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## Fuzzy-based landslide susceptibility modeling: applications to U.S. Forest Service Road Management

Jonah M. Stinson  
*Western Washington University*

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# Fuzzy-Based Landslide Susceptibility Modeling: Applications to U.S. Forest Service Road Management

By

Jonah M. Stinson

Accepted in Partial Completion  
of the Requirements for the Degree

Master of Science

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Moheb A. Ghali, Dean of the Graduate School

## ADVISORY COMMITTEE

---

Chair. Dr. Scott Miles

---

 Dr. Andy Bach

---

Dr. Thomas Terich

## MASTER'S THESIS

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**Fuzzy-Based Landslide Susceptibility Modeling:  
Applications to U.S. Forest Service Road Management**

A Thesis  
Presented to  
The Faculty of  
Western Washington University

In Partial Fulfillment  
Of the Requirements for the Degree  
Master of Science

By  
Jonah M. Stinson  
May 2009

## ABSTRACT

Landslides are a widely recognized hazard in forested and mountainous terrain. In the Pacific Northwest, these recurrent slope failures cause havoc on an expansive federal forest transportation system that is underfunded and inadequately maintained. Consequently, a need exists for development of techniques that can assist managers in planning and prioritization of U.S. Forest Service (USFS) road management activities. This work explores how new methods of landslide modeling act as decision support tools for mapping landslide susceptibility in roaded areas. Specifically, an original Fuzzy-based model using a G.I.S. is created, applied, and evaluated within the context of the Mount Baker-Snoqualmie National Forest. In this approach, a dataset is constructed of nine terrain parameters associated with landslide occurrence. Relationships between historic landslides and predictor datasets are quantified via likelihood ratios and fuzzy membership functions. Using these factors, a fuzzy logic system with fuzzy operators is then applied to assess the relative likelihood of landslide occurrence within the study area. Finally, model outputs in the form of landslide susceptibility maps are evaluated using 'area under the curve' technique. Results indicate reasonable predictive capabilities (76% accuracy) comparable to previous research. Following subsequent review of current USFS road policy and procedures, recommendations are made for incorporating model use into USFS Road Maintenance Management Systems and roads analyses required by the Forest Transportation System Management Policy.

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# Chapter 1: Introduction

In the Pacific Northwest, landslides are a common natural geological hazard that has direct socio-economic and ecological effects on the region. The impacts of such events are especially prevalent throughout federally managed national forests, where a vast amount of land is located in forested and mountainous terrain naturally prone for landslide occurrence. In Washington and Oregon, much of the 24 million acres of national forests (B.C. Ministry of Forests and Range 2009) lie within the Cascade range, where conditions characterized by steep topography, complex geology, and heavy winter rainfall can lead to frequent slope failures. These regional slope stability problems are compounded by the presence of thousands of miles of U.S. Forest Service roads of varying age, surface material, and maintenance conditions.

Such road systems have been shown to increase landsliding in forested areas. Numerous studies have found forest roads (such as those constructed for timber harvesting and fire suppression) can increase landslide erosion in steep terrain by several orders of magnitude compared to undisturbed forest land (Allison et al. 2004, Paulson 1997, Sidle et al. 1985). Mechanisms for such road-related mass wasting failures include removal of slope support in roadcuts, increased weight on hillslopes, groundwater saturation in the road prism, intercepting subsurface flow, hillslope drainage rerouting, and debris flows initiation at failed stream crossings (USDA Forest Service 1999, Larsen and Parks 1997). Improper road-building practices (such as placement of uncompacted fill) combined with poor road maintenance may also increase the potential for slope failure in these susceptible settings (Gorveski, 2003).

While the vast network of low-volume forest roads enables easy recreational access to some of the most visited national forests in the country (USDAFS, 2007), slope failures often lead to infrastructure problems or road closures due to unsafe conditions. These events are especially problematic in light of the strained financial budget and substantial use (recreational and logging) within national forest lands. Increased traffic levels directly affect road maintenance intensity, as increased erosion losses require increased maintenance to preserve drainage patterns and minimize downward movement of sediment (Grace and Clinton 2007). When limited financial resources are insufficient to meet necessary road maintenance needs, problems arise as below-standard roads have the potential to cause accelerated soil erosion losses and mass failures (Luce et al., 2001).

Amidst such circumstances, the U.S. Forest Service has a constant need for evaluation, planning, and decision making regarding road maintenance and deactivation activities. Several measures (such as travel analyses, condition surveys, and travel atlas upkeep) are currently utilized within the agency to assist in identifying road needs and improving participants' knowledge guiding road-related decisions. Understanding the likelihood of landslide events is an essential component in such analytical-deliberative processes (National Resource Council 1996), as improved insight into the physical hazards surrounding road networks strengthens the knowledge base for deliberations and management decisions. By better identifying areas that exhibit the greatest risk to human and ecosystem health, information regarding landslide susceptibility becomes vital for managers and agency personnel to effectively prioritize treatment and plan site-specific management strategies at various scales. Due to the inherent complexity involved in susceptibility inquiries, modeling strategies can be a valuable means for managing the

profusion of data needed to assess environments predisposed to landslide occurrence. With existing modes of assessment often lacking in robustness and/or clarity of results, new modeling methods have the potential for improved information generation and usability.

### **Research Question and Objectives**

This work seeks to answer the question of whether a new, fuzzy-based landslide susceptibility model can be used as a decision tool for U.S. Forest Service road applications. The objective of this research is twofold: 1) to develop a fuzzy-based, predictive landslide susceptibility model for use in prioritizing U.S. Forest Service (USFS) road management activities, and 2) determine how such information may best be used within current USFS' decision processes related to roads. To investigate these questions, a landslide model is developed, applied and evaluated within the context Washington's Mount Baker-Snoqualmie National Forest. The model in this study was created by constructing a database containing various terrain parameters contributing to past landslide occurrence. Terrain attributes at mapped landslide locations are assessed through a variety of GIS techniques and used in combination with likelihood ratio and fuzzy logic systems to assess relative likelihood of landslide occurrence within the study area. Model performance is then evaluated using the 'area under the curve' technique. Lastly, the usage and implications of the final model outputs (in the form of landslide susceptibility maps) are examined in order to propose ways this information may be best used within the complex decision analysis matrix for USFS road management.

### **Thesis Overview**

The remainder of this thesis is comprised of six chapters. Chapter Two provides background information on landslide susceptibility modeling in the context of road

management and introduces the project study area: Mount Baker-Snoqualmie National Forest. Chapter Three presents the methodology used in developing a fuzzy logic landslide susceptibility model, and describes the processes for model implementation and evaluation. Chapter Four provides interpretation of the model's application to the Mount Baker-Snoqualmie National Forest's Upper Finney Creek region, and discusses the usage of such modeling technology as decision tools within current USFS road decision processes. Lastly, Chapter Five provides conclusions and suggestions for future research.

## Chapter 2: Background

To meet the study objectives of developing and evaluating a decision support tool, it is important to understand the effects of landslides and the role these geomorphic events have in the context of current resource management frameworks. Thus, subsections in Chapter 2 are designed to: 1) discuss the impacts of landslides on existing forest resources, 2) apprise current USFS management policies, 3) introduce comparative examples of the regional landslide and management situation, and 4) present existing options for assessing landslide likelihood.

### ***2.1 Impacts of Landslides and Compounding Resource Problems for Transportation Systems***

When slope failures occur, the surrounding area may be physically altered causing both immediate and indirect impacts. In areas where failures extend to a stream channel, the initial failure and subsequent surface erosion of the slide will deliver sediment directly to the stream. This input results in degraded water quality and fish habitat due to increased sediment deposition, gravel scouring, and bank erosion (Gardner 2006). Landslides may also destroy riparian vegetation and affect road-stream crossing fills and transport materials to other stream channels (Gorsevski et. al 2000, USDAFS 1999). In roaded environments, slope failures may damage the structural integrity of the roadbed, leading to sometimes life-threatening problems for travelers and workers. The direct fiscal cost for road repair and mitigation for future mass wasting is often significant, with expenditures often reaching in the hundreds of thousands to millions of dollars (Rey 2007). Additionally, road damage indirectly compromises existing transportation routes as access for recreation and industry is impeded.

