is coniferous		2
2. Soil components have similar properties		3
3. Infinite slope probability of failures match GIS probability of failures	Use matching probability of failure values.	
3. Infinite slope probability of failures do not match GIS probability of failures		4
4. Check LISA input parameters. Determine that input distributions are accurate	Must obtain additional field data and/or use subjective judgement.	
4. Check LISA input parameters. Determine that input distributions are not accurate	Adjust LISA input distributions	3
2. Soil components do not have similar properties	Group component properties	5
5. GIS probability of failures match LISA probability of failures	Use matching probability of failure values.	
5. GIS probability of failures do not match LISA probability of failures	Check grouped component properties	6
6. LISA inputs are too broad	Examine aerial photos and soil data	5
6. LISA inputs are not too broad	Must obtain additional Field data and/or use subjective judgement.	

Table 13. Cont.

1. Map unit is not coniferous		7
7. Soil components have similar properties		8
8. Infinite slope probability of failures match GIS probability of failures	Use matching probability of failure values.	
8. Infinite slope probability of failures do not match GIS probability of failures		9
9. GIS landslide delineations are accurate using aerial photos	Adjust LISA values, obtain additional field data, and/or use subjective judgement.	
9. GIS landslide delineations are not accurate using aerial photos	Correct landslide delineations	8
7. Soil components do not have similar properties	Group component properties	10
10. GIS probability of failures match LISA probability of failures	Use matching probability of failure values.	
10. GIS probability of failures do not match LISA probability of failures		11
11. GIS landslide delineations are accurate using aerial photos	Adjust LISA values, obtain additional field data, and/or use subjective judgement.	
11. GIS landslide delineations are not accurate using aerial photos	Correct landslide delineations	10

SUMMARY AND CONCLUSIONS

This study used the results from the analysis of three pilot soil map units to develop a methodology for evaluation of relative slope stability on the Bridger-Teton National Forest. The methodology uses GIS and LISA based probability of failure determinations to estimate probability of failure and relative stability ratings for soil map units. Incorporation of landslide indicator data into this study provided supplemental stability ratings, but was not included in the proposed methodology due to the lack of availability of this data on the remainder of the Forest. This study is intended to provide the Forest with an efficient and systematic process for evaluating relative slope stabilities using existing data and technologies for level I slope stability assessments.

Three pilot soil map units were evaluated for relative slope stabilities by GIS processing, LISA processing, and landslide indicator processing. A comparison of relative slope stabilities from GIS and LISA processing showed general agreement of the methods for two of the three map units. Landslide indicator derived probability of failure values were more closely related to subjective ratings assigned during the Bridger-West Soil Survey. Each relative stability determination method had limitations.

GIS processing of existing landslide maps (Case, 1991) provided a quick and efficient method for deriving slope stabilities once an error free coverage was available. Much of the GIS processing in this study was aimed at improving the quality of the draft landslide coverage. For future use of this coverage in level I slope stability analyses, corrections documented in this study must be made, or the original mapping must be digitized after more thorough edge-matching and editing. GIS-derived probability of failure estimates were best in agreement with LISA derived probability of failure estimates in areas which lacked dense conifer cover and had components with similar soil properties. The presence of dense conifer cover inhibited detection of landslides.

LISA derived relative slope stability ratings were based on probabilistic analysis of infinite slope equation parameters. The use of soil survey data and reported literature values provided the foundation for many of the initial input parameters. DEM-derived slope distributions provided the best possible information for the parameter most highly correlated with factor of safety, percent ground slope. In map units consisting of vastly different soil components, the inability to distinguish slope distributions associated with each component from DEM derived data required groupings of component properties. Where groupings are required to characterize map unit properties, LISA derived probability of failure ratings may be misleading.

Logistic regression of landslide indicator data indicated that the factors most highly correlated with landslide occurrence were Cretaceous bedrock and hummocky topography. A logistic response function was determined which used the presence of these indicators to predict the occurrence of landslides. Contingency table processing revealed that many of the initial indicators were interdependent. While not directly included in the proposed methodology, these initial indicators should be considered if subjective judgements are required.

Several steps may be taken to increase the ease and accuracy associated with determinations of level I slope stability analyses. First, soil scientists should incorporate into survey practices estimates of soil depths and groundwater depths in excess of 60 inches. These data would have provided more accurate input distributions into the LISA model. Collection of these two simple data items would greatly increase the accuracy of probability of failure estimates for soil map units. Second, remote sensing and GIS technologies could be used to provide better estimates of groundwater conditions in a map unit. Moore et al. (1988) and Bell et al. (1992) presented GIS and statistical methodologies which could be incorporated into future level I analyses for more accurate estimations of soil groundwater. Finally, geotechnical engineers need to develop a consistent rating system to convert factor of safety values to probability of failure estimates.

Practicing natural resource management in steep forested terrain requires scientists to use every tool available to recognize and mitigate possible damages to humans and resources. Advances in computer technology have created the ability to incorporate probability assessments and spatial analyses into the process of determining an area's potential for landsliding. Even with these technologies, assigned slope stabilities are only a prediction of what may occur, and not necessarily what will occur in the future. Nevertheless, it is the responsibility of the resource specialist to provide to the land manager with the best assessment of the landscapes' capabilities and limitations.

REFERENCES

REFERENCES CITED

Alexander, E.B. 1995. Soil slope - depth relationships in the Klamath Mountains, California, and comparisons in Central Nevada. Soil Survey Horiz. 36(3): 94-103.

Bailey, R.G. 1972. Landslide hazards related to land use planning in Teton National Forest, Northwest Wyoming. USDA For. Serv. Intermountain Region.

Bell, J.C., R.L. Cunningham, and M.W. Havens. 1992. Calibration and validation of a soil-landscape model for predicting soil drainage class. Soil Sci. Soc. Am. J. 56:1860-1866.

Brabb, E.E. 1984. Innovative approaches to landslide hazard and risk mapping. in: Proc. 4th Int.Sym. on Landslides. Toronto, Can. 1: 307-324.

Campbell, R.H. 1985. Feasibility of a nationwide program for the identification and delineation of hazards from mud flows and other landslides. U.S. Geol. Surv. Open File Rep. 85-276.

Carrara, A., M. Cardinali, R. Detti, F. Guzzetti, V. Pasqui, and P. Reichenbach. 1991. GIS techniques and statistical models in evaluating landslide hazard. Earth Surf. Proc. Landforms. 16:427-445.

Carrara, A., E. Pugleise, and L. Merenda. 1977. Computer-based data bank and statistical analysis of slope instability phenomena. Z. Fur Geom. 21: 187-222.

Cannon, S.H., and S. Ellen. 1985. Rainfall conditions for abundant debris avalanches in the San Francisco Bay Region, California. Calif. Geol. 38(12): 267-272.

