A LANDSLIDE HAZARD RATING SYSTEM FOR COLORADO HIGHWAYS

by

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ABSTRACT

This thesis presents the Colorado Landslide Hazard Rating System (CLHRS), a framework for quantifying landslide risk as it applies to highways in the state of Colorado. A preliminary version of the CLHRS was developed based on a review of the current body of technical literature regarding the factors that contribute to landslide hazard, consequence, and risk. The preliminary CLHRS consisted of 11 Hazard Factors and 8 Consequence Factors that were used to calculate an overall risk score. The preliminary CLHRS was used to evaluate 69 landslides distributed throughout western Colorado. The resulting scoring distributions were subjected to a suite of statistical analyses in order to facilitate data screening and identify the factors that possessed the greatest statistical merit. Descriptive statistics were used to establish severity category breaks for hazard, consequence, and risk. Evaluation of the distribution of scores for each factor as well as correlation analysis, ordinal logistic regression, and stepwise regression were used to eliminate factors that lacked sufficient predictive power. Cluster analysis was applied as a secondary method for establishing boundaries on severity categories and compared to the descriptive statistics method.

The data screening steps allowed for the creation of a final functional version of the CLHRS consisting of 6 Hazard Factors: geology, vegetative cover, slope aspect, surface water influence, failure frequency, and slope angle, and 6 Consequence Factors: depth to slide plane, length of highway affected, average daily traffic, detour options, worst-case scenario detour time, and annual maintenance cost. Linear regressions comparing the 19 parameter system to the 12 parameter system indicate that consistent patterns in total score distributions are maintained. Furthermore, comparisons of the landslides with the highest risk scores to their respective case studies further corroborate the findings of this research.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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For Karen & Ben

CHAPTER 1
INTRODUCTION

Many vital transportation routes in Colorado pass through mountainous terrain that is susceptible to geological hazards such as rockfall and landslides. The Colorado Department of Transportation (CDOT) currently uses a rockfall hazard rating system (RHRS) to evaluate rockfall hazard potential and risk for such areas (Pierson, 1991; Santi et al., 2009). In addition to the RHRS, CDOT has created a risk rating system for landslides based in part on Washington State DOT's Unstable Slope Management System (Lowell and Morin, 2000). The aim of this research is to develop a more comprehensive landslide hazard rating system (LHRS) with the cooperation of CDOT for use as a companion to the RHRS. This new system will address deficiencies found in current landslide rating systems by including factors relating to climatic, seismic, geologic, and hydrologic influences on landslide stability. Additionally, the Colorado LHRS (CLHRS) will serve as a time-efficient and cost-effective means of assessing landslide risk by evaluating the potential for failure (i.e., hazard) and the resulting impacts of failure (i.e., consequences) separately to produce a final risk score. The advantage of this system is that it allows for the identification, ranking, and comparison of slopes that pose the most immediate threat to public safety as well as the justification of resources for mitigation. Also, through routine application of the CLHRS to known landslides, a working inventory of slope characteristics can be maintained, thus highlighting changes in slope conditions over time. In order to produce a final version of the CLHRS, a preliminary version of the CLHRS was first developed based on a thorough literature review and applied to 78 landslides that threaten transportation routes throughout western Colorado. Evaluation of the resulting scores and subsequent application of statistical analyses enabled the identification of the most salient factors that contribute to landslide hazard and risk in Colorado, thus allowing for further refinement of the CLHRS and the production of a final functional version.

CHAPTER 2

BACKGROUND AND DEFINITIONS

This chapter identifies key terminology that is used repeatedly throughout the discussion of this research. By clearly defining these terms, it is hoped that confusion with terminology found in discussions of other hazard rating systems will be avoided. Additionally, current landslide hazard rating systems are compared to the preliminary CLHRS.

2.1. Definitions of Hazard, Consequence, and Risk

As noted by Pantelidis (2010), many agencies do not distinguish between “hazard” and “consequence” nor do they adhere to a consistent definition of “risk” when calculating final scores. Therefore, it is necessary to define these terms and their specific applications within the CLHRS in order to avoid such ambiguities.

2.1.1 Consequence Definition

The “consequences” or “impacts” of landslide failure are defined as the negative effects caused by the hazard. Slope characteristics that do not influence slope stability but whose magnitudes affect the severity of the impacts of failure are represented by “Consequence Factors.” For example, the length of highway affected by a landslide is unrelated to the stability of the slide itself. However, landslides that affect longer sections of highway have the potential to produce more severe consequences in terms of cost, labor, and detoured traffic.

2.1.2 Hazard Definition

Crozier and Glade (2005) provide both physical and technical definitions of “hazard” as it applies to landslides. In the physical sense, a landslide is a process that has the potential to cause damage (i.e., the landslide is the “hazard”). In a technical sense, hazard is the probability of occurrence of a landslide of a specific magnitude at a given site. Since the CLHRS is intended to function as a tool for preliminary investigation and slope inventory, a field technician should not be expected to calculate or predict failure probabilities. Therefore, in order to quantify hazard, a series of “Hazard Factors” have been developed for use in the CLHRS. These Hazard Factors reflect slope conditions that may contribute to failure (e.g., a steep slope angle) as well as conditions that may function as triggering mechanisms to initiate failure (e.g., high annual precipitation). Evaluation of such factors yields a “Hazard Score” that serves as a semi-quantitative representation of the conditions that contribute to the probability of failure instead of a direct mathematical expression of failure probability.

2.1.3 Risk Definition

Crozier and Glade (2005) define “risk” as “the measure of probability and severity of loss to the elements at risk” and provide a general expression for risk calculation:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \times \text{Elements at Risk} \quad (2.1)$$

While comprehensive, the input values of this expression would require an investigator to appraise the value and assess the vulnerability of any possible element at risk, which is defined by Varnes (1984) as “the degree of loss to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude.” Elements at risk may range from man-made structures to the physical and mental well-being of the affected public (Crozier and Glade, 2005) and are judged to be prohibitively difficult to assess in the context of a rapid rating system. Alternatively, Pantelidis (2010) provides an expression for “risk” as the product of hazard and consequence, or:

$$\text{Risk} = \text{Hazard} \times \text{Consequence} \quad (2.2)$$

This simplified expression is ideal for use with the CLHRS because it allows for the creation of two distinct groups of factors, hazard and consequence, and ensures that the system does not become needlessly complex. This two-element system allows hazard and consequence to be evaluated separately then combined to estimate risk, which enables the creation of rankings in terms of the highest hazard, consequences, or risk, depending on the motives of inquiry.

2.2 Slope Movement Type Distinction

The term “landslide” encompasses a wide variety of slope mass movements. The classification of slope movements developed by Varnes (1978) is perhaps the most widely recognized scheme and involves classification of slope movements on the basis of movement type and material type. Movement types include falls, topples, slides, lateral spreads, flows, and complex landslides. The CLHRS is intended for use only in evaluating the hazard potential of landslides that have distinct zones of rupture along which earth material is displaced via shear failure or movement along rock discontinuities (i.e., landslides that fit into Varnes’ “slide” category). Movement types such as rockfalls and topples are better suited to evaluation by the Colorado RHRS (Pierson, 1991; Santi et al., 2009). Flow movement types, such as debris flows or earth flows, are not continuing, progressive failures and can only be evaluated by observing a current event or the resulting geomorphic expressions of an event (e.g., channels, fans, fresh deposits, etc.). Spreads are imperceptibly slow-moving progressive failures that lack distinct failure planes that could result in rapid failure and threaten roadways. Complex landslides may consist of combinations of more than one movement type, which would make attaining a representative hazard score difficult. Therefore, complex landslides are best evaluated through conventional fieldwork and thorough site investigation.

2.3 Current Landslide Rating Systems

Several scoring systems have been developed to assess the relative hazard and/or risk from landslides and are currently in use by several domestic DOTs and other agencies (Dalqamouni, 2011; Liang et al., 2006; Lowell and Morin, 2000; Oregon DOT, 2001; Saldivar-Sali and Einstein, 2007). These systems take into consideration a wide variety of factors that cover both slope and road characteristics. These characteristics typically encompass either the conditions that contribute to and/or trigger a landslide failure, or conditions related to the potential negative impacts or consequences of a landslide failure. Each characteristic is broken into three or four severity categories, each with a corresponding numerical score that increases exponentially with severity. Final scores are reported based on the system-specific scoring procedure to yield a value that reflects the overall hazard potential or risk. A matrix comparing factors and scoring procedures used in published hazard rating systems as well as the product of this research, the CLHRS, is presented in Table 2.1.

As shown in Table 2.1, most existing systems sum the numerical scores assigned to each factor to produce a risk value. The systems for Oregon (Oregon DOT, 2001) and the Philippines (Saldivar-Sali et al., 2007) differ in that multipliers are applied to the summed scores to arrive at a final value. The scoring process for the CLHRS involves multiplying the sum of eleven Hazard Factors with the sum of eight Consequence Factors to produce a final “Risk” score.

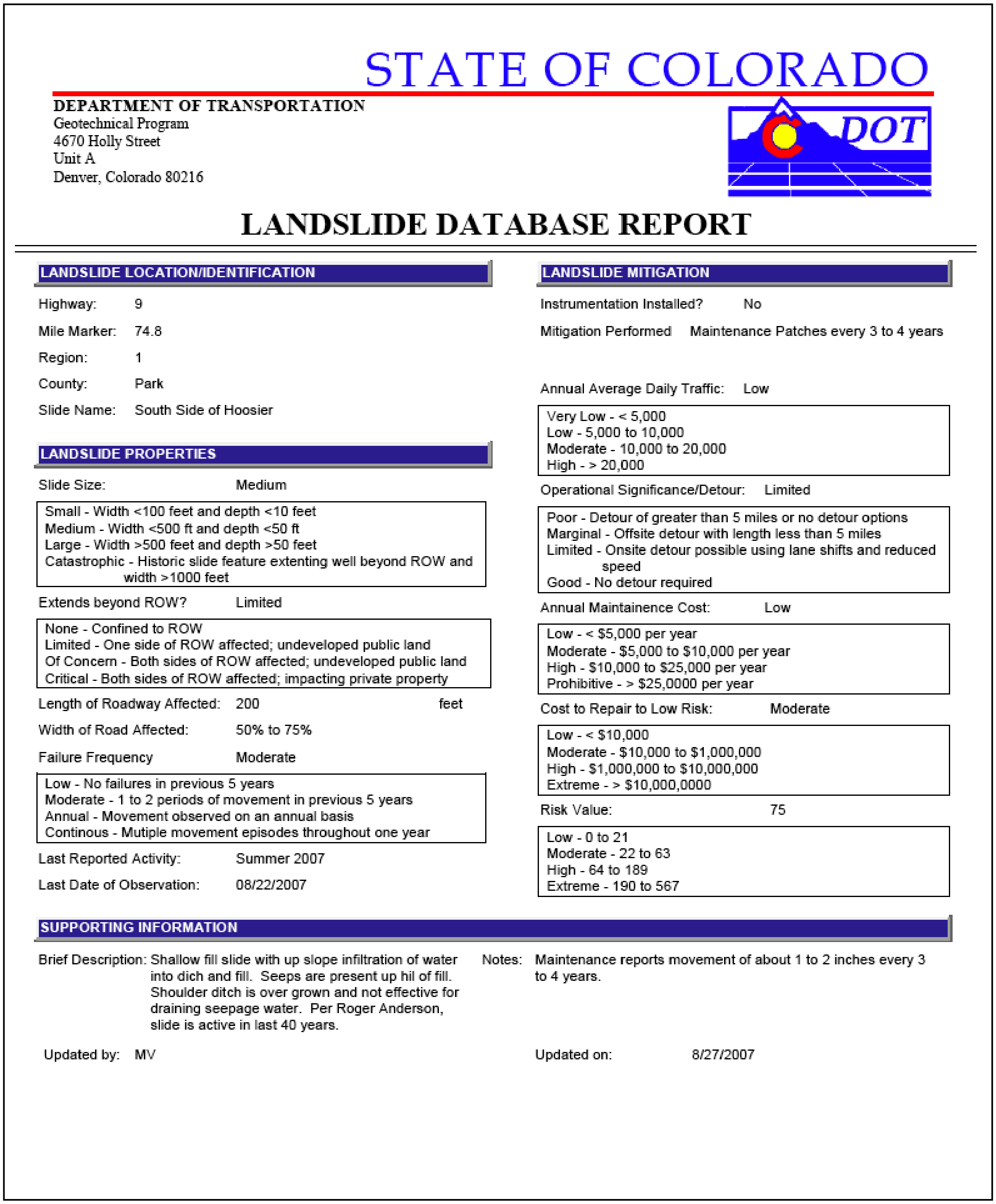
Table 2.1 makes the distinction between factors that are related to “consequence” as defined in Section 2.1.1 and the factors related to “hazard” as defined in Section 2.1.2. This distinction is not emphasized within the various systems presented in Table 2.1 and final scores are defined as either “hazard” or “risk” scores or values. The terminology associated with each system is preserved when discussing aspects of the corresponding system. However, all discussions related to the CLHRS developed through this study will adhere to the definitions described above in Chapter 2.

2.3.1 Current CDOT Risk Rating System

CDOT currently maintains a working database of risk characteristics for each landslide threatening Colorado transportation routes. These characteristics are summarized in “Landslide Database Reports” and are stored electronically as PDF documents. Landslides are located and identified by the number of the highway to which they are immediately adjacent, the closest mile marker measured to the nearest one-hundredth of a mile, county name, CDOT Engineering Region number, and slide name, if assigned. An example of a typical CDOT Landslide Database Report is presented as Figure 2.0.

Table 2.1 Comparison matrix of various current landslide hazard rating systems as well as the preliminary CLHRS. An “X” indicates that the factor is evaluated in the corresponding system. Note: the factors indicated by “X*” are evaluated in the CLHRS, but only one is selected for each landslide site.

Rating System Location		Colorado, USA	Washington, USA	Oregon, USA	Ohio, USA	Baguio, Philippines	Northeast Ohio, USA	Preliminary CLHRS
Reference		(current system)	(Lowell and Morin, 2000)	(Oregon Department of Transportation, 2001)	(Liang et al., 2007)	(Saldivar-Sali and Einstein, 2007)	(Dalqamouni, 2011)	(this study)
Hazard-Related Factors	Problem Type: Soil/Rock	-	X	-	-	-	-	X*
	USCS Classification	-	-	-	-	-	-	X*
	Rock Strength	-	-	-	-	-	-	X*
	Permeability	-	-	-	-	-	-	X*
	Jar Slake Test	-	-	-	-	-	-	X*
	Discontinuity Orientation	-	-	-	-	-	-	X*
	Bedrock Geology	-	-	-	-	X	-	-
	Liquidity Index	-	-	-	-	-	X	-
	Vegetation	-	-	-	-	X	-	X
	Annual Precipitation	-	-	-	-	-	-	X
	Slope Aspect	-	-	-	-	-	-	X
	Groundwater Seepage	-	-	-	-	-	-	X
	Surface Water Influence	-	-	-	-	-	-	X
	Drainage Condition	-	-	-	-	-	-	X
	Recharge Area	-	-	-	-	-	X	-
	Peak Ground Acceleration	-	-	-	-	-	-	X
	Failure Frequency	X	X	-	-	-	-	X
	Displacement Rate	-	-	-	X	-	-	-
	Pavement Damage	-	X	-	X	-	-	X
	Slope Angle	-	-	-	-	X	X	X
	Slope Height	-	-	-	-	-	X	-
	Slope Length	-	-	-	-	-	X	-
Consequence-Related Factors	Extent of Slide beyond ROW	X	-	-	X	-	-	X
	Depth to Slide Plane	-	-	-	-	-	-	X
	Size	X	-	-	-	-	-	X
	Detour Options	X	X	X	-	-	-	X
	Worst Case Detour Time	-	-	-	-	-	-	X
	Average Daily Traffic	X	X	X	X	-	X	X
	Annual Maintenance Costs	X	X	-	-	-	-	X
	Road Width Affected	X	X	-	-	-	-	-
	Maintenance Frequency	-	-	X	X	-	-	-
	Maintenance Response	-	-	-	X	-	-	-
	Decision Sight Distance	-	X	-	X	-	X	-
	Length of Roadway Affected	-	X	-	-	-	X	X
	Accident History	-	X	X	X	-	-	-
	Vehicle Risk	-	X	-	-	-	X	-
	Impact Potential	-	-	X	X	-	-	-
	Population Multiplier (PM)	-	-	-	-	X	-	-
	Land Use Multiplier (LU)	-	-	-	-	X	-	-
	Highway Importance (HI)	-	-	X	-	-	-	-
	Maint. Cost-Benefit (CB)	-	-	X	-	-	-	-
FINAL SCORE CALCULATION:		Σ7	Σ11	Σ5*CB*HI	Σ9	Σ3*LU*PM	Σ9	Σ11 x Σ8



STATE OF COLORADO

DEPARTMENT OF TRANSPORTATION
Geotechnical Program
4670 Holly Street
Unit A
Denver, Colorado 80216

LANDSLIDE DATABASE REPORT

LANDSLIDE LOCATION/IDENTIFICATION

Highway:	9
Mile Marker:	74.8
Region:	1
County:	Park
Slide Name:	South Side of Hoosier

LANDSLIDE PROPERTIES

Slide Size: Medium

Small - Width <100 feet and depth <10 feet
Medium - Width <500 ft and depth <50 ft
Large - Width >500 feet and depth >50 feet
Catastrophic - Historic slide feature extenting well beyond ROW and width >1000 feet

Extends beyond ROW? Limited

None - Confined to ROW
Limited - One side of ROW affected; undeveloped public land
Of Concern - Both sides of ROW affected; undeveloped public land
Critical - Both sides of ROW affected; impacting private property

Length of Roadway Affected: 200 feet

Width of Road Affected: 50% to 75%

Failure Frequency Moderate

Low - No failures in previous 5 years
Moderate - 1 to 2 periods of movement in previous 5 years
Annual - Movement observed on an annual basis
Continous - Mutiple movement episodes throughout one year

Last Reported Activity: Summer 2007

Last Date of Observation: 08/22/2007

LANDSLIDE MITIGATION

Instrumentation Installed? No

Mitigation Performed Maintenance Patches every 3 to 4 years

Annual Average Daily Traffic: Low

Very Low - < 5,000
Low - 5,000 to 10,000
Moderate - 10,000 to 20,000
High - > 20,000

Operational Significance/Detour: Limited

Poor - Detour of greater than 5 miles or no detour options
Marginal - Offsite detour with length less than 5 miles
Limited - Onsite detour possible using lane shifts and reduced speed
Good - No detour required

Annual Maintainence Cost: Low

Low - < $5,000 per year
Moderate - $5,000 to $10,000 per year
High - $10,000 to $25,000 per year
Prohibitive - > $25,0000 per year

Cost to Repair to Low Risk: Moderate

Low - < $10,000
Moderate - $10,000 to $1,000,000
High - $1,000,000 to $10,000,000
Extreme - > $10,000,0000

Risk Value: 75

Low - 0 to 21
Moderate - 22 to 63
High - 64 to 189
Extreme - 190 to 567

SUPPORTING INFORMATION

Brief Description: Shallow fill slide with up slope infiltration of water into dich and fill. Seeps are present up hil of fill. Shoulder ditch is over grown and not effective for draining seepage water. Per Roger Anderson, slide is active in last 40 years.

Notes: Maintenance reports movement of about 1 to 2 inches every 3 to 4 years.

Updated by: MV

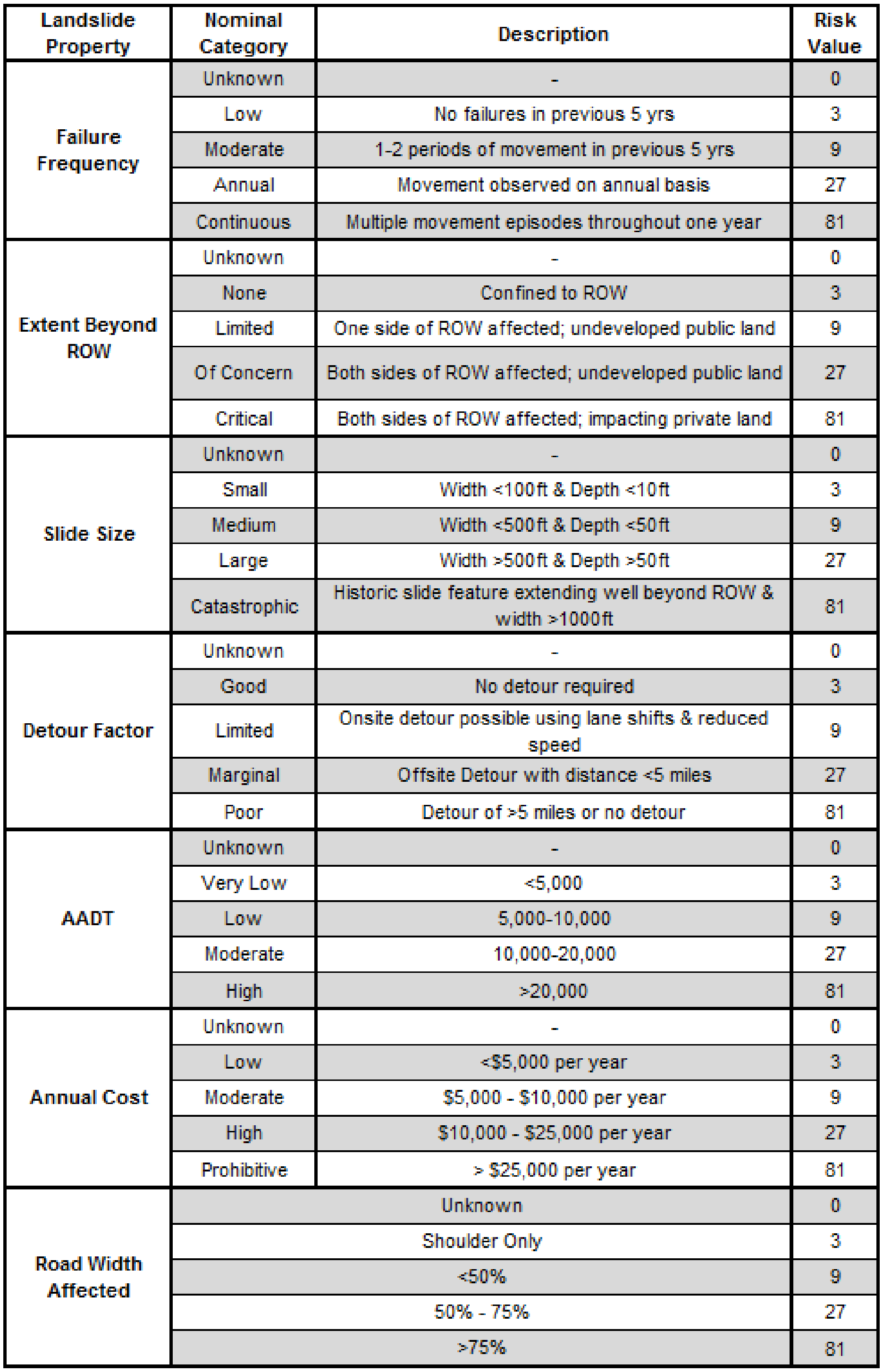
Updated on: 8/27/2007

Figure 2.0 Typical CDOT Landslide Database Report

A “Risk Value” is generated for each landslide based on the evaluation of seven “landslide properties” (see Table 2.2). For each landslide property there are five possible degrees of severity. The risk values assigned to each category increase exponentially with severity using a base of three (i.e., 0, 3, 9, 27, 81). Five of the seven landslide properties, as well as the scoring procedure have been directly adopted from WSDOT’s Unstable Slope Management System (USMS) (Lowell and Morin, 2000). Final Risk Values can range from 0 to 567. The risk categories used by CDOT for prioritization and decision-making are summarized in Table 2.3. Though six of the seven factors evaluated in the current CDOT system assess features associated with the consequences of failure, final scores are defined as “Risk Values.” In order to maintain consistency with current CDOT terminology, final scores are discussed as “risk” scores despite the discrepancy with terminology used in the development of the CLHRS in this study.

In addition to the seven properties listed in Table 2.2, some supporting information is recorded in the Landslide Database Reports but not included in the risk calculation. This includes the length of roadway affected, the estimated cost to mitigate the landslide to a low-risk state, the last reported activity and date of observation, installed instrumentation, and mitigation performed, if any.

The current CDOT system assigns a numerical value of zero to any landslide property that is unknown. Since risk severity increases with risk value, a zero value for any category implies zero risk. For example, a landslide for which little or no data has been collected could potentially yield an overall risk value that is quite low, despite its potential to pose a great threat to public safely or highway operations. For this reason, the category of “unknown” as well as the use of zero values has been avoided while developing the preliminary CLHRS, thus requiring an investigator to assign a score for every factor.



Landslide Property	Nominal Category	Description	Risk Value
Failure Frequency	Unknown	-	0
	Low	No failures in previous 5 yrs	3
	Moderate	1-2 periods of movement in previous 5 yrs	9
	Annual	Movement observed on annual basis	27
	Continuous	Multiple movement episodes throughout one year	81
Extent Beyond ROW	Unknown	-	0
	None	Confined to ROW	3
	Limited	One side of ROW affected; undeveloped public land	9
	Of Concern	Both sides of ROW affected; undeveloped public land	27
	Critical	Both sides of ROW affected; impacting private land	81
Slide Size	Unknown	-	0
	Small	Width <100ft & Depth <10ft	3
	Medium	Width <500ft & Depth <50ft	9
	Large	Width >500ft & Depth >50ft	27
	Catastrophic	Historic slide feature extending well beyond ROW & width >1000ft	81
Detour Factor	Unknown	-	0
	Good	No detour required	3
	Limited	Onsite detour possible using lane shifts & reduced speed	9
	Marginal	Offsite Detour with distance <5 miles	27
	Poor	Detour of >5 miles or no detour	81
AADT	Unknown	-	0
	Very Low	<5,000	3
	Low	5,000-10,000	9
	Moderate	10,000-20,000	27
	High	>20,000	81
Annual Cost	Unknown	-	0
	Low	<$5,000 per year	3
	Moderate	$5,000 - $10,000 per year	9
	High	$10,000 - $25,000 per year	27
	Prohibitive	> $25,000 per year	81
Road Width Affected	Unknown		0
	Shoulder Only		3
	<50%		9
	50% - 75%		27
	>75%		81

Table 2.2 Summary of landslide properties and corresponding risk values currently in use by CDOT.

Risk Category	Risk Values
Low	0-21
Moderate	22-63
High	64-189
Extreme	190-567

Table 2.3 CDOT risk category boundaries

CHAPTER 3

PROJECT GOALS, SCOPE, AND LIMITATIONS

This chapter describes the goals, project scope, and project limitations, and discusses the tasks performed in order to develop a final functional draft of the CLHRS.

3.1 Project Goals

The purpose of this research project was to develop a risk rating system specifically for landslide hazards that threaten transportation routes throughout the state of Colorado. The new system is partly a revision of the existing CDOT risk rating system with substantial additions. The primary goals of the project were as follows:

1. Incorporate new factors that specifically evaluate hazard by considering:
    - Local geologic conditions (e.g., soil slope vs. rock slope, etc.);
    - Climatic factors (e.g., annual precipitation, vegetation, slope aspect);
    - Hydrologic factors (e.g., seepage conditions, surface water influences);
    - Seismic susceptibility; and
    - Slope morphology (e.g., slope angle).
2. Use factors that rely on unambiguous numerical and descriptive criteria for evaluation.
3. Create a system that yields results that are easily reproducible by different investigators.
4. Create a system that can estimate landslide risk rapidly.
5. Validate the rating system through statistical methods and comparison of scores with actual mitigation efforts.

3.2 Project Scope and Limitations

At the time of commencing this research, 124 landslides had been documented with CDOT's Landslide Database Reports. According to CDOT personnel, the Landslide Database Reports have been created from existing hardcopy files on record with the agency. Many of these files document landslide features that are decades old and that have not been updated either due to lack of additional movement or because the problems have been mitigated sometime in the past by regional maintenance personnel without informing the main CDOT office. Important data, such as precise locations and boundaries of slides are often absent in the Landslide Database Reports generated from these older files. Of the original dataset, 78 landslides that experience movement regularly and/or continue to be of concern to CDOT are more completely documented and have been delineated within ArcGIS. In order to facilitate the development of the CLHRS within a reasonable timeframe, specific focus was placed on the 78 mapped landslides.

There are a number of published geologic and engineering geologic maps that delineate possible, probable, and known landslide features in populated cities and adjacent to active transportation routes. Some of these features have no record within CDOT's Landslide Database Reports but could reasonably be a hazard to highway operations. Locating, mapping, and collecting data for these sites is also beyond the scope of the project.

3.3 Development and Analysis of the CLHRS

In order to develop a final draft of the Colorado Landslide Hazard Rating System, a five-task process was executed. The five tasks consisted of a literature review, development of a preliminary rating system, field application of the preliminary system, statistical analysis, and development of a final functional draft. Each task is described in greater detail in the following sections:

3.3.1 Literature Review

The current body of technical and scientific literature was reviewed, covering the subjects of landslide risk assessment, the importance and significance of various factors, case studies, criticisms, and existing rating systems. The goal of the review was to provide insights and guidance for the development of a new preliminary hazard rating system tailored to the environmental conditions encountered in Colorado.

3.3.2 Development of a Preliminary CLHRS

A preliminary draft of the CLHRS was developed using the important components identified in the literature review. This process consisted of identifying factors that influence landslide stability and failure consequences and that are amenable to evaluation without detailed subsurface site investigations. The weight assigned to all factors used in the system was kept consistent with existing rating systems. The preliminary version of the CLHRS used for field evaluation is presented in Chapter 6.

3.3.3 Field Application of Preliminary System

The 78 landslides of concern to CDOT distributed throughout the state were visited during the summer of 2011. At each site, observations about general site conditions were made and necessary measurements were taken so that preliminary risk scores could be assigned. The results of the field application of the preliminary CLHRS are presented in Chapter 6.

3.3.4 Analysis & Validation

Upon completion of field evaluation, the resulting database of landslide characteristics was subjected to several forms of statistical analysis. The goal of these analyses was to examine the relationships that exist between the various factors included in the CLHRS as well as to validate the overall usefulness of the system. All analyses were performed using Minitab®, a statistical software package that allows for the rapid evaluation of datasets using a wide variety of statistical techniques. Minitab® was used to evaluate broad trends in the distribution of landslide data, evaluate the presence or absence of corollary relationships among variables and scores, generate predictive regression equations, and attempt to identify groups of landslides with similar characteristics. These methods are described in greater detail in Chapter 7 and Chapter 8.

3.3.5 Development of Final Draft

A final functional draft of the CLHRS intended for field application was developed based on the results of the data screening and statistical analyses described in

Chapters 7 and 8. The final hardcopy version of the CLHRS is presented in Chapter 9 along with conclusions regarding the strengths of the CLHRS, recommendations for improving the system in light of increased availability and resolution of spatial datasets in the future, and implications for extending the applicability of the CLRHS beyond identified landslide sites.

3.4 Function of the CLHRS

The CLHRS is intended to exclusively serve as a tool for rapidly summarizing the site-specific conditions that have the potential to influence landslide hazard, consequence, and risk. In this way, the CLHRS functions as a landslide inventory tool applied to existing landslides. The CLHRS is not intended to function in a predictive capacity in areas where landslides do not currently exist. The resulting total scores from the application of the CLHRS do not convey any information regarding the specific probability of failure, these scores simply allow for the ranking of landslides according to their relative total risk, which in turn is an expression of the total collection of negative characteristics associated with a known landslide.

CHAPTER 4
HAZARD FACTOR SELECTION AND EVALUATION METHODOLOGY

This Chapter describes the eleven Hazard Factors that were selected for use in the preliminary CLHRS. The Hazard Factors were developed based on a literature review of the current body of technical literature. Descriptions of the significance of each factor, evaluation method, and category break justifications are presented below. These factors were chosen in an effort to make the preliminary CLHRS more comprehensive in terms of adequately documenting the current environmental conditions that a given landslide experiences.

4.1 Hazard Factor Selection

As mentioned above, the factors used in the preliminary CLHRS were either retained from the current CDOT system, adopted from the published rating systems reference in Table 2.1, or were developed independently. Failure frequency was retained from the CDOT system. Evaluation of geologic problem type, vegetation, pavement damage, and slope angle were adopted from existing rating systems. New factors developed and implemented for the CLHRS involved the evaluation of USCS classification, rock strength, permeability, slaking, and discontinuity orientation, annual precipitation, slope aspect, groundwater seepage, influence of surface water bodies, integrity of drainage structures, and peak ground acceleration.

Several hazard-related factors used in other rating systems were deliberately omitted from the CLHRS mainly due to their lack of suitability for rapid evaluation. Specifically, the assessment of liquidity index and recharge area were judged to be too labor-intensive and out of sync with rapid field assessment. Bedrock geology was recorded as supporting information for field assessment but was not assigned a hazard factor because other more specific factors related to the geologic problem type were used to evaluate the hazard imposed by the bedrock or its soil constituents (e.g., USCS classification, strength, etc.). Descriptions of the Hazard Factors included in this study are presented below.

4.2 Geologic Problem Type

The occurrence and behavior of landslides is influenced by local geologic conditions such as weak or weathered subsurface units, unfavorably oriented natural discontinuities, and glacially-oversteepened slopes. An effort has been made to account for the site geology and its impact on landslide hazard. This has been accomplished by creating a multi-option Hazard Factor that allows the investigator to choose one of four geologic problem types: colluvial soils, interbedded rock units, weak rock, and rock discontinuity-controlled slides. The investigator selects the most appropriate problem type through direct observation as well as consultation of available geologic maps and United States Department of Agriculture (USDA) surficial soil maps.

4.2.1 Colluvial Soils

A mantle of colluvial soil covers the natural slopes in many areas throughout Colorado. In order to evaluate the hazard that a given colluvial soil imparts to a landslide, surficial soils obtained from a landslide are assigned a Unified Soil Classification System (USCS) designation (ASTM, 1985). Due to the ubiquity of the USCS, various correlations of USCS designation to engineering properties and desirability of using each soil type in analogous engineering applications exist (e.g., U.S. Army, 1997). Silts and clays of high plasticity and organics (i.e., MH, CH, PT, etc.) typically correlate with lower shear strengths and therefore represent the most hazardous condition, whereas predominately clean sands and gravels represent the least hazardous condition (i.e., GW, SW, etc.) due to their typically higher shear strengths. The hazard categories used for evaluating colluvial soils for the preliminary CLHRS are presented in Table 4.1:

Table 4.1 Hazard score categories for colluvial soil option of geologic problem type factor.

USCS Classification	Hazard Score
GW, SW, GP, GC, SP	3
GM, SM, SC	9
CL, ML	27
CH, MH, OL, OH, PT	81

In order to assign a USCS designation for colluvial soils encountered in the field, a representative soil sample from the surface of the slide mass was obtained by excavation to a depth of approximately six inches (15cm). The soil was transferred to the laboratory and evaluated using the common dilatancy test and soil ribbon test (U.S. Army, 1997).

Soil samples obtained from a single location within a landslide mass from a shallow depth cannot necessarily be considered to be representative of the entire slide mass. This evaluation method is intended to give an investigator a rapid, low-cost understanding of the type of soil that the slide is comprised of. The ideal investigative approach consists of advancing multiple borings throughout the slide and submitting soil samples for geotechnical analyses to an accredited laboratory.

4.2.2 Interbedded Rock Units

The state of Colorado is geologically diverse. Consequently, geomorphological expressions of igneous, metamorphic, and sedimentary terrains can be observed throughout the state. In such areas where landslides are present in predominately interbedded sedimentary rock strata, the differences in permeability or strength of the units can play an important role in slope stability. Permeability differences can create unstable pore water pressures that can potentially create a failure surface or contribute to failure along an existing surface. Also, significant differences in the strength of the units can focus stresses on the weakest layers, thus contributing to landslide hazard (Eberhardt et al., 2005). In order to evaluate the relative hazard associated with this geologic problem type, a two-option Hazard Factor was developed.