Landslide events are especially significant for the Forest Service because of the consequences discussed above and the agency's limited resources for management of the 380,000 miles of forest roads presently occupying the U.S. Forest Service transportation system. Most Forest Service roads that make up this road network were initially constructed for management activities like timber harvesting and fire prevention as early as the 1940s and 1950s, and thus were not intended to serve the purposes of today's needs (Grace and Clinton 2007). A large portion of roads have since evolved to serve multiple management objectives, including public access for dispersed camping, hunting, fishing, wildlife and scenic viewing, and trailhead access to both wilderness and non-wilderness areas (USDAFS, 2002). Due to the age of the roads and drainage structures, a significant portion of the system requires upgrading where access needs to be maintained (USDAFS 1998). In areas where access is not a priority, decommissioning treatment is often required to prevent unacceptable environmental damage such as fish migration blockages, sedimentation, erosion, etc. (USDAFS, 2002). With a \$4.1 billion backlog of deferred maintenance costs however, limited resources currently exist for road management (Rey 2007). Nationally, this cost may be even higher as estimates of deferred maintenance needs follow the Federal Accounting Standards Advisory Board protocols, which exclude some of the indirect and overhead costs borne by the Forest Service road program (Rey 2007). At a regional level, Washington State's maintenance backlog has been estimated at \$310 to \$760 million including decommissioning costs for 3,600 miles of roads. With current maintenance budgets insufficient to meet critical needs, (Rey 2007), the Forest Service is faced with the problem of maintaining, upgrading, and downsizing its existing road system.

## ***2.2 Landslide Modeling for Science-Intensive USFS Road Policies***

In order to assist Forest Supervisors and management personnel in this exigent pursuit, the agency utilizes implementation of the Forest Transportation System Management Policy (USDAFS, 2001), referred here as the USFS Roads Policy. This federal statute requires interdisciplinary, science-based roads analyses for all road management decisions. These analyses, called travel analyses, are designed to allow forest managers to adequately prioritize road-related management decisions in order to reduce the effects and impacts of the existing road system while balancing risk and access issues. The Roads Policy outlines scale-specific instructions for conducting analyses, including watershed or project scale requirements that call for the identification of environmental and public safety risks and site-specific opportunities for decommissioning (see USDAFS, 1999 for procedures). Such specific and comprehensive data collection is “intended to inform site-specific decisions, to set priorities for road management actions, and to identify special situations” (Pacific Rivers Council, 2002). Issues commonly examined in analyses include road effects on aquatics, fire prevention, vegetation, hydrologic connectivity, recreational access, and cultural considerations among others. While geomorphic processes and slope stability are significant factors for inclusion in these studies, these can be overlooked as can be seen in forthcoming examples.

Such omissions of geomorphic information pose significant limitations for making reliably comprehensive decisions. Landslide potential is an essential component in science-intensive decision processes like travel analyses, as the information is vital for managers to effectively plan site-specific deactivation and management strategies at various scales. A variety of inexact factors contribute to the complexity of a manager’s

decisions, such as “the nature of the relationship between roads and landslides, the variety of damage that can result from road related slides, and the random nature of weather events that are thought to trigger road related slides” (Allison, C., Tait, D, 2000, p. 2) Amidst this difficulty, the examination of slope stability issues remain paramount. A better understanding of the potential for landsliding throughout USFS’s districts not only improves evaluation and identification of a road’s social and environmental risks, but landslide knowledge may help economic forecasting in terms of maintenance and decommissioning costs. Roads exhibiting high susceptibility will likely require increased long term maintenance costs as slopes fail; if personnel and resources cannot be committed for such anticipated emergency maintenance for the life of the road, deactivation may become a higher priority.

### ***2.3 Mount Baker-Snoqualmie National Forest: Comparative Example of Regional Conditions***

The Mount Baker-Snoqualmie National Forest (MBSNF) is an area typifying the need for incorporating landslide concerns into such management decision processes. The Mount Baker-Snoqualmie National Forest extends across Washington State from the Canadian border to Mount Rainier National Park and encompasses approximately 524,719- acres (USDAFS, 2007) (Figure 1). Located predominantly within the North Cascades mountain range, the area is characterized by particularly steep and rugged terrain, with mountain elevations often reaching 7,000 to 8,000 feet (USDAFS, 2007). High elevations, combined with the forest’s geographic location in Western Washington, result in significant precipitation as both rain and snow. In addition, the Forest is actively utilized by the timber industry, with recent annual harvests approximating 89 million



board feet a year (USDAFS, 2007). The combination of geographic and environmental conditions of this region makes it ideal for the occurrence of landslides.

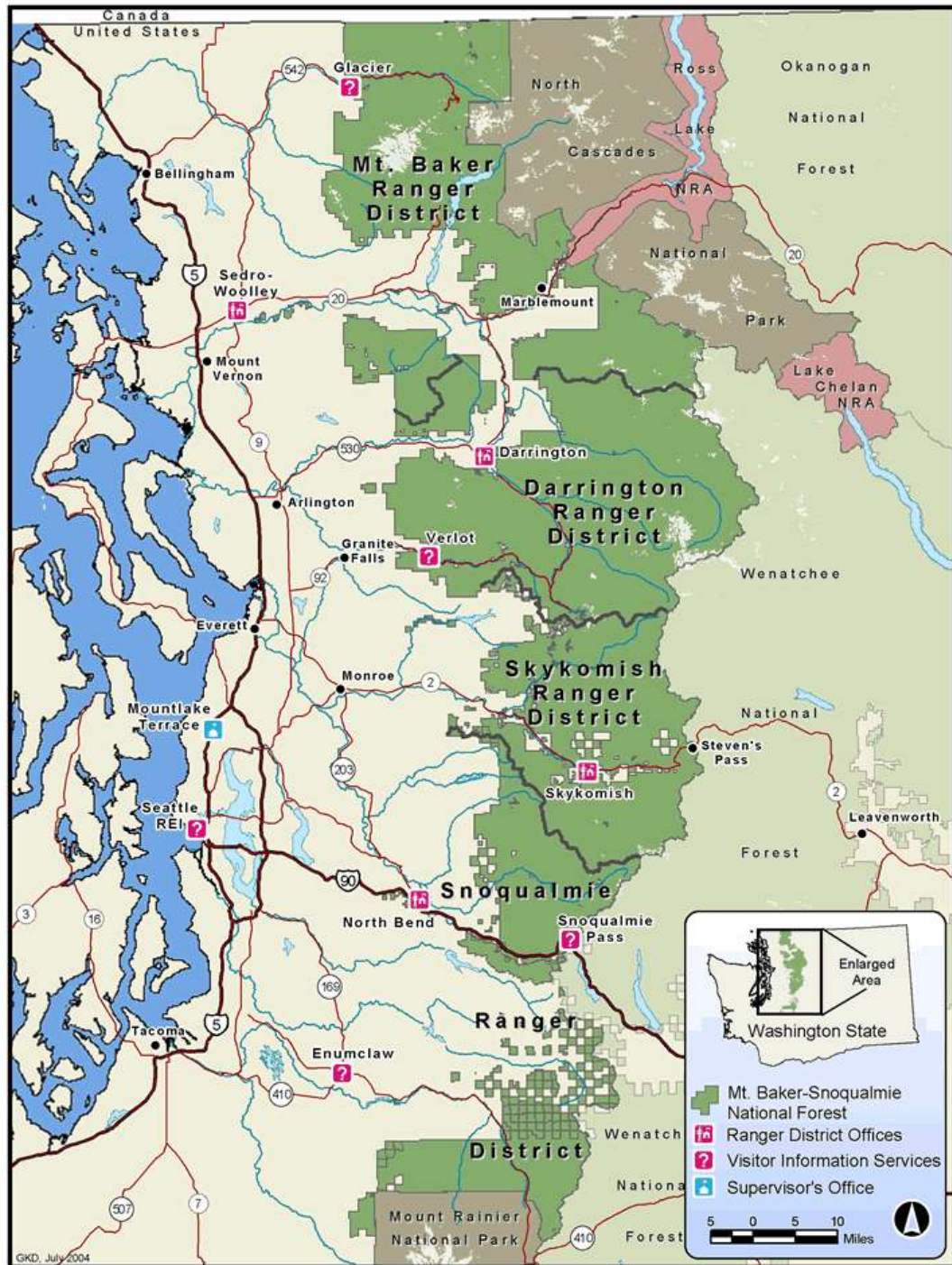


Figure 1. Location map of Mount Baker-Snoqualmie National Forest (USFS 2009).