Case, J., 1991. Landslide hazard maps of Wyoming (draft). Scale 1:24,000, Wyo. Geol. Surv. Laramie, WY.

Christian, J.T., C.C. Ladd, and G.B. Baecher. 1992. Reliability and probability in stability analysis. p. 1071-1111. in: Stability and Performance of Slopes and Embankments II: Proc. Spec. Conf., Am. Soc. Civil Eng. and Univ. Calif. Berkeley. Seed, R.B. and R.W. Boulanger (eds.).

Cooke, R.U., and J.C. Doornkamp. 1990. Geomporpology in environmental management: a new introduction. 2nd Edition. Oxford Univ. Press, London, England.

Coppin, N.J., and I.G. Richards. 1990. Use of vegetation in civil engineering. Coppin, N.J., and I.G. Richards (eds.). Const. Ind. Res. and Inf. Ass. Butterworths, London.

DePolo, C.M., and D.B. Slemmons. 1990. Estimation of earthquake size for seismic hazards. in: Krinitzsky, E.L., and Slemmons, D.B. (eds.). Neotectonics in Earthquake Evaluation, Geol. Soc. Am. Rev. Eng. Geol. 8:1-28.

Duncan, M.J. 1992. State-of-the-art: static stability and deformation analysis. p. 222-266. in: Stability and Performance of Slopes and Embankments II: Proc. Spec. Conf. Am. Soc. Civil Eng. and Univ. Calif. Berkeley. Seed, R.B. and R.W. Boulanger (eds.).

ERDAS, 1991. ERDAS image processing software, ver. 7.5. Earth Resources Data Analysis Systems, Atlanta, GA.

ESRI, 1992. ARC/INFO, ver. 6.0. Environmental Systems Research Institute, Redlands, CA.

Fallon, D., T. Svalberg, D. Tart, P. Maus, T. Wirth, and H. Lachowski. 1994. Use of satellite imagery and digital elevation models in the Bridger-Teton Integrated Resource Inventory. p. 77-83. in: Proc. 5th For. Serv. Remote Sens. Applic. Conf. Greer, J.D. (ed.). Am. Soc. Photogrammetry and Remote Sensing. Bethesda, Md.

Gao, J. 1993. Identification of topographic settings conducive to landsliding from DEM in Nelson County, Virginia, U.S.A. Earth Surf. Proc. Landforms, 18:579-591.

Gray, D.H. 1992. Biotechnical stabilization of cut & fill slopes. p. 1395-1411. in: Stability and Performance of Slopes and Embankments II: Proc. of a Spec. Conf. Am. Soc. Civil Eng. and Univ. Calif. Berkeley. Seed, R.B. and R.W. Boulanger (eds.).

Hammond, C., D. Hall, S. Miller, and P. Swetik 1992. Level 1 stability analysis (LISA) documentation for version 2.0. USDA For. Serv. Intermountain Resear. Sta., Gen. Tech. Rep. INT-285.

Hammer, R.D., N.C. Young, T.L. Wollenhaupt, T.L. Barney, and T.W. Haithcoate. 1995. Slope class maps from soil survey and digital elevation models. Soil Sci. Soc. Am. J. 59: 509-519.

Hansen, A. 1984. Landslide hazard analysis. p. 523-603. in: Slope Instability. Brundsen, D. and D.B. Prior (eds.). John Wiley and Sons, New York.

Hillel, D. 1982. Introduction to soil physics. Academic Press, Inc., San Diego, CA.

Iverson, R.M., and J.J. Major. 1987. Rainfall, ground-water flow, and seasonal movement at Minor Creek Landslide, Northwestern California: physical interpretation of empirical relations. Geol Soc. Am. Bull. 99: 579-594.

Keefer, D.K. 1984. Landslides caused by earthquakes. Geol. Soc. Am. Bull. 95: 406-421.

Kienholz, H. 1978. Maps of geomorphology and natural hazards of Grindelwald, Switzerland. Arc. Alp. Resear. 10: 169-184.

Klingebiel, A.A., E.H. Horvath, W.U. Reybold, D.G. Moore, E.A. Forsnight, and T.R. Loveland. 1988. A guide for the use of digital elevation model data for making soil surveys. U.S. Geol. Surv. Open File Rep.

Lee, D., and C.H. Juang. 1992. Evaluation of failure potential in mudstone slopes using fuzzy sets. p. 1-26. in: Stability and Performance of Slopes and Embankments II: Proc. Spec. Conf. Am. Soc. Civil Eng. and Univ. of Calif. Berkeley. Seed, R.B. and R.W. Boulanger (eds.).

Lunceford, R.A. 1976. Geology of a portion of the Pine Creek Quadrangle, Teton and Lincoln Counties, Wyoming. M.S. Thesis, Montana State Univ., Bozeman, MT.

McKenzie, J., R.L. Schaefer, and E. Farber. 1995. The student edition of Minitab for Windows users manual. Addison-Wesley Publ. Co.

Mendenhall, W., and T. Sincich. 1986. A second course in business statistics: regression analysis. Dellen Publish., Riverside, N.J.

Montagne, C. 1976. Slope stability evaluation for land capability reconnaissance in the Northern Rocky Mountains. Ph.D. Thesis in Crop and Soil Science, Montana State Univ., Bozeman, MT.

Moore, I.D, E.M. O'Loughlin, and G.J. Burch. 1988. A contour-based topographic model for hydrological and ecological applications. Earth Surf. Proc. Landforms. 13: 305-320.

Morgenstern, N.R. 1992. The evaluation of slope stability - a 25 year perspective. p. 1-26. in: Stability and Performance of Slopes and Embankments II: Proc. Spec. Conf. Am. Soc.Civil Eng. and Univ. Calif. Berkeley. Seed, R.B. and R.W. Boulanger (eds.).

Neter, J., W. Wasserman, and M.H. Kutner. 1989. Applied linear regression models. 2nd edition, Irwin Publishing, Homewood, IL.

Nilsen, T.H., F.A. Taylor, and R.M. Dean. 1976. Natural conditions that control landsliding in the San Francisco Bay Region - an analysis based on data from the 1968-69 and 1972-73 rainy seasons. Geol. Surv. Bull. 1424. U.S. Gov. Print. Off. Washington, D.C.

Olson, E., and J. McCaulpin. 1985. Geologic hazard inventory of the Teton National Forest. in: Soil Survey of the Teton National Forest. USDA For. Serv. and USDA Soil Cons. Serv. Portland,Oregon.

Palisade Corp., 1992. @RISK: risk analysis and simulation add-In for Microsoft Excel, Release 1.1, user's guide. Palisade Corp., Newfield, NY.

Pierce, K.L., and J.D. Good. 1992. Field guide to the quaternary geology of Jackson Hole, Wyoming. U.S. Geol. Surv. Open File Rep. 92-504.