If field observations and geologic maps suggest that a given terrain is primarily comprised of interbedded strata at the landslide site, an investigator will assign a score based on the contrast in values between interbedded units of either the unconfined compressive strength or the permeability. These engineering properties are difficult to evaluate without performing geotechnical analyses. However, they can be estimated by using published tables of typical ranges of values (e.g., EPFL LMR, 2013).

Divisions in hazard categories for this factor are based on the observed ranges of the average unconfined compressive strength of common sedimentary rock types (EPFL LMR, 2013), which range from an average of 53 MPa in the case of shale to an average of 140 MPa for limestone. The ratios of differential strength of interbedded rock units are used to define severity category breaks for this factor. Specifically, average strength ratios of 1:1 represent the least hazardous condition while average strength ratios greater than 3:1 represent the most hazardous condition. These divisions are based on the spread of maximum and minimum average strength values. It is important to note that actual unconfined compressive strength values for various rock types can vary considerably (e.g., 5 to 100 MPa for shale (EPFL LMR, 2013)). The evaluation of the strength difference option for this hazard factor has been simplified because of the difficulty in obtaining accurate strength values in the field. This hazard factor operates under the assumption that the average strength of a given rock type is adequate for the purposes of rapid slope investigation.

In a similar manner to defining hazard category breaks for the strength difference option, the breaks for the rock permeability difference option are based on averages of the ranges of typical published values of the physical properties of rock materials (EPFL LMR, 2013), specifically the coefficient of permeability; ranging from effectively zero m/s in the case of some shales to $5x10^{-9}$ m/s in the case of sandstones and conglomerates. Numerical values for category breaks were logically chosen and based on orders of magnitude and the difference between the maximum and minimum average coefficients of permeability, with differences of less than 10^2 m/s (two orders of magnitude) representing the least hazardous condition and differences greater than 10^4 m/s (four orders of magnitude) representing the most hazardous condition. Table 4.2 shows the strength and permeability differences that define each hazard category:

Table 4.2 Hazard score categories for interbedded rock option of geologic problem type factor.

Strength Difference (D_S)	Permeability Difference (D_P)	Hazard Score
1:1	$D_P < 10^2$	3
$1:1 < D_S \leq 2:1$	$10^2 < D_P \leq 10^3$	9
$2:1 < D_S \leq 3:1$	$10^3 < D_P \leq 10^4$	27
$D_S > 3:1$	$D_P > 10^4$	81

The most appropriate option is selected on the basis of field observations and consultation of available geologic maps or geotechnical reports. For example, the strength properties for a specific subset of geologic formations may be known while the permeability values may not. The accuracy of evaluating this Hazard Factor increases if detailed strength or permeability information is available from previous investigations conducted on-site or from nearby sites.

4.2.3 Weak Rock

For landslides developed on slopes consisting predominately of weak rock material (e.g., shale slopes), the results of a modified jar slake test (Santi, 2006) may be used to evaluate landslide hazard potential. Materials that slake can experience rapid physical degradation and a decrease in strength. The six possible outcomes of the modified jar slake test were divided into four hazard categories in the same manner used by Santi et al. (2009) for rockfall hazard assessment. A modified jar slake result of "no reaction" represents the least hazardous condition while degradation to flakes or mud represents the most hazardous condition. The hazard categories are presented in Table 4.3:

Table 4.3 Hazard score categories for weak rock option of geologic problem type factor.

Jar Slake Test	Hazard Score
No reaction	3
Slabs	9
Fractures or Chips	27
Flakes or Mud	81

When a landslide is judged to be comprised primarily of weak rock, a small hand sample of rock is collected and placed in a transparent container filled with water. Visual observations are made after a period of 30 minutes regarding the physical state of the sample. The criteria used to judge the relative degradation of the weak rock sample at the conclusion of the test follows the methodology presented by Santi (2006). Possible jar slake test result categories are presented as illustrations in Figure 4.1.

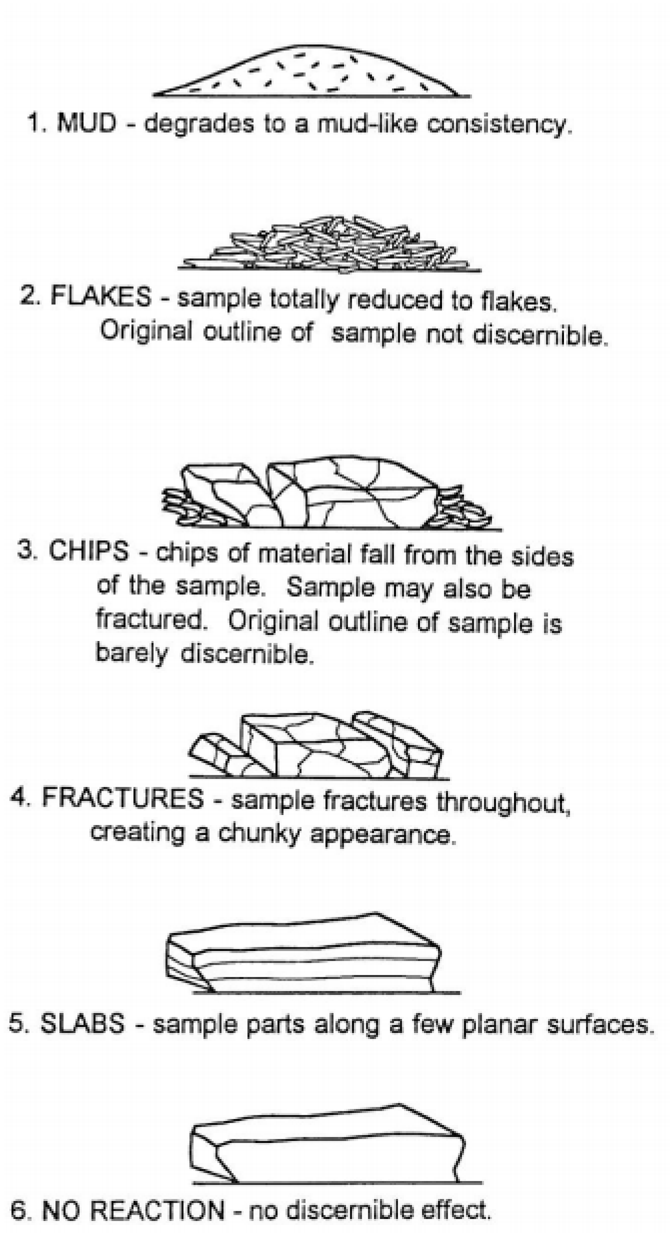


Figure 4.1 Illustrated representation of modified jar slake test categories (Santi, 2006)

4.2.4 Rock Slides

In areas of Colorado where exposed rock masses slide on discontinuities such as bedding planes or metamorphic foliations daylighting in a slope, potential sliding hazards exist (Norrish and Wyllie, 1996). For the CLHRS, the orientation of such discontinuities relative to the measured slope angle can be used as a form of rapid kinematic analysis of hazard potential. It is important to note that landslides within this geologic problem type are assumed to be experiencing translational movement along a single dominant set of discontinuities. Hazard assessment for rock slopes involving other types of movement (e.g., topple, wedge failure, etc.) is not the intended function of the CLHRS.

The hazard categories for this Hazard Factor are based on the principles of kinematic analysis and the structural conditions for planar failures summarized by Norrish and Wyllie (1996). Because the CLHRS specifically evaluates known, active landslides, several of the conditions required for planar failures to occur are assumed to be present. Specifically, the dip direction of the planar discontinuity is assumed to be within 20 degrees of the dip direction of the slope face, the dip of the planar discontinuity is assumed to be less than the dip of the slope face and greater than the angle of friction for the surface, and the lateral extent of the failure mass is assumed to be defined by lateral release surfaces that do not contribute to the stability of the mass (Norrish and Wyllie, 1996). Horizontal, vertical, and opposite dip directions of discontinuities relative to the slope angle, as well as discontinuities that dip more steeply then the slope angle are judged to represent zero sliding hazard conditions, either because planar geometry does not allow for failures to threaten the roadway or because discontinuities do not daylight in the slope. Therefore, hazard score increases with increasing steepness of the dip of the planar discontinuity due to increasing driving forces due to gravity. Breaks in hazard categories are expressed as a fraction of the slope angle and are evenly divided along logical continuous breaks (i.e., 0.25, 0.50, and 0.75 times the measured slope angle). Thus, discontinuity angles between horizontal and 25 percent of the slope angle represent the least hazardous condition while discontinuity angles greater than 75 percent but less than the slope angle represent the most hazardous condition. Hazard category breaks for the rock slide geologic problem type option are presented in Table 4.4.

Evaluation of this geologic problem type is accomplished using a standard Brunton pocket transit to measure the slope angle of the landside and the dip of the observed discontinuities. Where considerable variation exists, averaging of several values can be used to approximate the angles.

Table 4.4 Hazard score categories for rock slide geologic problem type.

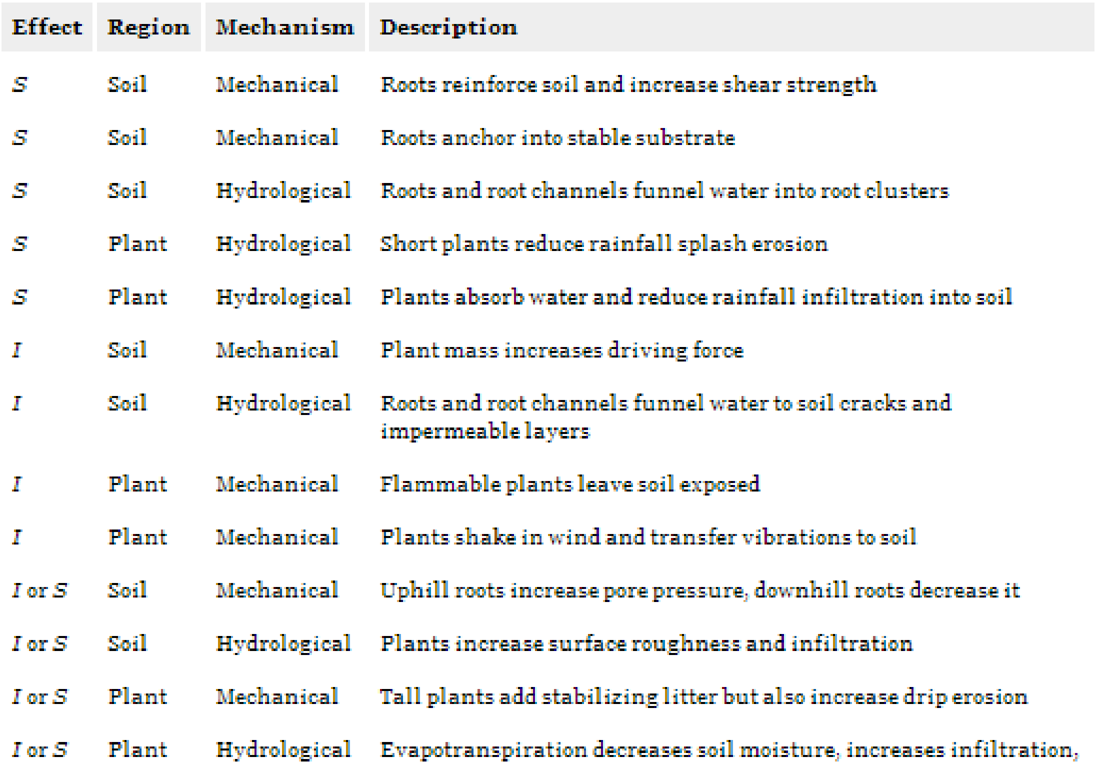
Discontinuity Angle (A_D) vs. Slope Angle (θ)	Hazard Score
$0 < A_D \leq 0.25\theta$	3
$0.25\theta < A_D \leq 0.5\theta$	9
$0.5\theta < A_D \leq 0.75\theta$	27
$0.75\theta < A_D < \theta$	81

4.3 Beneficial Vegetative Cover

The influence of vegetation on slope stability is complex and difficult to quantify and has historically been omitted from slope stability analyses (Greenway, 1987). However, more recent research regarding the occurrence of vegetation on slopes has demonstrated that vegetation can have a variety of effects that promote slope stability and/or instability due to the complex nature of the interactions between various plant species and the nuances of the local geologic conditions (Walker and Shiels, 2013). Research by Huat et al. (2006), Nott (2006), Sidle and Ochiai (2006), Goudelis et al. (2007), Morgan (2007), Stokes et al. (2009), and Ghestem et al. (2011) shows that vegetation can impart both mechanical and hydrological benefits to slope stability. This research is summarized in Table 4.5, reproduced from Walker and Shiels (2013).

In addition to the potential benefits imparted to slope stability by various plant types, the geometry of the landslide (i.e., the depth of the failure plane) specifically controls the relative value of vegetation on a given slope. For example, as mentioned, woody roots have the potential to anchor unstable soil slopes to stable substrate for shallow landslides. However, in the case of deep-seated landslides, the potential benefits imparted by such trees could be negligible if the failure plane is located deeper than the maximum depth of the tree roots. Canadell et al. (1996) and Crow (2005) give lists of maximum root depths for many plant species, which are useful guides for field evaluation. Specifically, the upper limit of root depths varies with soil type and plant species and reaches a maximum upper limit at approximately 10 to 15 feet (3.0 to 4.6 meters) below ground surface (Crow, 2005). Therefore, if the estimated depth to the slide plane is within this general region, the likelihood of trees providing anchoring support is small and the most severe hazard score should be assigned in order to reflect the absence of an important beneficial characteristic. Where grasses are present on a landslide mass, the relative benefit should be assessed while taking the characteristics listed in Table 4.5 into consideration. Because grasses and shrubs do not intuitively possess the same anchoring potential as trees, the relative benefit of grasses versus trees should be weighted in favor of the trees for shallow landslides.

Table 4.5 Mechanical and hydrological effects of vegetation on slope stability. “S” indicates stability while “I” indicates instability. Reproduced from Walker and Shiels, 2013. Sources include Huat et al. (2006), Nott (2006), Sidle and Ochiai (2006), Goudelis et al. (2007), Morgan (2007), Stokes et al. (2009), and Ghestem et al. (2011).



Effect	**Region**	**Mechanism**	**Description**
S	Soil	Mechanical	Roots reinforce soil and increase shear strength
S	Soil	Mechanical	Roots anchor into stable substrate
S	Soil	Hydrological	Roots and root channels funnel water into root clusters
S	Plant	Hydrological	Short plants reduce rainfall splash erosion
S	Plant	Hydrological	Plants absorb water and reduce rainfall infiltration into soil
I	Soil	Mechanical	Plant mass increases driving force
I	Soil	Hydrological	Roots and root channels funnel water to soil cracks and impermeable layers
I	Plant	Mechanical	Flammable plants leave soil exposed
I	Plant	Mechanical	Plants shake in wind and transfer vibrations to soil
I or *S*	Soil	Mechanical	Uphill roots increase pore pressure, downhill roots decrease it
I or *S*	Soil	Hydrological	Plants increase surface roughness and infiltration
I or *S*	Plant	Mechanical	Tall plants add stabilizing litter but also increase drip erosion
I or *S*	Plant	Hydrological	Evapotranspiration decreases soil moisture, increases infiltration,

In order to meet the goal of developing a rapid and comprehensive risk rating system, this study has simplified the assessment of vegetation’s effect on hazard by requiring an investigator to evaluate beneficial vegetative cover as a percentage of the landslide map area. In the field, and ideally with the aid of aerial photography and available site-specific data, an investigator must judge the relative amount of vegetation that is capable of imparting a benefit in terms of anchoring, soil binding, water interception, etc. as discussed above. The investigator must take into consideration 1) the type(s) of vegetation present on the slide, 2) the specific landslide characteristics (i.e., deep vs. shallow, soil vs. rock), 3) the potential benefits or detriments that the distribution of vegetation imparts to the slope, and 4) the relative amount of beneficial vegetation. Without detailed field study, this assessment is predominately subjective and estimates of beneficial vegetative cover should consequently be conservative.

Boundaries in hazard score categories for this factor are divided evenly along a scale from zero to 100 percent and are based on the assumption that landslide hazard decreases continuously with increasing beneficial vegetative cover. Therefore, an estimated beneficial vegetative coverage of 75 to 100 percent represents the least severe category while either an estimated beneficial coverage of 25 percent or less or a landslide with a failure plane beyond the root depth threshold represents the most severe category. The percentages used to define the hazard categories of the vegetation factor are presented in Table 4.6.

Table 4.6 Hazard score categories for beneficial vegetative cover factor.

Beneficial Vegetative Cover (BVC)	Hazard Score
BVC > 75%	3
50% < BVC ≤ 75%	9
25% < BVC ≤ 50%	27
BVC ≤ 25% or deep slide	81

As an example of field evaluation, if an investigator is evaluating what is judged to be a shallow soil slide and 50 to 75 percent of the landslide’s total map area is considered to be occupied by tree species capable of intersecting the slide plane based on a review of Canadell et al. (1996) or Crow (2005), a score of “9” would be assigned for the vegetation factor. Conversely, if the identical distribution of vegetation was observed on a deep-seated landslide, the investigator may conclude that the tree roots are not capable of imparting an appreciable benefit to slope stability, and may instead contribute to failure by increased mass and/or wind loading and thus assign a higher hazard score of “81” due to the complete absence of beneficial vegetation.

4.4 Average Annual Precipitation

Rainfall commonly functions as a triggering mechanism for shallow landslides. Specifically, the intensity and duration of rainfall leads to rapid water infiltration and a temporary rise in pore-water pressures that may ultimately trigger failure (Wieczorek, 1996). Rainfall intensity and duration data can be obtained through instrumenting landslide sites with rain gauges. However, such instrumentation may not be present at all landslide sites, thus precluding the use of rainfall intensity as a hazard factor in this study. Alternatively, average annual precipitation data on a regional level can be used to quantify hazard under the assumption that areas receiving more precipitation annually are generally more exposed to precipitation events that have the potential to contribute to or directly trigger failure. The average amount of precipitation received annually varies across the state, thus saturating landslide masses to varying degrees. Additionally, precipitation that occurs as snow adds weight to the landslide mass and has the potential to sustain saturation during subsequent melting. Average annual precipitation for a given area has been obtained from Figure 4.2. Hazard scores increase with increasing average annual precipitation with less than 15 inches (38 cm) per year representing the least hazardous condition and greater than 45 inches (114 cm) per year representing the most hazardous condition. The upper and lower rainfall boundaries were chosen based on the rainfall distribution presented in Figure 4.2. Specifically, no landslide in this study is located within an isopleth that delineates an area that receives less than 15 inches (38cm) or more than 45 inches (114cm) of rainfall on an average annual basis. These values were therefore considered to be the thresholds for describing the lowest and highest scores, respectively. The intermediate category boundaries were divided evenly between the upper and lower limits and are presented in Table 4.7.

Average annual precipitation was evaluated by generating an overlay of Figure 4.2 in ArcMap and panning to the landslide of interest. The color-coded regions serve to rapidly distinguish average annual precipitation for a given area. The accuracy of this factor as well as the resolution of the annual precipitation map can increase through the use of a dedicated rain gauge.

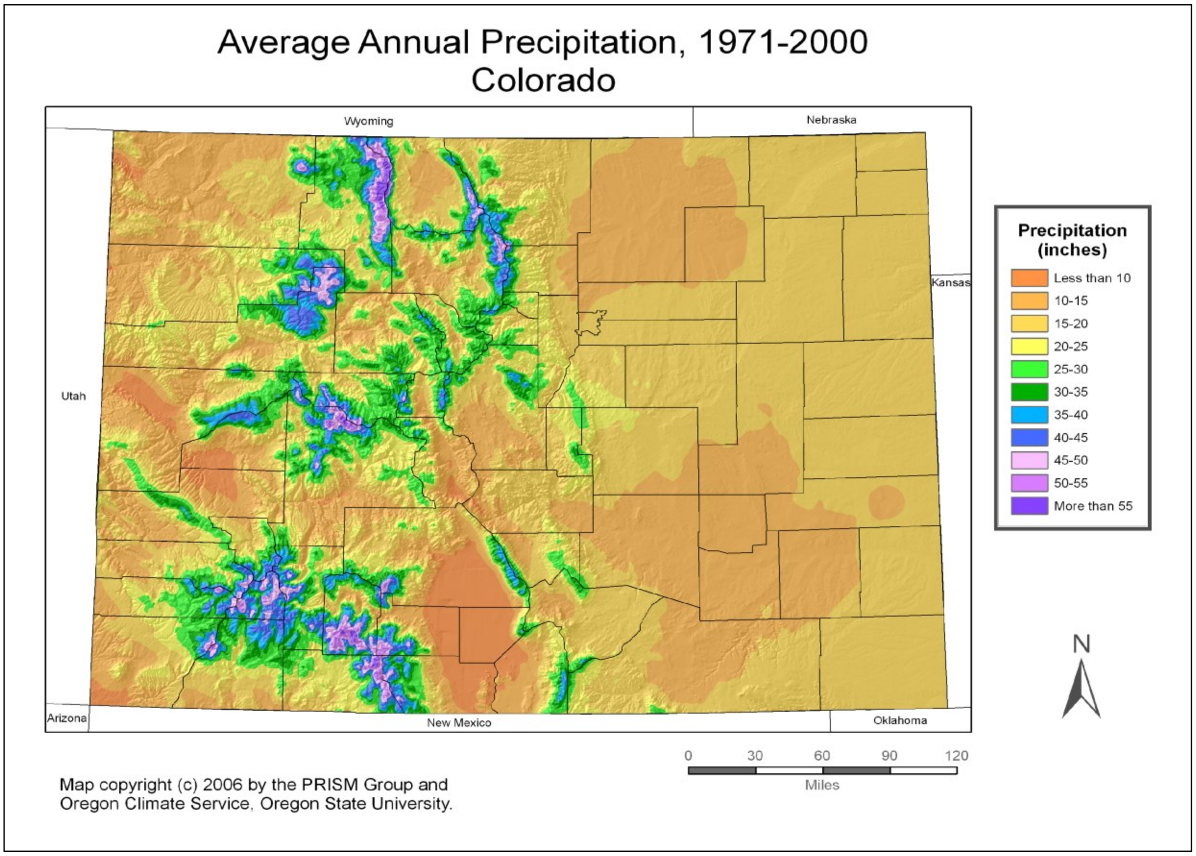


Figure 4.2 Average annual precipitation for the state of Colorado for the period from 1971 through 2000 (PRISM Group, 2006).

Table 4.7 Hazard score categories for annual precipitation factor.

Annual Precipitation (AP)	Annual Precipitation (metric)	Hazard Score
AP < 15"	AP < 38 cm	3
15" < AP ≤ 30"	38 cm < AP < 76 cm	9
30" < AP ≤ 45"	76 cm < AP < 114 cm	27
AP > 45"	AP > 114 cm	81

4.5 Slope Aspect

Slope aspect is defined as the compass direction in which a slope dips. According to Dai and Lee (2002), slope aspect affects moisture retention and the development of vegetation, which in turn may affect soil strength and landslide susceptibility. Furthermore, Wieczorek, et al. (1997) have shown slope aspect can influence the amount of rainfall that a slope receives in the case of rainfall direction controlled by a prevailing wind. Dai and Lee (2002) have shown that landslide frequency decreases with increasing northern orientation and increases to a maximum on south-facing slopes. Additionally, Maharaj (1993) has observed a similar trend of increased landslide frequency on slopes with more southerly aspects. Conversely, Gokceoglu and Aksoy (1996) have noted a greater occurrence of landslides on north-facing slopes.

The utility of using slope aspect in the context of landslide stability lacks general agreement among the scientific community (Ercanoglu and Gokceoglu, 2002). The differences in observed landslide frequencies relative to slope aspect may be attributable to the specific environmental conditions in a given region of the world. In Colorado, and in the context of rockfall hazard assessment, north-facing slopes generally experience less variation in solar radiation throughout the day and consequently more readily establish stabilizing vegetation. Conversely, south-facing slopes experience higher evaporation rates and temperature fluctuations due to extended exposure to sunlight, creating drier soils that lack stabilizing vegetation and experience more erosion (Santi et al., 2009).

Slope aspect was used as a hazard factor by Santi et al. (2009) for the purpose of rockfall hazard investigation and in relation to block-in-matrix slopes. For the purposes of this study, the favorable and unfavorable characteristics associated with slope aspect in Colorado were adopted under the assumption that the Santi et al. rockfall hazard investigation was analogous to the landslide hazard investigation conducted in this study. It is acknowledged that the specific effects of slope aspect and this property’s relationship to vegetation, moisture retention, and site-specific geology is complex and especially nuanced in the context of the types of micro-climates that may be encountered in mountainous regions such as western Colorado. For this study specifically, the slope aspect for each landslide site was recorded and the resulting frequency distribution (Figure 6.6, below) was evaluated. Based on the 69 landslide dataset used in this study, landslide occurrence appears to be greatest for slopes with south-facing aspects. Thus, the observed distribution of slope aspects was retroactively used to establish the hazard categories for this factor, with north-facing slopes judged to represent the least hazardous condition and south-facing slopes, the most hazardous condition. Hazard categories are summarized in Table 4.8.

Table 4.8 Hazard score categories for slope aspect factor.

Slope Aspect	Hazard Score
N	3
NW, NE	9
E, SE, SW, W	27
S	81

This Hazard Factor is rapidly assessed through the use of aerial photographs and/or a Brunton compass, either directly in the field or through the use of a GIS system.

4.6 Groundwater Seepage

The presence of water within a landslide mass contributes to the hazard by increasing the driving forces. High groundwater levels present on steep mountain slopes saturate existing landslide masses and decrease the effective strength of the soil material and/or create pore pressures within rock discontinuities (Regmi, et al., 2013). On-site observations regarding the presence and intensity of groundwater seepage are indicative of the subsurface hydrogeologic conditions. Hazard scores increase with increasing magnitudes of soil saturation, which are identified by surface observations regarding the presence or absence of moisture. Hazard categories are distinguished using identical criteria used Santi et al. (2009) in an analogous rockfall hazard investigation, with slopes observed to be completely dry representing the least hazardous condition and slopes observed to have a continuous flow of water emerging through the landslide mass representing the most hazardous condition. The descriptive characteristics that serve as the boundaries between hazard categories are presented in Table 4.9.

Table 4.9 Hazard score categories for groundwater seepage factor.

Groundwater Seepage	Hazard Score
Dry	3
Damp/Wet	9
Dripping	27
Running Water	81

This hazard factor is evaluated by walking the toe and body of the landslide and noting the moisture characteristics of the soil. “Dry” describes soils that lack any observable moisture or that only possess residual soil moisture. “Damp/Wet” describes soils that are immediately identifiable as possessing higher levels of moisture but not in sufficient quantities to exist as free water (i.e., no ponding or dripping). “Dripping” describes a landslide where soil is saturated to the point that water exists as small puddles and/or is visibly exiting the slide, but without flow. “Running Water” describes a landslide where water is actively flowing from any portion of the landslide mass.

In cases where multiple seepage states are identified, scores are assigned based on the most severe result in order to maintain conservatism. This evaluation is made easier by creating small excavations with a spade and inspecting the soil moisture by hand. Furthermore, consultation of topographic maps for the locations of mapped streams and springs within the body, along the flanks, or at the toe of the landslide are useful for obtaining an understanding of the anticipated seasonal seepage behavior of the slide.

The time of year for evaluating this factor is a key consideration. Seasonal variations in climate are to be expected, such as alternating wet and dry periods, variations in precipitation, the rate of snow melt, etc. In order to accurately assess the seepage characteristics of this Hazard Factor, multiple visits to a given landslide site are necessary. For example, during periods of drought conditions in Colorado or warm summer months, groundwater seepage may not be readily observable and yield uniform results of “no seepage observed.” Conversely, during the spring, widespread snowmelt could potentially result in steady seepage being observed at most landslide sites, thus also resulting in uniform results that reduce this factor’s ability to adequately distinguish hazard.

For this study, groundwater seepage was evaluated during the dry summer months of 2011, resulting in over 90 percent of the scores falling into the “none observed” category. For this reason, the possibility exists that the importance of this factor has been obscured. For subsequent investigations, it is strongly recommended that this factor be evaluated during a period of time that has the lowest potential to bias the results due to the overwhelming absence or presence of groundwater seepage.

4.7 Influence of Surface Water

In addition to instabilities created by groundwater seepage, the external influence of surface water bodies contributes to landslide hazard. For example, seasonal drainages and active streams can deliver water to a landslide and saturate the slope, thus increasing the driving forces. Rivers can actively cut the toe of a landslide, potentially removing support for the landslide mass and reducing resisting forces. Additionally, landslides developed on the margins of active reservoirs can experience regular movements due to rapid drawdown as the buttressing support of the water is removed faster than the water can drain from the slope thus increasing driving forces due to heavy saturation (e.g., Walker and Santi, 2004). Landslides that lack any visible indicators of proximity to surface water bodies or slides that are located at a great distance away from known surface water bodies are judged to represent the least hazardous condition. Conversely, slides that are in direct contact with a reservoir, lake, or river are judged to represent the most hazardous condition. Hazard categories for this factor are summarized in Table 4.10.

Table 4.10 Hazard score categories for surface water influence factor.

Influence of Surface Water Bodies	Hazard Score
None or Distant	3
Seasonal Drainages Only	9
Small Stream Erosion/Ponded Water	27
Direct Contact w/ River or Reservoir	81

4.8 USDA Available Water Capacity

The United States Department of Agriculture (USDA) has made surficial soil mapping data available to the public through its Web Soil Survey (WSS) website. The information available through the USDA is useful for establishing a rapid preliminary understanding of the types of soils in a given area, including various soil properties. The USDA defines available water capacity as “the amount of water that a soil can store that is available for use by plants" (USDA, 1998). This soil property was judged to serve as an acceptable indicator of the drainage behavior for a soil with the available water capacity serving as an expression of the potential saturation of a soil and the resultant effects on driving forces due to increased weight. Soils listed in USDA soil survey data as possessing very low to low available water capacity were considered to represent the least hazardous condition while soils listed as having "very high" available water capacity were considered to represent the most hazardous condition. Hazard categories for this factor are summarized in Table 4.11.

Table 4.11 Hazard score categories for USDA water capacity factor.

Drainage Structures	Hazard Score
Low to Very Low	3
Moderate	9
High	27
Very High	81

4.9 Peak Ground Acceleration

Landslides may be triggered by ground accelerations resulting from seismic activity (Jibson and Harp, 2011). Though Colorado is not typically associated with active seismicity, the diverse tectonic history of the Rocky Mountains has left a multitude of faults throughout the state. The United States Geological Survey, through the 2008 National Seismic Hazard Mapping Project has produced probabilistic seismic hazard maps for the United States. The map used for evaluating seismic hazard for the CLHRS shows peak ground accelerations as a percentage of gravitational acceleration with a two percent probability of exceedance in 50 years (Figure 4.3). Though the differences in peak ground acceleration among hazard categories are relatively small, the differences were judged to be significant in the context of critical landslide stability. The range of ground accelerations used for this factor was chosen based on the distribution of landslide sites relative to Figure 4.3 in an identical manner to the annual precipitation factor discussed above. Specifically, no landslide site within the study area is located within an isopleth with a peak ground acceleration of less than 12%g nor is any landslide site located within an isopleth that delineates a peak ground acceleration of greater than 16%g. Therefore, landslides located in areas with the potential for higher peak ground accelerations are assigned higher hazard scores with accelerations less than 12%g judged to represent the least hazardous condition and accelerations greater than 16%g judged to represent the most hazardous condition. Intermediate numerical values are divided evenly between the upper and lower boundaries. Hazard categories for this factor are summarized in Table 4.12.

Table 4.12 Hazard score categories for peak ground acceleration factor.

Peak Ground Acceleration (%g)	Hazard Score
%g ≤ 12	3
12 < %g ≤ 14	9
14 < %g ≤ 16	27
%g > 16	81

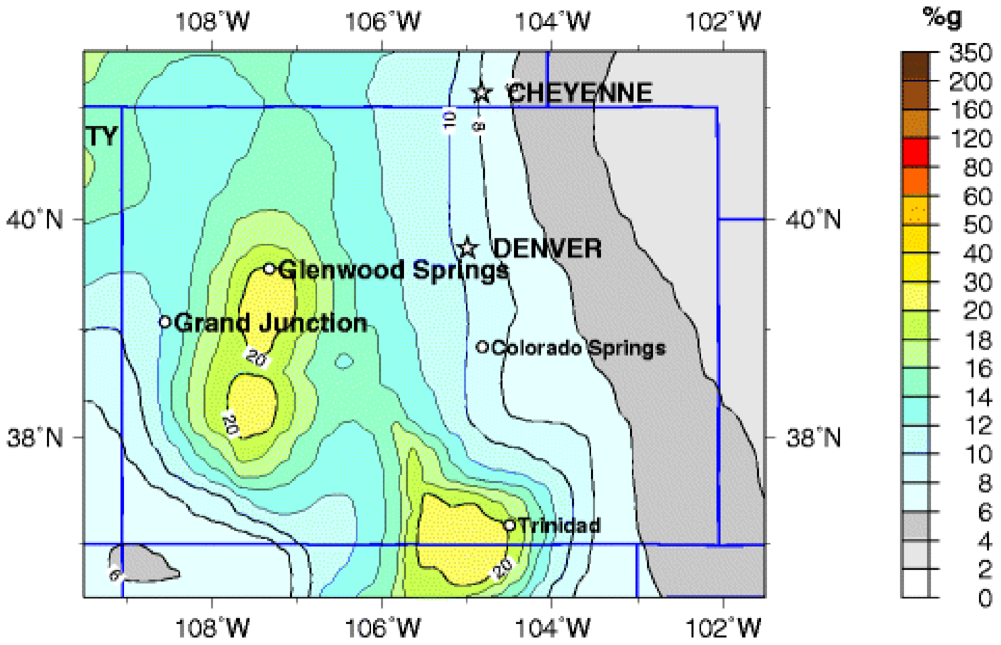


Figure 4.3 Peak acceleration (%g) with 2% probability of exceedance in 50 years (USGS, 2012).

This Hazard Factor is evaluated by importing figure 4.3 into ArcMap and panning to the geographic coordinates of a given landslide. The peak acceleration range for the site can be rapidly read from the legend in Figure 4.3.

4.10 Pavement Damage

Field observations of existing road damage serve as indicators of relative hazard with large cracks, bulges, and pavement displacements indicating recent or un-mitigated ground movements. These observations also indicate what types of pavement damages may be expected in the future. Hazard scores increase with increasing observed damage to pavement. Pavement that is warped with no appreciable displacement represent the least hazardous condition and pavement that displays more than six inches of vertical displacement are judged to represent the most hazardous condition. Hazard categories for this factor are summarized in Table 4.13.

Table 4.13 Hazard score categories for pavement damage factor.

Pavement Damage	Hazard Score
Warping only	3
No Cracking, 1-2" (3-5 cm) offset	9
Some Cracking, 2-6" (5-15 cm) offset	27
Extensive Cracking, >6" (15 cm)offset	81

4.11 Failure Frequency

Landslide failure frequency is retained from the current CDOT system. This factor may be evaluated by review of maintenance records from both recent slope movements and historical failures. Slopes that experience frequent failures are more hazardous because they are subject to conditions that may be sensitive to site-specific changes. For example, the Red Creek landslide in central Colorado is triggered or stabilized by fluctuations in the adjacent Blue Mesa Reservoir water level (Walker and Santi, 2004). High failure frequency landslides will consequently require repeated maintenance visits and can cause regular disruptions to highway operations*.* According to CDOT (CDOT, 2011), a landslide with no observed movement in the past five years is judged to represent the least hazardous condition while a landslide that is observed to fail continuously is judged to represent the most hazardous condition. The hazard categories used by CDOT are presented in Table 4.14.

Table 4.14 Hazard score categories for failure frequency factor.