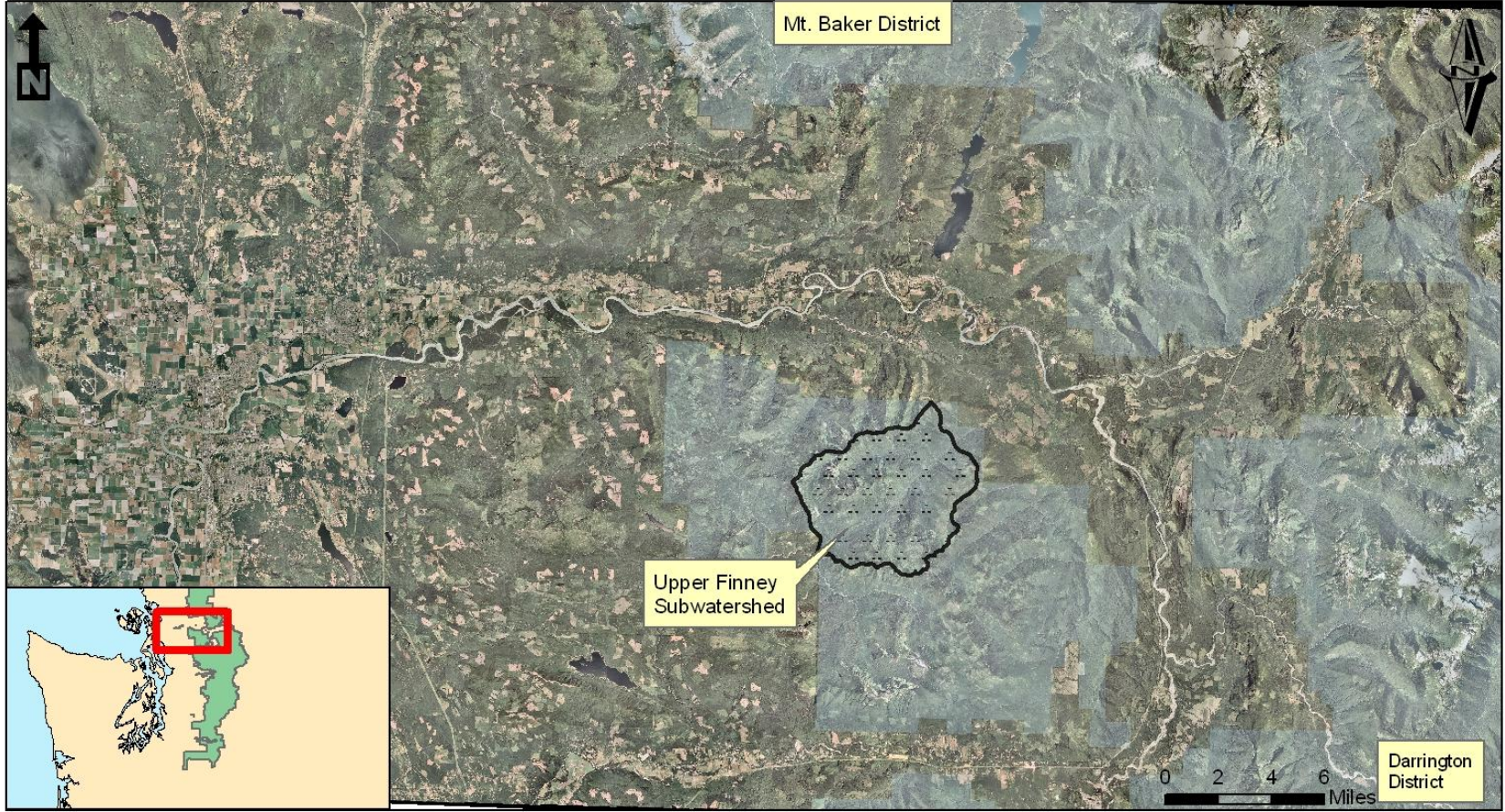
Here, circumstances are emblematic of the agency's road management problems. The Mount Baker-Snoqualmie National Forest's backlog is currently estimated at \$45 million, and it would cost an approximate \$3.7 million annually to maintain the Forest's 2,662 miles of road (USDAFS, 2003). Less than 25 percent of the MBSNF's roads are fully maintained to standards, and the gap between needs and available funds grows larger as limited timber sales lessen Forest income (USDAFS, 2003). Like other Forests in the region, the MBSNF has consequently adopted the national response to bring the road system into alignment with available funding: forest-wide annual maintenance decisions that reduce the availability and standards of roads accessible by public traffic. To aid in these endeavors, the MBSNF has performed travel analyses to assist in closure and upkeep decisions. While the assessments have incorporated various factors such as wildlife, aquatics, recreation, vegetation, fire, and cultural considerations, direct inclusion of geomorphic processes or slope stability is absent.

#### ***2.4 Landslide Modeling***

As the disconnect between important landslide information and related decision making processes becomes apparent, a new approach is needed to facilitate the generation and dissemination of information about landslide potential. Consequently, this work presents the creation of a new predictive model utilizing Geographic Information Systems (GIS). Determining and assessing the likelihood of these dynamic events is an involved and multifaceted process that takes into account a variety of factors; undoubtedly, some professional individuals have the expertise and familiarity with an area to do so heuristically via field work. However, the need remains for determining landslide susceptibility in a replicable manner, over wide ranges of areas, and in a way in

which resulting outputs are easily communicable and useful to the users. The purpose of this newly developed model is to fulfill these needs, so that information and results generated by scientific analyses may strengthen the knowledge base for complex, deliberative decision processes.

To construct the landslide model, information was utilized from a selected study area within the Mount Baker-Snoqualmie National Forest. The Finney Creek area, located south of State Highway 20 and the town of Concrete, WA, lies within the western portions of Mount Baker-Snoqualmie National Forest's Mount Baker District (Figure 2). The watershed encompasses approximately 72 sq. km (28 sq. mi) and contains notable relief, geologic complexity, and dense conifer forests. The Finney Creek area was specifically selected as a case study for implementation for several reasons. First, its location on the western side of the Cascades and proximity to major access routes assured that the area was visited and actively used by both the Forest Service and general public. Secondly, the Finney Creek region was identified as an area of interest by Forest Service personnel as a locale currently experiencing slope instability at multiple locations. As a result, mapping of past landslides had been performed for this area (Paulson 1996). The abundance of landslide features (184) mapped also helped to ensure a representative sampling of landslide occurrence. Additionally, the area's moderate density of Forest Service roads provides an opportunity to examine the relationships between forest roads and landslide susceptibility.



**Figure 2. Location map and 2001 aerial photograph of the Upper Finney Creek subwatershed and surrounding US Forest Service land (Photograph obtained from Western Washington University).**

## ***2.5 Existing Landslide Susceptibility Modeling Methods***

While a variety of methods exist to predict where landslides may occur in a given area, this work is focused on means of assessing landslide susceptibility as opposed to risk or hazard modeling. Landslide susceptibility refers to a specific concept that is often incorrectly equated with similar terms like risk and hazard. A natural hazard may be defined as either the probability that a reasonably stable condition may change abruptly or as the probability that a potential damaging phenomenon may occur within a given area in a given period of time (Varnes, 1984), with the latter definition more commonly accepted for maps portraying its distribution over a region (Guzetti et al. 1999). Such a definition incorporates notions of both geographic location and time recurrence. Thus, landslide hazard may be expressed as the probability of landslide occurrence at a given location within a specified time period. This determination requires explicit knowledge about both the causative factors that tend to place the slope in a marginally stable state (such as geology, slope gradient, aspect, soil properties, etc.) *and* the triggering factors which shift the slope to an unstable state and initiate slope failure (such as earthquakes or heavy rain) (Dai et al. 2002). Difficulties often arise when estimating the cause-effect relationships associated with the triggering variables, however, as triggers may change over a very short time period (Dai et al 2002). Additionally, complete historical data concerning the frequency of these events is often lacking, making it all the more difficult to determine actual probabilities of landslide occurrence. If the temporal probabilities relating to triggering factors are not taken into account, then the term ‘susceptibility’ is more appropriately used to define the likelihood of landslide occurrence in an area (Soeters and Van Western, 1996).