Prellwitz, R.W. 1985. A complete three level approach for analyzing landslides on National Forests. p. 94-98. in: Proceedings of a Workshop on Slope Stability: Problems and Solutions in Forest Management. Gen. Tech. Rep. PNW-180. USDA For. Serv., Pacific Northwest Forest and Range Exp. Sta. Portland, OR.

Rib, H.T., and T. Liang. 1978. Landslide recognition and identification. p. 34-79. in: Landslide Analysis and Control: Trans. Resear. Board Spec. Rep.-176. Nat. Research Council. Washington, D.C.

Ritter, D.F. 1982. Process geomorphology. Wm. C. Brown, Dubuque, IA.

Roberds, W.J. 1991. Methods for developing defensible subjective probability assessments. p. 183-190. in: Geotechnical Engineering, 1990. Trans. Res. Rec. 1288.Trans. Res. Board, National Research Council.Washington, D.C., pp. 183-190.

Robertson, F., D. 1985. Landslides on steep forested terrain: the problem and resource management implications. p. 2. in: Proceedings of a Workshop on Slope Stability: Problems and Solutions in Forest Management. Gen. Tech. Rep. PNW-180. USDA For. Serv. Pacific Northwest Range and Exp. Sta., Portland, OR.

SAS Institute, 1993. SAS/INSIGHT users guide, vers. 6, second edition. SAS Institute, Cary, N.C.

Schroeder, W.L. 1985. The engineering approach to landslide risk analysis. p. 43-50. in: Proceedings of a Workshop on Slope Stability: Problems and Solutions in Forest Management. Gen. Tech. Rep. PNW-180. USDA For. Serv. Pacific Northwest Range and Exp. Sta. Portland, OR.

Schroeder, W.L., and D.N. Swanston. 1987. Application of geotechnical data to resource planning in Southeast Alaska. Geotechnical Rep. PNW-198. USDA For. Serv., Pacific Northwest Range and Exp. Sta. Portland, OR.

Thomas, B.R. 1985. Uses of soils, vegetation, and geomorphic information for road location and timber management in the Oregon Coast Ranges. p. 68-77. in: Proceedings of a Workshop on Slope Stability: Problems and Solutions in Forest Management. Gen. Tech. Rep. PNW-180. USDA For. Serv. Pacific Northwest Range and Exp. Sta. Portland, OR.

USDA Forest Service, 1992. Bridger-Teton National Forest: Bridger National Forest, Western Part, Wyoming: Soil Surv. Rep., Draft, 1992. Supervisors Office. Jackson, WY.

USDA Forest Service, 1994a. Slope stability reference guide for National Forests in the United States, USDA For. Serv. Eng. Staff. Hall, D.E., M.T. Long, and M.D. Remboldt (eds).Washington, D.C., EM-7170-13.

USDA Forest Service, 1994b. Ecological subregions of the United States: section descriptions. McNab, W.H., and P.E. Avers, compilers. Ecosystem Manage. Group (ECOMAP). Washington, D.C. WO-WSA-5.

USDA Natural Resources Conservation Service, 1995. Soil survey laboratory information manual. National Soil Surv. Cen. Lincoln, NE. Soil Surv. Inv. Rep. No. 45, version 1.0.

USDA Soil Survey Division Staff, 1993. Soil survey manual. United States Department of Agriculture Handbook No. 18. U.S. Gov. Prin. Off. Washington, D.C.

Varnes, D.J. 1978. Slope movement types and processes. p. 11-28. in: Landslide Analysis and Control: Transport. Resear. Board Spec. Rep.-176. Nat. Resear. Coun. Washington, D.C.

Varnes, D.J. 1958. Landslide types and processes. in: Landslides and Engineering Practice, Eckel, E. (ed.). Washington: Highway Resear. Res. Board. Spec. Rep. 29: 20-47.

Ward, T.J., Ruh-Ming Ri, and D.B. Simons. 1979. Mathematical modeling approach for delineating landslide hazards in watersheds. p. 109-142. in: Proc.17th Ann. Eng. Geol. and Soils Eng. Sym. Idaho Trans. Dep.- Div.of Highways.

Warrington, G.E. 1991. Soil / landslide data management for the Bridger-Teton National Forest. Draft Report. Warrington Ecological Systems Analysis, Fort Collins, CO.

Webster, R., and M.A. Oliver. 1990. Statistical methods in soil and land resource survey. Oxford University Press, New York, NY.

Wirth, T., P. Maus, H. Lachowski, and D. Fallon. 1996. Mapping ecosystems: geotechnologies provide valuable tools for mapping ecological units. Earth Obs. Mag. 5(1):14-18.

Wu, W. R.C. Sidle. 1995. A distributed slope stability model for steep forested basins. Water Resour. Res. 31(8):2097-2110.

Wu, T.H. 1995. Slope stabilization. p. 221-263. in: Slope Stabilization and Erosion Control: A Bioengineering Approach. Morgan, R.P.C., and R.J. Rickson (eds.). E&FN Spons. London.

Young, A. 1972. Slopes: geomorphology texts-3. Longman Inc. New York, NY.