Failure Frequency	Hazard Score
No failures in previous 5 years	3
1-2 periods of movement in previous 5 years	9
Movement observed annually	27
Multiple movement episodes throughout year	81

4.12 Slope Angle

The slope angle is defined as the angle of inclination of a landslide mass with reference to a horizontal plane. Slope angle is considered in most soil slope stability analysis methods and is typically used to calculate stability factors from empirical charts or for use in factor of safety (FS) calculations. In general, FS values decrease with increasing slope angle. This relationship can be demonstrated by examining the Ordinary Method of Slices approach to soil slope stability. This approach involves dividing the soil mass into discrete slices and analyzing the static equilibrium of each slice. The weight of an individual slice in contact with the assumed failure plane can be divided into force vector components perpendicular and parallel to the failure plane. The normal component of the weight mobilizes cohesive and/or frictional resistances to sliding, while the parallel component tends to drive the slice to failure. The relative magnitudes of the resultant stresses depend on the orientation of the surface on which the forces act. With increasing slope angle, the parallel (driving) force component increases while the normal (resisting) force component decreases.

Research conducted on landslides developed in mudstone terrain by Iwahashi et al. (2003) in the northern highlands of Japan show that mean slope angle frequency distributions for nearly 7,800 landslide masses are most closely approximated by Weibull distributions. Through the use of equations taken from the field of reliability engineering, they generated failure probability curves as a function of slope angle. The breaks in severity for this hazard category are based on their findings, and are presented in the following table. Slope angles less than 20 degrees represent the least hazardous condition and slope angles greater than 40 degrees represent the most hazardous condition. Hazard categories for this factor are summarized in Table 4.15.

Table 4.15 Hazard score categories for slope angle factor.

Slope Angle (β)	Hazard Score
$\beta < 20^\circ$	3
$20^\circ < \beta \leq 30^\circ$	9
$30^\circ < \beta \leq 40^\circ$	27
$\beta > 40^\circ$	81

The slope angle for a landslide was evaluated in the field using a Brunton pocket transit. Where slopes were undulating, several measurements were taken and averaged. For increased accuracy in slope angle measurement, and provided that the resources are available, a digital elevation model (DEM) derived slope map may yield a better representation of the overall slope angle, especially when the landslide surface is irregular.

CHAPTER 5

CONSEQUENCE FACTOR SELECTION AND EVALUATION METHODOLOGY

This Chapter describes the eight Consequence Factors that were selected for use in the preliminary CLHRS. The Consequence Factors were developed based on a review of the current body of technical literature. Descriptions of the significance of each factor, evaluation method, and category break justifications are presented below. While the Hazard Factors described in Chapter 4 are intended to evaluate environmental contributors to landslide failure, the Consequence Factors discussed in this chapter were chosen in an effort to make the preliminary CLHRS more comprehensive in terms of specifically evaluating the potential negative impacts of landslide failure on an affected roadway.

5.1 Consequence Factor Selection

As mentioned above, the current CDOT rating system predominantly evaluates factors related to the consequences of a landslide failure. Five of the six consequence-related factors in the current CDOT system were retained for use in the new CLHRS: extent of the slide beyond right-of-way, size, detour options, average daily traffic (ADT), and annual maintenance costs. The length of roadway affected by the landslide is currently recorded in CDOT's landslide database reports but not factored into the risk score calculation. However, in the new CLHRS, affected road length has been included as a Consequence Factor. In addition to the CDOT-derived Consequence Factors, two new factors were developed for this study: depth to slide plane and worst case scenario detour time.

Several consequence-related factors identified in other published rating systems and presented in Table 2.1 were deliberately omitted from the new CLHRS. "Width of roadway affected" was judged to be redundant because the "proximity of slide to road" factor discussed below assesses consequence by evaluating the extent to which a landslide intersects a roadway. Maintenance frequency and maintenance response were omitted due to a lack of easy access to the corresponding documentation.

Decision sight distance and accident history were judged to be more applicable to rockfall hazards than landslide hazards and were thus omitted. Vehicle risk and impact potential were judged to be too qualitative for inclusion in the CLHRS. Finally, the various multipliers used in the Oregon DOT and Philippines systems were judged to be too site-specific and the inclusion of multipliers in the scoring procedure was considered to be an undesirable deviation from the intended method. Descriptions of the Consequence Factors included in this study are presented below.

5.2 Depth to Slide Plane

The consequences of failure of a landslide are related to the total volume of the slide mass. More massive slides can deposit greater volumes of material on a roadway and adjacent structures, thus necessitating mobilization of labor to remove larger quantities of material. The depth to the slide plane is significant because it relates directly to the volume of the mass. Information about the depth to the slide plane may be available from agency records where investigations have been conducted in the past. For slides that lack exact measurements, the depth to the slide plane can be estimated by observing the boundaries and geometry of the slide in the field and using conservative judgment. According to Turner and McGuffey (1996), the depth of movement below the ground surface is not typically greater than the width of the zone of surface motion. Additionally, the maximum depth to the slide plane is typically equal to the distance from the break in the original ground surface slope to the most uphill crack or scarp (McGuffey, 1991).

The consequence categories are presented in the following table and are defined in five foot intervals with depths less than five feet (approximately two meters) judged to represent the least severe impact and depths greater than 15 feet (approximately five meters) judged to represent the most severe impact. Consequence category breaks for this factor are summarized in Table 5.1.

Table 5.1 Consequence score categories for depth to slide plane factor.

Depth to Slide Plane (D_{sp})	Depth to Slide Plane (metric)	Consequence Score
$D_{sp} < 5ft$	$D_{sp} < 1.5m$	3
$5ft \leq D_{sp} < 10ft$	$1.5m \leq D_{sp} < 3.0m$	9
$10ft \leq D_{sp} < 15ft$	$3.0m \leq D_{sp} < 4.6m$	27
$D_{sp} \geq 15ft$	$D_{sp} \geq 4.6m$	81

5.3 Map Area Affected (Landslide Size)

The map area affected by the landslide has been used as a substitute for landslide "size" by CDOT. The boundaries for a given slide feature can be observed directly in the field and corroborated by aerial photography (or vice versa), and approximate boundaries can be traced in ArcGIS to create closed polygons for each landslide. The total map area can be calculated for each polygon and expressed in the attribute table for the landslide layer. Landslides that cover larger map areas have the potential to affect larger segments of roadway as well as any additional structures, waterways, lifelines, or topography, either via ground displacements or deposition of slide material in problematic areas. The "small," "medium," and "large" nominal categories have been retained. The "Catastrophic" category has been changed to "Massive" in order to avoid any assumptions of the severity of possible damages. The breaks in consequence categories are based on order of magnitude differences, with slide areas less than 1,000 square meters judged to represent the least severe impact and areas greater than 100,000 square meters judged to represent the most severe impact. Consequence score categories for this factor are summarized in Table 5.2.

Table 5.2 Consequence score categories for landslide size factor.

Map Area Affected (A_m)	Consequence Score
$A_m \leq 1{,}000\ m^2$	3
$1{,}000\ m^2 < A_m \leq 10{,}000\ m^2$	9
$10{,}000\ m^2 < A_m \leq 100{,}000\ m^2$	27
$A_m > 100{,}000\ m^2$	81

5.4 Length of Roadway Affected

The length of the roadway affected by a landslide refers to the total length of road segment that intersects the landslide mass or the total length of roadway that is immediately adjacent to the slide mass measured perpendicular to the slide axis and parallel to the road. Larger exposed segments of road will suffer more severe consequences from failure due to the increased size of the section of road that must be repaired or replaced. Affected road lengths of 100 feet (approximately 30 meters) or less are judged to represent the least hazardous condition while road lengths greater than 1,000 feet (approximately 305 meters) are judged to represent the most hazardous condition. The range of road lengths used for this factor was chosen in order to fully encompass the measured affected road lengths encountered in this study. The breaks in consequence categories used in the preliminary CLHRS are presented in Table 5.3.

Table 5.3 Consequence score categories for affected road length factor.

Length of Highway Affected (L_h)	Length of Highway Affected (metric)	Consequence Score
$L_h \leq 100$ ft	$L_h \leq 30$ m	3
100 ft $< L_h \leq$ 500 ft	30 m $< L_h \leq$ 152 m	9
500 ft $< L_h \leq$ 1,000 ft	152 m $< L_h \leq$ 305 m	27
$L_h >$ 1,000 ft	$L_h >$ 305 m	81

5.5 Proximity of Slide to Road

The current CDOT system evaluates both the extent of the landslide beyond the established right-of-way (ROW) and the width of roadway affected by the slide. Both characteristics are judged qualitatively with the emphasis of the former on impacts on areas beyond the highway boundaries and the latter on impacts on the highway exclusively. Both of these factors have been replaced in the preliminary CLHRS by a single Consequence Factor. For example, considering the toe of a landslide, the closer the toe is to the roadway, irrespective of its vertical distance from that roadway, the greater the consequences of failure. In an exaggerated case, if the toe of a landslide is located a great distance from the ROW, its ability to affect the road via gradual displacements is significantly diminished. Furthermore, in the event of a sudden total failure the runout length required to reach the ROW is increased, thus decreasing the consequences of failure. The worst-case scenario involves the roadway passing through the landslide with the toe and headscarp located on opposite sides of the ROW. Intuitively, such an arrangement would cause serious if not total damage to the highway section affected. The breaks in consequence categories used for the preliminary CLHRS are presented in Table 5.4.

Table 5.4 Consequence score categories for landslide proximity factor.

Proximity of Slide to Road (P_r)	Proximity of Slide to Road (metric)	Consequence Score
$P_r \geq 40$ ft	$P_r \geq 12$ m	3
40ft > $P_r \geq$ 15ft	12 m > $P_r \geq 5$ m	9
$P_r \leq$ 15ft	$P_r \leq 5$ m	27
Intersecting	Intersecting	81

5.6 Average Annual Daily Traffic (AADT)

The interstate highway system is a vital commercial network that allows for the rapid transit of goods, commuters, and tourists throughout the United States. Disruptions of segments of this system are not only inconvenient for the travel plans of individual motorists, but the economic losses due to the delay and/or rerouting of commercial traffic may result in considerable economic losses. Therefore, routes that receive larger volumes of traffic daily are assigned higher consequence scores. This factor is retained from the original CDOT system and the breaks in consequence categories are unchanged. Consequence categories for this factor are summarized in Table 5.5.

Table 5.5 Consequence score categories for AADT factor.

Annual Average Daily Traffic (vehicles/day)	Consequence Score
<5,000	3
5,000-10,000	9
10,000-20,000	27
> 20,000	81

5.7 Detour Options

This consequence factor refers to the most likely detour solution for a given landslide site and is retained unchanged from the original CDOT system. This factor is intended to reflect the impacts of a given landslide on the state DOT responsible for coordinating the detour. Sites that lack expedient detour options will require more effort on the part of the DOT to design, implement, and maintain a detour for the duration of repairs.

Through observations in the field of the landslide geometry, size, historical movement behavior, and current damage area, a reasonable detour solution can be assumed based on the area affected and likely mitigation/repair efforts. Situations in which onsite detour options are very limited or impossible are assigned higher consequence scores. Consequence score categories for this factor are summarized in Table 5.6.

Table 5.6 Consequence score categories for detour option factor.

Detour Options	Consequence Score
None required	3
Onsite, lane shift, reduced speed	9
Offsite, <5 mi (8 km)	27
>5 (8 km) mi or none	81

5.8 Worst-Case Scenario Detour Time

In the event of the total failure of a landslide such that a segment of a road is completely destroyed or damaged severely enough that mitigation efforts require temporary closure of the road (i.e., no on-site detour), a worst-case scenario detour time Consequence Factor has been included in the system. This factor is intended to assess the sociological and or economic impacts of a road closure specifically on motorists (i.e., local commuters, tourists, commercial traffic, etc.) rather than the state DOT (see section 5.7). Longer detour times can be extremely inconvenient for individuals who must use the damaged roadway on a daily basis, tourists can have a negative experience through long delays, and business entities can suffer through lost tourist income, commercial traffic delays, and increased costs for commercial transportation of goods.

The detour time is evaluated by treating the landslide location as an impassable point on a highway map. Two points are arbitrarily chosen on either side of this restriction point and the shortest alternative path is found through trial and error via any conventional internet-based mapping site (e.g., GoogleMaps) (Figure 5.1). The highways that pass through Colorado tend to be isolated relative to other states due to the rugged terrain that restricted route placement options during original construction.

Consequently, in more isolated areas, detour times can be exceedingly long to resume travel on the obstructed roadway. Higher consequence scores are assigned to landslides that create longer detour times in the event of a total failure with times less than 10 minutes representing the least severe impact and detour times in excess of 60 minutes representing the most severe impact. Consequence categories for this factor are summarized in Table 5.7.

Table 5.7 Consequence score categories for detour option factor.

Worst Case Detour Time	Consequence Score
<10 min	3
10-30 min	9
30-60 min	27
>60 min	81

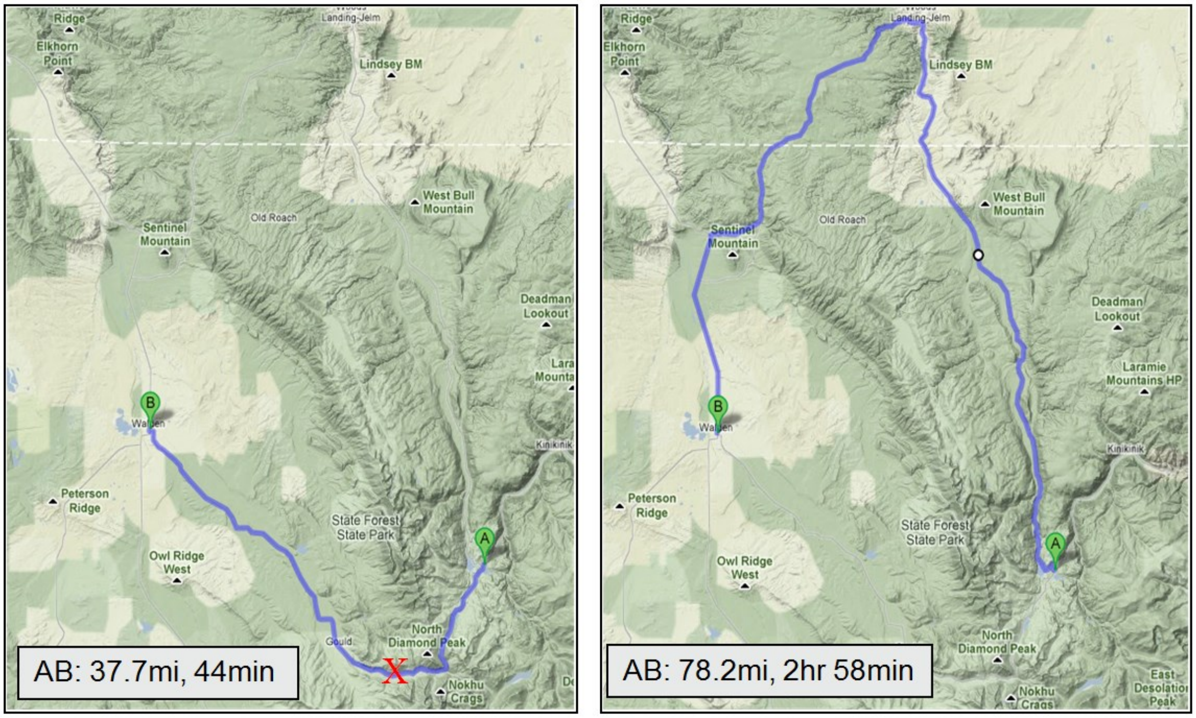


Figure 5.1 Worst-Case Scenario Detour Option for Landslide on US 14. The “X” indicates the location of the landslide. The image on the left shows the unobstructed travel distance and time. The right image shows the shortest alternative path to continue travel along the same highway if the road was blocked due to landslide failure or mitigation.

5.9 Annual Maintenance Costs

Landslides that experience movements frequently and cause significant damage to the roadway require frequent, monitoring, maintenance, and mitigation. These efforts have their associated costs in terms of labor and materials. As more funds are devoted to continued repairs of landslide damage, less funds become available for other existing landslide sites and/or new landslides that may suddenly develop. As mentioned in Section 2.3.1, the current CDOT system is largely based on Lowell and Morin's (2000) USMS. The dollar amounts (i.e., $5k, $10k, and $25) established for use in the USMS have been adjusted for inflation using the United States Department of Labor's Bureau of Labor Statistics Consumer Price Index (CPI) Calculator (USDL, 2013) in order to more accurately reflect the buying power of 2013 dollars. Higher consequence scores are assigned to slides that have high annual maintenance costs, with costs of less than $7,000 annually representing the least severe impact and annual costs in excess of $34,000 representing the most severe impact. The adjusted breaks in consequence severity categories are presented in Table 5.8.

Table 5.8 Consequence score categories for annual maintenance cost factor.

Annual Maintenance Cost	Consequence Score
<$7K	3
$7-14K	9
$14-34K	27
> $34K	81

CHAPTER 6

APPLICATION OF PRELIMINARY RATING SYSTEM AND SCORING RESULTS

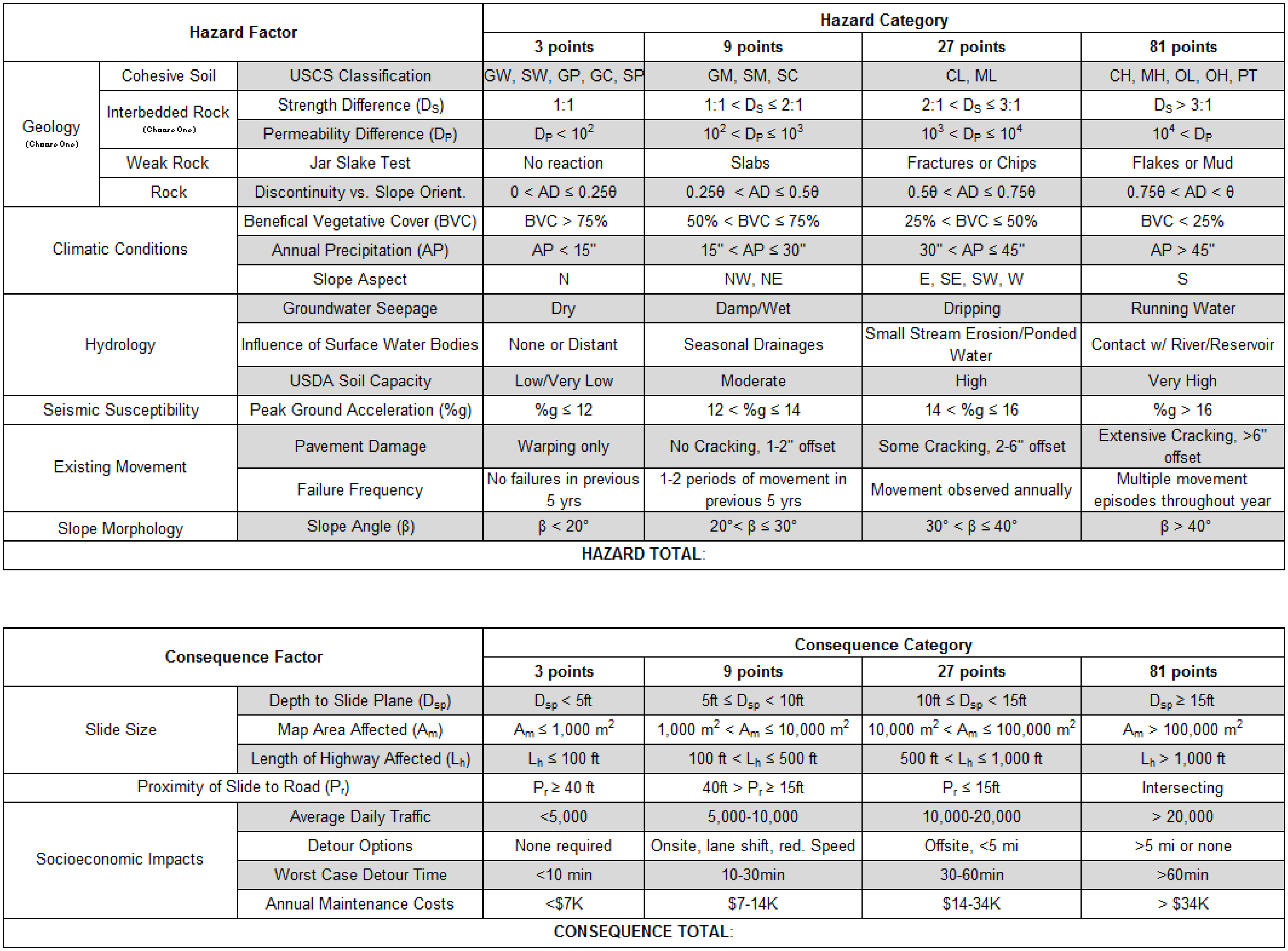
The factors described in Chapters 4 and 5 were combined to form the preliminary version of the CLHRS that is summarized in Figure 6.1. The landslides in the dataset provided by CDOT were evaluated by the author during the summer of 2011. This chapter presents the distributions of scores for all CLHRS factors as well as the distributions of total hazard, consequence, and risk scores.

6.1 Initial Landslide Screening

As defined in Section 3.2, the scope of this project involved the evaluation of the initial dataset comprised of the 78 landslides that were completely documented by a corresponding landslide database report and fully delineated by CDOT in ArcGIS. Specific focus was devoted to these slides in order to facilitate rapid evaluation in the field and avoid out of scope mapping activities. Of these 78 slides, nine were eliminated from the dataset because they represented failures of mechanically-stabilized earth (MSE) walls. While these nine features are failures involving earth material, it was judged that the geometry of these features and the set of factors that contribute to their failure are sufficiently unique to exclude them from further evaluation. Therefore, all subsequent analyses were developed based on a dataset consisting of 69 landslides. The spatial distribution of the 69 landslide sites throughout western Colorado is presented in Figure 6.2.

6.2 Hazard Distributions

This section presents the distribution of scores for individual hazard factors by category as well as the overall distribution of hazard scores. Additionally, the distribution of geologic problem types is presented.



Hazard Factor			Hazard Category			
			3 points	9 points	27 points	81 points
Geology (Choose One)	Cohesive Soil	USCS Classification	GW, SW, GP, GC, SP	GM, SM, SC	CL, ML	CH, MH, OL, OH, PT
	Interbedded Rock (Choose One)	Strength Difference (D_S)	1:1	$1:1 < D_S \leq 2:1$	$2:1 < D_S \leq 3:1$	$D_S > 3:1$
		Permeability Difference (D_P)	$D_P < 10^2$	$10^2 < D_P \leq 10^3$	$10^3 < D_P \leq 10^4$	$10^4 < D_P$
	Weak Rock	Jar Slake Test	No reaction	Slabs	Fractures or Chips	Flakes or Mud
	Rock	Discontinuity vs. Slope Orient.	$0 < AD \leq 0.25\theta$	$0.25\theta < AD \leq 0.5\theta$	$0.5\theta < AD \leq 0.75\theta$	$0.75\theta < AD < \theta$
Climatic Conditions		Benefical Vegetative Cover (BVC)	BVC > 75%	50% < BVC ≤ 75%	25% < BVC ≤ 50%	BVC < 25%
		Annual Precipitation (AP)	AP < 15"	15" < AP ≤ 30"	30" < AP ≤ 45"	AP > 45"
		Slope Aspect	N	NW, NE	E, SE, SW, W	S
Hydrology		Groundwater Seepage	Dry	Damp/Wet	Dripping	Running Water
		Influence of Surface Water Bodies	None or Distant	Seasonal Drainages	Small Stream Erosion/Ponded Water	Contact w/ River/Reservoir
		USDA Soil Capacity	Low/Very Low	Moderate	High	Very High
Seismic Susceptibility		Peak Ground Acceleration (%g)	%g ≤ 12	12 < %g ≤ 14	14 < %g ≤ 16	%g > 16
Existing Movement		Pavement Damage	Warping only	No Cracking, 1-2" offset	Some Cracking, 2-6" offset	Extensive Cracking, >6" offset
		Failure Frequency	No failures in previous 5 yrs	1-2 periods of movement in previous 5 yrs	Movement observed annually	Multiple movement episodes throughout year
Slope Morphology		Slope Angle (β)	$\beta < 20°$	$20° < \beta \leq 30°$	$30° < \beta \leq 40°$	$\beta > 40°$
HAZARD TOTAL:						

Consequence Factor		Consequence Category			
		3 points	9 points	27 points	81 points
Slide Size	Depth to Slide Plane (D_{sp})	$D_{sp} < 5ft$	$5ft \leq D_{sp} < 10ft$	$10ft \leq D_{sp} < 15ft$	$D_{sp} \geq 15ft$
	Map Area Affected (A_m)	$A_m \leq 1{,}000\ m^2$	$1{,}000\ m^2 < A_m \leq 10{,}000\ m^2$	$10{,}000\ m^2 < A_m \leq 100{,}000\ m^2$	$A_m > 100{,}000\ m^2$
	Length of Highway Affected (L_h)	$L_h \leq 100$ ft	100 ft $< L_h \leq 500$ ft	500 ft $< L_h \leq 1{,}000$ ft	$L_h > 1{,}000$ ft
Proximity of Slide to Road (P_r)		$P_r \geq 40$ ft	$40ft > P_r \geq 15ft$	$P_r \leq 15ft$	Intersecting
Socioeconomic Impacts	Average Daily Traffic	<5,000	5,000-10,000	10,000-20,000	> 20,000
	Detour Options	None required	Onsite, lane shift, red. Speed	Offsite, <5 mi	>5 mi or none
	Worst Case Detour Time	<10 min	10-30min	30-60min	>60min
	Annual Maintenance Costs	<$7K	$7-14K	$14-34K	> $34K
CONSEQUENCE TOTAL:					

Figure 6.1 Preliminary CLHRS evaluation sheet used in the

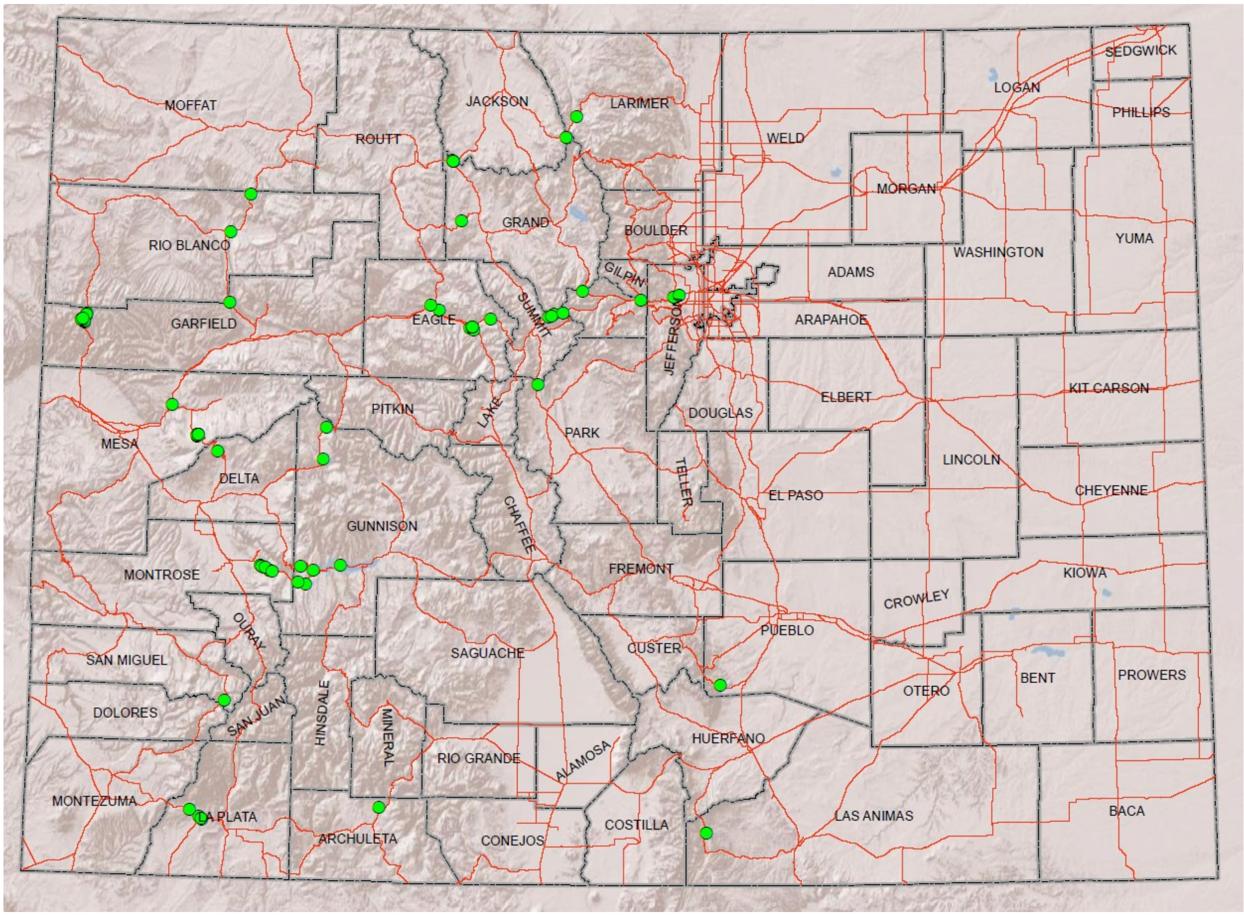


Figure 6.2 Landslide location map. Green circles indicate locations of 69 landslide centroids

6.2.1 Geologic Problem Type Distribution

As discussed in Chapter 4, the geologic component of hazard is evaluated through a multi-option Hazard Factor, Geologic Problem Type. Figure 6.3 depicts the distribution of the geologic problem types considered to be dominant for each of the 69 landslide sites. Note that approximately 81 percent of the sites are comprised of predominately colluvial soil while approximately one percent of the sites are judged to be comprised of weak rock.

6.2.2 Hazard Factor Distributions

The distributions of scores for each category for the 11 Hazard Factors included in the CLRHS are presented as histograms in Figures 6.4 through 6.15. For each factor, four categories of severity were possible and increased exponentially with a score of three representing the least severe category and a score of 81 representing the most severe category.

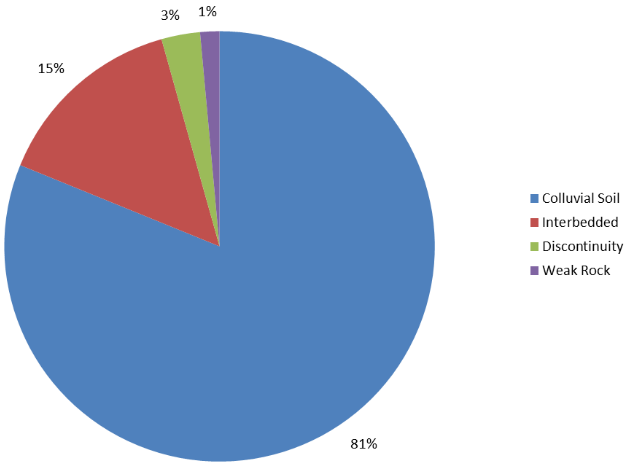


Figure 6.3 Distribution of geologic problem types observed for the 69 landslide sites in the dataset.