Numerous approaches have been developed over the years to spatially model landslide occurrence. These methods can be characterized as heuristic, deterministic, or statistic in nature (Guzetti et al. 1999). Determining the appropriate approach to use for analysis will often depend on the expertise of the analyst as well as the availability of data and the spatial scale of the study (Gardner, 2006).

Heuristic investigations are qualitatively based on expert opinions and utilize the spatial similarities between landslide location and the factors contributing to slope instability (Gardner 2006). Such tactics include geomorphological field analysis and use of index maps, where susceptibility is determined after fieldwork on the basis of a detailed map taking into account a range of factors related to landslide occurrence. The relative importance of these variables may be ranked and weighted by the investigator, after which data layers can be overlaid to produce an overall susceptibility map. Disadvantages associated with heuristic models include the length of operations involved, the subjectivity in attributing weighted values, and limited reproducibility of results (Huabin et al. 2005, Aleotti and Chowdhury, 1999).

In deterministic modeling, the potential for landsliding is determined by quantifying the main physical properties of a specific slope site and applying these data to slope stability models (Aleotti and Chowdhury, 1999). Such models can be used to calculate a factor of safety (FS), which is a numerical index of estimated slope stability. FS calculations are largely based on limit equilibrium theory and define the ratio of the stresses resisting failure (i.e. friction, root strength, cohesion, etc.) to those stresses driving downward movement (such as gravity, pore pressure, shear stress, and external ground shaking factors). These process-based models are useful in helping pinpoint

causes of mass-movement and generating detailed spatial patterns on fine-scale gradations of instability (Huabin et al. 2005). Limitations associated with deterministic models include 1) an inherently high degree of simplification; 2) requirements for uniform ground conditions and large amounts of data, and 3) restricted applications to individual slopes or small areas (Huabin et al. 2005, Van Western 2005).

A third approach to analyzing landslide susceptibility involves using statistical models in combination with landslide inventories. In this approach, the relationship between the spatial distribution of past landslides and environmental variables responsible for landslide causation is examined on a statistical basis. Assuming that slope failures in the future are more likely to occur under the conditions which led to past and present slope movements (Varnes, 1984), the spatial distribution of environmental variables can be used to estimate the distribution of relative landslide susceptibility in that region (Carrara et al, 1995). Several intrinsic attributes in particular have been found to directly affect the potential for slope failure including vegetation, underlying geology, soil properties, and hydrology (Sidle et al. 1985). Previous modeling work has also shown the topographic attributes of slope, aspect, elevation, and curvature to be particularly influential in determining a slope's susceptibility (Gardner 2006, Aniya 1985, Gorsevski, et al. 2000, Gorsevski, et al. 2003). Examination of the spatial distribution of such attributes is important to landslide prediction as it is the complex interaction amongst such preparatory conditions that may lead to eventual slope failure.

A range of quantitative statistical techniques have been used within the past several decades to determine landslide likelihood, including bivariate analysis and multivariate methods like discriminate analysis, multiple regression, Bayesian probability, and logistic

regression modeling (Dai et al. 2002). While such statistical techniques require the collection of large amounts of data to produce reliable results (Ercanoglu and Gokceoglu 2004), their utilization lends to a more objective and effective approach in situations when other modeling methods become difficult to evaluate susceptibility.

As a new approach for evaluating landslides using GIS, fuzzy logic and artificial neural networks models have also been successfully applied in recent years (Tangestani 2003, Chi et al. 2002, Gorsevski, P. et al. 2003, Miles and Keefer 2009). While arguably considered a hybrid of heuristic and statistical techniques, Fuzzy logic has a variety of advantages over other methods due to its unique ability to compute with words. While scale and data limitations may preclude the use of certain methods, fuzzy logic is advantageous because of its ability to handle uncertainty and ‘nonlinearities’ within a system, accommodate any measurement scale and data type, and allow users complete control of weighting evidence (Lee 2007). Fuzzy logic is relatively straightforward to understand and implement, and can be used with different types and levels of data (e.g. qualitative, quantitative, etc). This allows for more flexibility as numerical values, ranges, and ordinal categories can all be incorporated, regardless of the inherent vagueness or uncertainty of nonnumeric information. Fuzzy logic models can also be designed to perform with incomplete data or missing data, as well as data that is weighted by the designer (Miles and Keefer, 2009). The linguistic rules of fuzzy systems allow users to easily understand the make-up of the model components and influence of inputs, while the system outputs can be implemented with a GIS modeling language. Combining fuzzy systems with GIS enables pixel by pixel computation for enhanced resolution, visualization, and communication of the results. Several studies to date have



demonstrated the utility of fuzzy methods for landslide applications (Ercanoglu and Gokceoglu 2004, Dewitte et al. 2006, Champati Ray et al. 2007, Lee 2007, Miles and Keefer 2007, Miles and Keefer 2009).

For this study, fuzzy techniques were chosen over other approaches based upon the purpose of the assessment, extent of the study area, availability of data, and limiting environmental conditions. A strictly heuristic approach was abandoned due to the inherent high levels of subjectivity involved and difficulties associated with performing field work with limited resources. Additionally, heuristic methods seemed impractical for long term use for the Forest Service given staffing issues. Consistent analysis becomes difficult with multiple evaluators; thus contract work, personnel turnovers, and group assessments pose replication problems for heuristic interpretation. Likewise, a deterministic approach was found to be unsuitable for the research question because of the high degree of simplification needed to assess engineering properties of the varied ground conditions present within the MBSNF. Statistical techniques, however, are the most appropriate for susceptibility mapping at this scale because it is possible to map out occurrence of past landslides and to collect adequate information on the intrinsic variables that are considered to be relevant to the occurrence of slope failure (Huabin et al. 2005). As this spatial scale allows for distinctions to be made between different slope segments, medium scale (<1:100,000) susceptibility maps are often used in similar contexts for the development of priority measures and for work in areas affected by large engineering structures and roads (Aleotti and Chowdhury 1999, Soeters and Van Western 1996). Incorporating statistical strategies also ensures a level of replicability for future

work, enabling others to apply the modeling development method to other locations with new data.

## Chapter 3: Model Development

To better answer the question of whether new capabilities in landslide prediction can be effective in road management applications, a new type of landslide susceptibility model is developed for delineating environments (including roadside areas) predisposed to landslide occurrence. Examining the application of this decision support tool to areas representative of the regional landslide conditions and management circumstances allows for new insights in determining the significance and utility of such tools. Furthermore, this exercise assists in ascertaining how these tools may be best used within current USFS management practices.

Like other predictive models of regional landslides, this work is designed to identify where landslides may occur over a region based on a set of relevant environmental characteristics. The causal factors selected for analysis are chosen for their documented ability to act upon a slope in a manner that weakens stability and helps lead to eventual slope failure. To evaluate the abundance of spatial information associated with the complex interaction of these variables, a fuzzy logic system is employed to assess landslide susceptibility in a clear and understandable manner.

The following chapter expounds upon the process of creating and using a fuzzy logic-based model for landslide susceptibility based upon the general methodology of Lee (2007). The chapter includes preliminary background on fuzzy logic systems and components, as well as information on each variable selected for the analysis. The design of the fuzzy system is presented and rules for relating the inputs are explained. Steps for model integration with GIS are then described, and the model results for the Mount

Baker-Snoqualmie National Forest application are presented. Lastly, susceptibility outputs are evaluated through area-under-the-curve techniques.