APPENDICES

APPENDIX A
SOIL MAP UNIT DESCRIPTIONS

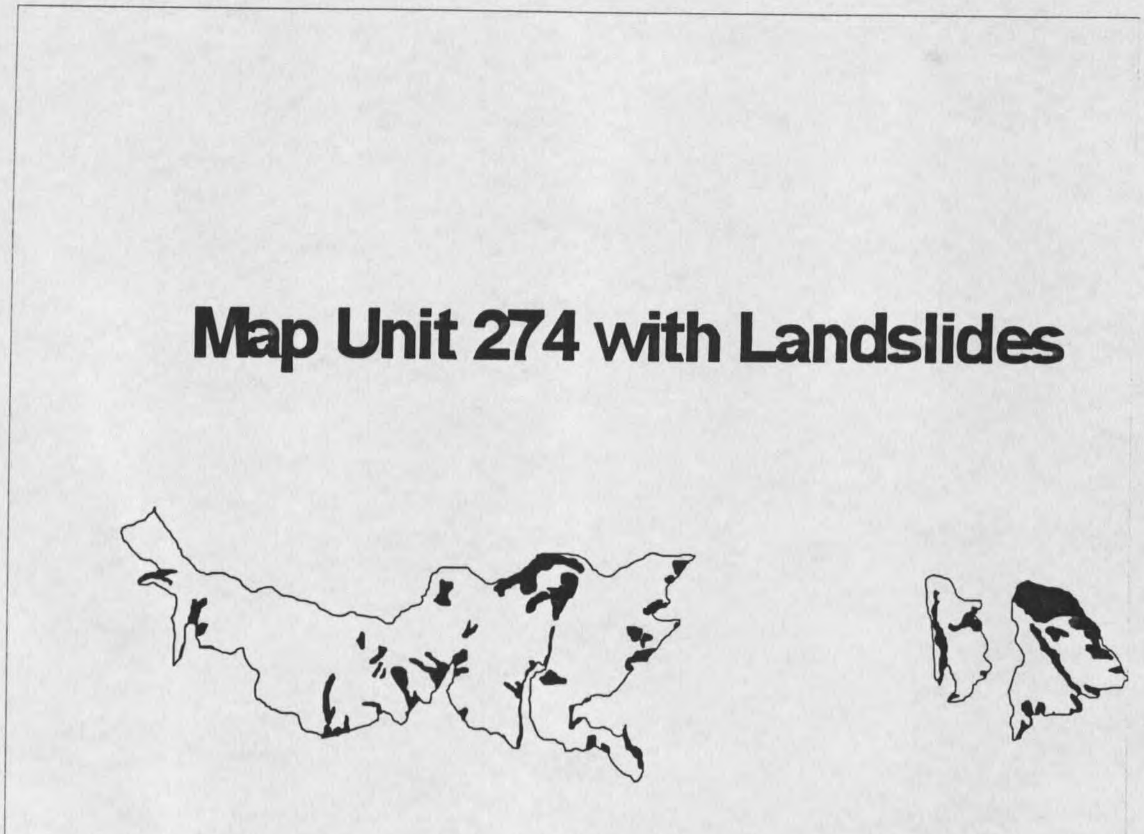


Figure 10. Spatial Distribution of Map Unit 274 with Landslides.

Map Unit 274 - Midfork - Targhee Families complex, 30 to 70 percent slopes.

SETTING

The map unit consists of oversteepened sideslopes and backslopes. Parent material is colluvium derived from sandstones and siltstones from the Gannet Group geologic formation. Elevation ranges from 6,500 to 8,000 feet. Aspects are generally south to west. Average annual precipitation ranges from 25 to 35 inches. The stability rating is marginally unstable. This unit is mapped in the Little Greys River area.

VEGETATION

The map unit supports a mosaic of vegetation. The overstory is composed of Douglas fir, subalpine fir, and quaking aspen. Common shrubs include mountain big sagebrush, white spirea, mountain snowberry, and Rocky Mountain maple. Common forbs and grasses include wyethia, coneflower, yarrow, sticky geranium, horsemint, and bluebunch wheatgrass.

COMPONENTS

The Midfork Family is approximately 45 percent of the map unit. The Targhee Family is approximately 40 percent of the unit. The remaining 15 percent includes Hiwan Family soils.

The Midfork Family soils are very deep, well drained, and intermixed throughout the map unit. The surface layer is brown very gravelly loam, 11 inches thick. The subsoil, to a depth of 20 inches, is light brown extremely cobbly loam. The substratum, to a depth of 60 inches, is brown extremely cobbly fine sandy loam. Reference Pedon #91CE328.

Permeability of the Midfork Family soils is moderate. Surface runoff is rapid. Available water capacity is very low. The habitat type is ARVA/SYOR/BRCA; mountain big sagebrush/mountain snowberry/mountain brome.

The Targhee Family soils are very deep, well drained, and intermixed throughout the map unit. The surface layer is brown gravelly loam, 7 inches thick. The subsoil, to a depth of 22 inches, is pale brown gravelly sandy clay loam. The substratum, to a depth of 60 inches, is pale brown very gravelly sandy clay loam.

Reference Pedon #91CG337.

Permeability of the Targhee family soils is moderate. Surface runoff is rapid. Available water capacity is moderate. The habitat type is ABLA/SPBE; subalpine fir/white spirea.

MANAGEMENT

The map unit has a high erosion hazard rating because of slopes greater than 30 percent. The map unit generally has a moderate compaction hazard rating because of high clay content. The map unit has a severe revegetation limitation primarily because of slopes greater than 25 percent.

The map unit has a severe equipment use and off-road vehicle rating primarily because of slopes greater than 40 percent. The map unit generally has a moderate cut and fill slopes erosion hazard rating because of slopes greater than 40 percent. The map unit has a high cut slope stability rating since mass movements may occur when slopes are excavated or wet. The map unit has a severe cut and fill revegetation limitation primarily because of slopes greater than 25 percent.