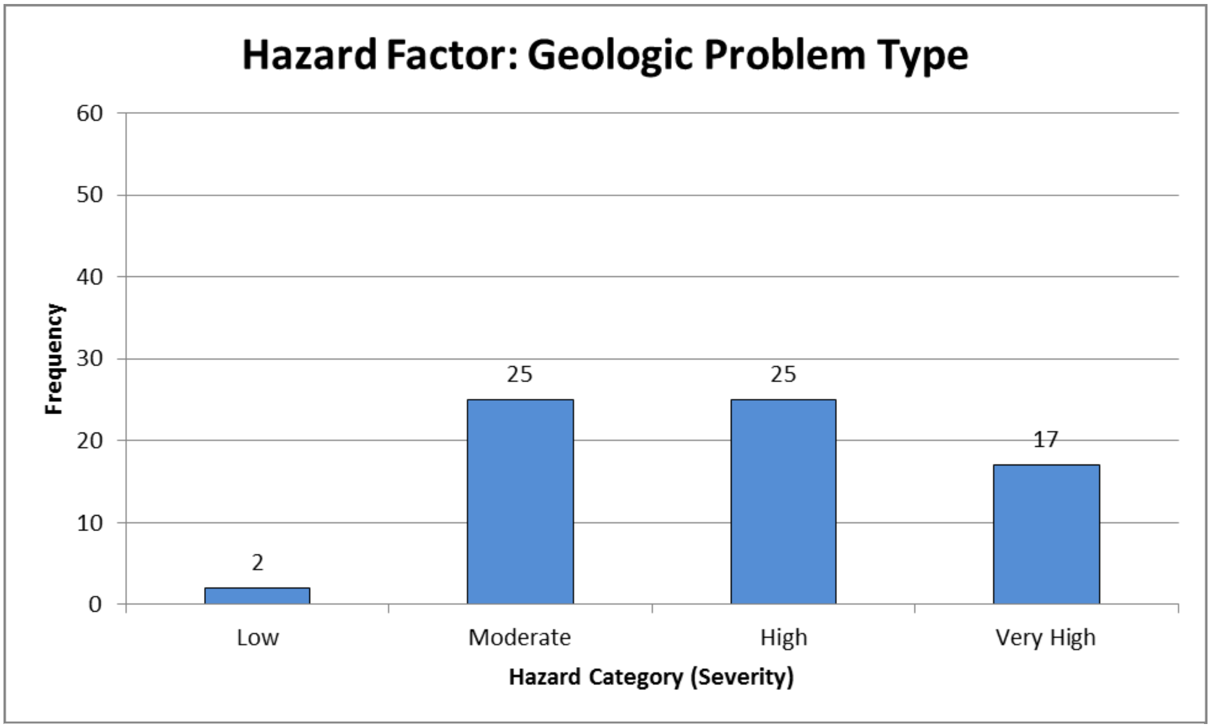


Figure 6.4 Histogram of hazard scores for geologic problem type factor

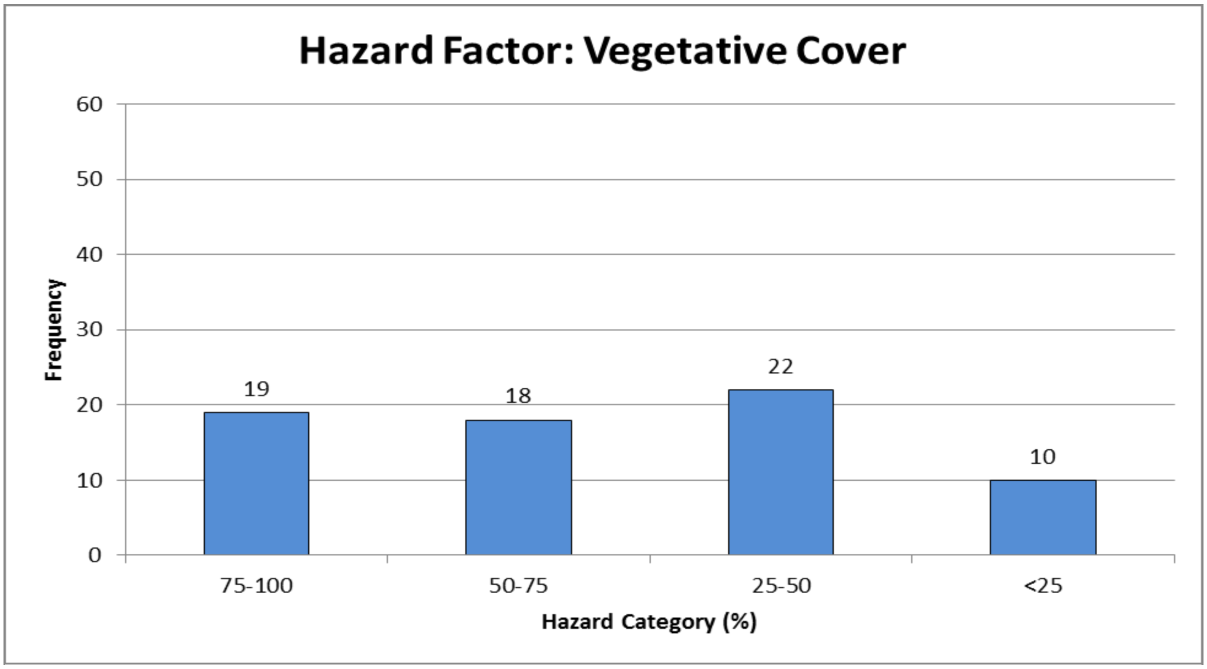


Figure 6.5 Histogram of hazard scores for vegetative cover factor

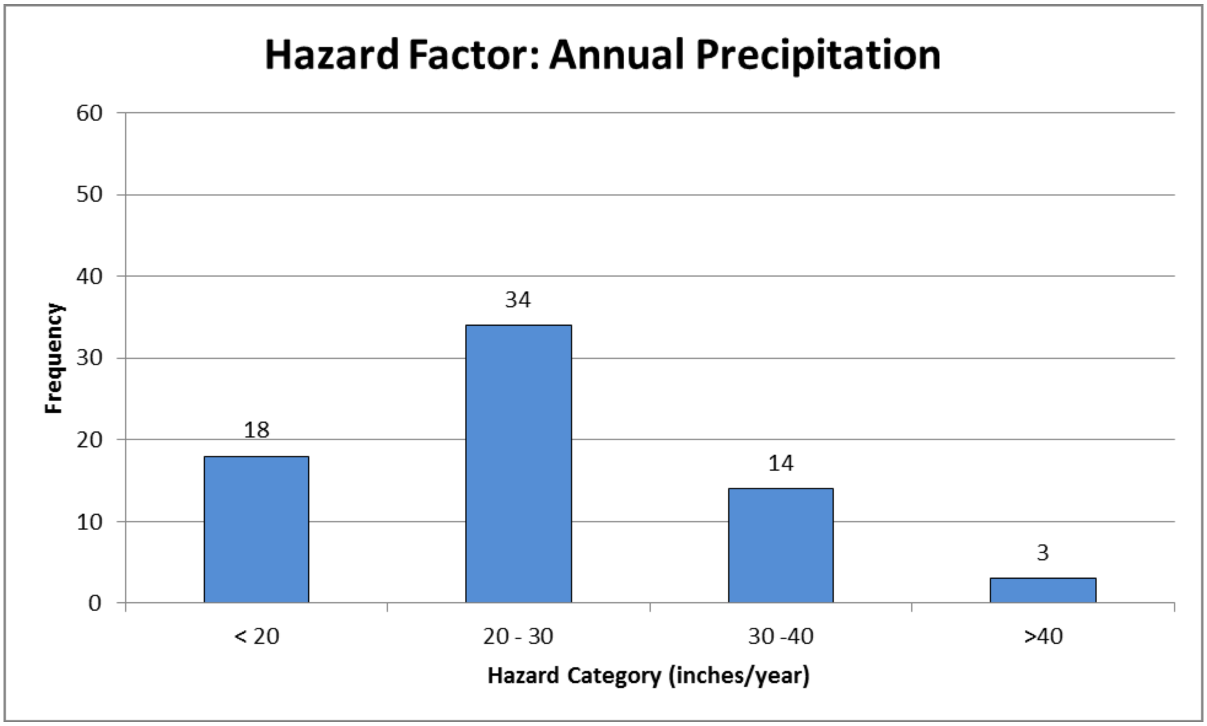


Figure 6.6 Histogram of hazard scores for average annual precipitation factor

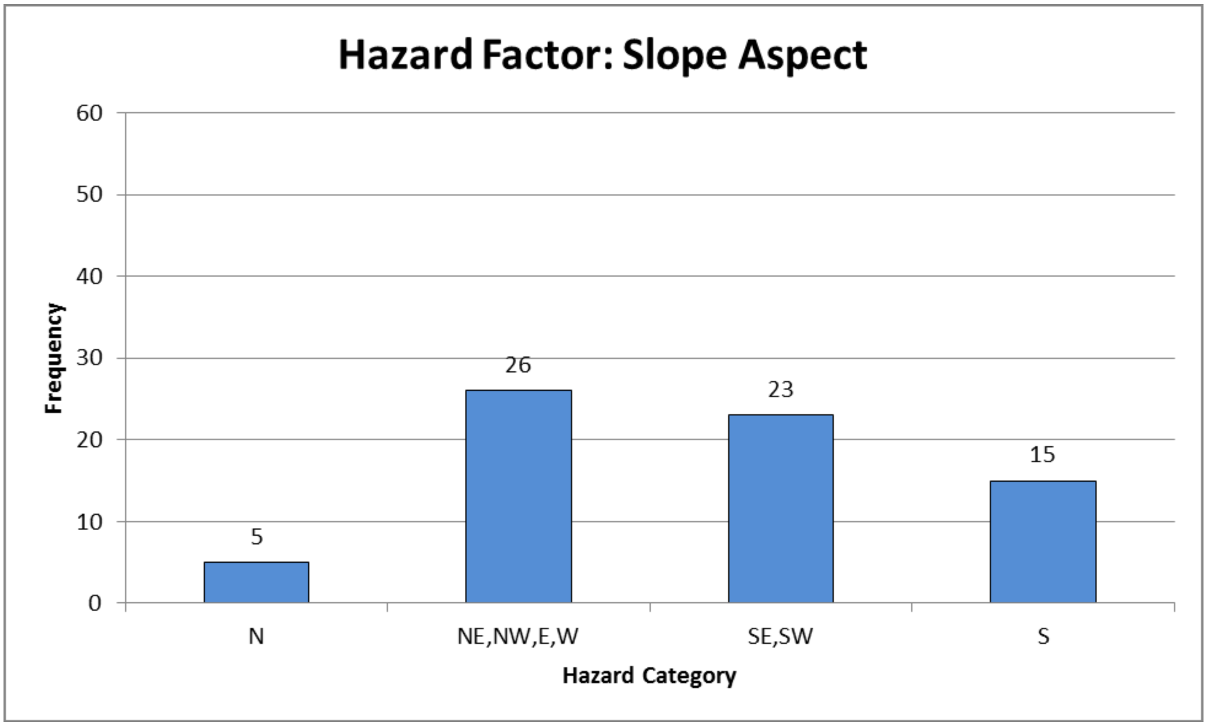


Figure 6.7 Histogram of hazard scores for slope aspect factor

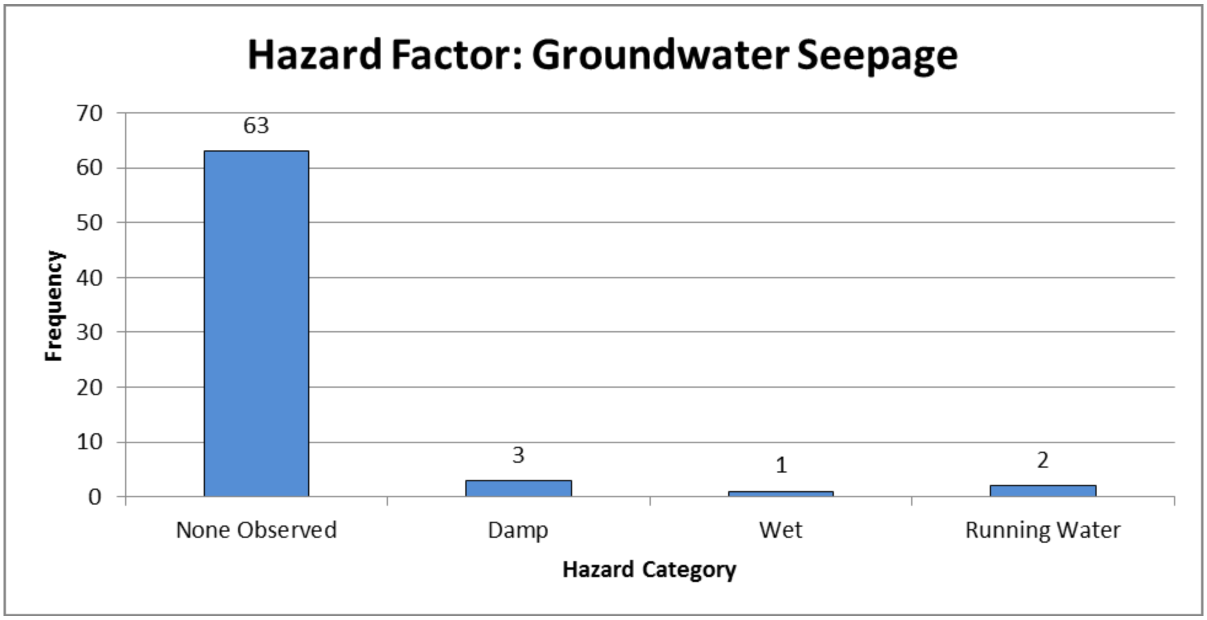


Figure 6.8 Histogram of hazard scores for groundwater seepage factor

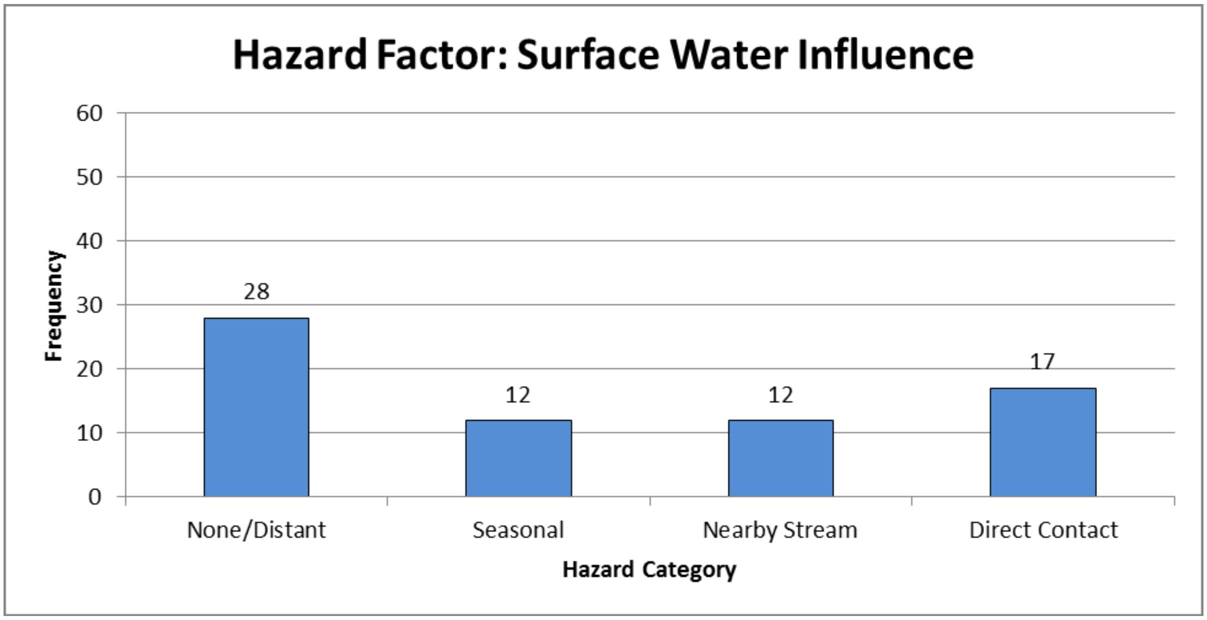


Figure 6.9 Histogram of hazard scores for surface water influence factor

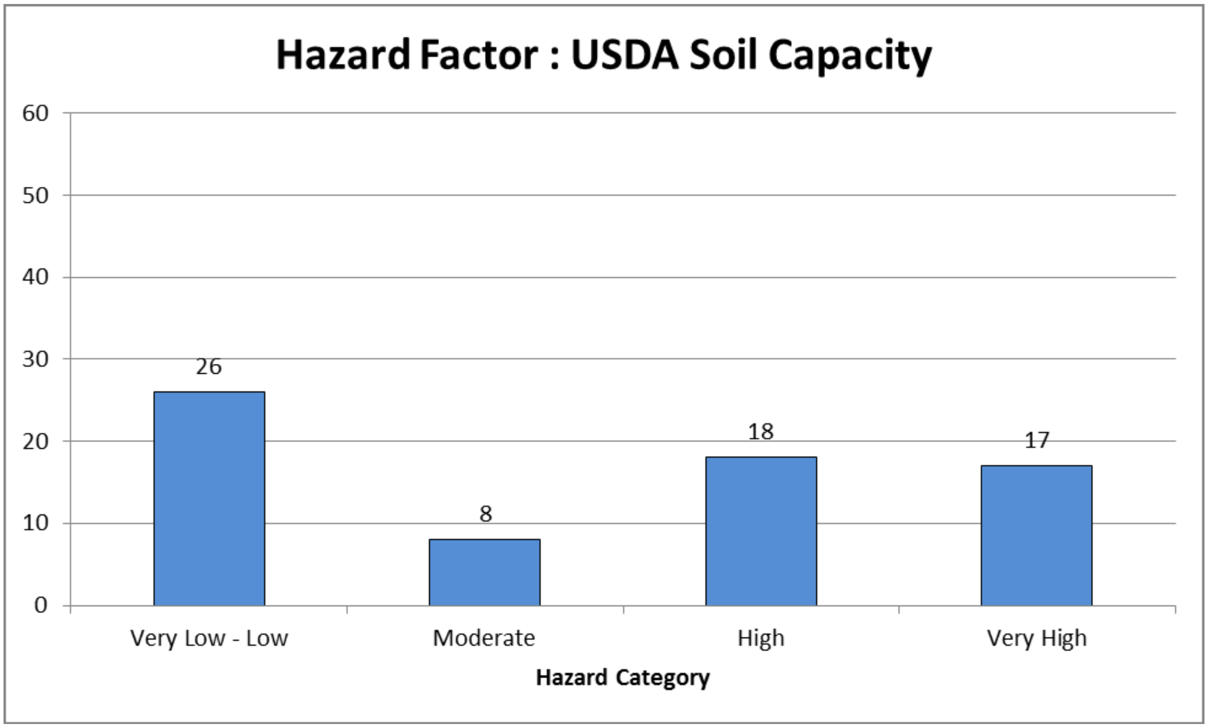


Figure 6.10 Histogram of hazard scores for USDA soil capacity factor

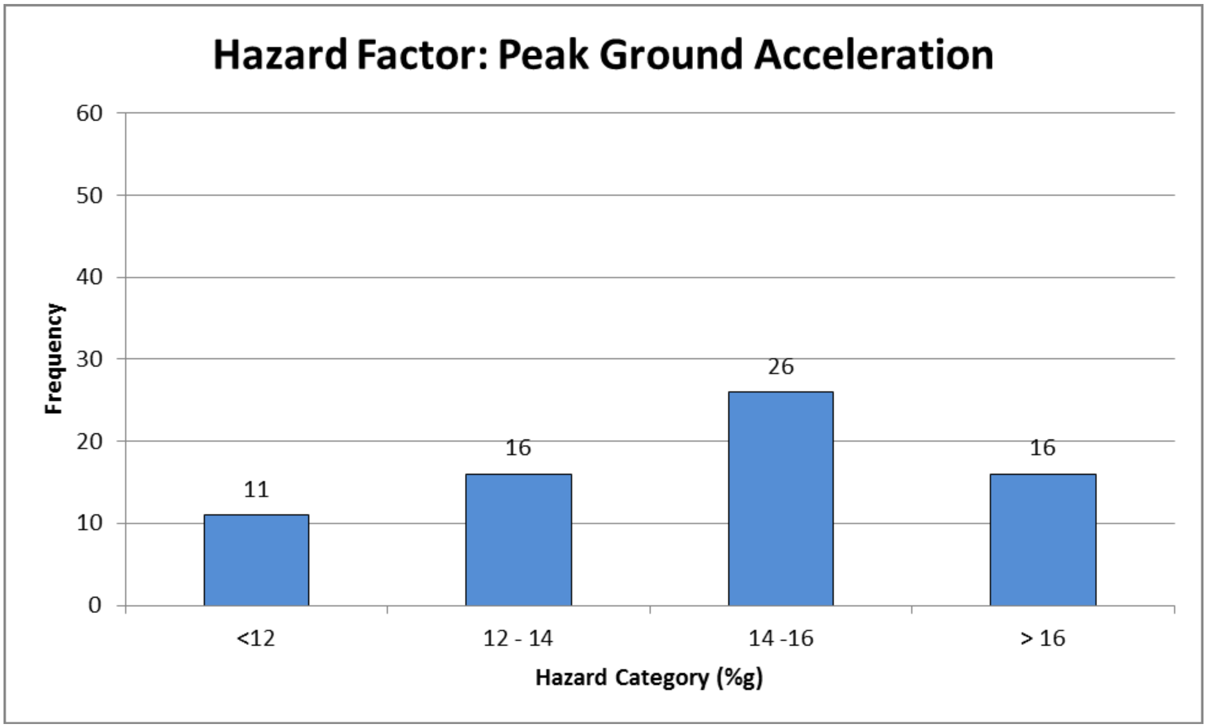


Figure 6.11Histogram of hazard scores for peak ground acceleration factor

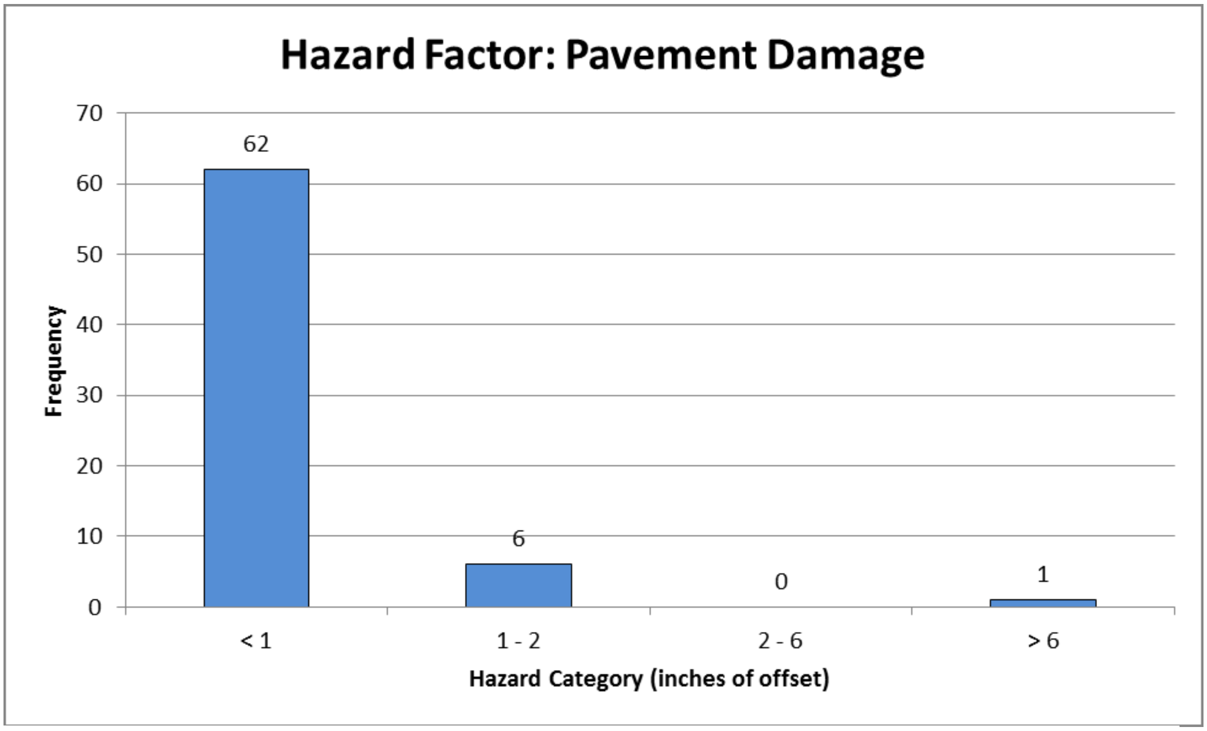


Figure 6.12 Histogram of hazard scores for pavement damage factor

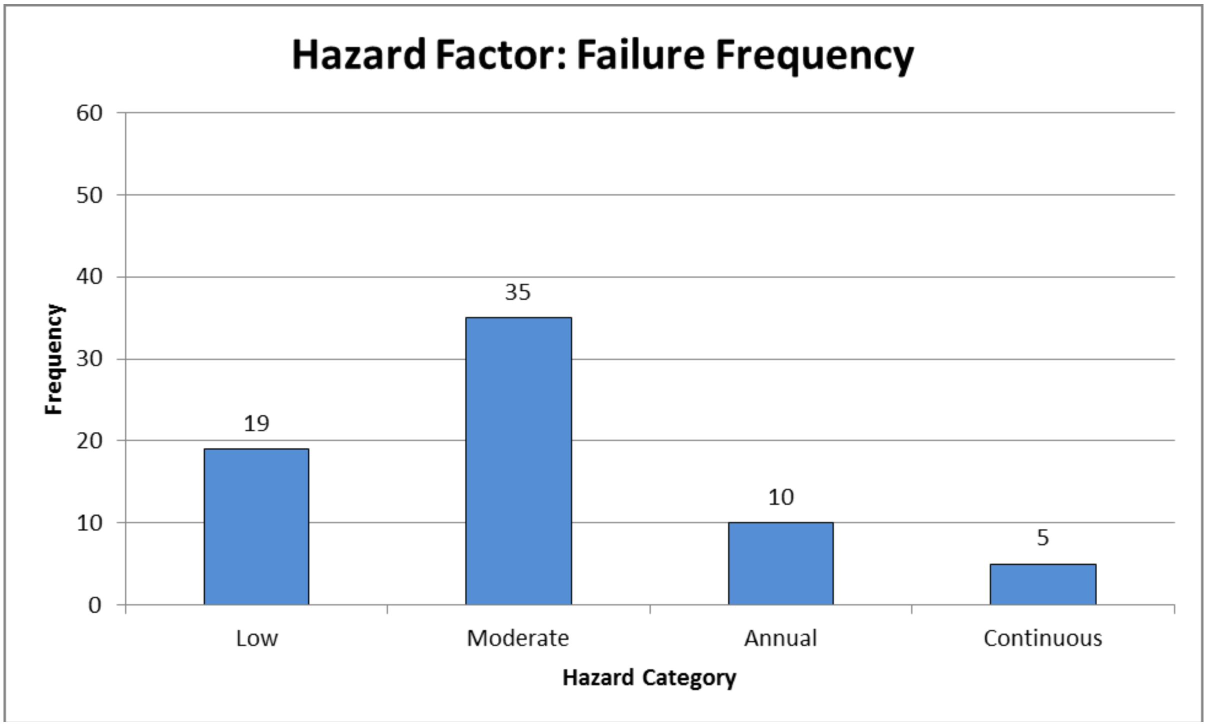


Figure 6.13 Histogram of hazard scores for failure frequency factor

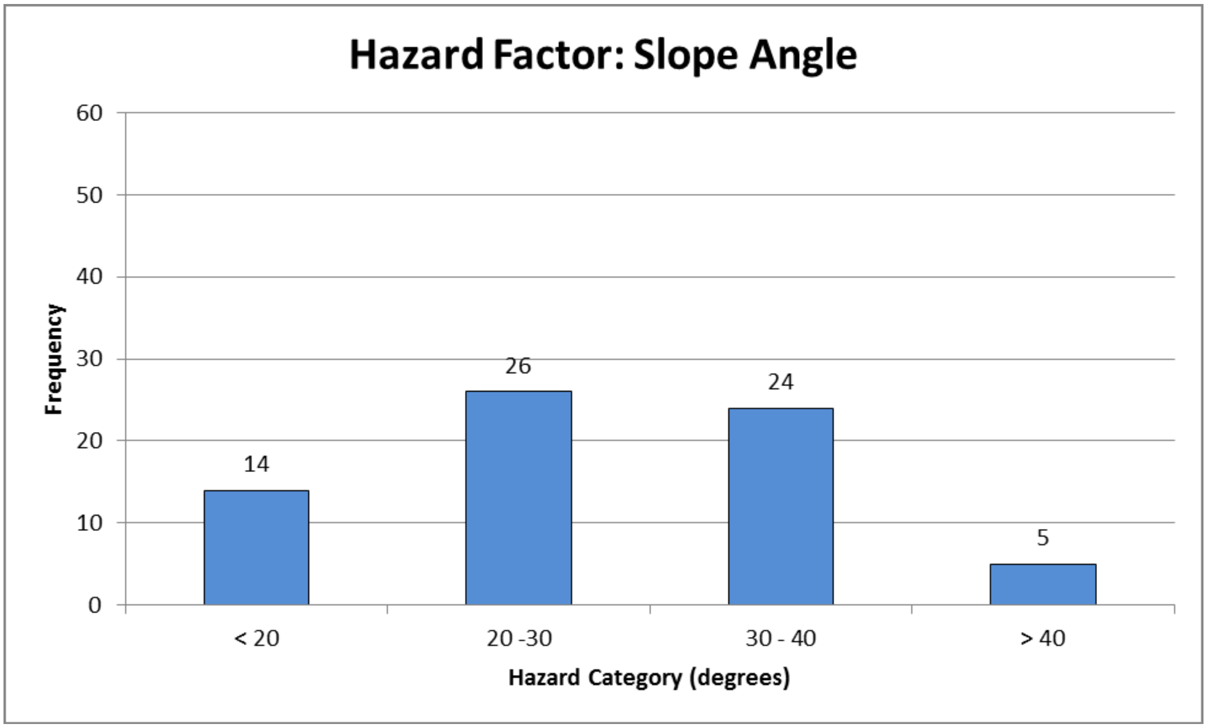


Figure 6.14 Histogram of hazard scores for slope angle factor

6.2.3 Hazard Score Distribution

The distribution of total hazard scores for each of the 69 landslides is presented as Figure 6.15. The hazard scores were obtained by summing the individual hazard scores for each of the 11 Hazard Factors included in the preliminary CLHRS. Possible total hazard scores range from a minimum of 33 up to a maximum of 891.

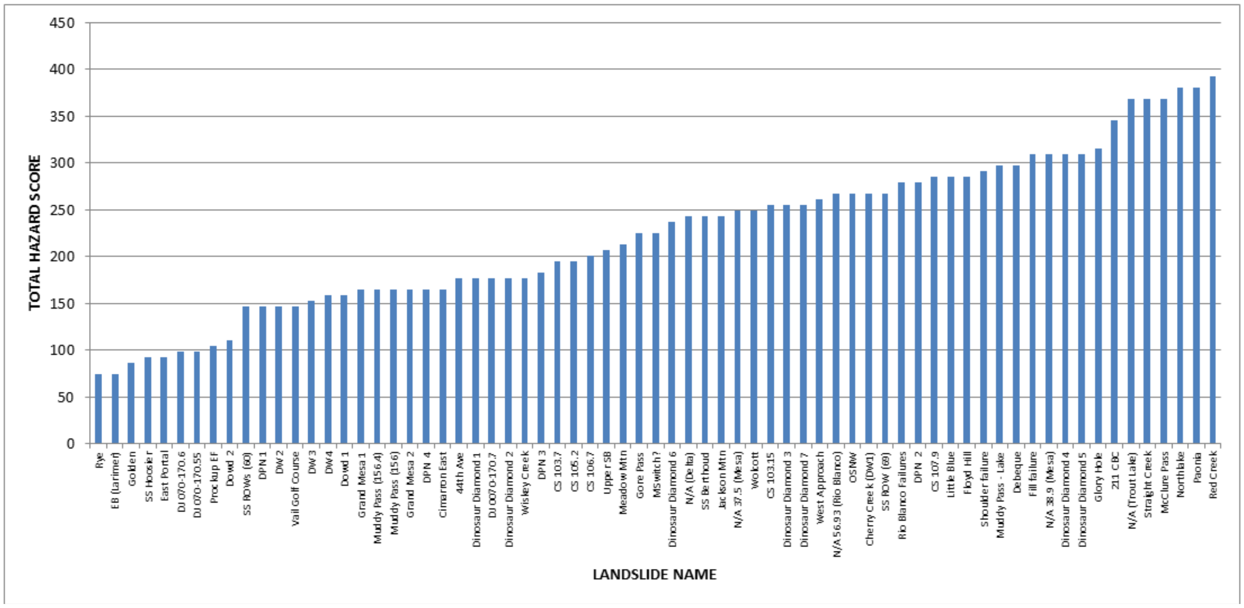


Figure 6.15 Distribution of total hazard scores for the 69 landslides in the dataset.

6.3 Consequence Factor Distributions

The distributions of scores for each category for the eight Hazard Factors included in the CLRHS are presented as histograms in Figures 6.16 through 6.23. For each factor, four categories of severity were possible and increased exponentially with a base of three with a score of three representing the least severe category and a score of 81 representing the most severe category.