### ***3.1 Fuzzy Logic for Landslide Modeling***

In order to effectively evaluate landslide susceptibility, a fuzzy logic system was devised and incorporated as a modeling strategy to better characterize the uncertainties associated with such natural processes. Fuzzy logic, which was developed by Zadeh (1965), is based upon the fuzzy set, which describes the degree in which an object belongs to some category. Fuzzy sets differ from traditional Boolean set theory in the way membership within a category is represented. In traditional set theory, only two degrees of membership are possible for an object: an object can either belong completely (degree of membership is 1), or not at all (degree of membership is 0). With fuzzy sets, the degree of membership, known as the truth value, can take on any continuous value in the real number interval [0, 1] (Dewitte et al 2006). Variables consist of a collection of membership functions made up of fuzzy sets, which can then be related to those of one or more output variables through a configuration of IF-THEN rules known as the fuzzy logic system.

In order to represent the relation among the variables and to derive solutions to a problem, most fuzzy-based systems use a series of “IF-THEN” rules to combine membership functions of the various inputs. Such fuzzy rules are comprised of two parts: the antecedent condition (IF), and the consequent conclusion (THEN). The IF-part can consist of more than one variable linked together by fuzzy operators: conjunctions like AND or OR that express conditions in the rule base, as will be explained in later portions. This “IF-THEN” form of expression can be constructed using one variable for the input

and one variable for the output. For instance, “If slope is 25 to 35 degrees, then landslide susceptibility is highest.”

Constructing a fuzzy logic system to model a given system requires deliberate and structured design work. As shown in Aksoy and Ercanoglu (2006), the fuzzy system design process can be broken down into several key steps: (a) specifying the problem and defining the variables, (b) determination of membership functions, (c) elicitation and construction of fuzzy rules, (d) encoding the membership functions, fuzzy rules, and procedures to perform fuzzy inference in the model. The following subsections expound upon each step of the design process, and include explanations for any deviation from Lee’s (2007) processes.

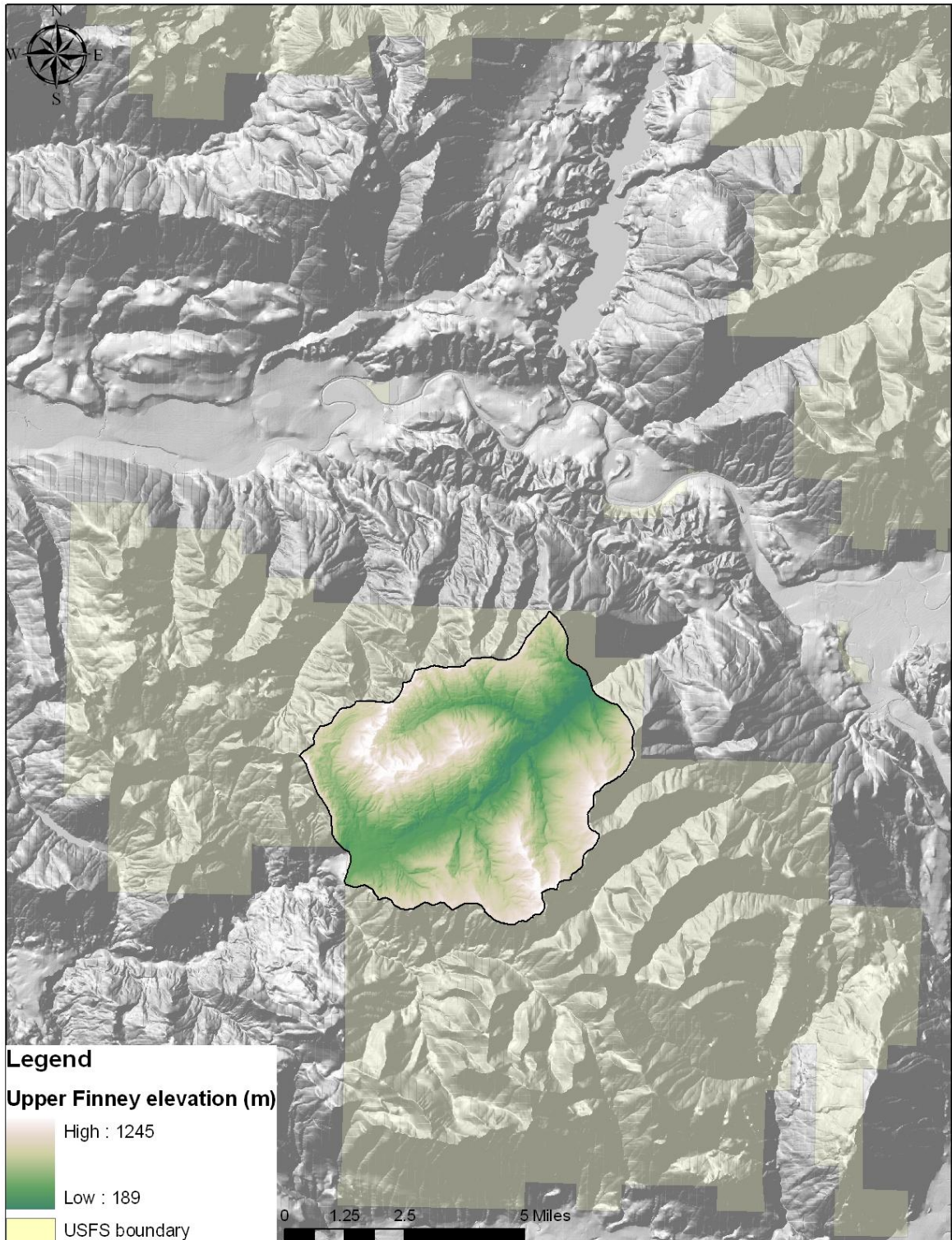
The general method used to develop the susceptibility model is based on the work of Lee (2007), in which fuzzy logic systems were applied to susceptibility mapping in Korea. Lee (2007) utilized a landslide inventory and maps of topography, lineaments, soil, forest, and land cover to extract data on eight factors influencing landslide occurrence. The spatial relationships between the detected landslide locations and each landslide-related factor were analyzed through the use of frequency ratio statistics to obtain a landslide ratio. The landslide ratio is a ratio signifying the frequency of landslide occurrence within a given area. This ratio was normalized and used to establish truth values and fuzzy sets for each factor. Fuzzy sets were in turn used to define membership functions, which were combined through a fuzzy operator (conditional expression for relating the combinations of truth values) in order to compute a landslide susceptibility index. These susceptibility values were then mapped across the 68 km<sup>2</sup> study area for

visual interpretation. Lastly, the landslide susceptibility analysis results were verified by comparison with existing landslide locations for prediction accuracy.

### ***3.2 Problem Specification and Variable Definition***

The first step in creating the new model was to identify the geographic boundaries/region for analyses and define which input variables to use. After eliciting knowledge by talking with Forest Service personnel (geologists, road managers, etc.), the Upper Finney Creek subwatershed was selected as the study site in which model inputs would be based upon. The study area was selected for its range in topography, ample landslide features, and typical forest road configuration (Figure 3), and is approximately equal in size to that used in Lee (2007).

Once the physical area was selected, causal factors were narrowed down by examining literature sources and comparing other models (Aniya 1985, Ercanoglu and Gokceoglu 2004, Gardner 2006, Gorsevski, et al. 2000, Gorsevski, et al. 2003, Lee 2007). A total of 9 factors were determined to have the potential to affect landslide susceptibility within the greater area. These factors include slope aspect, slope angle, elevation, curvature, geology, distance to roads, distance to streams, soil types, and vegetation. Information pertaining to each of the 9 selected factors was compiled from different sources and assembled as unique GIS themes, or layers. The parameters differ slightly from those chosen by Lee (2007), as lineament, soil texture, and land cover information was omitted from this study: numerous faults were not present within the study area, land cover was relatively homogenous, and soil texture was represented by soil type. The following subsection details the various thematic layers in ArcGIS that are used as inputs into the model.