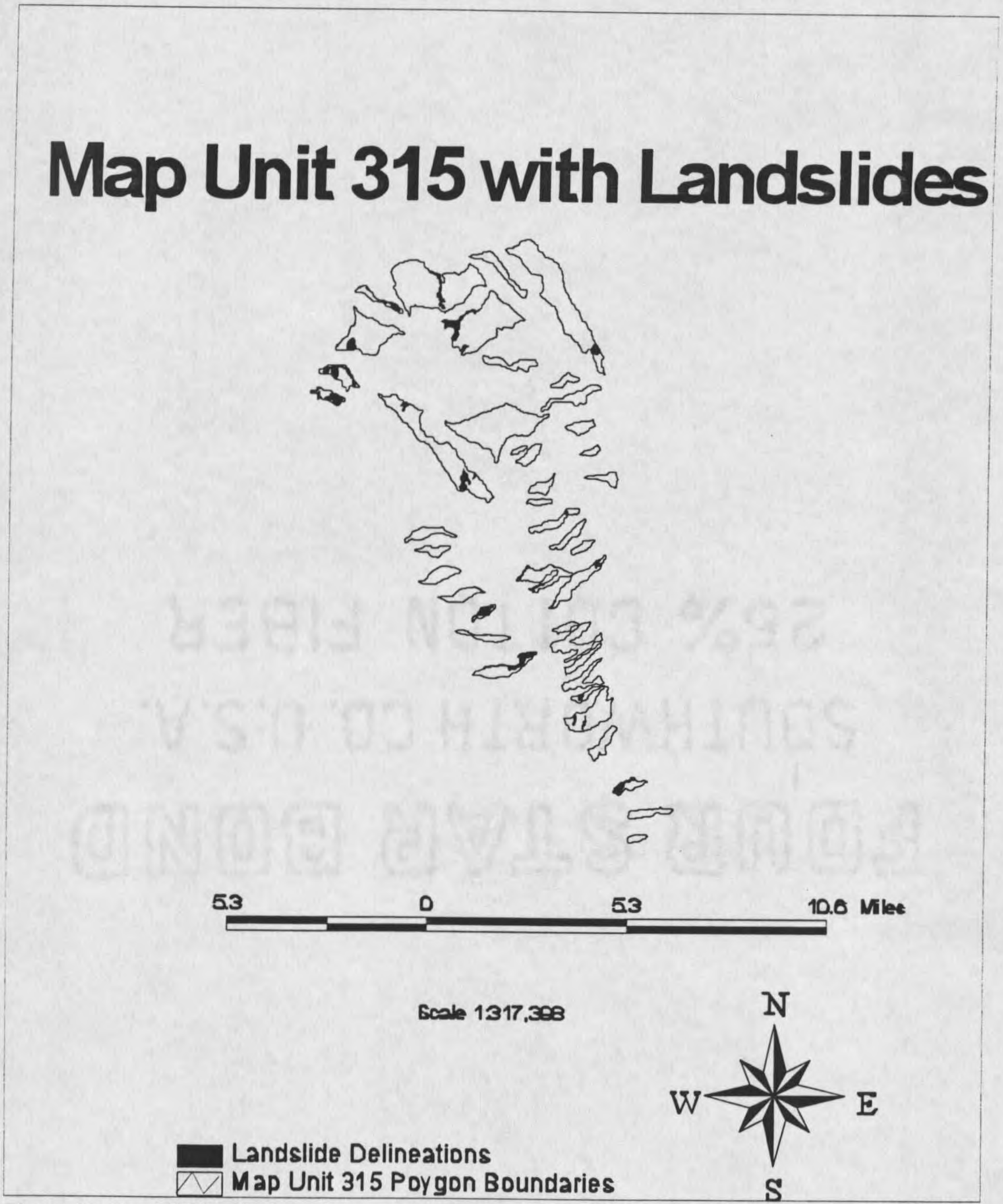


Figure 11. Spatial Distribution of Map Unit 315 with Landslides.

Map Unit 315 - Targhee Family - Mollic Paleboralfs, cobbly subsoil complex, 30 to 60 percent slopes.

SETTING

The map unit consists of sideslopes. Parent material is colluvium derived from the Aspen Shale geologic formation. Elevation ranges from 6,500 to 8,500 feet. The aspect is north to northwest. Average annual precipitation ranges from 40 to 50 inches. The stability rating is marginally unstable. The map unit is mapped in the Greys River area.

VEGETATION

The map unit supports conifer forests with an overstory consisting of subalpine fir, lodgepole pine, and Douglas fir. Understory shrubs include mountain snowberry, common snowberry, russett buffaloberry, myrtle pachistima, and serviceberry. Common forbs and grasses include lupine, cinquefoil, and pinegrass.

COMPONENTS

The Targhee Family is approximately 50 percent of map unit. Mollic Paleboralfs, cobbly subsoil soils are approximately 35 percent of the unit. The remaining 15 percent includes Reck Family soils.

The Targhee Family soils are very deep, well drained, and on steep sideslopes. The surface layer is covered with duff, 1 inch thick. The surface layer is brown gravelly loam, 5 inches thick. The subsurface layer, to depth of 15 inches, is pale brown gravelly sandy loam. The subsoil, to a depth of 60 inches, is very pale brown very gravelly sandy clay loam. Reference Pedon #91CJ348.

Permeability of Targhee Family soils is moderate. Surface runoff is rapid. Available water capacity is moderate. The habitat type is ABLA/SYAL; subalpine fir/common snowberry.

Mollic Paleboralfs, cobbly subsoil soils are very deep, well drained, and on sideslopes. The surface layer is covered with duff, 2 inches thick. The surface layer is brown gravelly fine sandy loam, 7 inches thick. The subsurface layer, to a depth of 24 inches, is light brownish gray gravelly fine sandy loam. The upper subsoil, to a depth of 34 inches, is pale brown very cobbly clay loam. The lower subsoil, to a depth of 60 inches, is pale brown very cobbly clay. Reference Pedon #91CJ351.

Permeability of Mollic Paleboralfs, cobbly subsoil soils is slow. Surface runoff is rapid. Available water capacity is moderate. The habitat type is ABLA/CARU; subalpine fir/pinegrass.

MANAGEMENT

The map unit has a high erosion hazard rating primarily because of slopes greater than 30 percent. The map unit has a high compaction hazard rating primarily because of soil characteristics and textures. The map unit has a severe revegetation limitation primarily because of slopes greater than 25 percent.

The map unit has a severe equipment use and off-road vehicle rating primarily because of slopes greater than 40 percent. The map unit has a high cut and fill slopes erosion hazard rating primarily because of slopes greater than 40 percent. The map unit has a high cut slope stability rating since mass movements may occur when slopes are excavated or wet. The map unit has a severe cut and fill revegetation limitation primarily because of slopes greater than 25 percent.