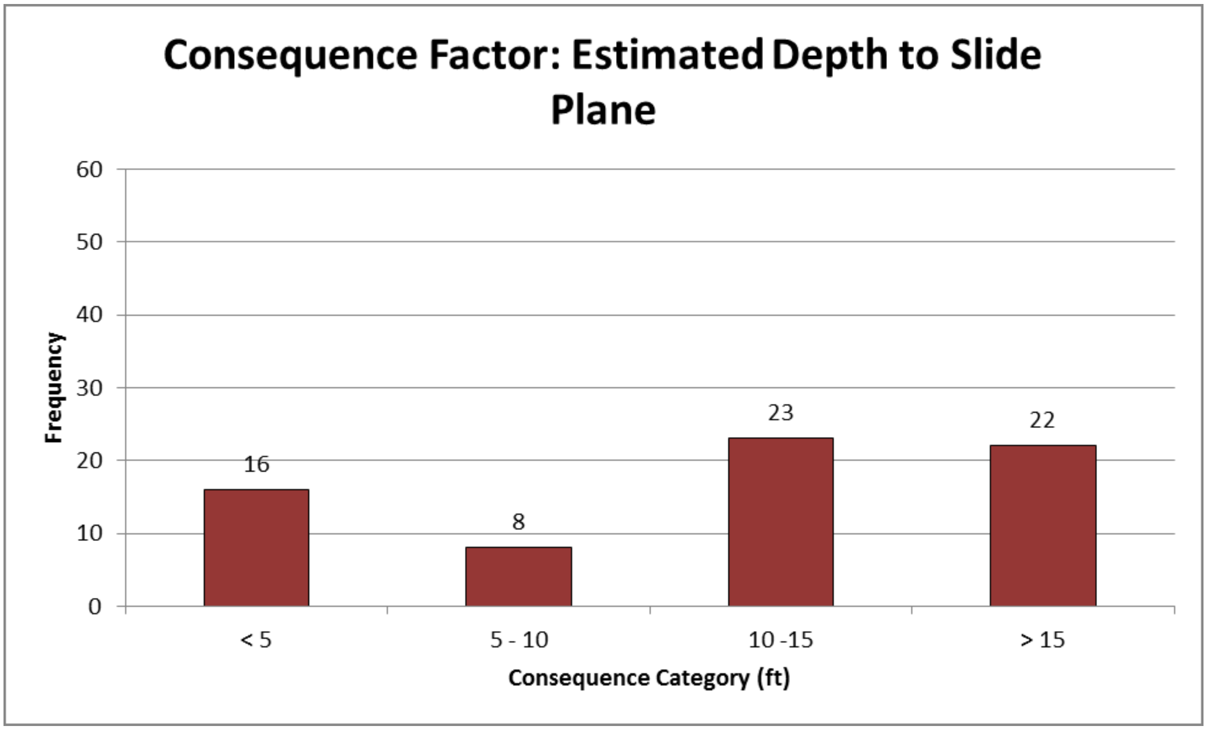


Figure 6.16 Histogram of consequence scores for depth to slide plane factor

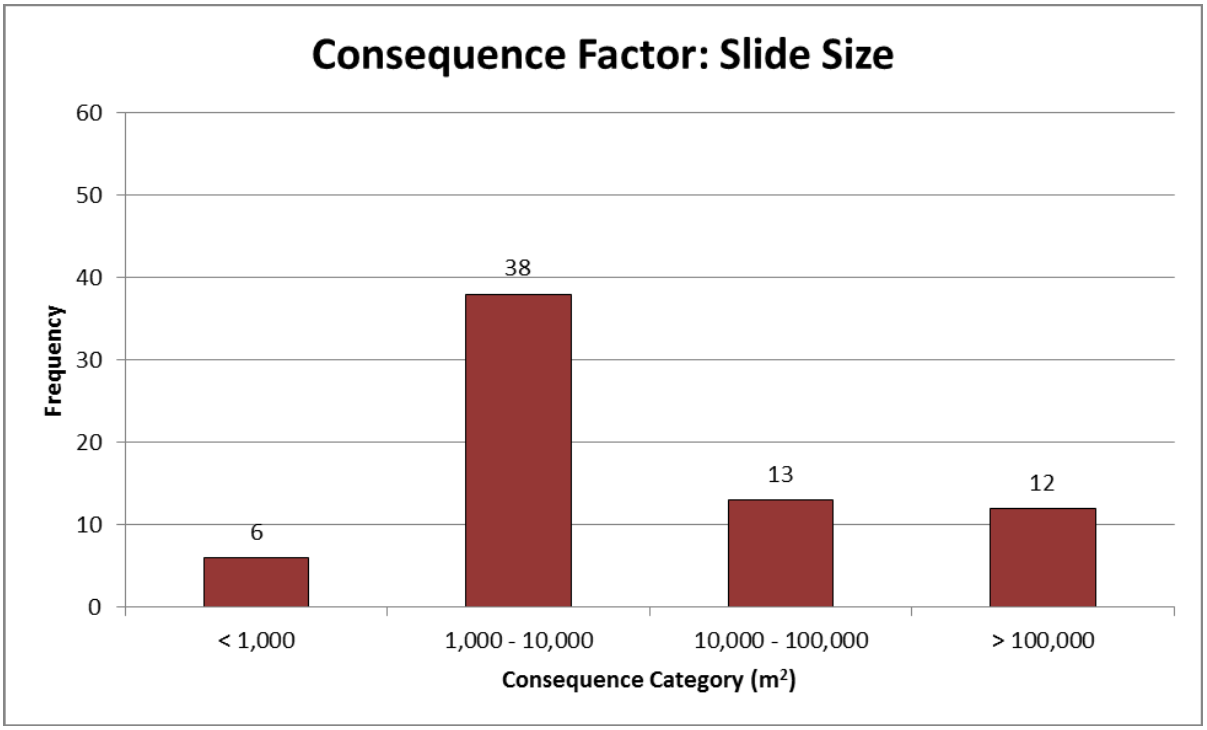


Figure 6.17 Histogram of consequence scores for slide size factor

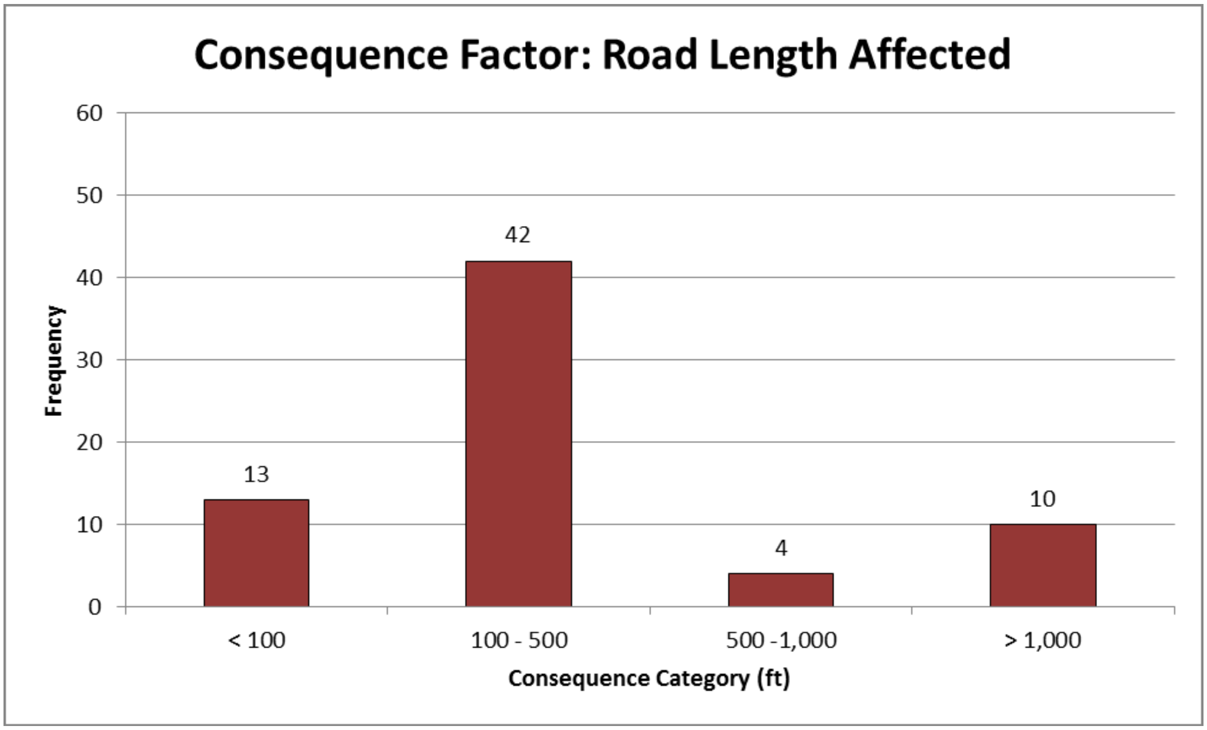


Figure 6.18 Histogram of consequence scores for road length affected factor

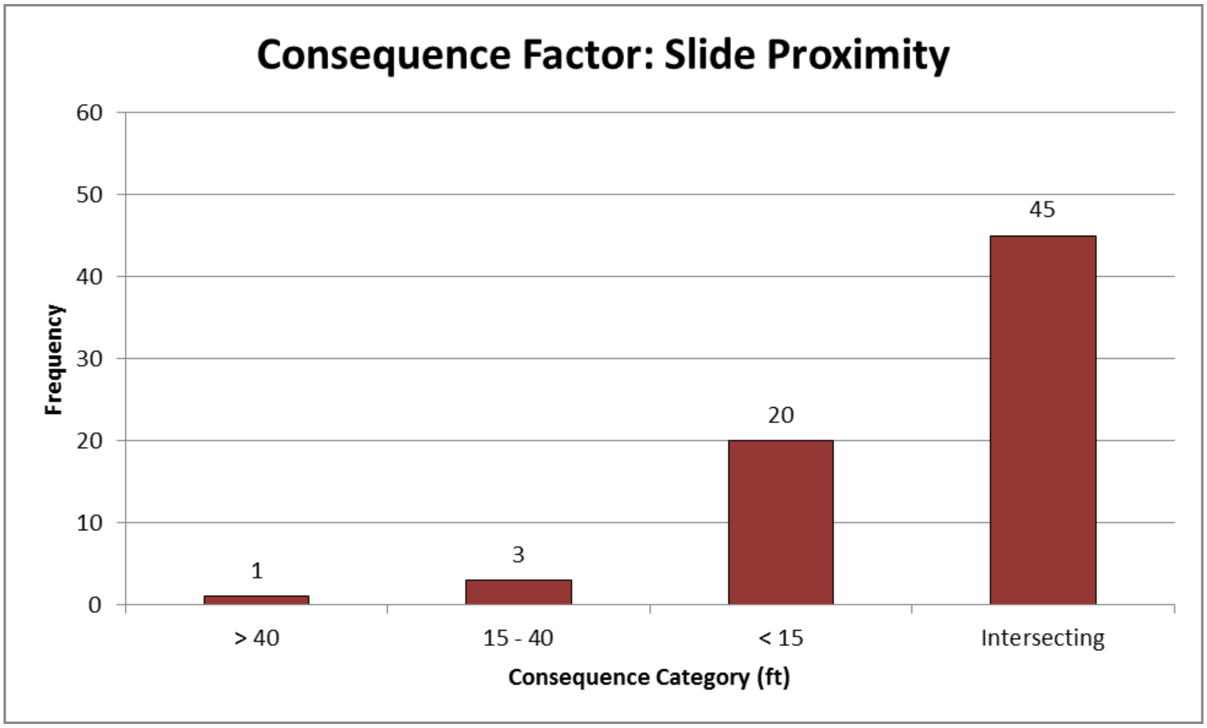


Figure 6.19 Histogram of consequence scores for slide proximity factor

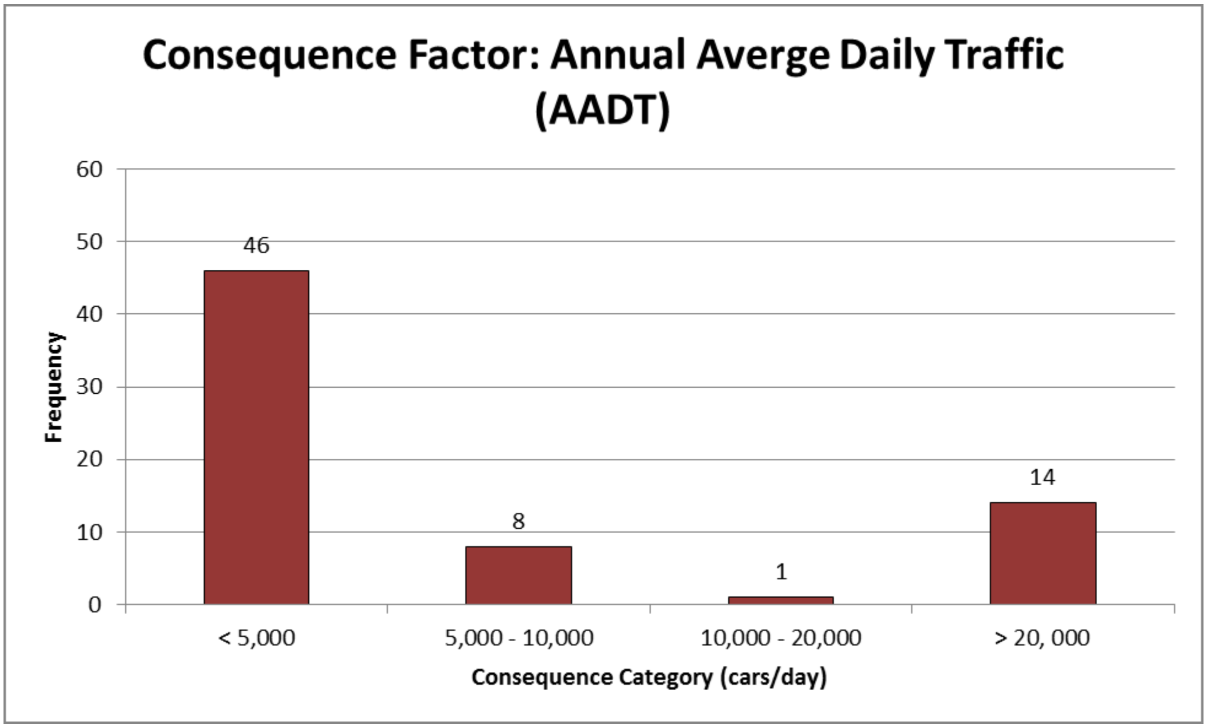


Figure 6.20 Histogram of consequence scores for average daily traffic factor

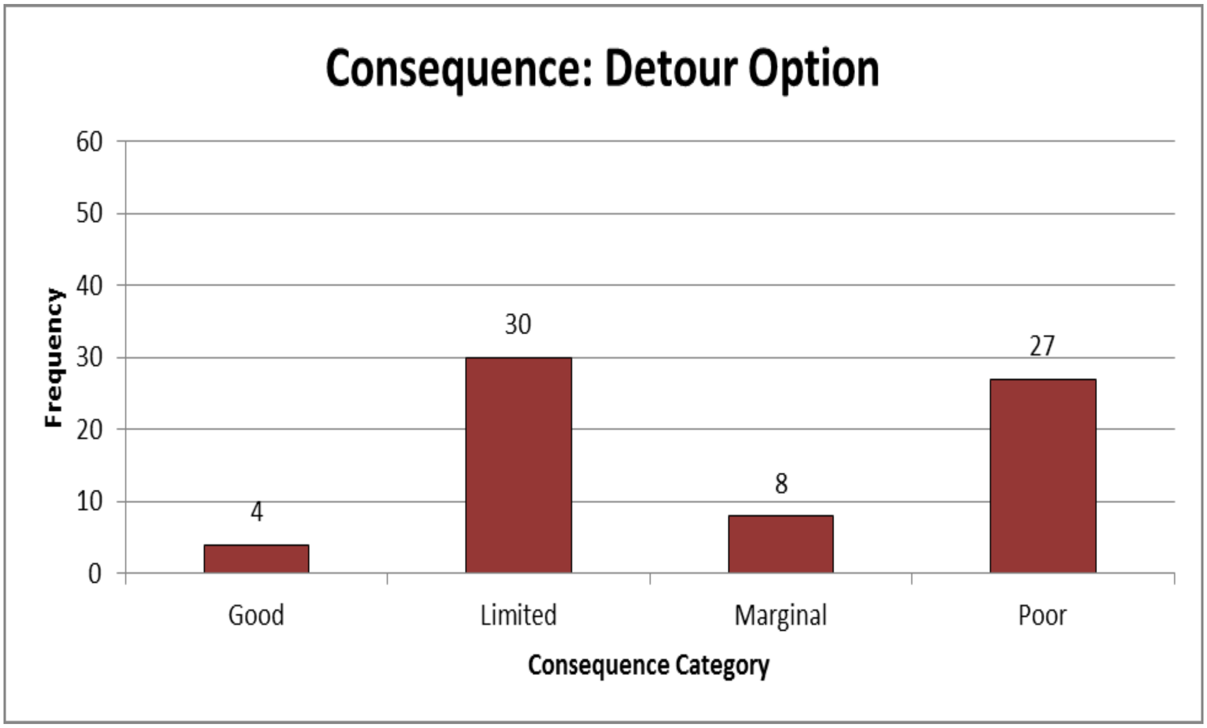


Figure 6.21 Histogram of consequence scores for detour option factor

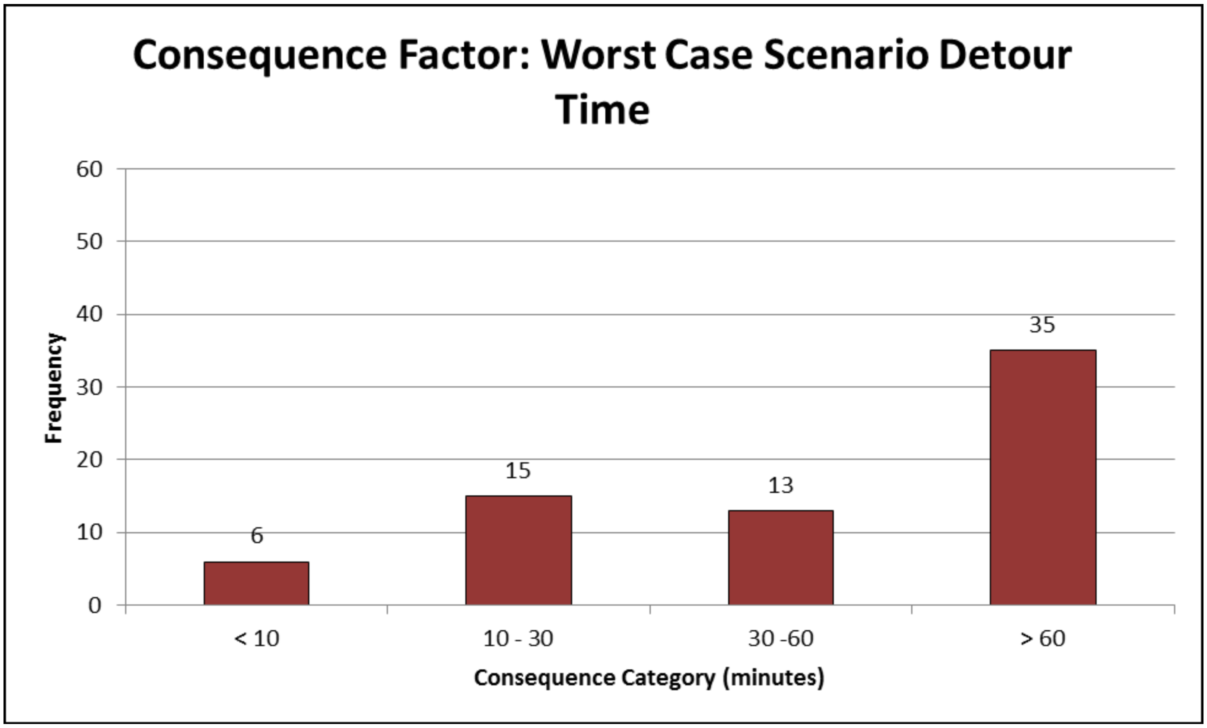


Figure 6.22 Histogram of consequence scores for detour time factor

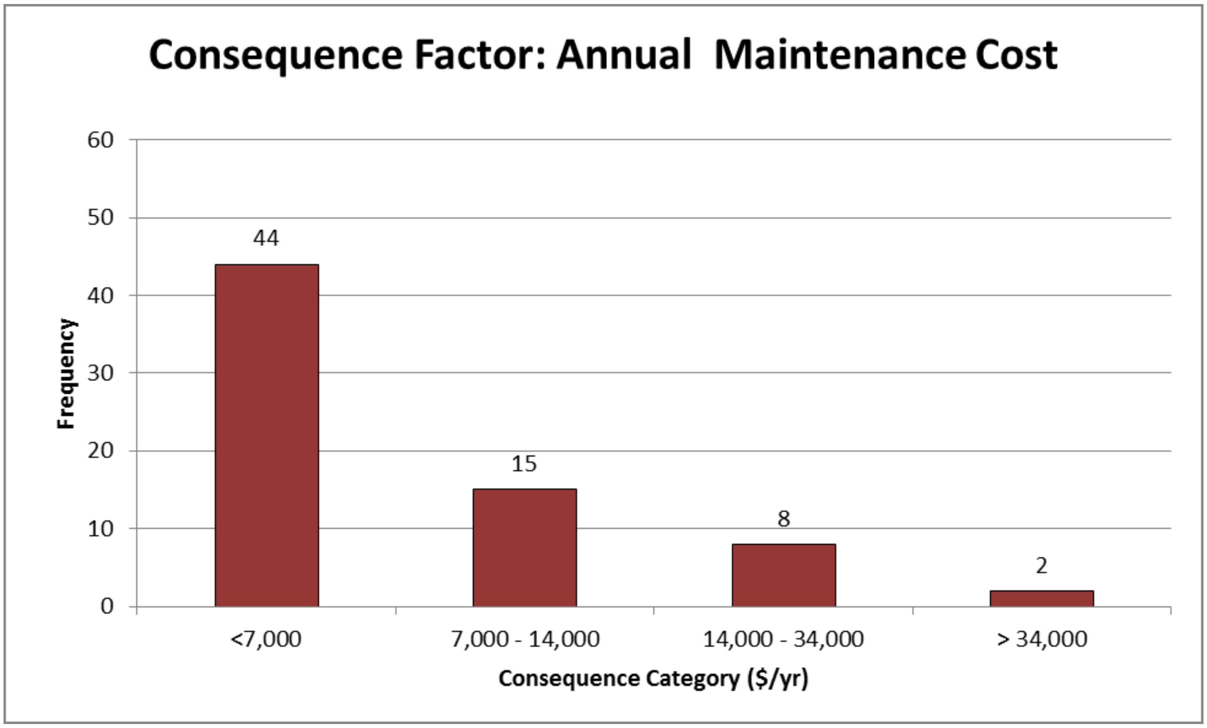


Figure 6.23 Histogram of consequence scores for annual maintenance cost factor

6.3.1 Consequence Score Distribution

The distribution of total consequence scores for each of the 69 landslides is presented as Figure 6.24. The consequence scores were obtained by summing the individual hazard scores for each of the eight Consequence Factors included in the preliminary CLHRS. Possible total consequence scores range from a minimum of 24 up to a maximum of 648.

6.4 Total Risk Score Distribution

The total risk score for each landslide was calculated by multiplying the hazard score for a given landslide with the corresponding consequence score. Using this scoring procedure, total risk scores may range from a minimum of 792 up to maximum of 577,368. The preliminary distribution of total landslide risk scores are presented in ascending order in Figure 6.25.

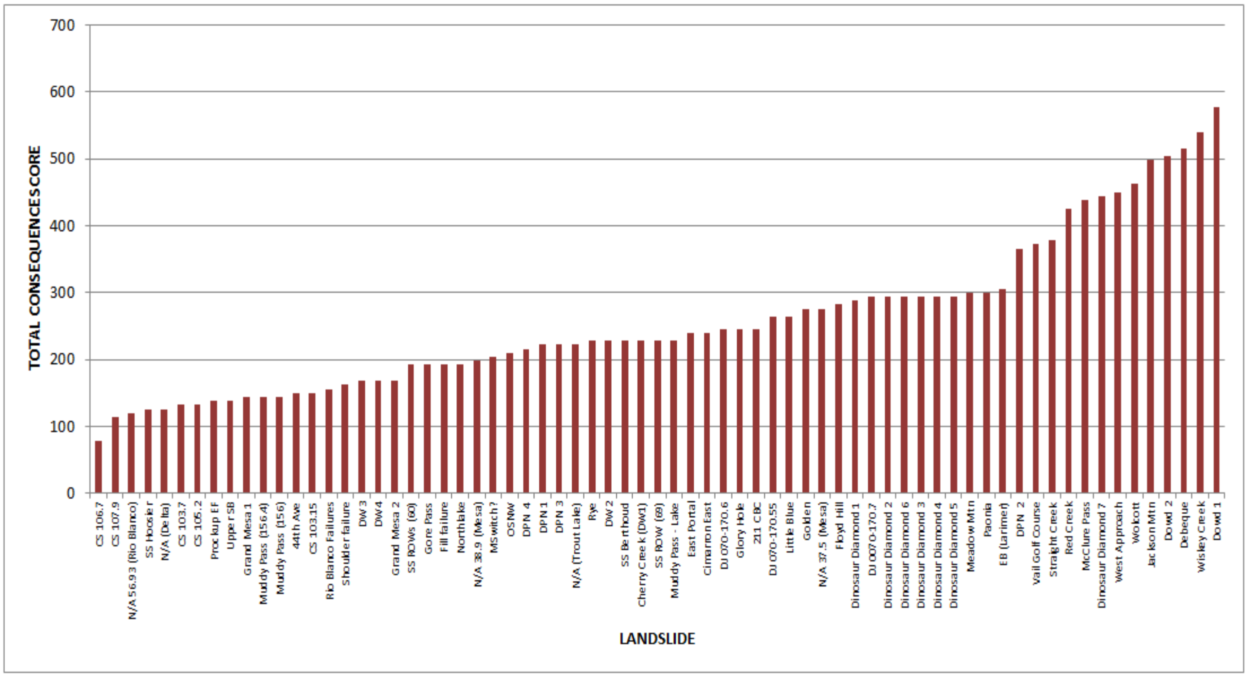


Figure 6.24 Distribution of total consequence scores for the 69 landslides in the dataset.

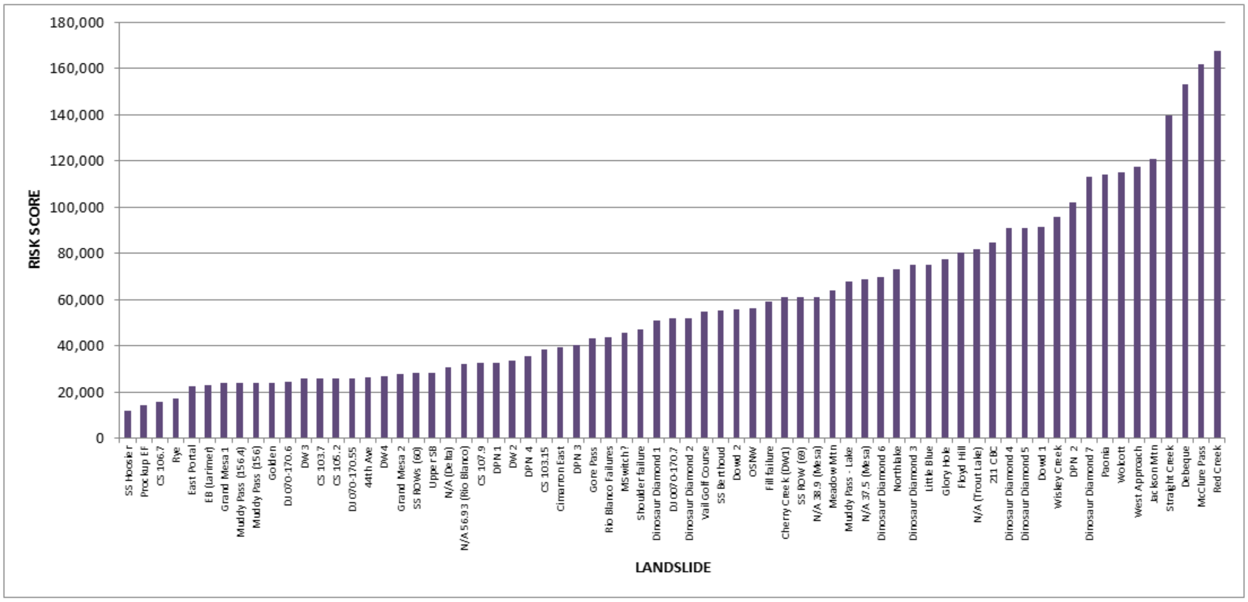


Figure 6.25 Distribution of total risk scores for the 69 landslides in the dataset.

CHAPTER 7

DATA ANALYSIS & RESULTS

This chapter presents the statistical analyses conducted on the dataset in order to validate the CLHRS. Basic descriptive statistics were used to establish severity categories for hazard, consequence, and risk. Several steps of data screening, beginning with the evaluation of the distribution of scores for each factor, followed by correlation analyses and ordinal logistic regressions, allowed for the generation of predictive equations obtained through stepwise regression. Cluster analysis was used in an attempt to identify meaningful relationships among groups of landslides. Field observations and supplementary information are tabulated in the Appendix. Explanations of each statistical analysis as well as the accompanying results are presented below.

7.1 Data Screening

Initial data screening was intended to identify factors that lack sufficient variability and thus, do not serve the goal of distinguishing subdivisions of landslides. This step involved evaluating the hazard and consequence score histograms presented for the initial 19 factors presented in Chapter 6. The most desirable factors that were retained for the final version of the CLHRS were those possessing two categories that contained at least 15 percent of the data points. Parameters that showed a narrow distribution of scores were considered for deletion on the grounds that the lack of variation would not be useful for describing how that parameter contributes to landslide hazard or consequence (Santi et al., 2009). Using this criterion, two Hazard Factors, groundwater seepage and pavement damage, were eliminated because 90 percent or greater of the observations fell into one hazard category. Therefore, these factors were not considered to be meaningful in the context of evaluating landslide risk in Colorado and were not included in subsequent statistical analyses.

7.2 Descriptive Statistics

Descriptive statistics were generated in order to evaluate the general characteristics and distribution of the dataset and also in order to serve as a basis for establishing severity category boundaries for hazard, consequence, and risk that are founded on their respective statistical characteristics. Minitab®'s Stat > Basic Statistics > Graphical Summary function was used to rapidly generate summaries of the descriptive statistics for total hazard, consequence, and risk scores (Figures 7.1 – 7.3) in order to identify the general characteristics of the datasets.

The Anderson-Darling Normality Test indicates whether a frequency distribution is adequately approximated by the normal distribution. The smaller the A-squared values, the better the normal distribution fits the data. P-values listed as less than the confidence interval (i.e., <0.005) indicate that the data do not follow the normal distribution (Minitab v. 16). In this case, total Hazard Scores appear to fit a normal distribution while Total Consequence Scores and Total Risk Scores do not.

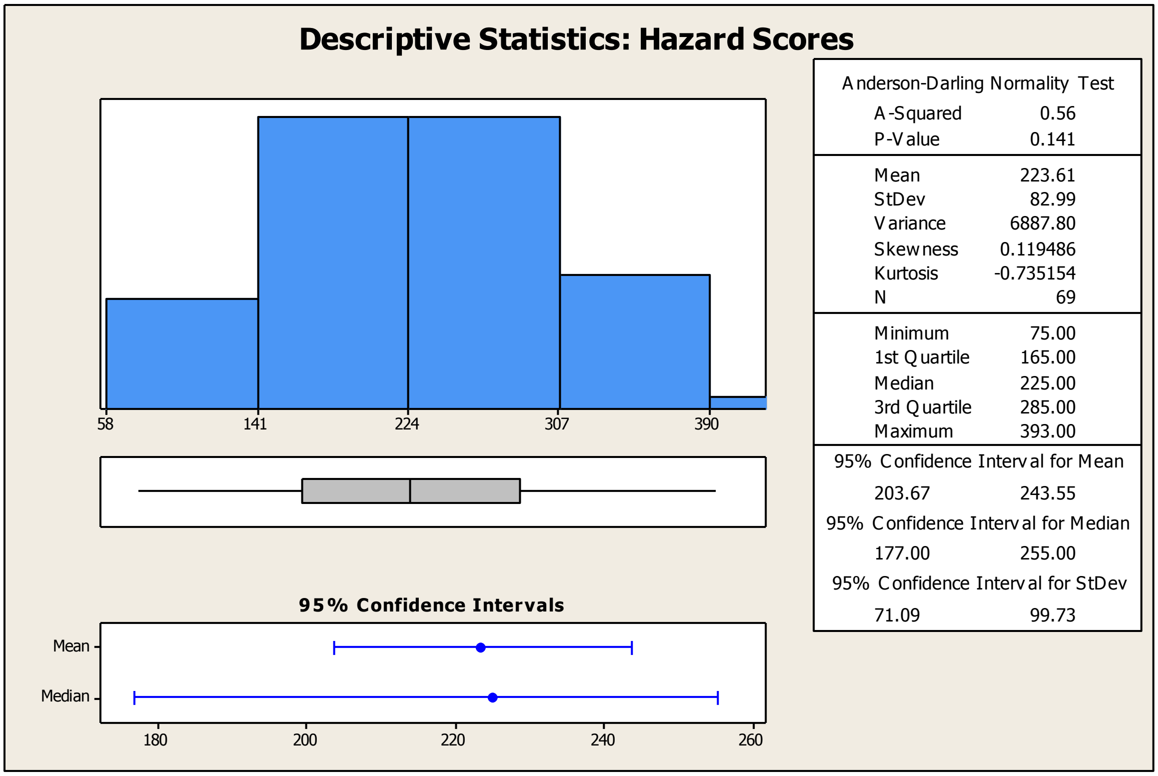
The mean or arithmetic average for each of the score distributions is listed and well as two measures of dispersion, standard deviation and variance. Total Hazard Scores demonstrate the least amount of dispersion (i.e., on average, Total Hazard Scores deviate from the mean by approximately 83 points) while Total Risk Scores demonstrate the most dispersion from the mean.

Skewness values indicate the symmetry of the distributions. Normally-distributed data typically have a skewness value close to zero. Positive numbers indicate data that is "right skewed" (i.e., the "tail" of the distribution points to the right) while negative values indicate data that is left skewed. The magnitude of the value corresponds to how pronounced the dataset appears to be skewed visually. In this case, Total Hazard Scores appear to be normally distributed while Total Consequence and Risk scores are right skewed.

Kurtosis is a measure of the degree to which a data set is "peaked" (Minitab v. 16). A kurtosis value of zero indicates a perfect normal distribution. Data sets with large positive values will have sharp peaks while data sets with large negative values will be more flat. In this case, Total Consequence and Risk scores are more peaked than Total Hazard Scores with the latter being close to normal but slightly flat.

Boxplots accompany the histograms in Figures 7.1-7.3. These plots graphically summarize the central tendency information listed on the right-hand side. 25 percent of the data are less than the first quartile, 50 percent of the data are less than the median, and 75 percent of the data are less than the third quartile. The gray box represents the interquartile range and corresponds to the middle 50 percent of the data. “Whiskers” extend outward from the interquartile range to the minimum and maximum values of the dataset. Outliers are indicated by an asterisk, “*” (Minitab v. 16).

The 95 percent confidence intervals are shown graphically for the mean, median, and standard deviation for each score distribution and are accompanied by their respective confidence limits. Using Total Hazard Scores as an example, this information communicates that 95 percent of the time, the mean Hazard Score for all landslides in Colorado can be expected to fall within the listed confidence limits of 204 and 244.



Anderson-Darling Normality Test	
A-Squared	0.56
P-Value	0.141
Mean	223.61
StDev	82.99
Variance	6887.80
Skewness	0.119486
Kurtosis	-0.735154
N	69
Minimum	75.00
1st Quartile	165.00
Median	225.00
3rd Quartile	285.00
Maximum	393.00
95% Confidence Interval for Mean	
203.67	243.55
95% Confidence Interval for Median	
177.00	255.00
95% Confidence Interval for StDev	
71.09	99.73

Figure 7.1 Graphical summary of descriptive statistics for total hazard scores.

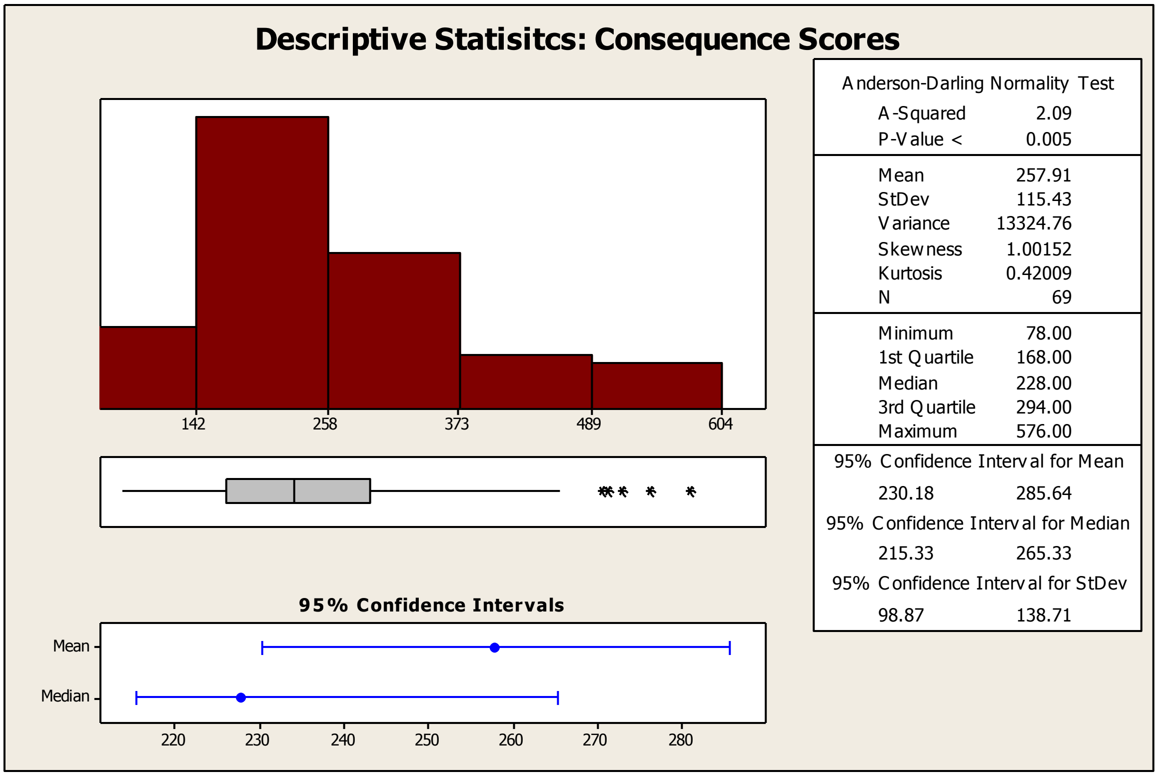


Figure 7.2 Graphical summary of descriptive statistics for total consequence scores

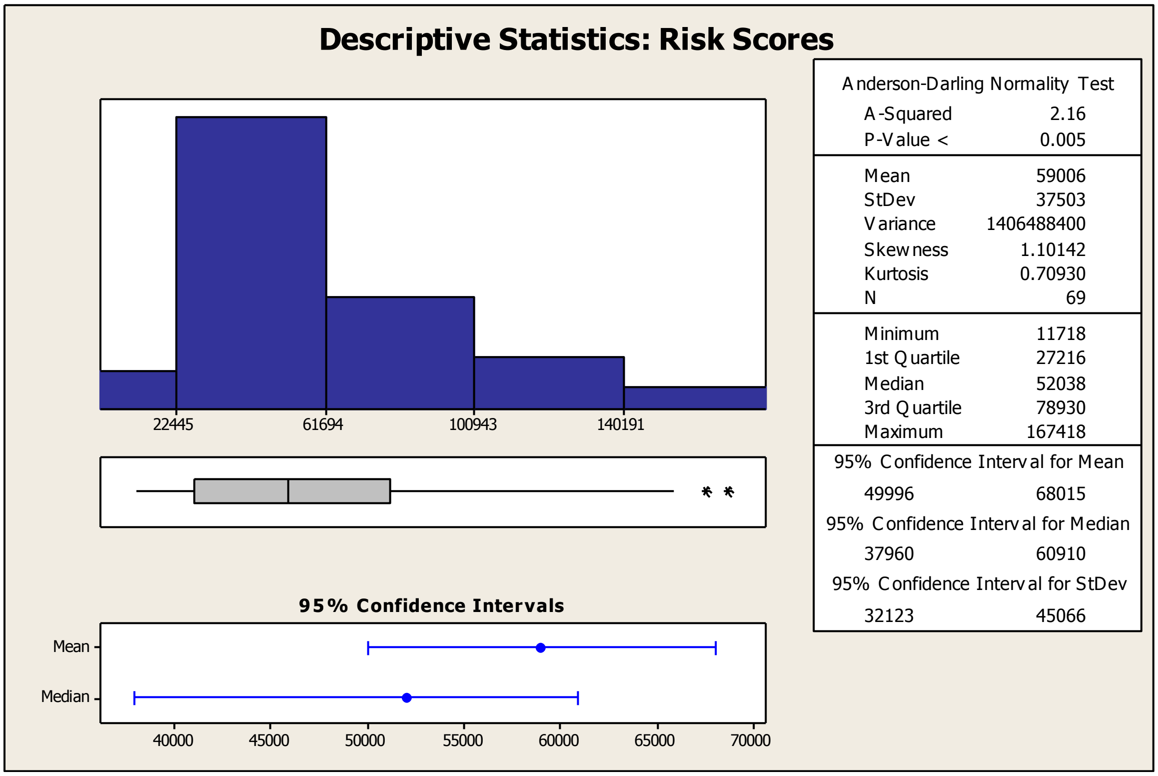


Figure 7.3 Graphical summary of descriptive statistics for total risk scores

In in order to maintain even spacing for ease of interpretation, the binning (i.e., the intervals that establish the breaks for each histogram bar) for each graphical summary was manually spaced according to the corresponding standard deviation of the data set. Using Consequence Scores as an example, the mean (rounded to 258) forms the boundary between the second and third bars. The break between the first and second bar is approximately 142 or one standard deviation less than the mean (all values automatically rounded by Minitab®). These statistically-rooted breaks conveniently divided each score distribution into five groups.

Because hazard scores were found to be normally distributed, the standard deviation statistic was used to establish boundaries for severity categories. Using this method, a landslide falls within one of five severity categories named “Class I” through “Class V” and is assigned a nominal severity identifier ranging from “very low” to “severe.” For example, if the total hazard score for a landslide falls between 141 and 224, the score is less than the mean (i.e., 224) and no greater than one standard deviation (i.e., 83) below the mean. This range corresponds to a Class II Hazard or “Low Hazard.” Severity category breaks for total hazard scores are presented in Table 7.1.