**Figure 3. Shaded relief of Upper Finney Creek subwatershed and adjoining USFS boundaries. See figure 2 for site location. (Data from USDAFS 2008).**

### **3.2.1 GIS Data Layers**

#### ***Landslides***

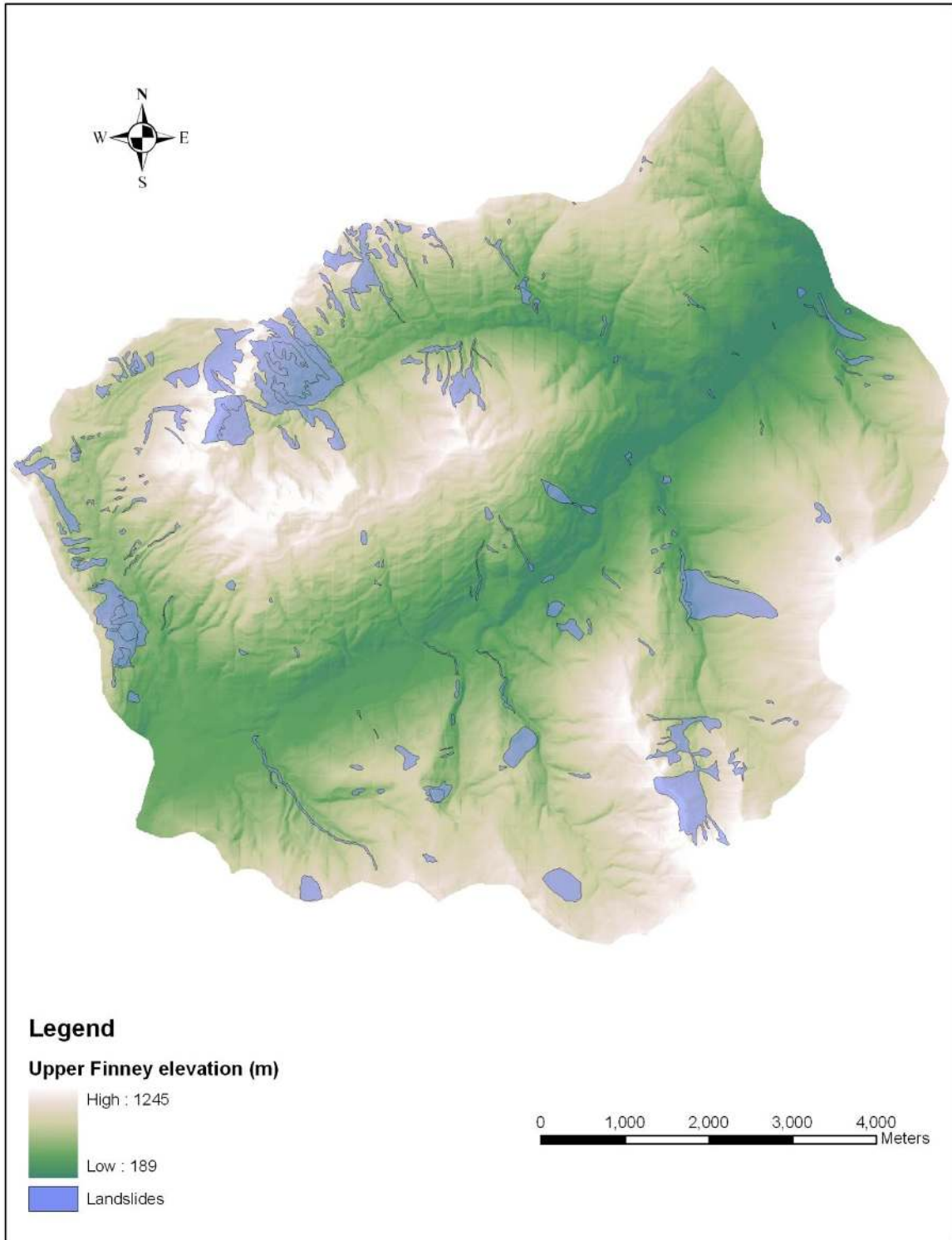
The primary source of existing landslide data came from the Washington Department of Natural Resources (WADNR) statewide landslide inventory (WADGER 2005). This database is a compilation of landslide datasets gathered from multiple agencies including WADNR, USFS, tribal entities, and universities. This inventory is updated quarterly and was selected for its polygon coverage of mass wasting events (which provides more detail than simple point locations). While the dataset is quite comprehensive in the inclusion of numerous small landslide features, no statements can be made about the accuracy of the attributes due to the multiple authors and agencies involved. Additionally, landslides are ongoing phenomena and as such, datasets are never complete for non-static processes. However, a relatively high confidence level is associated with the mapping of the study area due to visual comparison of previous mapping efforts like Paulson (1996). Within the WADNR inventory, each landslide feature contains corresponding attributes including area and perimeter measurements, landslide process, year of identification, mapping certainty, land use type, and author information (Figure 4). The inventory contains 184 mapped landslides in the study area, representing a density of 2.5 landslides/km<sup>2</sup>. Features were primarily identified by the authors through the use of aerial photographs dating as far back as 1940.

#### ***Elevation***

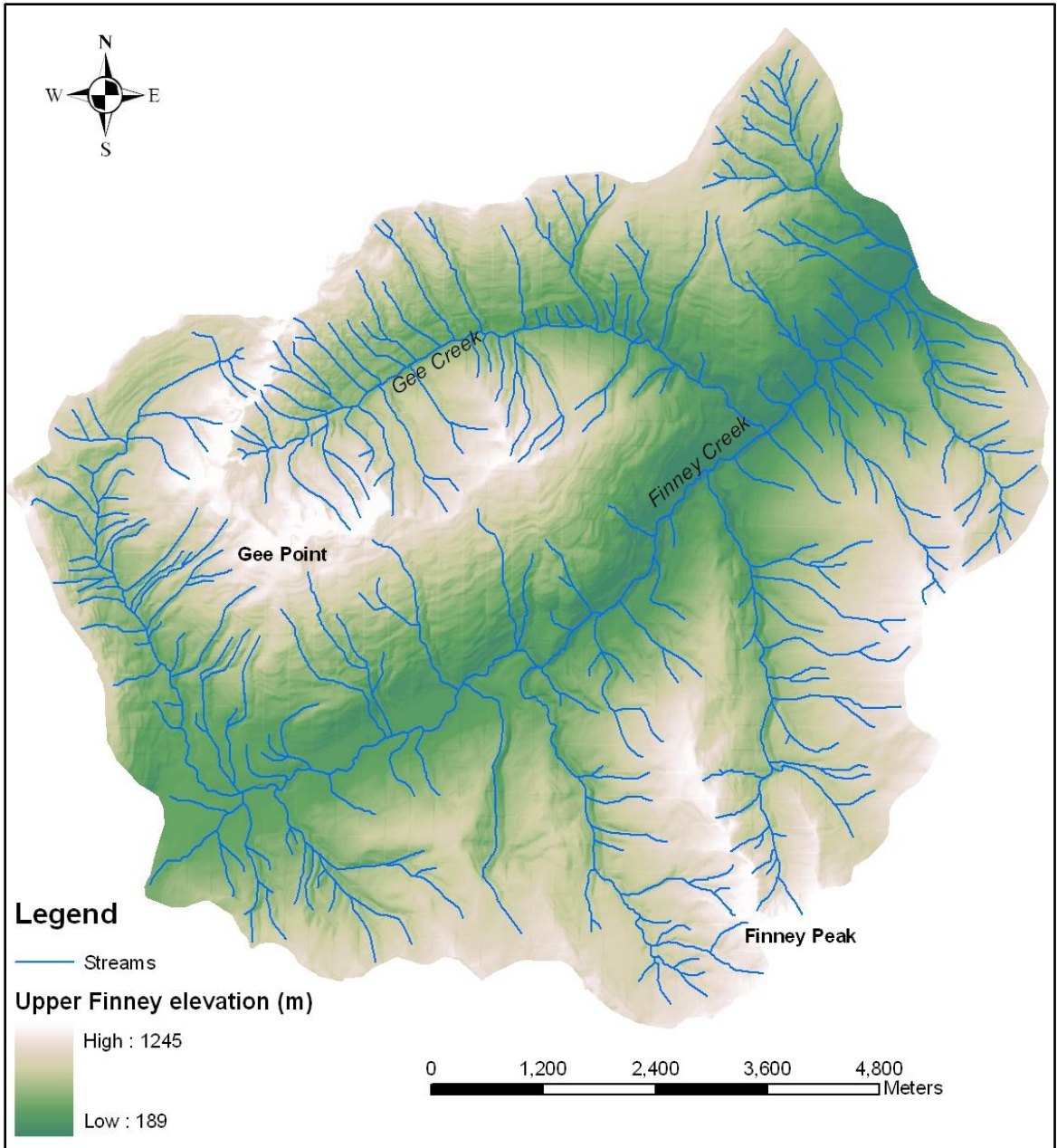
Elevation of a site is important because weather and climate conditions vary greatly at different elevations, and this is reflected in differences in soil and vegetation (Aniya 1985). High elevations may facilitate increased weathering of rocks due to freeze-thaw processes, while low elevations tend to enable thicker colluviums deposits to be