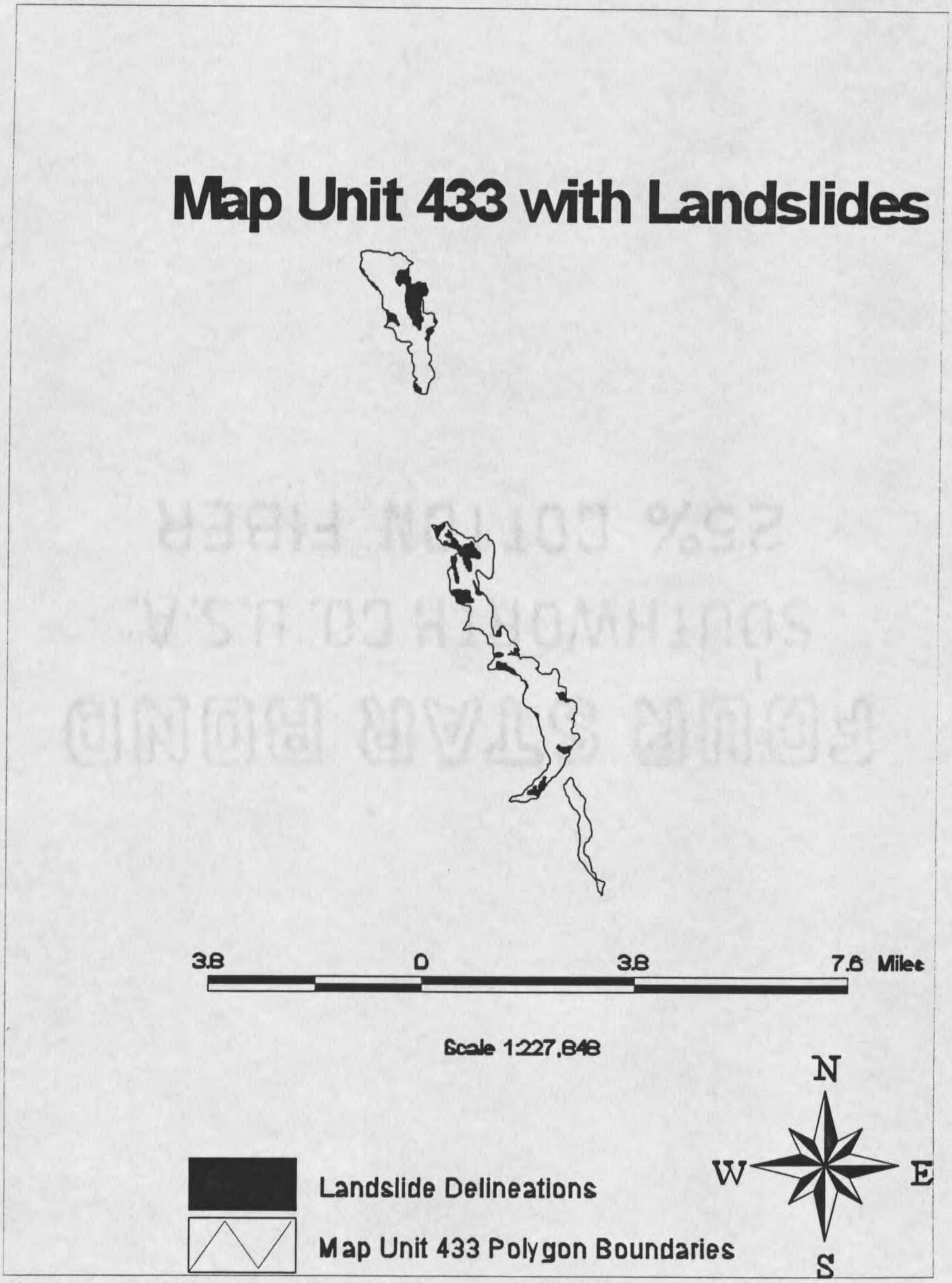


Figure 12. Spatial Distribution of Map Unit 433 with Landslides.

433 - Beaverdam - Cowdrey Families complex, 0 to 30 percent slopes.

SETTING

The map unit consists of broad ridgetops on dipslopes of major thrust faults. Parent materials are residuum and colluvium derived from sandstones, mudstones, limestones, shales, and siltstones from the Bear River and Gannett Group geologic formations. Elevation ranges from 7,500 to 8,500 feet. Aspects are predominantly west. Average annual precipitation ranges from 30 to 40 inches. The stability rating is marginally stable. This unit is mapped in the Elk Mountain and Middle Ridge areas.

VEGETATION

The map unit supports rangeland vegetation. Common shrubs include mountain big sagebrush and mountain snowberry. Common forbs and grasses include yarrow, lupine, aster, wyethia, arrowleaf balsamroot, bluebunch wheatgrass, and Idaho fescue.

COMPONENTS

The Beaverdam Family is approximately 50 percent of the map unit. The Cowdrey Family is approximately 35 percent of the unit. The remaining 15 percent includes Buckskin Family soils.

The Beaverdam Family soils are very deep, well drained, on dipslopes formed in colluvium and alluvium. The surface layer is brown clay loam, 11 inches thick. The upper subsoil, to a depth of 26 inches, is pinkish gray clay loam. The lower subsoil, to a depth of 60 inches, is pinkish gray clay. Reference Pedon #91CD330.

Permeability of Beaverdam Family soils is slow. Surface runoff is rapid. Available water capacity is high. The habitat type is ARVA/SYOR-AGSP; mountain big sagebrush/mountain snowberry-bluebunch wheatgrass.

The Cowdrey Family soils are moderately deep, well drained, and on dipslopes formed in limestone colluvium. The surface layer is brown silty clay loam, 3 inches thick. The upper subsoil, to a depth of 15 inches, is pale brown silty clay loam. The next subsoil, to a depth of 30 inches, is pale brown silty clay. The lower subsoil, to a depth of 35 inches, is pale brown very stony silty clay. Limestone bedrock is at a depth of 35 inches. Reference Pedon #91CD326.

Permeability of the Cowdrey Family soils is slow. Surface runoff is rapid. Available water capacity is moderate. The habitat type is ARVA/SYOR-AGSP; mountain big sagebrush/mountain snowberry-bluebunch wheatgrass.

MANAGEMENT

This map unit has a high erosion hazard rating primarily because of slopes greater than 30 percent. This map unit has a high compaction hazard rating primarily because of soil characteristics and textures. This map unit has a severe revegetation limitation primarily because of slopes greater than 25 percent.

This map unit has a severe equipment use and off-road vehicle rating because the lack of rock fragments limits load supporting ability. This map unit generally has a moderate cut and fill slopes erosion hazard rating because of slopes greater than 25 percent. This map unit has a high cut slope stability rating because of high clay content. This map unit has a severe cut and fill revegetation limitation primarily because of slopes greater than 25 percent.

APPENDIX B

SOIL TAXONOMIC UNIT DESCRIPTIONS

Beaverdam Family

The Beaverdam Family soils are very deep and moderately well or well drained. Permeability is slow. These soils formed in glacial till, alluvium, landslide deposits, colluvium derived from Cretaceous Bear River Formation, Cretaceous Gannet Group, siltstone, Cretaceous shale, and sandstone and claystone of the Cretaceous Ephriam and Bechler conglomerates. These soils are located on fan terraces, toeslopes, basins, dipslopes, terraces, troughs, lower sideslopes and landslides. Slopes range from 0 to 60 percent.

Taxonomic Classification: Argic Cryoborolls, fine, montmorillonitic.

Location of typical pedon: Map Unit 141. Red Castle Creek quadrangle, NW 1/4 section 24 Township 31 N Range 115 W, North Piney Creek, Big Piney Ranger District, Sublette County, Wyoming. **Latitude: 42°39'52"N Longitude: 110°29'10"W.** Reference Pedon #TSW6M/89.

These soils are also in map units 121, 243, 255, 405, 411 and 433.

Horizon Description

A1	0 to 6 inches; reddish brown (5YR 5/3), silty clay loam, dark reddish brown (5YR 3/2) moist; weak fine subangular blocky structure; soft, very friable, sticky and slightly plastic; 3 percent gravel; many very fine, fine, and medium roots; many very fine, fine, common medium pores; slightly effervescent; slightly acid (pH 6.5); clear smooth boundary.
A2	6 to 14 inches; reddish brown (5YR 5/3), silty clay loam, dark reddish brown (5YR 3/2) moist; weak fine and medium subangular blocky structure; slightly hard, firm, very sticky and slightly plastic; 3 percent gravel; common very fine,

fine, and medium roots; many very fine, common fine and medium pores; neutral (pH 7.0); abrupt wavy boundary.

Bt1 14 to 32 inches; reddish brown (5YR 5/3), clay, reddish brown (5YR 4/3) moist; weak coarse prismatic parting to strong fine and medium angular blocky structure; extremely hard, extremely firm, very sticky and very plastic; many thick clay films on faces of peds; 3 percent gravel; common very fine, fine, few medium roots; common very fine, fine, and medium pores; slightly effervescent; moderately alkaline (pH 8.0); clear wavy boundary.