Table 7.1 Total hazard score severity classes

Hazard Class	Hazard Score Range	Severity Identifier
I	$H < 141$	Very Low
II	$141 \leq H \leq 224$	Low
III	$224 < H \leq 307$	Moderate
IV	$307 < H \leq 390$	High
V	$H > 390$	Severe

Conversely, consequence and risk scores were shown to be right-skewed and therefore establishing severity category breaks based on mean and standard deviation was not judged to be appropriate. Alternatively, central tendency data (i.e., median, quartiles, and outliers) were used instead. The four corresponding quartiles for consequence and hazard summarized in Figures 7.2 and 7.3 were used to establish boundaries for Classes I through IV. The boundaries between Class IV and Class V for both consequence and risk were defined by the highest respective score that was not identified as an outlier by Minitab®. Thus, the Class V category is specifically reserved for scores that are especially high relative to the rest of the dataset (i.e., the outliers). The severity category breaks for consequence and risk are summarized in Tables 7.2 and 7.3, respectively.

Table 7.2 Total consequence score severity classes

Consequence Class	Consequence Score Range	Severity Identifier
I	C < 168	Very Low
II	168 ≤ C ≤ 228	Low
III	228 < C ≤ 294	Moderate
IV	294 < C ≤ 462	High
V	C > 462	Severe

Table 7.3 Total risk score severity classes

Risk Class	Risk Score Range	Severity Identifier
I	R < 27,216	Very Low
II	27,216 ≤ R ≤ 52,038	Low
III	52,038 < R ≤ 78,930	Moderate
IV	78,930 < R ≤ 139,482	High
V	R > 139,482	Severe

7.3 Correlation Analysis

The purpose of correlation analysis was to identify the existence and magnitude of corollary relationships between the various factors and their respective total scores. The results of these analyses were intended to serve as justification for the removal of factors that lacked predictive power and tracked poorly with their total score. Two factors were removed through the evaluation of the scoring histograms, leaving 17 factors for correlation analysis.

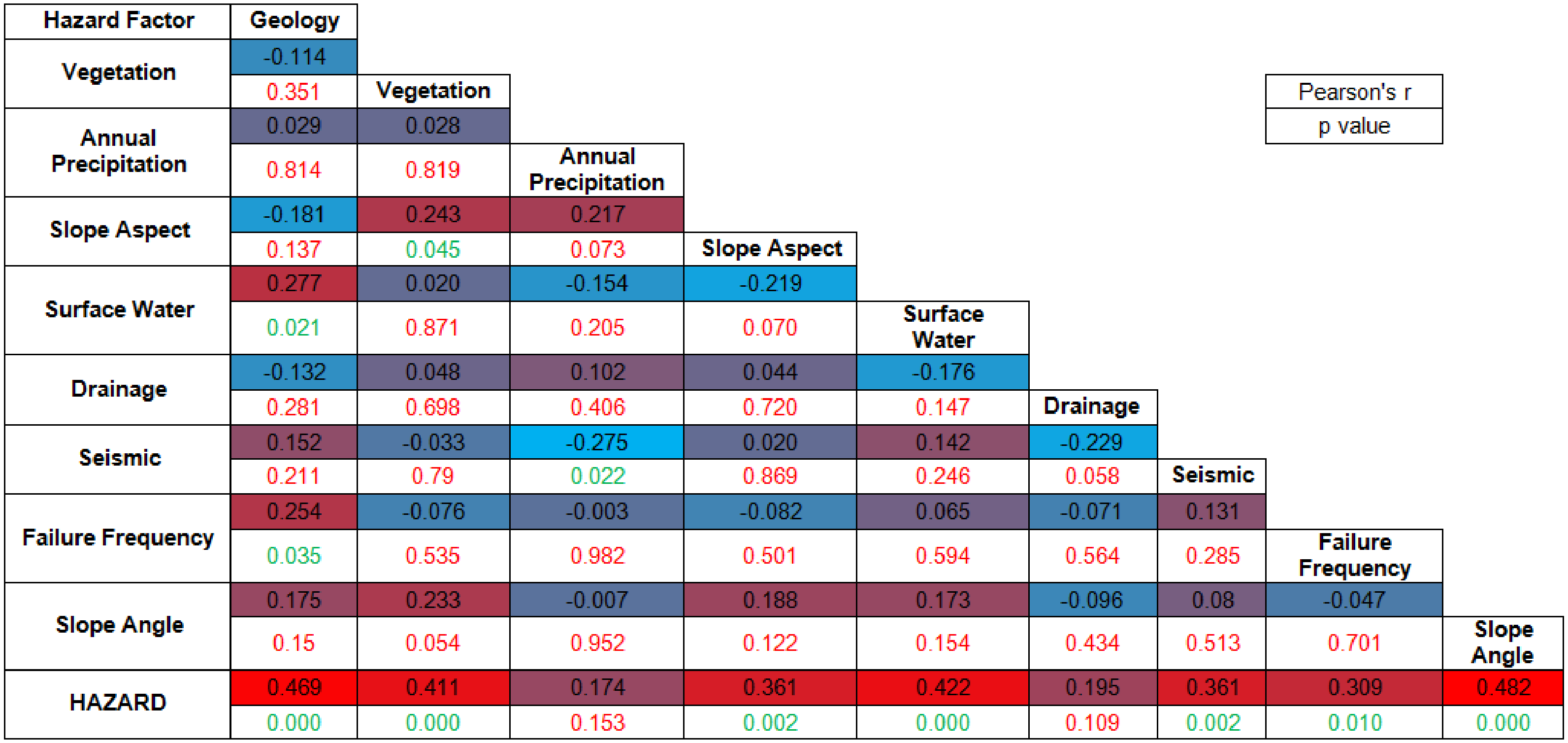
Minitab® 16 software is capable of calculating the Pearson product moment correlation coefficient for many variables simultaneously. The Stat > Basic Statistics > Correlation function was used to evaluate the relationship between each factor and its respective total score. Factors that demonstrated statistically significant corollary relationships with the corresponding total score were retained for further statistical analyses while factors with statistically insignificant relationships were omitted.

Each subset (i.e., hazard and consequence) was analyzed separately in Minitab®. The output for each analysis is summarized in a color-coded correlation matrix (Figures 7.4-7.6). Minitab® takes each factor and compares it to all of the other factors as well as the total score. The output consists of a list of Pearson's r values and p values. The Pearson's r value assesses whether two variables are linearly related. Possible values range from -1 to +1 with +1 representing a perfect positive correlation and -1 representing a perfect negative correlation. Correlation analyses were performed using an alpha level of 0.05. P values less than 0.05 represent statistically significant corollary relationships (Minitab v.16).

Figures 7.4-7.6 were conditionally formatted in Microsoft Excel to graphically represent the strength of the correlation presented in each matrix. Warmer colors in the Pearson's r field indicate stronger positive relationships while cooler colors represent stronger negative relationships. The p values for all statistically significant relationships were color-coded green while statistically insignificant relationships to the total score were color-coded red.

Figure 7.4 indicates that two Hazard Factors, annual precipitation and drainage, do not have a statistically significant relationship to the total hazard score. Thus, these factors were judged to lack the sufficient predictive power for continued statistical analyses.

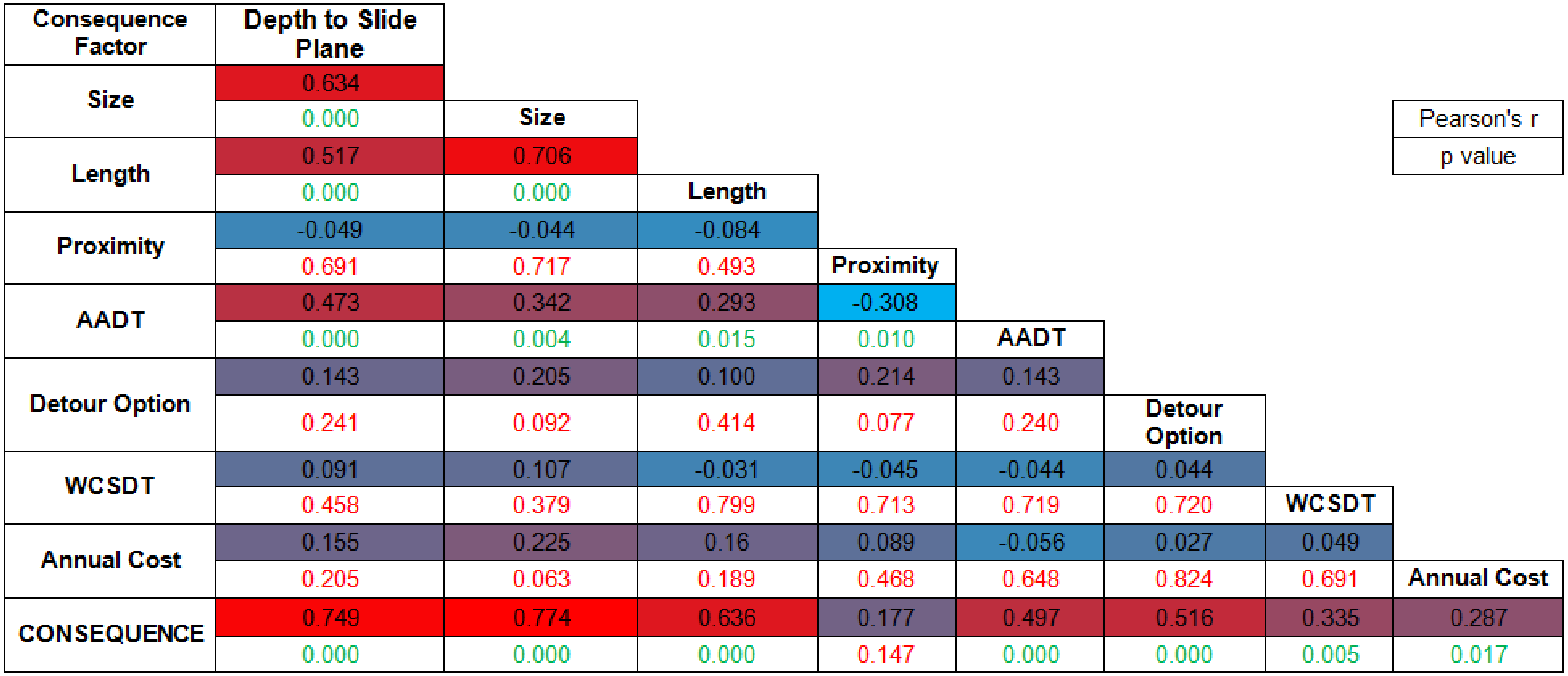
Figure 7.5 Indicates that the Consequence Factor, proximity of slide to roadway, does not have a statistically significant relationship to total consequence score. All other factors in both cases have statistically significant relationships to their respective scores and were retained for further screening and analysis. Figure 7.6 indicates that total hazard and consequence scores both demonstrated strong, positive, statistically significant relationships with total risk score.



Hazard Factor	Geology	Vegetation	Annual Precipitation	Slope Aspect	Surface Water	Drainage	Seismic	Failure Frequency	Slope Angle
Vegetation	-0.114								
	0.351								
Annual Precipitation	0.029	0.028							
	0.814	0.819							
Slope Aspect	-0.181	0.243	0.217						
	0.137	0.045	0.073						
Surface Water	0.277	0.020	-0.154	-0.219					
	0.021	0.871	0.205	0.070					
Drainage	-0.132	0.048	0.102	0.044	-0.176				
	0.281	0.698	0.406	0.720	0.147				
Seismic	0.152	-0.033	-0.275	0.020	0.142	-0.229			
	0.211	0.79	0.022	0.869	0.246	0.058			
Failure Frequency	0.254	-0.076	-0.003	-0.082	0.065	-0.071	0.131		
	0.035	0.535	0.982	0.501	0.594	0.564	0.285		
Slope Angle	0.175	0.233	-0.007	0.188	0.173	-0.096	0.08	-0.047	
	0.15	0.054	0.952	0.122	0.154	0.434	0.513	0.701	
HAZARD	0.469	0.411	0.174	0.361	0.422	0.195	0.361	0.309	0.482
	0.000	0.000	0.153	0.002	0.000	0.109	0.002	0.010	0.000

Pearson's r
p value

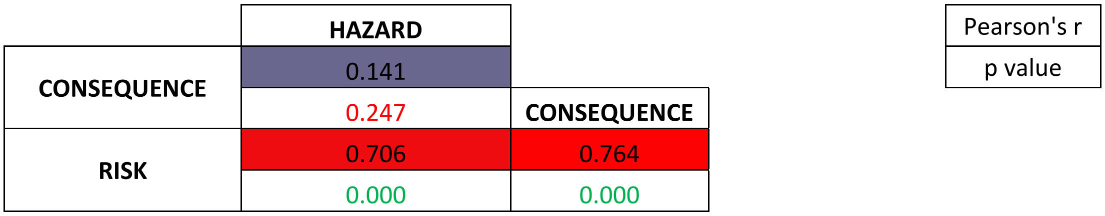
Figure 7.4 Correlation matrix for Hazard Factor versus Hazard Score. Pearson's r values are color-coded with hotter colors (e.g., red) indicating a stronger positive correlation and cooler colors (e.g., blue) representing a stronger negative correlation. P-values have been color coded according to statistical significance (α = 0.05). Green values indicate a significant relationship while red values indicate a statistically insignificant relationship.



Consequence Factor	Depth to Slide Plane	Size	Length	Proximity	AADT	Detour Option	WCSDT	Annual Cost
Size	0.634							
	0.000							
Length	0.517	0.706						
	0.000	0.000						
Proximity	-0.049	-0.044	-0.084					
	0.691	0.717	0.493					
AADT	0.473	0.342	0.293	-0.308				
	0.000	0.004	0.015	0.010				
Detour Option	0.143	0.205	0.100	0.214	0.143			
	0.241	0.092	0.414	0.077	0.240			
WCSDT	0.091	0.107	-0.031	-0.045	-0.044	0.044		
	0.458	0.379	0.799	0.713	0.719	0.720		
Annual Cost	0.155	0.225	0.16	0.089	-0.056	0.027	0.049	
	0.205	0.063	0.189	0.468	0.648	0.824	0.691	
CONSEQUENCE	0.749	0.774	0.636	0.177	0.497	0.516	0.335	0.287
	0.000	0.000	0.000	0.147	0.000	0.000	0.005	0.017

Pearson's r
p value

Figure 7.5 Correlation matrix for Consequence Factor versus Consequence Score. Pearson's r values are color-coded with hotter colors (e.g., red) indicating a stronger positive correlation and cooler colors (e.g., blue) representing a stronger negative correlation. P-values have been color coded according to statistical significance ($\alpha = 0.05$). Green values indicate a significant relationship while red values indicate a statistically insignificant relationship.



	HAZARD	CONSEQUENCE
CONSEQUENCE	0.141 0.247	
RISK	0.706 0.000	0.764 0.000

Pearson's r
p value

Figure 7.6 Correlation matrix for total hazard, consequence and risk scores. Pearson's r values are color-coded with hotter colors (e.g., red) indicating a stronger positive correlation and cooler colors (e.g., blue) representing a stronger negative correlation. P-values have been color coded according to statistical significance (α = 0.05). Green values indicate a significant relationship while red values indicate a statistically insignificant relationship.

7.4 Ordinal Logistic Regression

Ordinal logistic regression was performed in order to identify which factors tracked well with their corresponding total score and also to evaluate and rank the influence of each factor relative to one another. Since the previous analytical step removed three factors from further analysis, 14 of the original 19 factors were subjected to ordinal logistic regression.

Ordinal logistic regression models relationships between predictor variables and a categorical response variable and is intended for use with categorical response variables with a natural ranked ordering of levels but not necessarily with equal intervals (Minitab v. 16). Such a categorical response variable (e.g., hazard score: 3, 9, 27, 81) can be represented by a continuous range of values by redefining the data through coding (Russell, 2007).

Minitab ® 16 can fit a mathematical model with multiple predictors (covariates) using an iterative-reweighted least squares algorithm to obtain the most likely estimates of the parameters (McCullagh and Nelder, 1992). All factors that were found to have statistically significant relationships with their respective total scores were included in the ordinal logistic regression analyses.

As in previous statistical analysis steps, hazard and consequence were analyzed separately. First, both the individual factor scores and total scores were converted into continuous data sets by redefining the variables through coding. Specifically, the five severity categories for total scores described in Section 7.2 and presented in tables 7.1 through 7.3 were coded into five groups: very low, low, moderate, high, and severe: which were coded, 5, 4, 3, 2, and 1, respectively. Similarly, the exponentially increasing individual factor scores were coded into four groups: 3, 9, 27, and 81; which were coded 1, 2, 3, and 4, respectively. The coding for the total scores was deliberately reversed in order to ensure the proper sign on the resulting coefficients. According to Russell (2007), the order of the coding determines the signs of the coefficients for the variables obtained by software packages (Hosmer and Lemeshow, 2000). The reverse coding was employed to avoid counterintuitive and/or misleading results.

Minitab® provides three link functions to model relationships through logistic regression. For this study, the logit link function was used because it provides the simplest interpretation of the parameters used in the model. Use of this link function provides each parameter with a coefficient and an associated odds ratio that can be used to rank the parameters against one another (Russell, 2007).

The coefficients for each parameter represent the estimated change in the log of P(event) / P(not event) for a one-unit change in a parameter's score, assuming the other parameters remain constant (Minitab v. 16). In other words, a coefficient for a parameter indicates the log odds of the probability of whether or not the total hazard score will increase given a one-unit increase in that parameter's score while all the other parameters within the model remain constant (Russell, 2007). Because the exponential factor score data was made continuous through coding, a one-unit increase now represents a shift from one severity category to the next, and it can be observed what effect this shift has on the resulting total score.

The odds ratios are simply computed by taking $e^{\text{Coefficient}}$ for each parameter. If the odds ratio is not equal to one, then a change in the parameter will produce a statistically significant change in the odds for the response (Vandewater et al., 2005). For example, if the slope aspect parameter has an odds ratio of 5.06, then it is approximately five times more likely that the total hazard score will increase if the slope aspect score increases. The odds ratios for each parameter can be used to rank the parameters against one another to determine which has the most influence on the total score (Russell, 2007).

Minitab® also provides the option of displaying both the Pearson and Deviance goodness of fit tests. These tests indicate how well the model created by the logistic regression fits the data. For this these analyses, the null hypothesis is that the model fits the data. If the associated P values for these tests are greater than 0.05, then there is insufficient evidence to reject the null hypothesis; therefore the model fits the data. However, if the P values are less than 0.05, the null hypothesis is rejected and the model created does not fit the data (Minitab v. 16). This option was chosen to estimate the validity of the models created by the logistic regression.

The landslide data set was subjected to ordinal logistic regression analysis using Minitab® 16's Stat > Regression > Ordinal Logistic Regression function. The outputs of the separate analyses are tabulated and summarized in Tables 7.4 and 7.5. Based on p values and an α-level of 0.05, the seismic Hazard Factor and the size Consequence Factor both lack statistically significant relationships to the scores they are respectively trying to predict. In both cases, both goodness of fit indicators, the Pearson test and the deviance test, possess p values greater than the α-level of 0.05 which allows for the conclusion that there is insufficient evidence to claim that the model does not fit the data adequately (Minitab v. 16).

Table 7.4a Results of ordinal logistic regression for Hazard Factors and Total Hazard Score. Note the seismic factor lacks a statistically significant relationship to hazard (colored red).

Predictor	Coefficient	Standard Error of Coefficient	Z-Value	P-Value	Odds Ratio	95% Confidence Interval	
						Lower	Upper
Geology	1.969	0.451	4.37	0.0000	7.16	2.96	17.33
Slope Aspect	1.622	0.402	4.03	0.0000	5.06	2.30	11.13
Vegetation	1.167	0.337	3.46	0.0010	3.21	1.66	6.22
Failure Frequency	0.970	0.348	2.79	0.0050	2.64	1.33	5.22
Slope Angle	0.919	0.358	2.56	0.0100	2.51	1.24	5.06
Surface Water	0.700	0.247	2.84	0.0050	2.01	1.24	3.27
Seismic	0.198	0.282	0.70	0.4820	1.22	0.70	2.12

Table 7.4b Goodness of fit tests for ordinal logistic regression for hazard. Note that p-values exceed the α-level of 0.05 allowing for the conclusion that the model adequately fits the data

Method	Chi-Square	Degrees of Freedom	P-Value
Pearson Test	125.558	229	1.000
Deviance Test	96.954	229	1.000

Table 7.5a Results of ordinal logistic regression for Consequence Factors and Total Consequence Score. Note the size factor lacks a statistically significant relationship to consequence (colored red).

Predictor	Coefficient	Standard Error of Coefficient	Z-Value	P-Value	Odds Ratio	95% Confidence Interval	
						Lower	Upper
Road Length Affect.	3.217	0.859	3.74	0.000	24.96	4.63	134.47
Detour Option	3.140	0.692	4.54	0.000	23.09	5.95	89.58
Annual Cost	2.625	0.743	3.53	0.000	13.8	3.22	59.19
WCSDT	2.459	0.653	3.77	0.000	11.69	3.25	42.04
Depth to Slide Plane	1.922	0.628	3.06	0.002	6.84	2.00	23.43
Size	1.527	0.790	1.93	0.053	4.61	0.98	21.67
AADT	1.333	0.475	2.81	0.005	3.79	1.49	9.63

Table 7.5b Goodness of fit tests for ordinal logistic regression for consequence. Note that p-values exceed the α-level of 0.05 allowing for the conclusion that the model adequately fits the data.

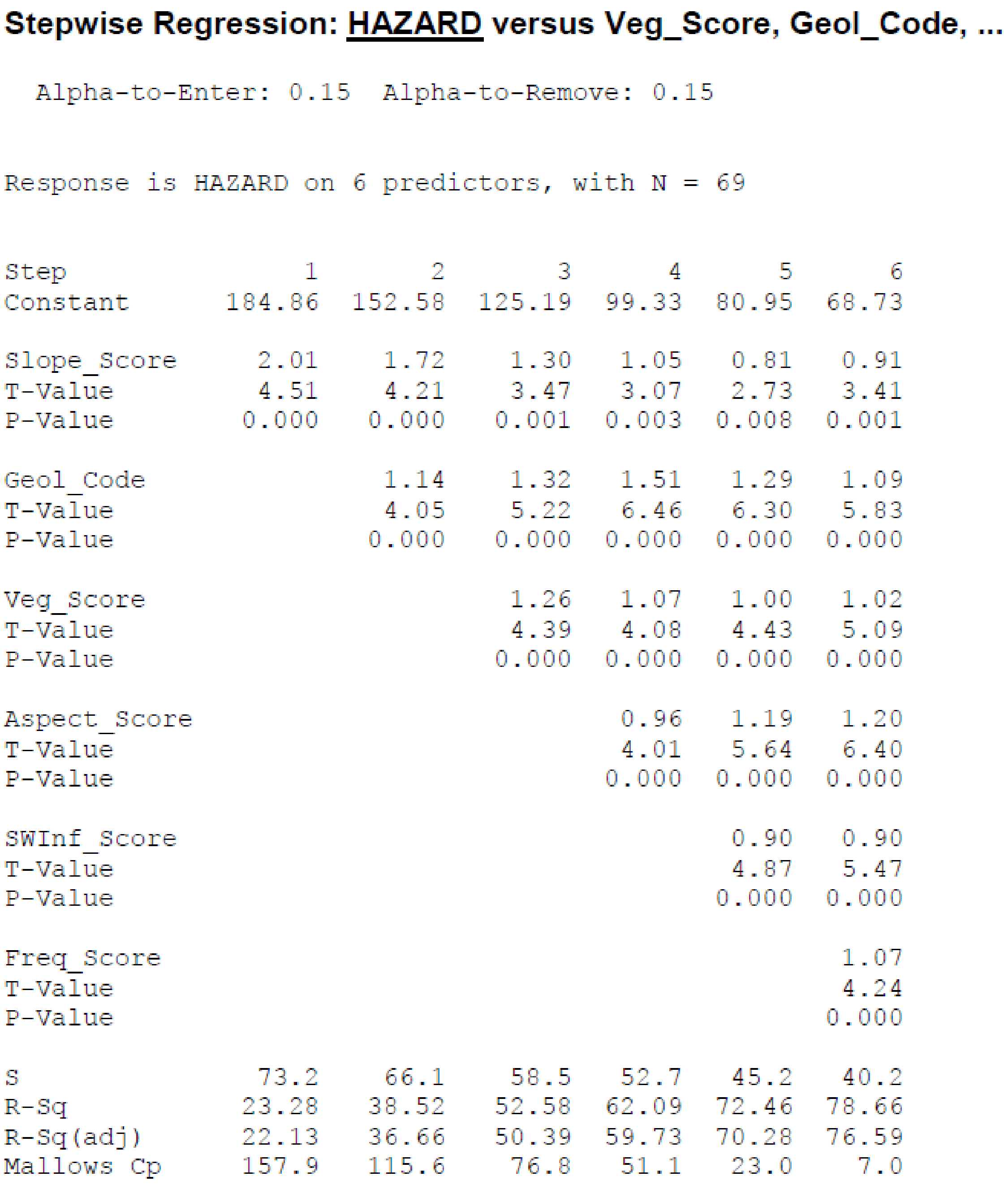
Method	Chi-Square	Degrees of Freedom	P-Value
Pearson	123.905	225	1.000
Deviance	52.08	225	1.000

7.5 Stepwise Regression

Since ordinal logistic regression eliminated two factors from further analyses, stepwise regression was performed on the remaining twelve of the initial nineteen factors. The primary goal of applying this analytical step was to verify the importance of the remaining factors through their removal from or retention within a regression model. Because the end product of stepwise regression is a mathematical model, the secondary goal of this step was to confirm that similar results to those generated initially (using all nineteen factors) could reliably be obtained using fewer parameters by comparing the total initial scores to the ones predicted by the models through the evaluation of fitted line plots and their respective r-squared values.

Linear regression techniques can be used for multivariate applications in order to generate predictive equations. Minitab® is capable of plotting the collected data in multi-dimensional space and producing an equation that predicts a risk score based on the input of several variables. This was accomplished through an iterative process that involved generating a series of predictive models beginning with all variables and gradually deleting variables. For each model, the quality of fit and statistical significance were evaluated with the goal of producing equations that can predict the risk score based on fewer input variables. This multiple regression technique has been used successfully on hazard rating systems to generate predictive models by Santi et al. (2009).

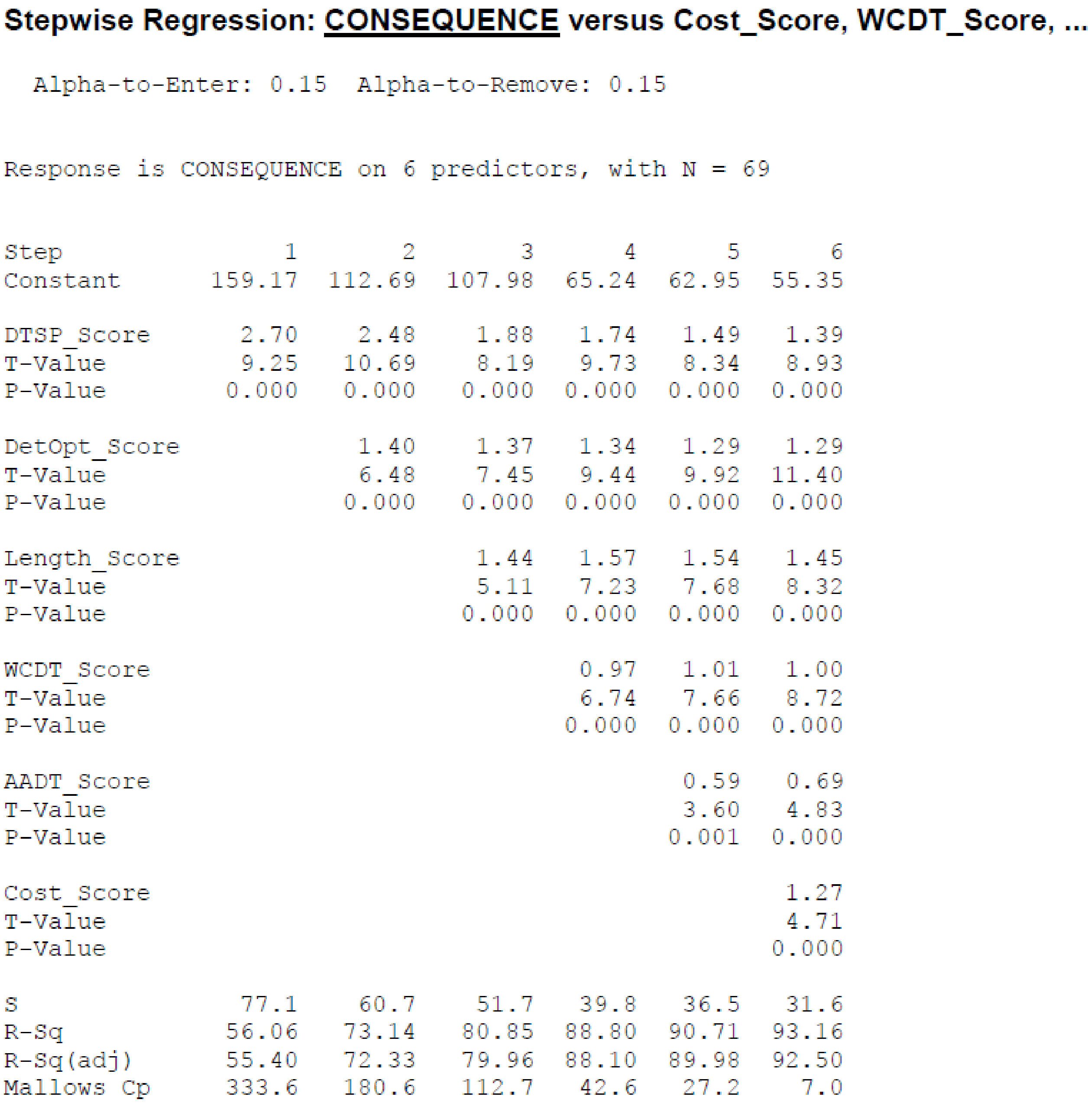
Minitab's Stat > Regression > Stepwise function was used on the remaining factors that were not eliminated through the screening steps discussed earlier. Six hazard factors and six consequence factors were entered as predictors of their corresponding variable (i.e., total hazard and consequence scores). Minitab® offers three stepwise regression procedures that systematically add the most significant variable or remove the least significant variable during each step. For this analysis, the "standard" stepwise regression procedure was used in order to maintain simplicity. Standard stepwise regression both adds and removes predictors as needed in each step. The process ceases when all variables excluded from the model have p-values greater than the specified Alpha-to-Enter value and when all variables included in the model have p-values that are less than or equal to the specified Alpha-to-Remove value. The default alpha values of 0.15 for both entry and removal were used for the stepwise regressions in this study. Minitab®'s outputs for the standard stepwise regressions for hazard and consequence are presented in Figure 7.7 and Figure 7.8 below:



Stepwise Regression: HAZARD versus Veg_Score, Geol_Code, ...

```
  Alpha-to-Enter: 0.15  Alpha-to-Remove: 0.15


Response is HAZARD on 6 predictors, with N = 69


Step                1       2       3      4      5      6
Constant       184.86  152.58  125.19  99.33  80.95  68.73

Slope_Score      2.01    1.72    1.30   1.05   0.81   0.91
T-Value          4.51    4.21    3.47   3.07   2.73   3.41
P-Value         0.000   0.000   0.001  0.003  0.008  0.001

Geol_Code                1.14    1.32   1.51   1.29   1.09
T-Value                  4.05    5.22   6.46   6.30   5.83
P-Value                 0.000   0.000  0.000  0.000  0.000

Veg_Score                        1.26   1.07   1.00   1.02
T-Value                          4.39   4.08   4.43   5.09
P-Value                         0.000  0.000  0.000  0.000

Aspect_Score                            0.96   1.19   1.20
T-Value                                 4.01   5.64   6.40
P-Value                                0.000  0.000  0.000

SWInf_Score                                   0.90   0.90
T-Value                                       4.87   5.47
P-Value                                      0.000  0.000

Freq_Score                                           1.07
T-Value                                              4.24
P-Value                                             0.000

S                73.2    66.1    58.5   52.7   45.2   40.2
R-Sq            23.28   38.52   52.58  62.09  72.46  78.66
R-Sq(adj)       22.13   36.66   50.39  59.73  70.28  76.59
Mallows Cp      157.9   115.6    76.8   51.1   23.0    7.0
```

Figure 7.7 Stepwise regression Minitab® output for remaining hazard factors.



Stepwise Regression: CONSEQUENCE versus Cost_Score, WCDT_Score, ...

```
  Alpha-to-Enter: 0.15  Alpha-to-Remove: 0.15


Response is CONSEQUENCE on 6 predictors, with N = 69


Step                 1       2       3      4      5      6
Constant        159.17  112.69  107.98  65.24  62.95  55.35

DTSP_Score        2.70    2.48    1.88   1.74   1.49   1.39
T-Value           9.25   10.69    8.19   9.73   8.34   8.93
P-Value          0.000   0.000   0.000  0.000  0.000  0.000

DetOpt_Score              1.40    1.37   1.34   1.29   1.29
T-Value                   6.48    7.45   9.44   9.92  11.40
P-Value                  0.000   0.000  0.000  0.000  0.000

Length_Score                      1.44   1.57   1.54   1.45
T-Value                           5.11   7.23   7.68   8.32
P-Value                          0.000  0.000  0.000  0.000

WCDT_Score                               0.97   1.01   1.00
T-Value                                  6.74   7.66   8.72
P-Value                                 0.000  0.000  0.000

AADT_Score                                      0.59   0.69
T-Value                                         3.60   4.83
P-Value                                        0.001  0.000

Cost_Score                                             1.27
T-Value                                                4.71
P-Value                                               0.000

S                 77.1    60.7    51.7   39.8   36.5   31.6
R-Sq             56.06   73.14   80.85  88.80  90.71  93.16
R-Sq(adj)        55.40   72.33   79.96  88.10  89.98  92.50
Mallows Cp       333.6   180.6   112.7   42.6   27.2    7.0
```

Figure 7.8 Stepwise regression Minitab® output for remaining consequence factors.

The columns of the Minitab® outputs show the progression of regression steps beginning with one predictor and advancing to six. P-values less than 0.05 indicate statistical validity and r-squared values indicate goodness of fit. Within each output, it is clear that no parameters were excluded from the regression models and that in both cases, the six-parameter final steps possess the best overall fit with the data. The regression models are distilled into predictive mathematical expressions by incorporating the coefficients listed above as Equations 7.1 and 7.2.

$$HAZ = 68.73+0.91(SP)+1.09(GL)+1.02(VG)+1.20(AS)+0.9(SW)+1.07(FF) \quad (7.1)$$

SP = Slope angle score
GL = Geology score
VG = Vegetation score
AS = Slope aspect score
SW = Surface water influence score
FF = Failure frequency score

$$CONS = 55.35+1.39(DP)+1.29(DT)+1.45(LT)+WC+.69(DT)+1.27(CT) \quad (7.2)$$

DP = Depth to slide plane score
DT = detour option score
LT = road length affected score
WC = worst-case scenario detour time score
DT = Average annual daily traffic score
CT = Annual maintenance cost score

Based on the results of the stepwise regression, total hazard, consequence, and risk scores can be reasonably approximated through the evaluation of eleven factors instead of the 19 factors initially included in the preliminary CLHRS.

In order the evaluate the predictive power of the equations resulting from the stepwise regression, the actual scores for hazard, consequence, and risk were plotted against the results from entering the same factor scoring data into the equations with fewer input parameters. Fitted line plots for hazard, consequence, and risk are plotted in Figure 7.9, 7.10, and 7.11, respectively.