formed (Dai and Lee, 2001). Elevation will also influence whether precipitation falls as rain or snow events, as well as quantities. To create an elevation input grid for this application (Figure 5), elevations were taken directly from a 10-meter Digital Elevation Model (DEM) and converted from decimeters to feet using a conversion in raster calculator. The DEM used for analysis was a mosaic of 10-meter resolution USGS DEMs of the Cascades region encompassing UTM Zone 10 (University of Washington, 2008).



**Figure 4. Landslides mapped by WA DNR within the Upper Finney Creek subwatershed (WADGER 2005).**

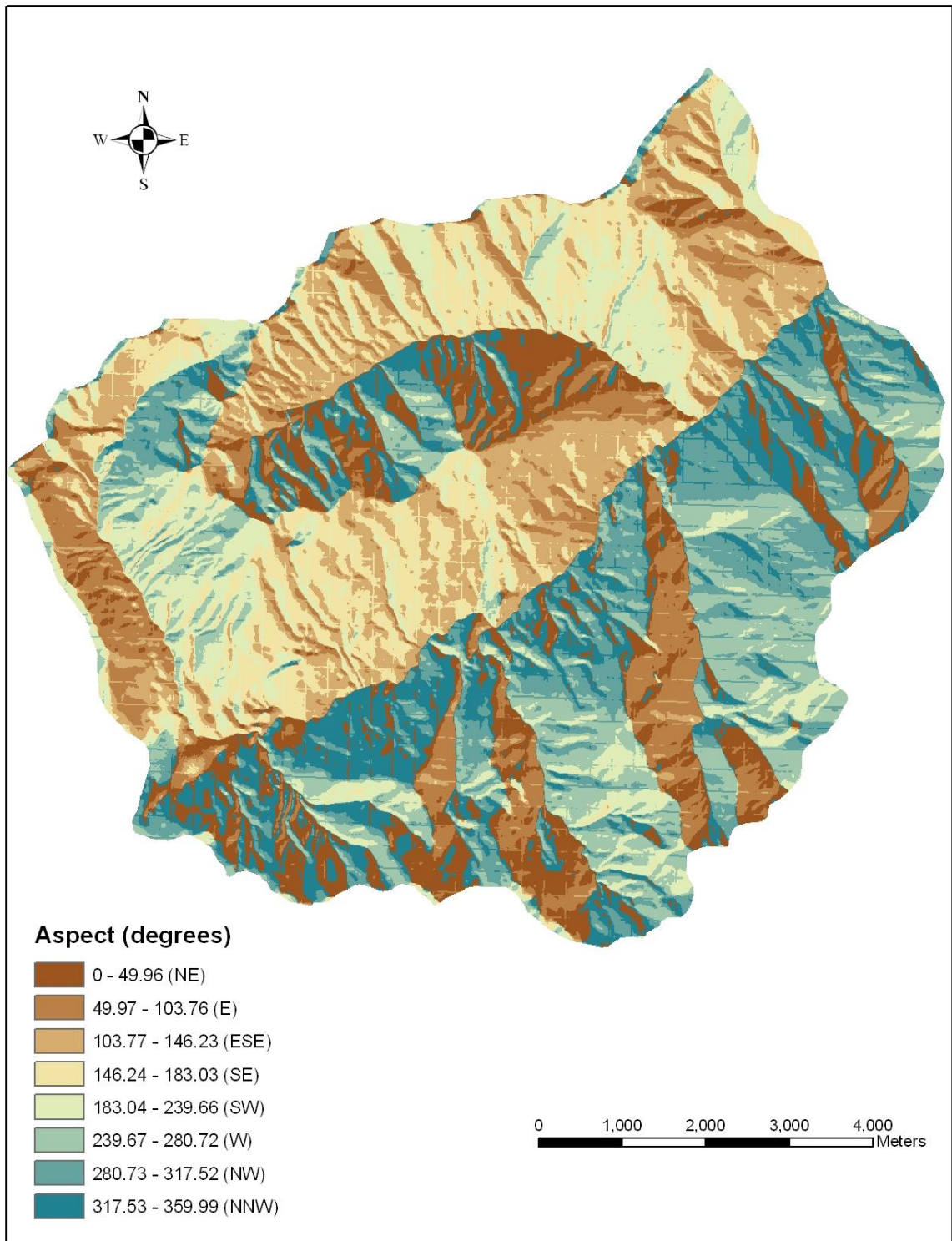


**Figure 5. Elevation and hydrology of the Upper Finney Creek subwatershed.**

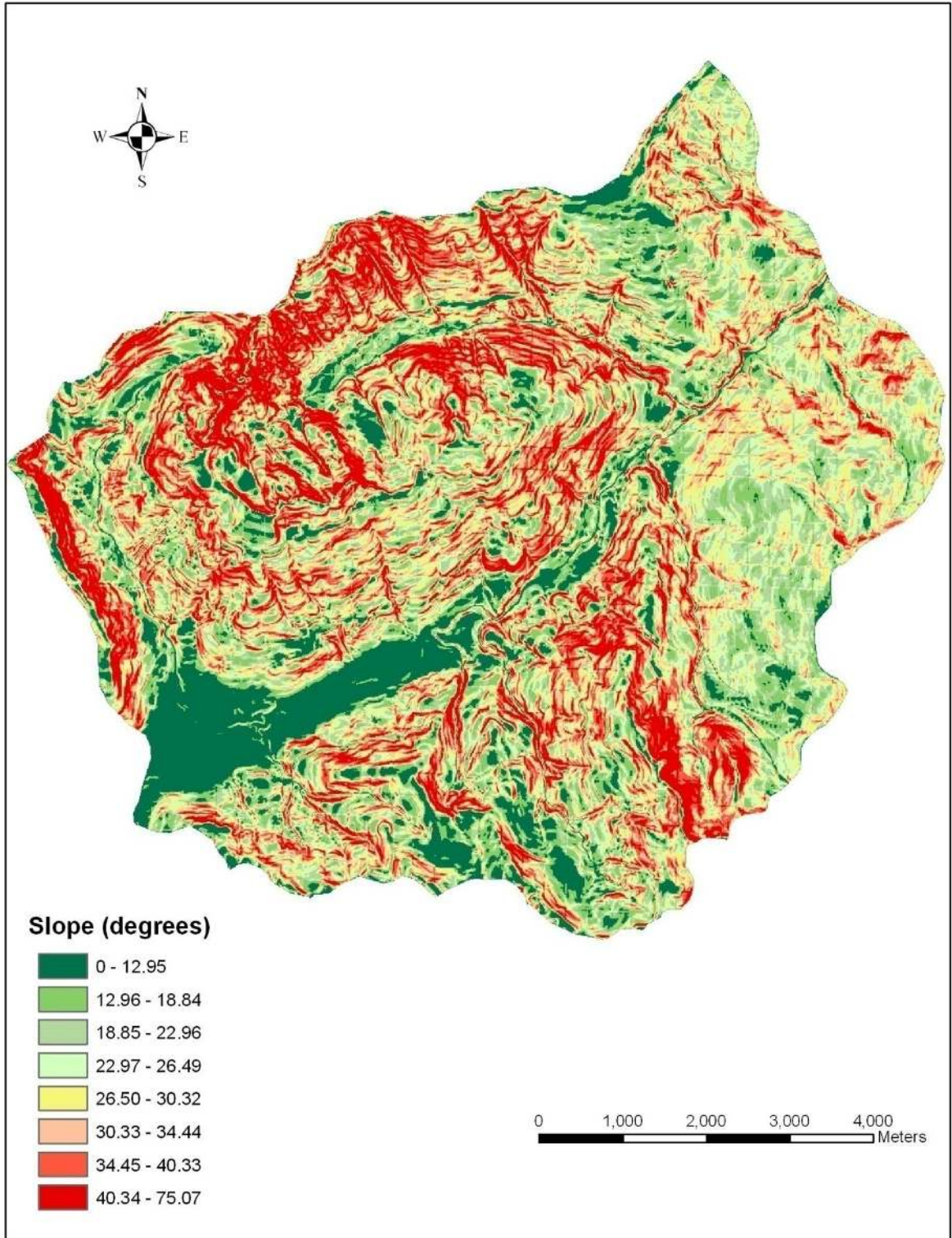
### ***Slope, Curvature, & Aspect***

The slope angle is one of the most important and frequently used factors in landslide susceptibility mapping (Champati ray et al. 2007, Aleotti and Chowdhury 1999). In addition to controlling the overland flow of water and other materials, slope angle influences the ability of the slope to remain intact. As slope angle increases, the shear stress in the soil and rock rises and the slope is more likely to fail (Lee and Min 2001). A slope's curvature or morphology is also an important factor in limiting the spatial extent of landslides, because it controls the movement of surficial materials, surface runoff, and flow acceleration and velocity (Gorsevski et al. 2000, Aniya 1985). Convex parts of surfaces, like ridges, are generally exposed and drain to other areas. Concave parts of surfaces, like channels, are generally more sheltered and accept drainage from other areas. Aspect also influences the soil moisture content, in addition to the amount of solar radiation, flora distribution, and rainfall distribution during storms (Gorsevski, et al. 2003). Slopes that receive more precipitation, such as western and southern facing slopes (which face toward the prevailing storm track) are more likely to fail versus those that receive less moisture (Gardner 2006).