Bt2 32 to 49 inches; reddish brown (5YR 5/3), clay, reddish brown (5YR 5/3) moist; moderate coarse prismatic parting to strong fine and medium angular blocky structure; extremely hard, extremely firm, very sticky and very plastic; many thick clay films on faces of peds; 3 percent gravel; 10 percent cobbles; few very fine roots; few very fine pores; strongly effervescent; moderately alkaline (pH 8.3); clear wavy boundary.

2C 49 to 70 inches; light reddish brown (5YR 6/3), very gravelly silty clay loam, dark reddish gray (5YR 4/2) moist; massive; slightly hard, firm, sticky and slightly plastic; 30 percent gravel, 10 percent cobbles, 10 percent stones; few very fine roots; common fine, medium, and coarse pores; strongly effervescent; moderately alkaline (pH 8.3).

Thickness of the mollic epipedon ranges from 10 to 15 inches. Surface texture is silty clay loam, clay loam, or loam. The A horizon is 0 to 5 percent gravel. The reaction class in the A horizon is slightly acid through slightly alkaline. Some pedons have an E horizon with a texture of loam. The texture of the Bt horizon is dominately clay, clay loam, silty clay, and gravelly clay. Thin layers of very cobbly clay loam also occur in the Bt horizon in some pedons. The Bt horizons are 0 to 15 percent gravel and 0 to 10 percent cobbles. The Bt horizons are noneffervescent to strongly effervescent. Calcium carbonate equivalent in the Bt horizons ranges from 0 to 10 percent. The reaction class in the Bt horizons is neutral through moderately alkaline. The 2C horizon is 25 to 35 percent gravel, 5 to 10 percent cobbles, and 5 to 10 percent stones. The 2C horizon is absent in some pedons. Some pedons have a Bk horizon. Texture of the Bk horizon is very gravelly sandy loam, very gravelly silty clay loam, or gravelly clay. Calcium carbonate equivalent ranges from 5 to 10 percent in the Bk and 2C horizons. Some pedons have a rare flooding frequency and a high water table at 4 to 6 feet depth May through July.

Cowdrey Family

The Cowdrey Family soils are moderately deep and moderately well or well drained. Permeability is slow. These soils formed in landslide deposits, colluvium, and residuum derived from siltstone, sandstone, claystone, limestone, mudstone and shale of Cretaceous Blind Bull, Bear River, Gannett and Aspen formations. These soils are located on sideslopes and dipslopes. Slopes range from 0 to 50 percent.

Taxonomic Classification: Typic Cryoboralfs, fine, montmorillonitic.

Location of typical pedon: Map Unit 334. Park Creek quadrangle, section N/A Township 32 N Range 116 W, North Three Forks Creek, Greys River Ranger District, Lincoln County, Wyoming. **Latitude: 42°47'13"N Longitude: 110°43'21"W.** Reference Pedon #TVW31A/90.

These soils are also in map unit 433.

Horizon Description

Oi 5 inches to 0; duff.

E 0 to 4 inches; light gray (10YR 7/2), sandy clay loam, brown (10YR 5/3) moist; weak fine subangular blocky structure; soft, very friable, sticky and slightly plastic; 10 percent gravel, 2 percent cobbles; many very fine and fine, common medium roots; many fine and medium pores; moderately acid (pH 6.0); clear wavy boundary.

Bt1 4 to 11 inches; pale yellow (2.5Y 7/4), clay, light olive brown (2.5Y 5/4) moist; weak fine and medium subangular blocky structure; very hard, very firm, very sticky and very plastic; common moderately thick clay films on faces of peds; 5 percent gravel; many very fine and fine roots; common fine and medium pores; slightly acid (pH 6.5); clear wavy boundary.

Bt2 11 to 22 inches; grayish brown (2.5Y 5/2), clay, dark grayish brown (2.5Y 4/2) moist; moderate medium granular and subangular blocky structure; very hard, very firm, very sticky and very plastic; many moderately thick clay films on faces of peds; 10 percent gravel; common very fine and fine roots; few fine and medium pores; neutral (pH 7.0); clear wavy boundary.

Cr 22 to 67 inches; decomposed siltstone and shale.

R 67 inches; interbedded siltstone and shale.

Thickness of the ochric epipedon ranges from 3 to 7 inches. Some pedons have an A horizon. Some pedons do not have an E horizon. Texture of the E and A horizons is sandy clay loam or silty clay loam. The reaction class of the E and A horizons is moderately acid through neutral. The E and A horizons are 5 to 10 percent gravel and 0 to 5 percent cobbles. The argillic ranges in thickness from 15 to 35 inches. Texture of the Bt horizons is dominantly clay, silty clay or silty clay loam with 5 to 10 percent gravel. Thin layers of very stony silty clay also occur in the Bt horizons immediately above the bedrock in some pedons. These thin layers are 10 to 15 percent gravel, 20 to 25 percent cobbles, and 20 to 25 percent stones. The reaction class of the Bt horizons is slightly acid through moderately alkaline. Calcium carbonate equivalent ranges from 0 to 10 percent in the lower part of the Bt horizon. The Bt horizon is noneffervescent to strongly effervescent. Depth to the Cr horizon ranges from 20 to 40 inches.

Midfork Family

The Midfork Family soils are very deep and well drained. Permeability is moderate or moderately rapid. These soils formed in colluvium and residuum derived from Triassic Ankareh Red Beds, Woodside Redbeds, Dinwoody, Jurassic Nugget, Cretaceous Gannet Group, and Permian, Pennslyvanian, and Mississippian Wells, Amsden, and Madison formations. These soils are located on sideslopes. Slopes range from 30 to 90 percent.

Taxonomic Classification: Typic Cryoborolls, loamy-skeletal, mixed.

Location of typical pedon: Map unit 276. MT. Schidler quadrangle, NW 1/4 of SE 1/4 of SE 1/4 Section 19 Township 31 N Range 115 W, North Piney Lake, Big Piney Ranger District, Sublette County, Wyoming. **Latitude 42°39'19"N Longitude 110°34'33"W.** Reference pedon #M1/88.

These soils are also in map units 266, 274, and 275.

Horizon Description

A 0 to 9 inches; brown (10YR 5/3), very gravelly sandy loam, dark brown (10YR 3/3) moist; weak fine granular and weak fine subangular blocky structure; soft, very friable, nonsticky and nonplastic; 40 percent gravel, 15 percent cobbles; many very fine and fine, common medium and coarse roots; many fine, common medium pores; moderately acid (pH 6.0); clear smooth boundary.

C 9 to 60 inches; brownish yellow (10YR 6/6), extremely cobbly sandy loam, dark yellowish brown (10YR 4/6) moist; weak medium subangular blocky structure; soft, very friable, nonsticky and nonplastic; 20 percent gravel, 25 percent cobbles, 15 percent stones; common very fine, fine, medium, and few coarse roots; common fine and medium pores; slightly acid (pH 6.3).