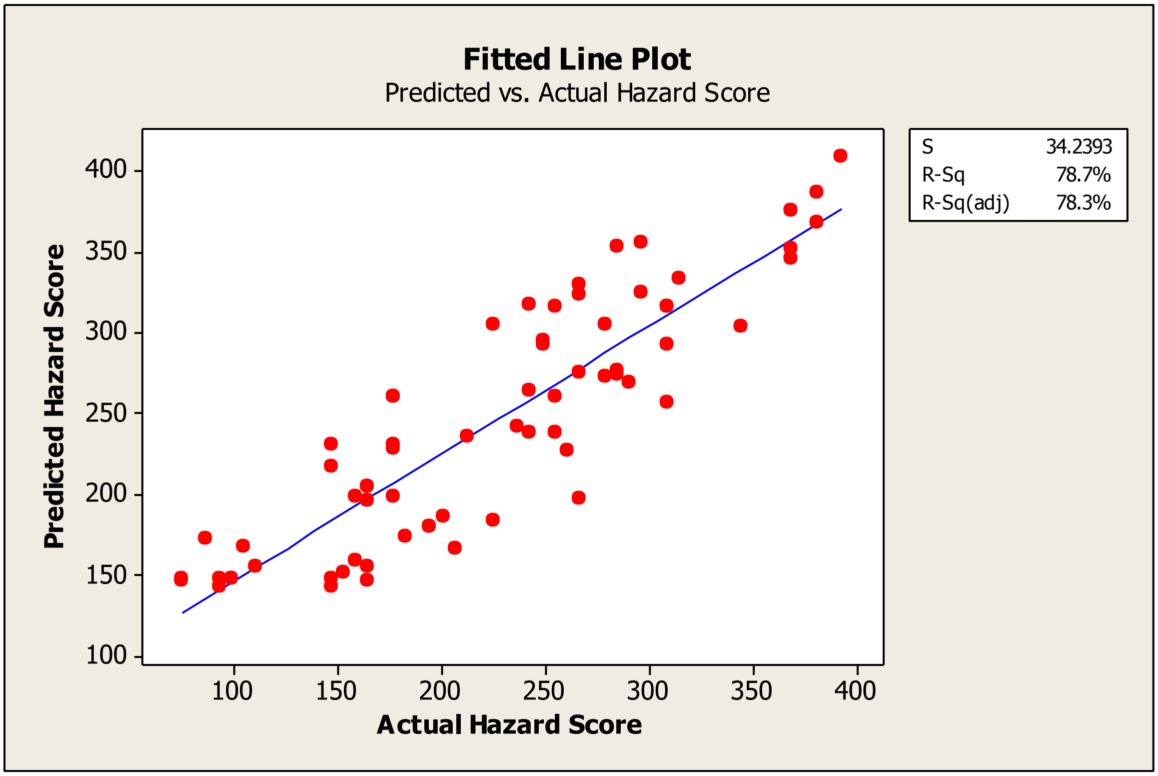


Figure 7.9 Fitted line plot of predicted hazard score (6 parameter) versus actual hazard score (11 parameter).

7.6 Cluster Analysis

Cluster analysis was performed in an attempt to identify distinct subsets of landslides based on a broad and iterative analysis of the raw data and classify the landslides according to severity based on this information. Furthermore, the subgroups rooted in cluster analysis were compared to those established based on descriptive statistics in order to identify the optimal point of reference for justifying severity category breaks. Cluster analysis was performed on the 12 factors that remained after the implementation of the various screening steps discussed above.

Cluster analysis is a multivariate statistical analysis method for classifying observations into interpretable groups when such groups are initially unknown. The procedure uses an agglomerative hierarchical method that begins with all observations being separate (i.e., forming their own clusters).

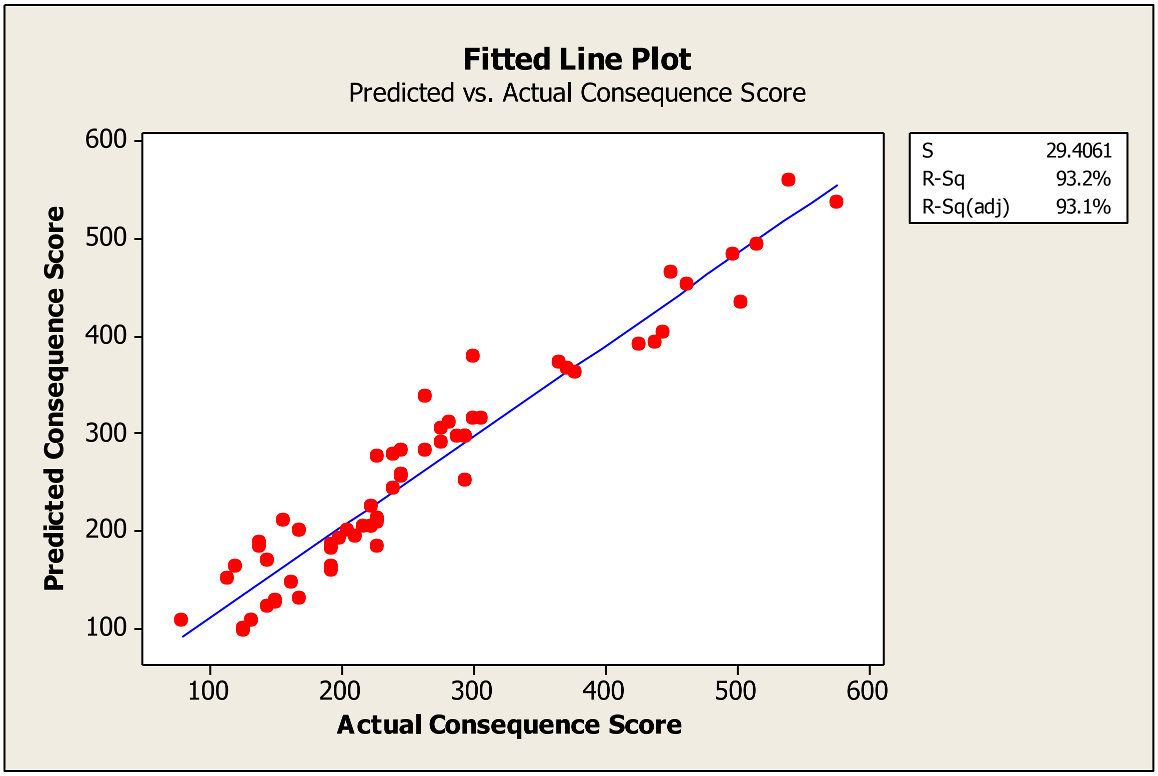


Figure 7.10 Fitted line plot of predicted consequence score (6 parameter) versus actual hazard score (8 parameter).

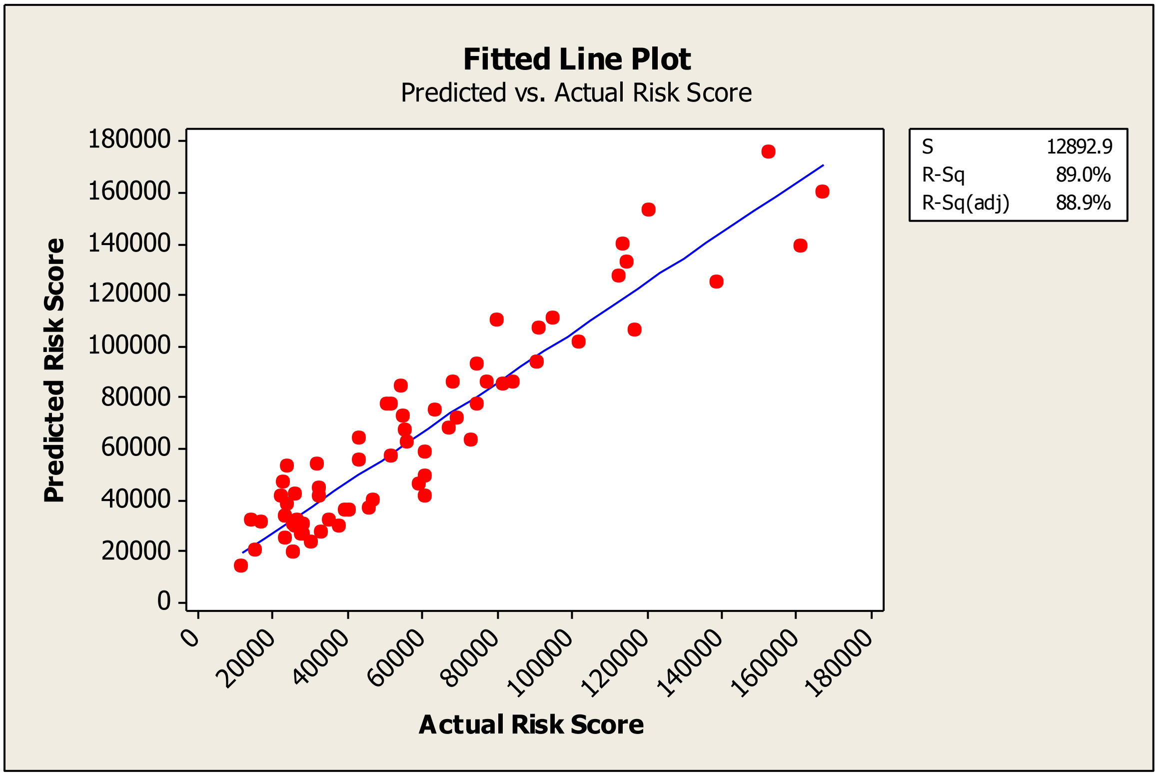


Figure 7.11 Fitted line plot of predicted risk score (12 parameter) versus actual hazard score (19 parameter)

The first step of this process involves joining the two observations that are closest. Next, either a third observation is joined to the first two, or two separate observations are joined to form a new and different cluster. This process carries on until all clusters are joined to form a single, all-encompassing cluster. The final output must be evaluated so that an appropriate number of groups can be differentiated and classified at the discretion of the user (Minitab, v.16).

Minitab® software is capable of performing cluster analysis following a procedure outlined by Kachigan (1991) using the Stat > Multivariate > Cluster Observations function. The input for cluster analysis is raw data. Initially, the user must select a linkage method and distance measure to define clusters. The linkage method determines how the distance between two clusters is defined while the distance measure refers to how that distance is calculated. Minitab ® 16 is capable of using seven different linkage methods and five different distance measures that possesses various advantages relative to one another. According to Minitab®'s help literature, the selection of a linkage method may not yield an appreciable difference in results. Furthermore, the goal of cluster amalgamation is somewhat subjective and the relative appropriateness of a given combination of linkage method and distance measure is, again, at the discretion of the user (Minitab v.16).

For this analysis, complete linkage and squared Euclidian distance were selected. Complete linkage, also known as "furthest neighbor," defines the distance between clusters as the maximum distance between an observation in one cluster and an observation in another cluster. Complete linkage ensures that all observations in a cluster are within a maximum distance and tends to produce clusters with similar diameters. This method can potentially be sensitive to outliers (Milligan, 1980).

The Euclidian distance measure is a standard mathematical measure of distance and is defined as the square root of the sum of squared differences. The squared Euclidian distance measure is simply the square of the Euclidean. This method tends to make large distances under the Euclidian method even larger. The squared Euclidian measure was chosen over the non-squared Euclidean because the similarity values generated by the former were marginally closer to 100 than the latter.

The twelve factors that remained after the data screening steps discussed above, as well as the total hazard, consequence, and risk scores for each landslide were input as variables for the cluster analysis. The amalgamation steps were executed by Minitab® 16 and the results are summarized graphically by a dendrogram (Figure 7.12). The dendrogram shows observations along the x-axis (i.e. the landslides) and similarity along the y-axis. The horizontal lines that represent splits in the dendrogram can be interpreted as measures of similarity between clusters. In other words, the lower a split occurs in the dendrogram, the more similar are the two attached clusters. Mathematically, the similarity, $s(ij)$, between two clusters i and j is given by $s(ij) = 100(1 - d(ij) / d\,(max)$, where $d(max)$ is the maximum value in the original distance matrix, D (Minitab, v.16).

Because five severity categories were established on the basis of descriptive statistics in Section 7.2, the number of final partitions for the cluster analysis was manually set at five in order to evaluate whether the landslides would naturally cluster in a similar fashion. The five clusters identified by Minitab® are color-coded in Figure 7.12. The results of the cluster analysis placed landslides of widely disparate charateristics, geographic locations, and overall scores in similair clusters. For example, slides in Cluster 1, which encompasses 59% of the observations, correspond to the majority of slides that were previously classified as Class I, II, and III Risk. Clear and distinct relationships between landlside characterisitcs and statistically-based severity categories are apparently lacking and match poorly. For these reasons, severity categories founded on clustering relationships were judged to be inadequate for this specific study.

7.7 Final Modified CLHRS

Based on the results of the statistical analyses, a final modified draft of the CLHRS has been produced and is presented as Figure 7.13. The final CLHRS is comprised of the twelve factors that passed the various screening and validation steps discussed above. New total hazard, consequence, and risk scores distributions are presented in Figures 7.14 through 7.16. Additionally, new graphical summaries for the descriptive statistics for hazard, consequence and risk are presented in Figures 7.17

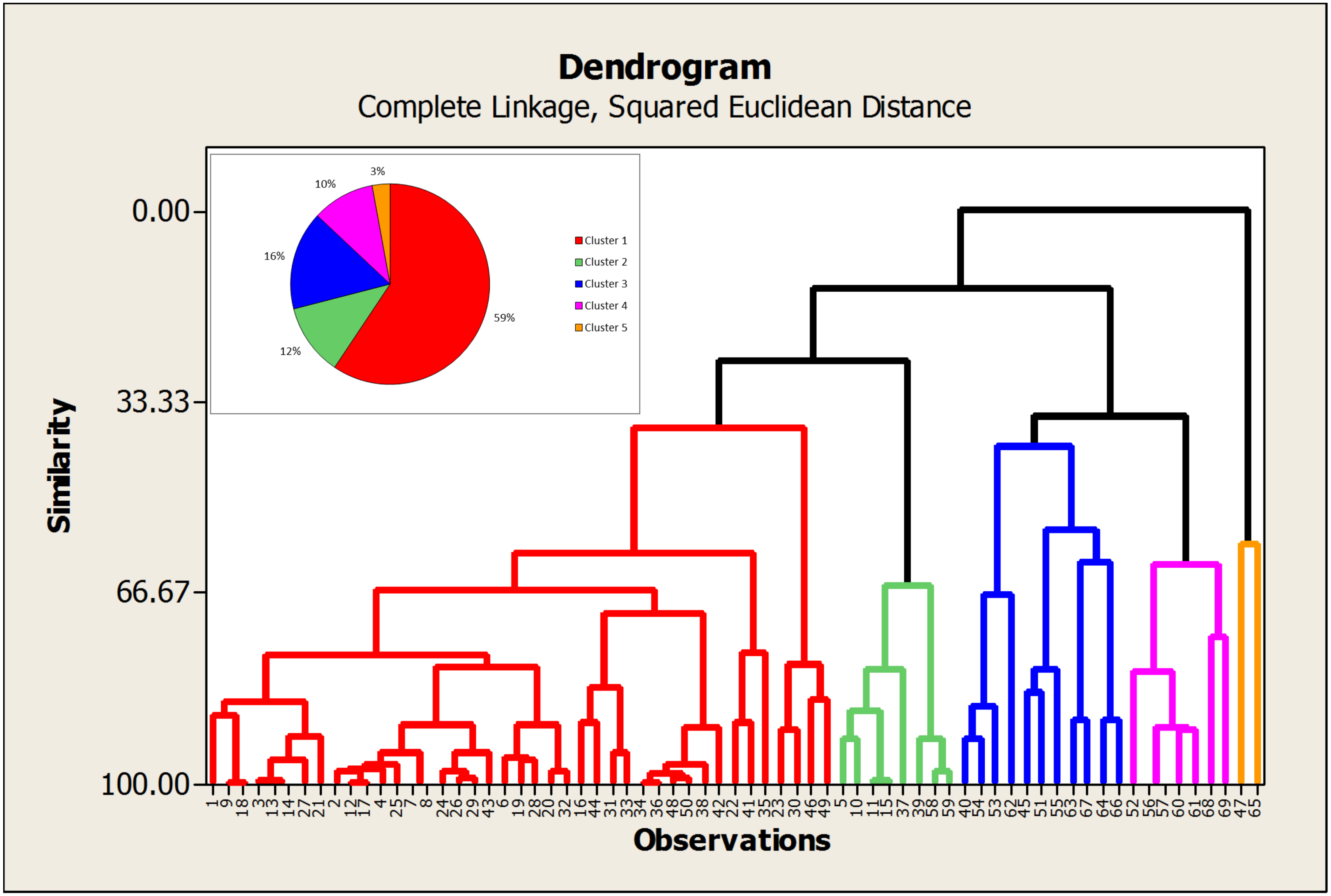
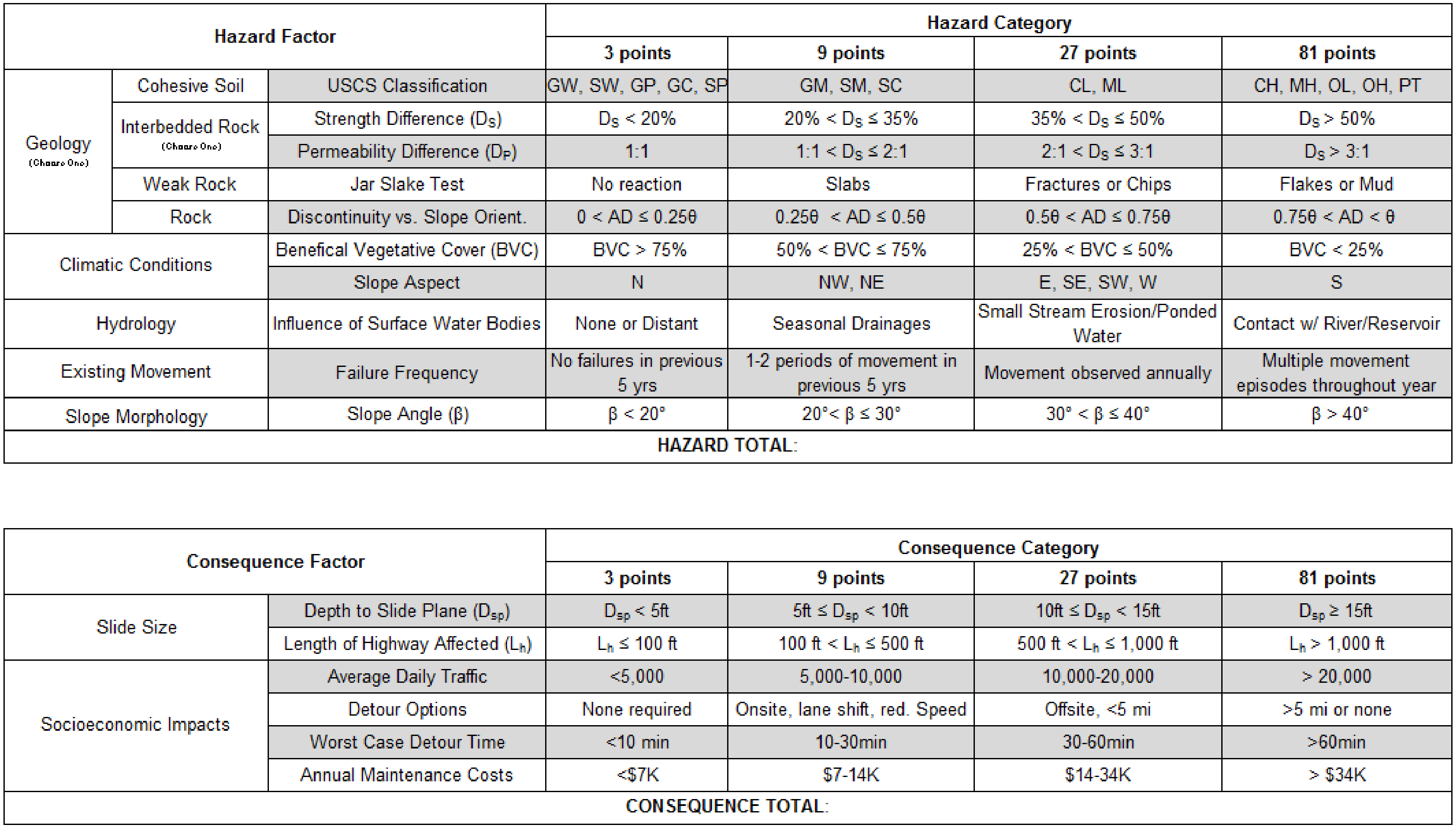


Figure 7.12 Dendrogram showing five clusters of landslides. Numbers along x-axis correspond to individual landslides. For this plot, the input data was sorted by ascending total risk score. Therefore, higher numbered observations also have higher risk scores.

through 7.19. The same rationale for establishing severity category breaks presented in Section 7.2 was implemented with the final CLHRS. The severity categories for hazard, consequence, and risk are presented in Tables 7.6 through 7.8. The results of the stepwise regression indicate that the twelve parameter system can reasonably approximate landslide risk.

7.7.1 Comparison of Preliminary and Final CLHRS

The total scores for hazard, consequence, and risk for the preliminary CLHRS developed using nineteen factors and the total scores generated by the final CLHRS based on twelve factors were compared to one another using fitted line plots (Figures 7.20 through 7.22). Based on the high r-squared values for hazard, consequence, and risk (i.e., 78%, 91%, and 88%, respectively), the twelve factor final CLHRS generates total scores that are reasonably similar to the scores one would obtain using the nineteen factor preliminary CLHRS.



Hazard Factor			Hazard Category			
			3 points	9 points	27 points	81 points
Geology (Choose One)	Cohesive Soil	USCS Classification	GW, SW, GP, GC, SP	GM, SM, SC	CL, ML	CH, MH, OL, OH, PT
	Interbedded Rock (Choose One)	Strength Difference (D_S)	$D_S < 20\%$	$20\% < D_S \leq 35\%$	$35\% < D_S \leq 50\%$	$D_S > 50\%$
		Permeability Difference (D_P)	1:1	$1{:}1 < D_S \leq 2{:}1$	$2{:}1 < D_S \leq 3{:}1$	$D_S > 3{:}1$
	Weak Rock	Jar Slake Test	No reaction	Slabs	Fractures or Chips	Flakes or Mud
	Rock	Discontinuity vs. Slope Orient.	$0 < AD \leq 0.25\theta$	$0.25\theta < AD \leq 0.5\theta$	$0.5\theta < AD \leq 0.75\theta$	$0.75\theta < AD < \theta$
Climatic Conditions		Benefical Vegetative Cover (BVC)	BVC > 75%	50% < BVC ≤ 75%	25% < BVC ≤ 50%	BVC < 25%
		Slope Aspect	N	NW, NE	E, SE, SW, W	S
Hydrology		Influence of Surface Water Bodies	None or Distant	Seasonal Drainages	Small Stream Erosion/Ponded Water	Contact w/ River/Reservoir
Existing Movement		Failure Frequency	No failures in previous 5 yrs	1-2 periods of movement in previous 5 yrs	Movement observed annually	Multiple movement episodes throughout year
Slope Morphology		Slope Angle (β)	$\beta < 20°$	$20° < \beta \leq 30°$	$30° < \beta \leq 40°$	$\beta > 40°$
HAZARD TOTAL:						

Consequence Factor		Consequence Category			
		3 points	9 points	27 points	81 points
Slide Size	Depth to Slide Plane (D_{sp})	$D_{sp} < 5$ft	5ft $\leq D_{sp} <$ 10ft	10ft $\leq D_{sp} <$ 15ft	$D_{sp} \geq$ 15ft
	Length of Highway Affected (L_h)	$L_h \leq$ 100 ft	100 ft $< L_h \leq$ 500 ft	500 ft $< L_h \leq$ 1,000 ft	$L_h >$ 1,000 ft
Socioeconomic Impacts	Average Daily Traffic	<5,000	5,000-10,000	10,000-20,000	> 20,000
	Detour Options	None required	Onsite, lane shift, red. Speed	Offsite, <5 mi	>5 mi or none
	Worst Case Detour Time	<10 min	10-30min	30-60min	>60min
	Annual Maintenance Costs	<$7K	$7-14K	$14-34K	> $34K
CONSEQUENCE TOTAL:					

Figure 7.13 Final CLHRS evaluation reference sheet used in the field.

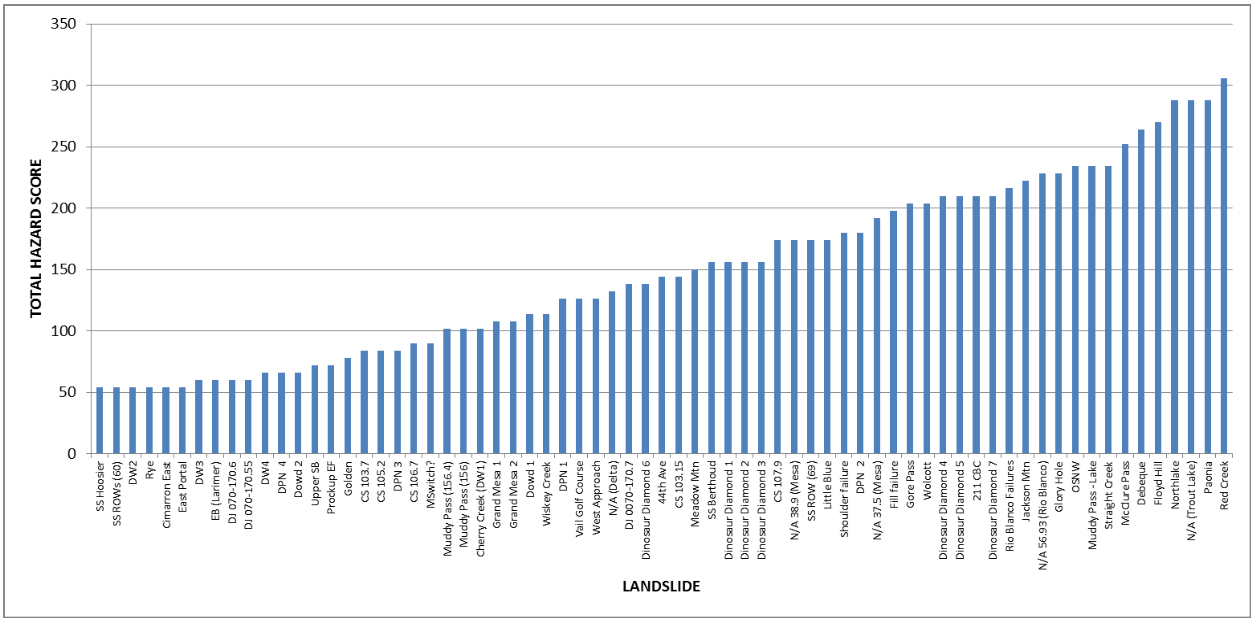


Figure 7.14 Distribution of total hazard scores based on the six statistically-validated factors.

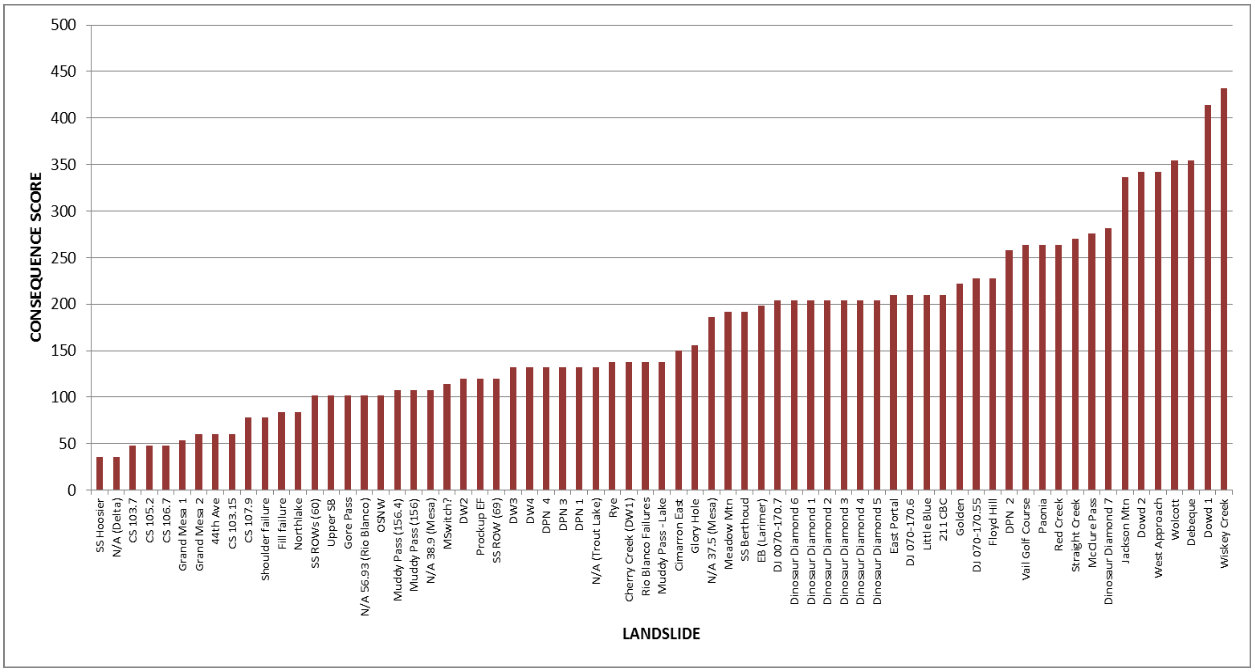


Figure 7.15 Distribution of total consequence scores based on the six statistically-validated factors.

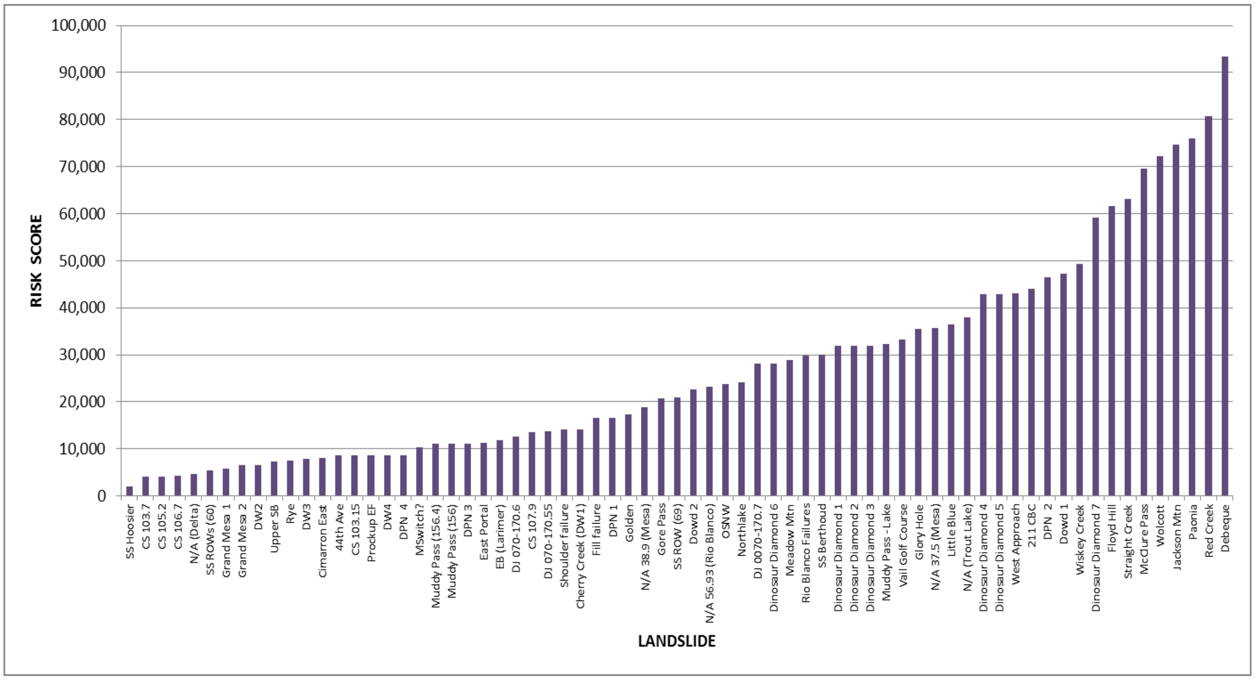
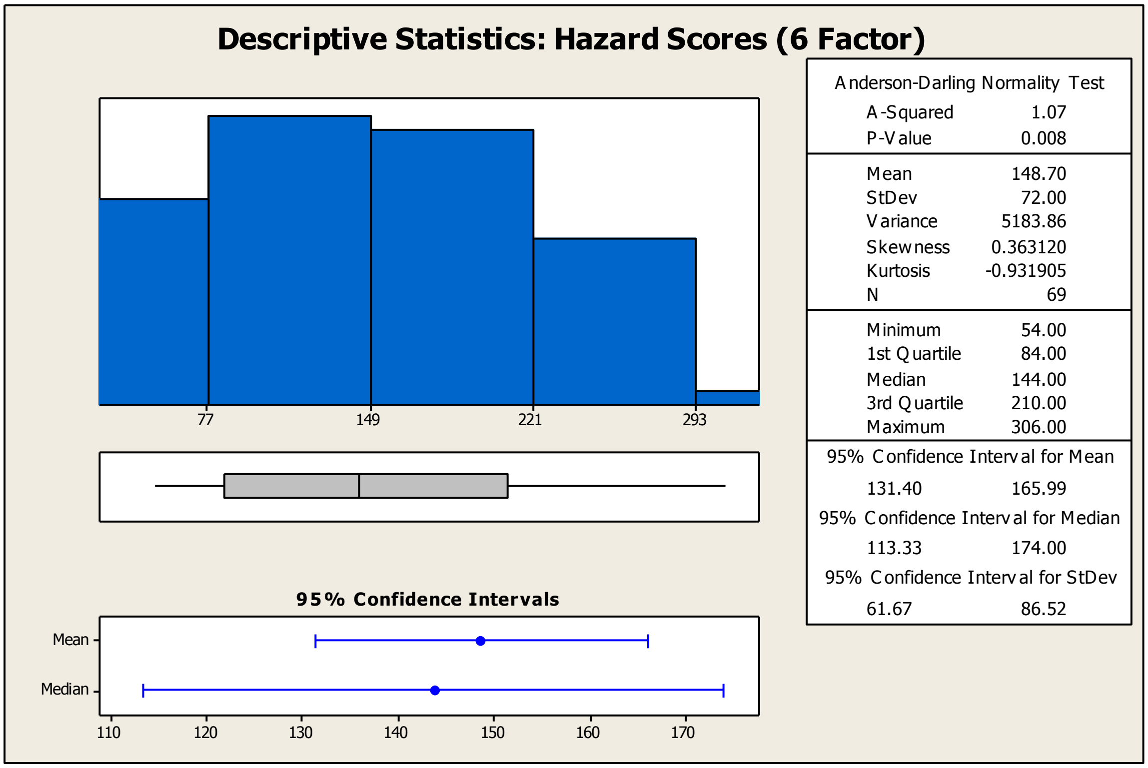


Figure 7.16 Distribution of total risk scores based on the twelve statistically-validated factors.



Anderson-Darling Normality Test	
A-Squared	1.07
P-Value	0.008
Mean	148.70
StDev	72.00
Variance	5183.86
Skewness	0.363120
Kurtosis	-0.931905
N	69
Minimum	54.00
1st Quartile	84.00
Median	144.00
3rd Quartile	210.00
Maximum	306.00
95% Confidence Interval for Mean	
131.40	165.99
95% Confidence Interval for Median	
113.33	174.00
95% Confidence Interval for StDev	
61.67	86.52

Figure 7.17 Graphical summary of descriptive statistics for total hazard scores based on the six statistically-validated factors.

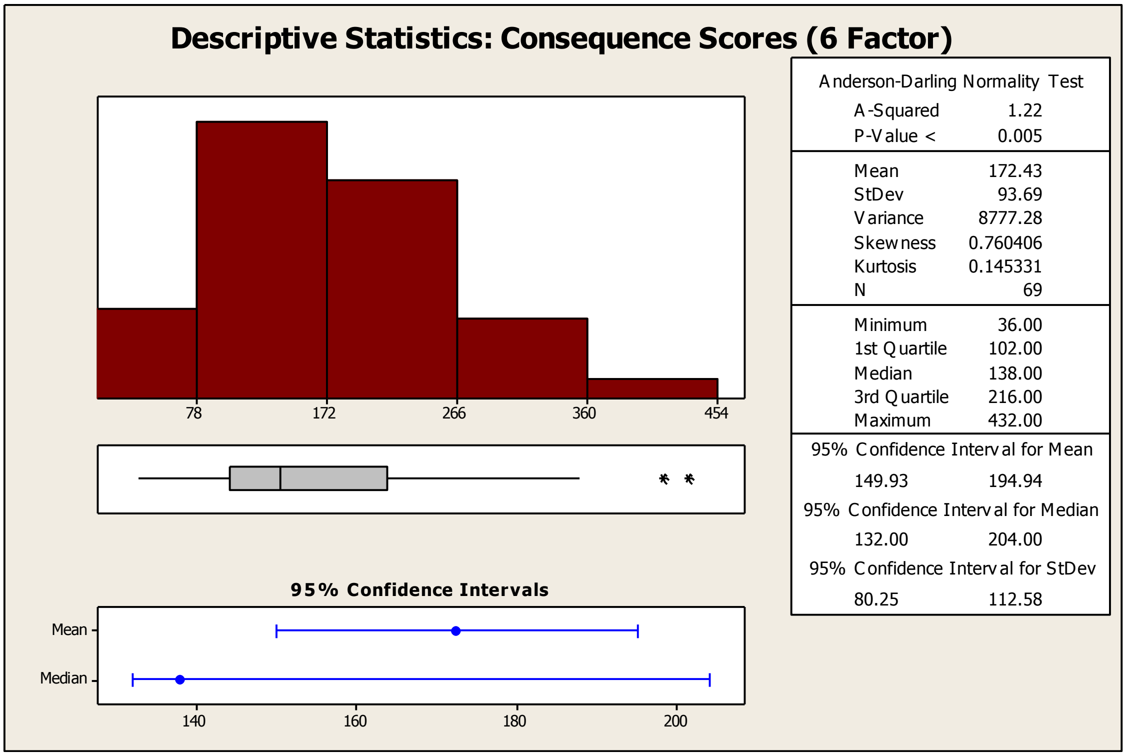


Figure 7.18 Graphical summary of descriptive statistics for total consequence scores based on the six statistically-validated factors.

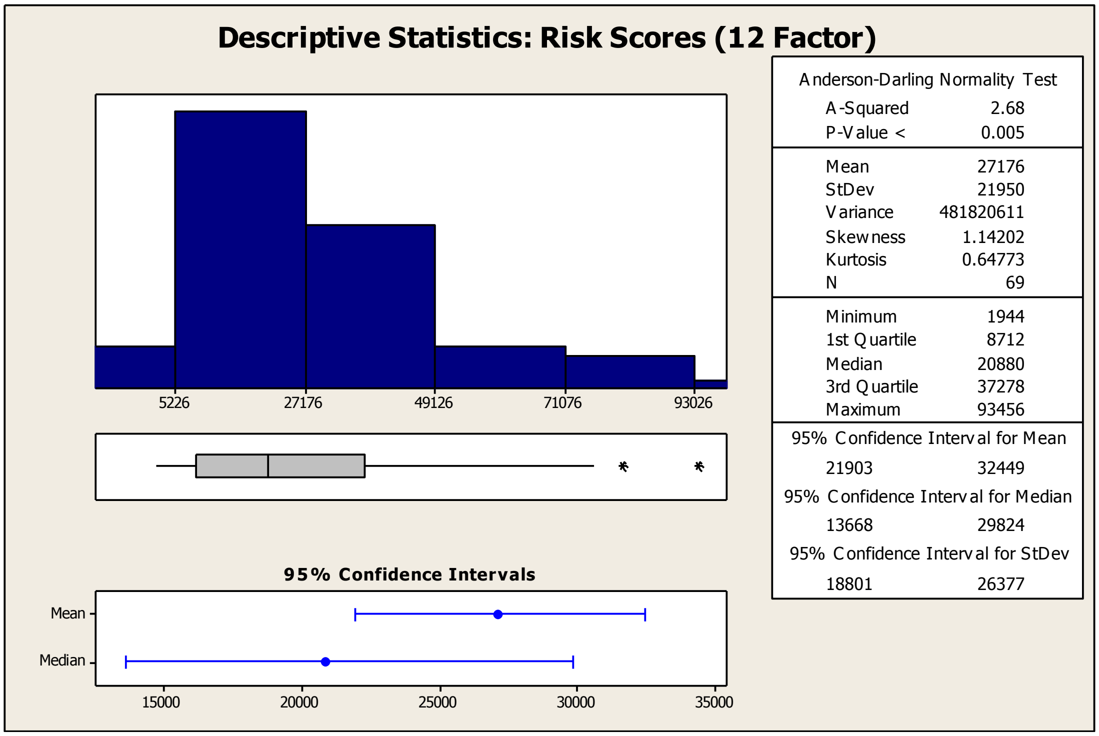


Figure 7.19 Graphical summary of descriptive statistics for total risk scores based on the twelve statistically-validated factors.

Table 7.6 Total hazard score severity classes (6 Factor)

Hazard Class	Hazard Score Range	Severity Identifier
I	H < 77	Very Low
II	77 ≤ H ≤ 149	Low
III	149 < H ≤ 221	Moderate
IV	221 < H ≤ 293	High
V	H > 293	Severe

Table 7.7 Total consequence score severity classes (6 Factor)

Consequence Class	Consequence Score Range	Severity Identifier
I	C < 102	Very Low
II	102 ≤ C ≤ 138	Low
III	138 < C ≤ 216	Moderate
IV	216 < C ≤ 354	High
V	C > 354	Severe

Table 7.8 Total risk score severity classes (12 Factor)

Risk Class	Risk Score Range	Severity Identifier
I	R < 8,712	Very Low
II	8,712 ≤ R ≤ 20,880	Low
III	20,880 < R ≤ 37,278	Moderate
IV	37,278 < R ≤ 76,032	High
V	R > 76,032	Severe

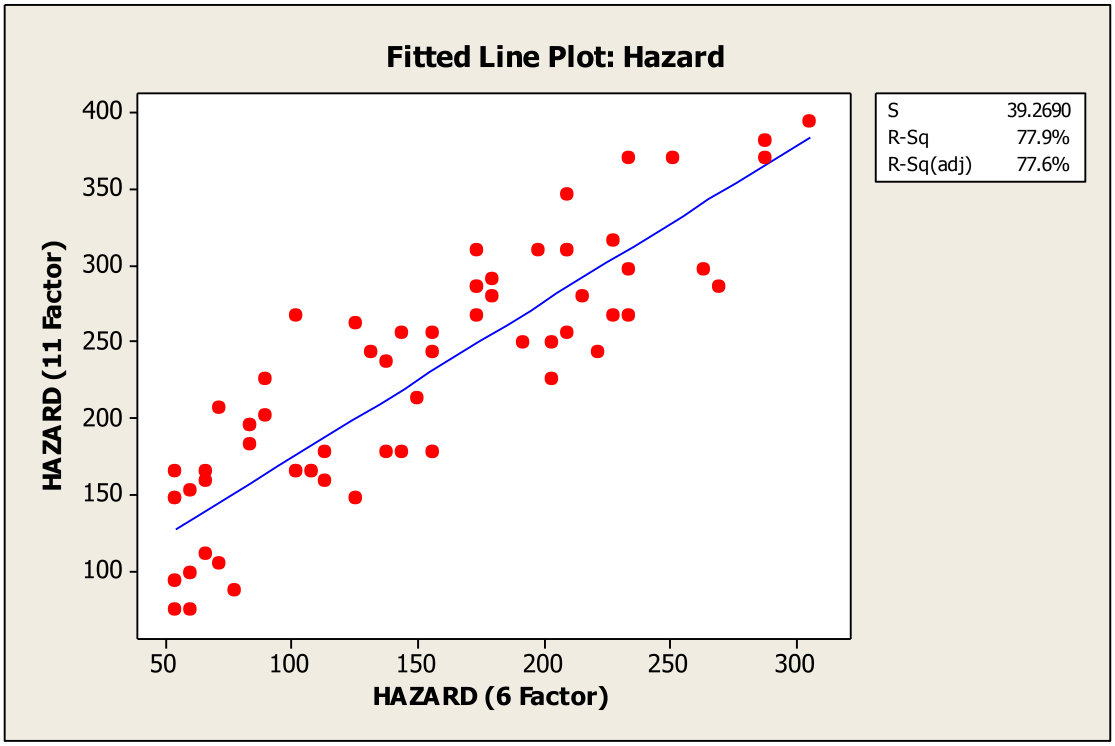


Figure 7.20 Fitted line plot for total hazard scores: 6 factor versus 11 factor.

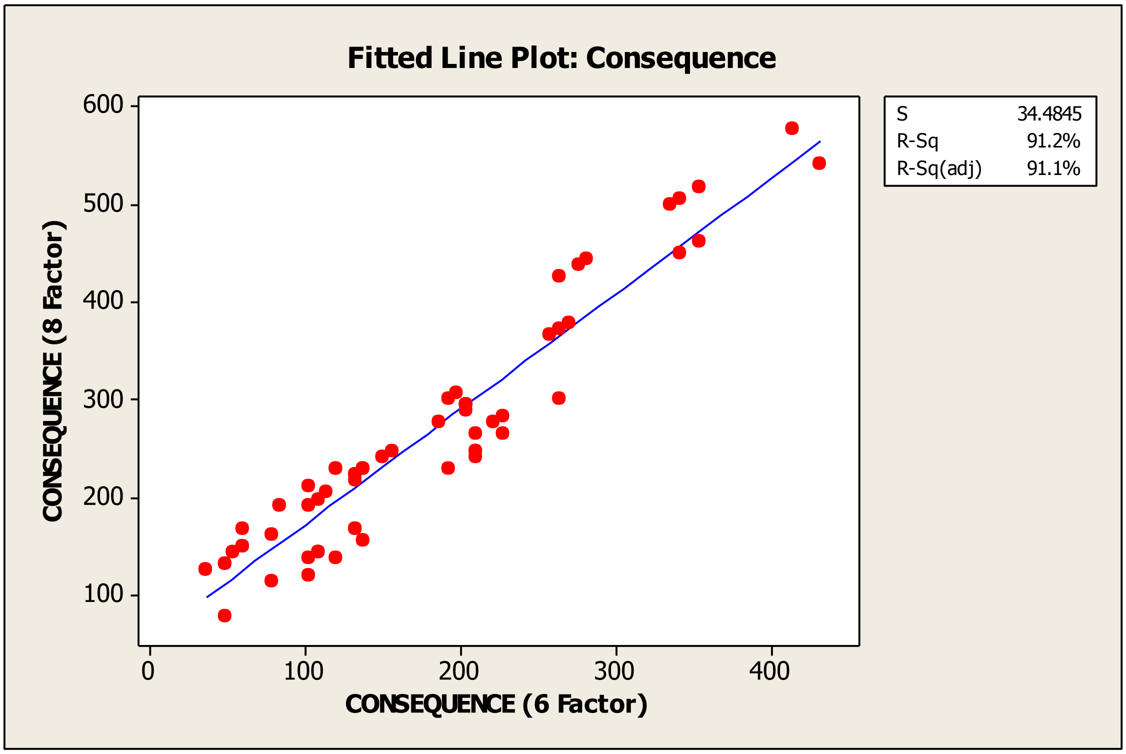


Figure 7.22 Fitted line plot for total consequence scores: 8 factor versus 6 factor.

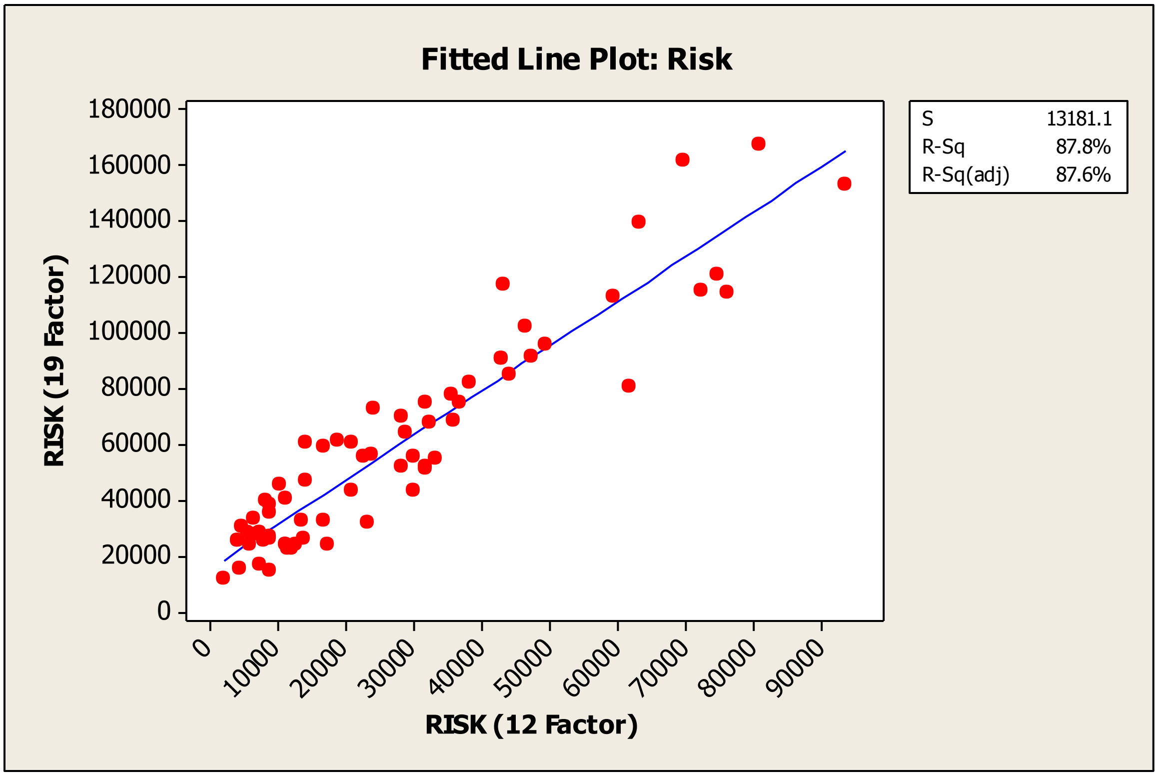


Figure 7.21 Fitted line plot for total risk scores: 19 factor versus 12 factor.

Chapter 8
DISCUSSION

This chapter discusses the results of the statistical analysis steps presented in Chapter 7, the decision to simplify complex geological/environmental relationships, approaches to ensuring data quality, and details regarding the highest risk landslides encountered in the study.

8.1 Simplification of Environmental Systems

In creating a rating system that evaluates geologic environments, it becomes necessary to simplify complex and interrelated environmental and geological relationships in order to meet the project goals of creating a simple and rapidly applicable system. Specifically in the case of hazard, many of the factors presented in this study are interrelated in complex ways. For example, as discussed in Chapter 4, slope aspect influences moisture retention in a slope, as well as the establishment of vegetation and all three of these parameters have nuanced relationships with the site-specific geology. Furthermore, each of the aforementioned characteristics are represented as hazard factors in this study and each one is deliberately evaluated separately despite the fact that they are all are capable of influencing each other.

The fundamental caveat for developing a system such as the CLHRS presented in this study is that there is simply no substitute for a thorough investigation of any phenomenon that poses a potential threat to human health and safety, property, or critical infrastructure. It is fully acknowledged that complex relationships have been simplified in this study for the sake of obtaining a rapid field inventory of the current environmental conditions present at an existing landslide site. The CLHRS functions as a tool for providing a current “snapshot” of risk-related conditions and is not intended to function in a predictive capacity nor as a foundation for designing a mitigation program.

8.2 Factors Removed through Initial Data Screening

Based on the individual score distributions for factors presented in Chapter 6, two factors, groundwater seepage and pavement damage, were removed from further study due to their lack of variability. In the case of groundwater seepage, 91% of all observations were “none observed.” A potential explanation for this result is the influence of broad climatic fluctuations in the state of Colorado. The landslide dataset was evaluated during the summer of 2011 during a period of “abnormal dryness” to “exceptional drought” throughout central and southern Colorado (NDMC, 2013). It is possible that these environmental conditions and their impacts on adjacent areas of the state may have resulted in the lack of observed seepage. It is acknowledged that groundwater seepage is an important indicator of the relative hazard of a landslide failure and it is recommended that evidence of seepage be routinely sought and noted during future investigations. For the creation of the CLHRS in this study, there was simply not enough variability to make this factor viable for continued use. Improvements in data quality could possibly be achieved through routine inspections by DOT staff, perhaps on a quarterly or bi-monthly frequency in order to better assess seasonal variability of seepage.

Similarly, pavement damage is an important direct indicator of landslide hazard. However, 90% of all observations consisted of “no pavement damage” or “warped pavement.” These observations are likely due to that fact at any sort of appreciable offset in the roadway is an immediate threat to motorists and is promptly repaired by maintenance personnel typically by filling in depressions or offset with fresh asphalt. Like groundwater seepage, damage to pavement should always be noted. However, based on the results of this study, there is not enough variability within the dataset to justify its continued inclusion as a Hazard Factor.

8.3 Factors Removed through Correlation Analysis

As presented in Section 7.3, the hazard factors associated with average annual precipitation and soil drainage, and the consequence factor associated with landslide proximity to roadway were eliminated from further analysis due to the lack of a statistically significant relationship (i.e., p values greater than 0.05) to the variable they were intended to predict (i.e., hazard or consequence).

The removal of annual precipitation was perhaps the most surprising considering the notoriously negative role water plays in slope stability. It seems counter-intuitive that the relationship would not possess statistical merit. Furthermore, the Pearson's r, 0.174, indicates a positive but weak correlation. Many landslides in this study are located immediately adjacent to or in direct contact with water bodies. Perhaps the resulting saturation, cutting, and/or steeper groundwater gradients play a more significant role in landslide hazard as evidenced by the associated factor's survival through the various screening steps conducted.

Similarly, soil drainage as approximated by USDA available water capacity data possessed a positive, weak, and statistically insignificant relationship with hazard. This result seems less surprising given the experimental nature of the factor. The original factor had been intended to assess the integrity of existing drainage structures (i.e., horizontal drains, ditches, etc.) however, during the initial development of the preliminary CLHRS, this factor was prohibitively difficult to assess without a more complete knowledge of the history of the site or records/maps indicating the exact location and layout of such structures. As a proxy, readily available USDA soil data was accessed and the "available water capacity" of the soil was used in an attempt to obtain more quantitative data that reflected a soil's ability to hold water. It is acknowledged that this information is possibly more appropriately applicable to agricultural investigations. This imperfect fit may explain why the factor did not track well with total hazard score.

The consequence factor, proximity of slide to road, possessed a weak, positive, statistically insignificant relationship to consequence. Slightly more than 65% of the landslides directly intersect the roads that they threaten. Though adequate variability in scores for this specific consequence factor allowed for its initial inclusion for analyses, perhaps the dominance of the intersecting condition eliminated enough variability to meaningfully track with total consequence score.

8.4 Factors Removed through Ordinal Logistic Regression

As shown in Section 7.4, the hazard factor associated with seismic susceptibility and the consequence factor associated with landslide size were removed from further evaluation due to their lack of statistically significant predictive power with respect to hazard and consequence.

Figure 4.3 shows peak ground acceleration (%g) with a 2% probability of exceedance in 50 years. It is acknowledged that the variation in possible ground accelerations throughout the state of Colorado and especially in the western mountainous region is not very broad. While such small differences may not have an appreciable effect in a slope stability model, the factor was initially judged to be appropriate for inclusion in the preliminary CLHRS assuming that the landslides are in a near critical state where subtle differences in any contributing factor could have a pronounced effect on stability. It appears likely that this narrow range of peak ground accelerations is the reason that this factor was removed.

Landslide size, as evaluated through areal extent, was also removed through ordinal logistic regression. This result seems counterintuitive considering the remedial efforts likely to be mobilized in the event of a very large total failure. It is worth noting that this factor was removed due to its marginal exceedance of the α-level (i.e., 0.053 versus 0.05). Though the areal coverage of a slide mass was removed from further analyses, the “size” influence of a given landslide is still represented by the depth to slide plane consequence factor. Greater than 55% of the landslides were measured to fall within one category. This concentration of results may serve as a possible explanation of this factor’s lack of statistical significance.

8.5 Predictive Power of Stepwise Regression Equations

The results of the stepwise regressions, Equations 7.1 and 7.2, presented in Section 7.5 provide a means of attaining a final risk score through the evaluation of 12 factors instead of the initial 19 factors presented in the preliminary CLHRS. As shown in Figures 7.9 and 7.10, the predictive models generated through stepwise regression track very well with the actual hazard and consequence scores when plotted against each other, with r-squared values of 79% in the case of hazard and 93% for consequence. Furthermore, when the predicted hazard and consequence scores are multiplied and compared to the actual risk scores, the fit is also very good with an r-squared of 89%. These high r-squared values indicate that consistent risk values can be obtained through the evaluation of fewer parameters. Because of this, landslide risk evaluation can be conducted in a more time-efficient and cost-effective manner.

8.6 Severity Category Breaks: Descriptive Statistics vs. Cluster Analysis

In order to for any risk scoring system to be useful, the final calculated risk score must be meaningful. Severity category breaks for the CLHRS were created without any a priori assumptions and instead were intentionally left to be dictated by the nuances of the dataset. Specifically, logical breaks tied to the statistics (i.e., mean, standard deviation, quartiles, etc.) of individual scoring distributions were judged to adequately differentiate the five severity categories.

Cluster analysis was included in this study because of its previous use to establish landslide hazard rating system severity category breaks by Liang et al. (2006). Cluster analysis allows for significant variation in approach by a user due to the many combinations of distance measures and linkage methods. The selection of these features as well as the interpretation of the results are highly subjective. For example, in this study specifically, an iterative approach to generating different cluster patterns through the selection of various linkages and distance measures gradually began to feel like the results were being tailored to the data instead of the data dictating the results. Overall, generated clusters matched poorly to the statistically-rooted severity categories mentioned above. For these reasons, cluster analysis was not judged to be as potent of a basis for establishing severity category breaks in this case.

8.7 Addressing Uncertainty and Data Gaps

The evaluation of many of the factors discussed in this study can be achieved through direct measurements, consultation of spatial data, or field observations. Despite efforts to maintain unambiguous criteria for evaluation, inevitably uncertainty in evaluation will occur commensurate with any geological investigation. Where this is the case, every effort has been made and should be made to arrive at a reasonable conclusion or an educated assumption. It is assumed that any user of the CLHRS will be a qualified individual with adequate understanding of engineering geology and especially geological hazards.

In this study, there are several factors that cannot be measured directly and require varying degrees of semi-quantitative estimation to evaluate. For example, without access to a conventional drill rig or bore logs, it is difficult to accurately estimate the correct depth to a slide plane. However, given an investigator’s experience and using the guidelines discussed in Section 5.2, a reasonable estimate can be produced.

In addition to estimation, some factors depend on the ability to consult available agency records. Convenient access to these records is not always available and the records that can be accessed may not always be complete. This was true in the case of the hazard factor associated with failure frequency and the consequence factor associated with annual maintenance costs. Such issues are addressed in an identical manner to factors that are uncertain. For example, though agency records regarding failure frequency can be incomplete, a reasonable estimate of movement frequency can be obtained through inspection of pavement damage or evidence of repairs. Annual maintenance costs can similarly be estimated when unknown by seeking evidence of maintenance activities such as fresh pavement, safety measures, staged equipment or machinery, etc. In either case, when there is doubt, conservatism must be maintained when establishing a reasonable estimate. Obtaining accurate data in the future only serves to improve the efficacy of the CLHRS.

8.8 Highest Risk Landslides and Mitigation History

The validity of the CLHRS can also be measured without the use of statistical methods. Both presently and in the recent past, CDOT has taken steps to mitigate, both partially and fully, a number of the landslide sites involved in this research. Because most of the proposed hazard and consequence factors involve characteristics that contribute to risk irrespective of whether or not mitigation has taken place, the final risk scores can be directly compared to mitigation records. The expectation is that sites with the highest risk scores have been mitigated, are currently being mitigated, or are scheduled to be mitigated in the immediate future. A full review of CDOT's landslide mitigation records is beyond the scope of this study, but it is helpful to review a limited number of cases. As shown in Figure 7.16, the top two landslides by total risk score in ascending order are the Red Creek landslide and Debeque Canyon landslide. Each of these sites is briefly discussed below.

8.8.1 Red Creek Landslide

The Red Creek Landslide is located in Gunnison County, Colorado and threatens U.S. Highway 50. The slide has experienced episodes of movement for more than 35 years resulting in extensive and frequent repair costs and traffic delays. According to Walker and Santi (2004), the slide is the partial reactivation of a paleolandslide and experiences movement within weak clay layers of the ubiquitous Morrison Formation. These unfavorable geologic conditions are exacerbated by the effects of the rapid drawdown of the adjacent Blue Mesa Reservoir to the South.

According to the severity categories presented in Tables 7.9 through 7.11, the Red Creek Landslide is classified as a Severe Hazard/High Consequence landslide with an overall risk classification of Severe. This slide is primarily hazard-driven mainly due to the proximity of the reservoir and the size of the slide. The consequence component is significant because of the poor detour options and excessive detour times, despite the comparatively smaller amount of traffic.

8.8.2 Debeque Canyon Landslide

The Debeque Canyon landslide is a massive landslide complex located in Mesa County, Colorado. The slide threatens a critical transportation corridor that includes Interstate 70, a railroad, and the Colorado River. Three major reactivations of the complex have been recorded throughout the 20th century. These events involved the displacements of the roadway in excess of 20 vertical feet (approximately six meters) and up to six horizontal feet (approximately two meters) towards the Colorado River. According to the Colorado Geological Survey, “the DeBeque Canyon Landslide developed during the Late Pleistocene due to fissuring along pre-existing shear zones and prominent jointing, in response to downcutting of the Colorado River. The downcutting exposed thick, weak shale beds that later failed, creating the bulk of the central Rubble Zone. The landslide is continuously active and in a state of perpetual creep (CGS, 2010).”

According to the severity categories presented in Tables 7.9 through 7.11, the Debeque Canyon Landslide is classified as a High Hazard/High Consequence landslide with an overall risk classification of Severe. The risk imposed on Interstate 70 by the

Debeque Landslide is largely consequence-driven. The slide is extremely large and affects approximately 1,200 feet (approximately 366 meters) of intersected roadway. Detour options are poor and detour times are excessive. This slide represents a significant threat to the highly travelled I-70 and has experienced extensive study and instrumentation, including tiltmeters, extensometers, inclinometers, a rainfall gauge, survey base stations, and rockfall warning fences (CGS, 2010).

The CLHRS appears to accurately classify landslides into appropriate risk categories. The past damages recorded historically as well as the recent efforts to mitigate and/or monitor these landslides serve to validate the final CLHRS by confirming that these severe risk slides truly represent ever-present threats to roadways and necessitate the mobilization of consultants, maintenance personnel, and state resources.

8.9 Final CLHRS vs. Preliminary CLHRS

The final modified version of the CLHRS consists of the 12 remaining parameters after statistical analysis and validation. While the final version of the CLHRS has been shown to closely approximate total risk scores based on fewer parameters, it is possible that some of the utility of the CLHRS could be lost depending on the motives of inquiry. The preliminary CLHRS may lack the statistical merit of the final version, but its inclusion of more factors makes it more comprehensive in its assessment of landslide risk. In other words, if the CLHRS is used as a cataloging and inventory tool, the preliminary CLRHS may be more appealing to investigators due to the larger number of items evaluated.

Conversely, if time or cost is an issue, the final CLHRS may be more appealing and reliable due to its statistical validation. Ultimately, the approach to applying the CLHRS and the use of the information collected is at the discretion of the investigator and their corresponding agency. It is important to note, however, that the total scores obtained through application of the CLHRS do not communicate failure probability and are not intended to be used in a predictive capacity. Instead, the CLHRS allows for the ranking of known landslides according to their overall risk in order to aid decision making regarding resource allocation and related initiatives.

Chapter 9
CONCLUSION

This chapter provides conclusions and recommendations based on the analyses and results discussed in previous chapters. Suggestions for improvement and expansion of the CLHRS, especially regarding the future availability of spatial datasets as well as applicability of the system beyond landslide evaluation are presented below.

9.1 Improvements to the CLHRS

Should the CLHRS be subjected to further refinement and application by graduate students in the future, a number of ways to improve the efficacy and validity of the system have been identified upon review of the results of this research.

9.1.1 Testing Reproducibility

Though the CLHRS has been streamlined and validated through multiple screening steps and statistical analyses, the final CLHRS presented in this study (or any future iteration) would benefit from field application on a subset of local landslides by groups of geological engineering students and instructors. Individual scores and total scores can be tracked and compared in order to evaluate how accurately two or more investigators can assess landslide risk with the hope that results are rapidly attained and reasonably similar. Such efforts could help to establish error bars around hazard, consequence, and risk scores.

9.1.2 Factor-Specific Research

The utility of the various factors retained, incorporated, or developed for this study could individually benefit from more in-depth study regarding their relationships to slope stability as well as relationships to one another. For example, the vegetative cover hazard factor would benefit from investigation of the effects of various plant species, relative sizes of individual organisms, comparison of grasses and shrubs to trees, potential negative influences such as transferred wind loading, etc. Similarly, the effects of seismic loading on various types of slides and the sensitivity to small variations in ground accelerations would be of interest

9.1.3 Expanded Dataset

The Colorado Geological Survey maintains a landslide database that consists of mapped landslide areas compiled from various sources for the state of Colorado. It is highly likely that many more unmapped landslides that threaten Colorado's transportation corridors exist. Also, there is always the possibly that new slides can occur given certain environmental or anthropogenic changes to the environment. Efforts to map and catalog additional slides and evaluate them using the CLHRS will help to increase the utility of the system and further explore the relationships among variables through statistics.

9.1.4 Benefits of Data Availability

Given the current pace of technological advancement, especially with respect to spatial datasets, GPS technology, and increased data resolution, the implications for the applicability of these technologies to geologic inquiry in general and hazard assessment specifically are intriguing. As more spatial data becomes available, many interesting features can be evaluated rapidly and simultaneously. For example, seismic and climatic data, digital elevation models, and wildfire databases could be layered to create comprehensive interactive hazard maps. Broad trends in the spatial distribution of various features could potentially be evaluated in limitless ways. Diligent monitoring of the changing data environment will be beneficial to the improvement of the CLHRS and systems like it.

9.1.5 Implications beyond Landslides Sites

Keaton and Roth (2008) have indicated the importance of beginning to assess landslide risk more broadly and endeavoring to communicate risk to the public in a concise and meaningful way. Regression techniques such as stepwise regression generate predictive models that rely on the input of various measurements and/or observations. If the regression models in this study were combined with comprehensive spatial datasets, risk evaluation could theoretically be applied over broad (i.e., statewide) areas to generate more detailed landslide risk maps for areas beyond those with mapped slides in an effort to predict landslide occurrence. Such risk-based spatial data can be used in developmental planning for state DOTs, establishing a basis for landslide insurance as discussed by Keaton and Roth (2008), or simply serving as a platform for further academic inquiry.

9.1.6 Landslide Inventory

It is recommended that re-evaluation of existing slides be carried out on a regular basis in order to track temporal and seasonal changes and fluctuations in environmental conditions and landslide characteristics. Doing so will help to interpret changing conditions over time and possibly serve to warn of a potentially dangerous situation in development.

9.1.7 Modification and Customization of the CLHRS

Any potential user of the CLHRS is encouraged to modify the system as needed in order to best serve the goals of inquiry. Experimentation on and expansion of the CLHRS can help to tailor hazard investigations to specific regions or perhaps other states possibly through the development and application of new factors.

9.1.8 How to Apply the CLHRS

In order to apply the CLHRS in the field, an investigator must take a printed copy of Figure 7.13 for reference and record notes and observations in a standard field notebook. Recording of general site information such as date and time, weather conditions, construction activities, or any other observations is encouraged. Next, the 12 factors that comprise the CLHRS should be systematically evaluated according to the guidelines discussed in Chapter 4 and Chapter 5, which are summarized in Table 9.0.

Available surficial and bedrock geologic maps should be observed in advance of entering the field in order to facilitate the selection of the appropriate geologic problem type and develop a site conceptual model. Factors such as failure frequency, average daily traffic, worst case scenario detour time and annual maintenance costs can easily be evaluated before entering the field. All factors are subject to user error in measurement and or judgment. Consequently, conservative judgment and reasonable estimates should be maintained throughout field evaluation. For rapid organization, ranking, or analysis it is recommended that all field observations be transcribed from field notes and electronically tabulated.

As mentioned in Section 8.1, complex geological and environmental relationships have been simplified in order to facilitate the rapid assessment of landslide risk. It must be emphasized again that the CLHRS is intended to function as a rapid inventory tool used for the purposes of developing an expression of overall risk that allows for the ranking of landslides relative to one another. The CLHRS is not intended to function in a predictive capacity and the resulting scores from any aspect of the application of the CLHRS should not serve as the basis of any engineering calculations or design.

Risk Factors			Evaluation Method	Sources of Error
Geology [Choose One]	Cohesive Soil	USCS Classification	Field tests: grain size measurement for granular soils, ribbon test and dilatancy test for cohesive soils, estimation of relative proportions	User error in distinguishing particle sizes, ribbon diameters, and water content
	Interbedded Rock [Choose One]	Strength Difference (D_S)	Identify rock types and consult tables in EPFL LMR, 2013	Broad ranges in strengths have been averaged in absence of lab tests
		Permeability Difference (D_P)	Identify rock types and consult tables in EPFL LMR, 2013	Broad ranges in permeability have been averaged in absence of lab tests
	Weak Rock	Jar Slake Test	Obtain hand sample, observe after 30 minutes, assess degradation and consult Figure 4.1 (Santi et al., 2009)	User error in identifying breaks and judging fragment types
	Rock	Discontinuity vs. Slope Orient.	Measure slope and discontinuity orientations using a Brunton pocket transit	User error in measurement
Climatic Conditions		Beneficial Vegetative Cover (BVC)	Identify vegetation types, beneficial qualities, and amounts (%), obtain root depths from Canadell et al. (1996) or Crow (2005), consider estimated slide plane depth (below), and qualitatively assign hazard score	Misjudging significance of benefits, assumptions regarding root depth
		Slope Aspect	Can be assessed qualitatively or measured with Brunton pocket transit	User measurement error
Hydrology		Influence of Surface Water Bodies	Consult maps and aerial photos before entering field, ground-truth spatial relationships through direct observation. Appraise significance of influence	Misjudging significance of surface water influence
Existing Movement		Failure Frequency	Consult current agency records, look for evidence of current or recent movement in field	Inaccurate or outdated reporting of values
Slope Morphology		Slope Angle (β)	Measure with brunton pocket transit in field. Can calculate slope using computer software, if available	User measurement error, averaging of too few points
Slide Size		Depth to Slide Plane (D_{SP})	Develop reasonable estimate through observing landslide geometry and considering depth to be <1/2 width (Turner and McGuffey, 1996). Confirm with borings, if feasible	Actual depths vary, rough estimate without borings
		Length of Highway Affected (L_h)	Measure directly, with spool measuring tape. For large distances, measure in ArcGIS.	User measurement error
Socioeconomic Impacts		Average Daily Traffic	Consult available agency records, update annually	Inaccurate or outdated reporting of values
		Detour Options	Qualitative estimate informed by assumed failure mode.	User error in judgment of detour feasibility
		Worst Case Detour Time	Find shortest alternative path using common mapping tools, e.g. Google Maps	Misidentifying infeasible alternative routes as viable options, lack of recognition of shorter path
		Annual Maintenance Costs	Consult available agency records, update annually	Inaccurate or outdated reporting of values

Table 9.0 Summary of evaluation methods and sources of error for the final CLHRS

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APPENDIX
SUPPLEMENTAL ELECTRONIC FILES

A spreadsheet is included as a supplemental electronic file to this thesis. The tabulated data includes descriptions and scores assigned to all hazard and consequence factors developed during this study. Total scores for each of the 69 landslide sites are calculated as formulas. Additional observational information is tabulated with each slide regarding site-specific geology, corresponding CDOT Engineering Regions, counties, and original notes from CDOT. The data contained in this spreadsheet was imported to Minitab® 16 software for the statistical analyses discussed in Chapter 7.

LandslideData.xls	Tabulated data regarding observed landslide characteristics and assigned risk scores.