Thickness of the mollic epipedon ranges from 7 to 12 inches. Texture of the A horizon is very gravelly sandy loam, gravelly loam or very gravelly loam. The A horizon is 20 to 45 percent gravel and 0 to 15 percent cobbles. The reaction class of the A horizon is moderately acid or slightly acid. The texture of the control section is dominantly extremely cobbly sandy loam, very gravelly loam, extremely cobbly loam, extremely cobbly fine sandy loam or very cobbly sandy clay loam. The control section is 10 to 45 percent gravel, 5 to 35 percent cobbles and 0 to 20 percent stones. The reaction class of the control section is slightly acid or neutral. A Bw horizon may be present in some pedons.

Mollic Paleboralfs, cobbly subsoil Family

The Mollic Paleboralfs, cobbly subsoil Family soils are very deep and well drained. Permeability is slow. These soils formed in colluvium derived from the Cretaceous Aspen Shale formation. These soils are located on sideslopes. Slopes range from 30 to 60 percent.

Taxonomic Classification: Mollic Paleboralfs, clayey-skeletal, mixed.

Location of typical pedon: Map Unit 315. Deer Creek quadrangle, NW 1/4 of NW 1/4 section 29 Township 36 N Range 117 W, Hot Foot Creek, Greys River Ranger District, Lincoln County, Wyoming. **Latitude: 43°04'47N" Longitude:110°50'03W".** Reference Pedon #91CJ351.

Horizon Description

Oi	2 inches to 0; duff.
A	0 to 7 inches; brown (10YR 5/3) gravelly fine sandy loam, dark brown (10YR 3/3) moist; weak fine subangular blocky structure; soft, very friable, nonsticky and nonplastic; 15 percent gravel; many very fine and fine, common medium and coarse roots; many fine, medium and coarse pores; moderately acid (pH 6.0); clear smooth boundary.
E	7 to 24 inches; light brownish gray (10YR 6/2) gravelly fine sandy loam, dark grayish brown (10YR 4/2) moist; weak fine subangular blocky structure; soft, very friable, nonsticky and nonplastic; 15 percent gravels, 5 percent cobbles; many very fine and fine, few medium and coarse roots; many fine, medium and coarse pores; moderately acid (pH 6.0); gradual wavy boundary.
Bt1	24 to 34 inches; pale brown (10YR 6/3) very cobbly clay loam, brown (10YR 4/3) moist; common faint light gray (10YR 7/2) interfingering of albic materials; moderate fine subangular blocky structure; slightly hard, firm, sticky and plastic; few thin clay films bridging sand grains; 15 percent gravel, 20 percent cobbles, 5 percent stones; common fine roots; common fine pores; slightly acid (pH 6.5); clear wavy boundary.

Bt2 34 to 60 inches; pale brown (10YR 6/3) very cobbly clay, brown (10YR 4/3) moist; strong fine and medium angular blocky structure; hard, firm, very sticky and very plastic; common moderately thick clay films on faces of peds; 15 percent gravel, 25 percent cobbles, 5 percent stones; few fine roots; few fine pores; neutral (pH 7.0).

Thickness of the ochric epipedon ranges from 6 to 10 inches. The argillic horizon ranges in thickness from 30 to 40 inches. The A horizon is 15 to 25 percent gravel. The E horizon is 15 to 25 percent gravel and 0 to 10 percent cobbles. The Bt horizons are 10 to 20 percent gravel, 15 to 25 percent cobbles, and 5 to 10 percent stones.

Targhee Family

The Targhee Family soils are very deep and well drained. Permeability is moderate or moderately rapid. These soils formed in colluvium derived from sandstone, mudstone, limestone, siltstone, quartzite and conglomerate. The formations are the Jurassic Stump, Twin Creek and Ankareh Red Bed, and Cretaceous Gannet Group, Ephraim, and Aspen Shale. These soils are located on sideslopes and escarpments. Slopes range from 30 to 90 percent.

Taxonomic Classification: Typic Cryochrepts, loamy-skeletal, mixed.

Location of typical pedon: Map Unit 306. Mt Wagner quadrangle, East side North Fork Smiths Fork, Kemmerer Ranger District, Lincoln County, Wyoming. **Latitude: 42°31'02"N Longitude: 110°49'02"W.** Reference Pedon #M20/84.

These soils are also in map units 226, 274, 315 and 326.

Horizon Description

Oe	2 inches to 0; duff.
A	0 to 13 inches; light reddish brown (5YR 6/3) dry; sandy loam, reddish brown (5YR 4/3) moist; weak fine and moderate medium granular structure; soft, friable, nonsticky and nonplastic; 2 percent gravel; many fine and medium roots; many fine and medium pores; slightly acid (pH 6.5); gradual wavy boundary.
Bw	13 to 21 inches; reddish brown (5YR 5/4), gravelly sandy loam; dark reddish brown (5YR 3/4) moist; weak fine granular and weak medium subangular blocky structure; soft, friable, nonsticky and nonplastic; 30 percent gravel, 5 percent cobbles; few fine and coarse roots; common fine and medium pores; slightly acid (pH 6.5); gradual wavy boundary.
C1	21 to 28 inches; light reddish brown (5YR 6/3) dry; gravelly sandy loam; reddish brown (5YR 4/3) moist; single grain; loose; 30 percent gravel, 2 percent cobbles; common fine and medium pores; slightly acid (pH 6.5); gradual wavy boundary.
C2	28 to 60 inches; light reddish brown (5YR 6/3) dry; extremely gravelly sandy loam; reddish brown (5YR 4/3) moist; single grain; loose; 50 percent gravel, 20 percent cobbles; common fine and medium, few coarse pores; slightly acid (pH 6.5).

Thickness of the ochric epipedon ranges from 5 to 13 inches. Texture of the A horizon is sandy loam, gravelly sandy loam, very gravelly loam or gravelly loam. The A horizon is 0 to 50 percent gravel and 0 to 5 percent cobbles. The reaction class of the A horizon is moderately acid or slightly acid. Texture of the

Bw horizon is gravelly sandy loam, very gravelly sandy loam, very gravelly loam, sandy loam, gravelly sandy clay loam, very gravelly sandy clay loam or extremely gravelly loam. The Bw horizon is 15 to 70 percent gravel, 0 to 15 percent cobbles and 0 to 15 percent stones. The control section averages 45 to 75 percent rock fragments. Texture of the C horizon is gravelly sandy loam, very gravelly sandy clay loam, or extremely gravelly sandy loam. The C horizon is 25 to 60 percent gravel and 0 to 20 percent cobbles. Some pedons have an E horizon with a texture of gravelly sandy loam.