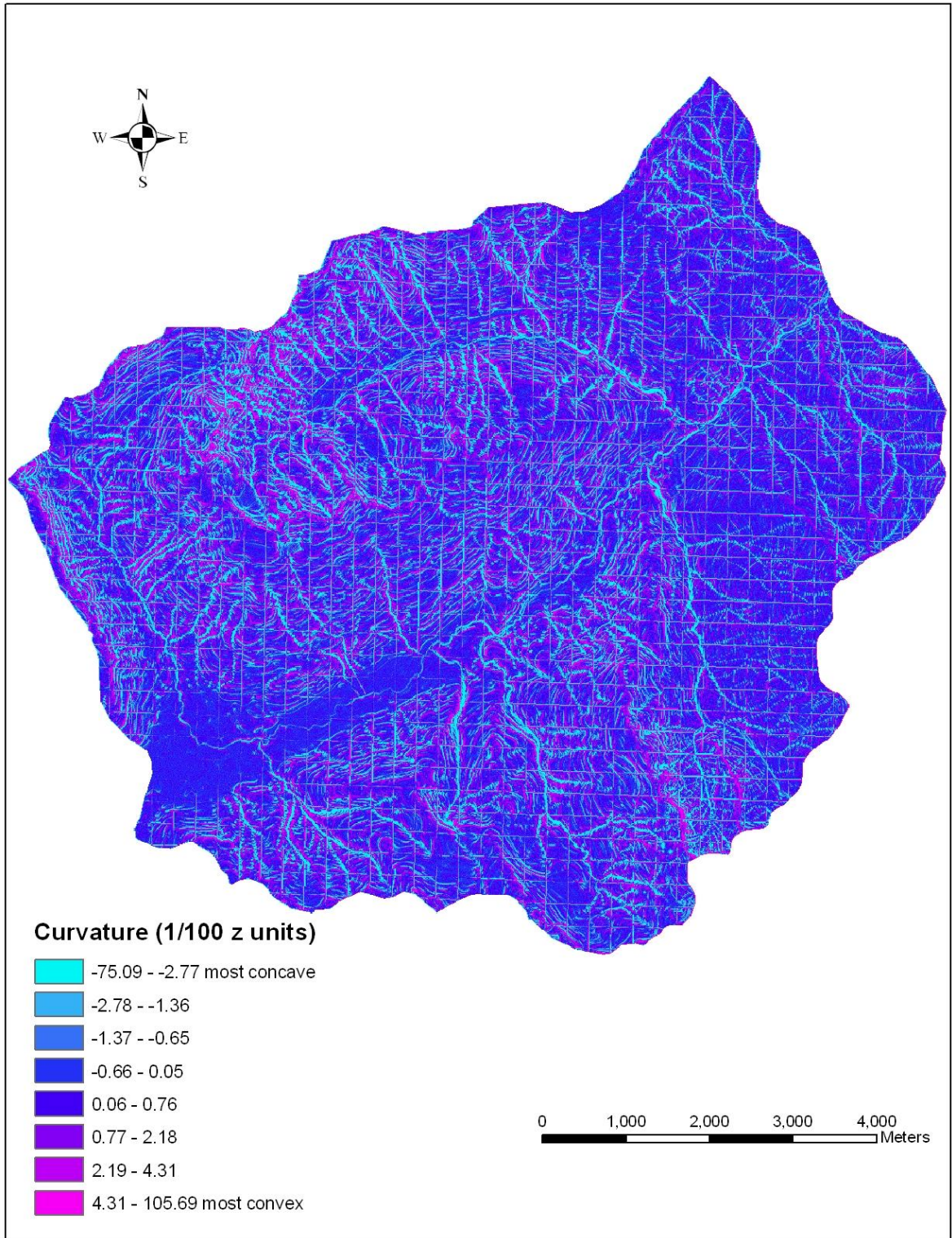
Slope, curvature, and aspect were derived using surface analysis functions in ArcGIS 9.2 Spatial Analyst in combination with the 10-meter DEM. Aspect was first calculated to identify direction each slope is facing (Figure 6). Slope angle, known as the maximum rate of change in elevation for each cell, was calculated using a z-factor of 0.1 (Figure 7). Curvature (the second derivative of the surface, i.e. the slope of the slope) was subsequently calculated via the curvature tool to show whether a given part of a surface is convex or concave (Figure 8).



**Figure 6. Aspect (in degrees) for the Upper Finney Creek subwatershed; zero is north and degrees are measured clockwise.**



**Figure 7. Slope (in degrees) within the Upper Finney Creek subwatershed.**



**Figure 8. Curvature showing convex and concave areas of the Upper Finney Creek subwatershed, zero representing flat surfaces.**

### ***Roads and Streams***

The presence of roads in mountainous environments can directly affect an area's likelihood for slope failure. Instability associated with roads results from a variety of factors such as increased weight on the hillslope from fill, hillslope oversteepening, removal of slope support in roadcuts, alteration of surface runoff paths, and enhanced runoff rates (Sidle et al. 1985). Roads placed across steep slopes alter the geometry of the slope (as road cuts are steeper than natural hill slopes) and may have adverse impacts on surfaces where roads intercept water flowing downhill (Gorseyski and Gessler 2003). Proximity to streams may also influence landsliding potential as processes that remove lateral support, such as erosion by streams, increase shear stress and help destabilize slopes. With elevated groundwater levels during storms, terrain modification via stream gully erosion and undercutting may facilitate landslide initiation (Dai and Lee 2001).

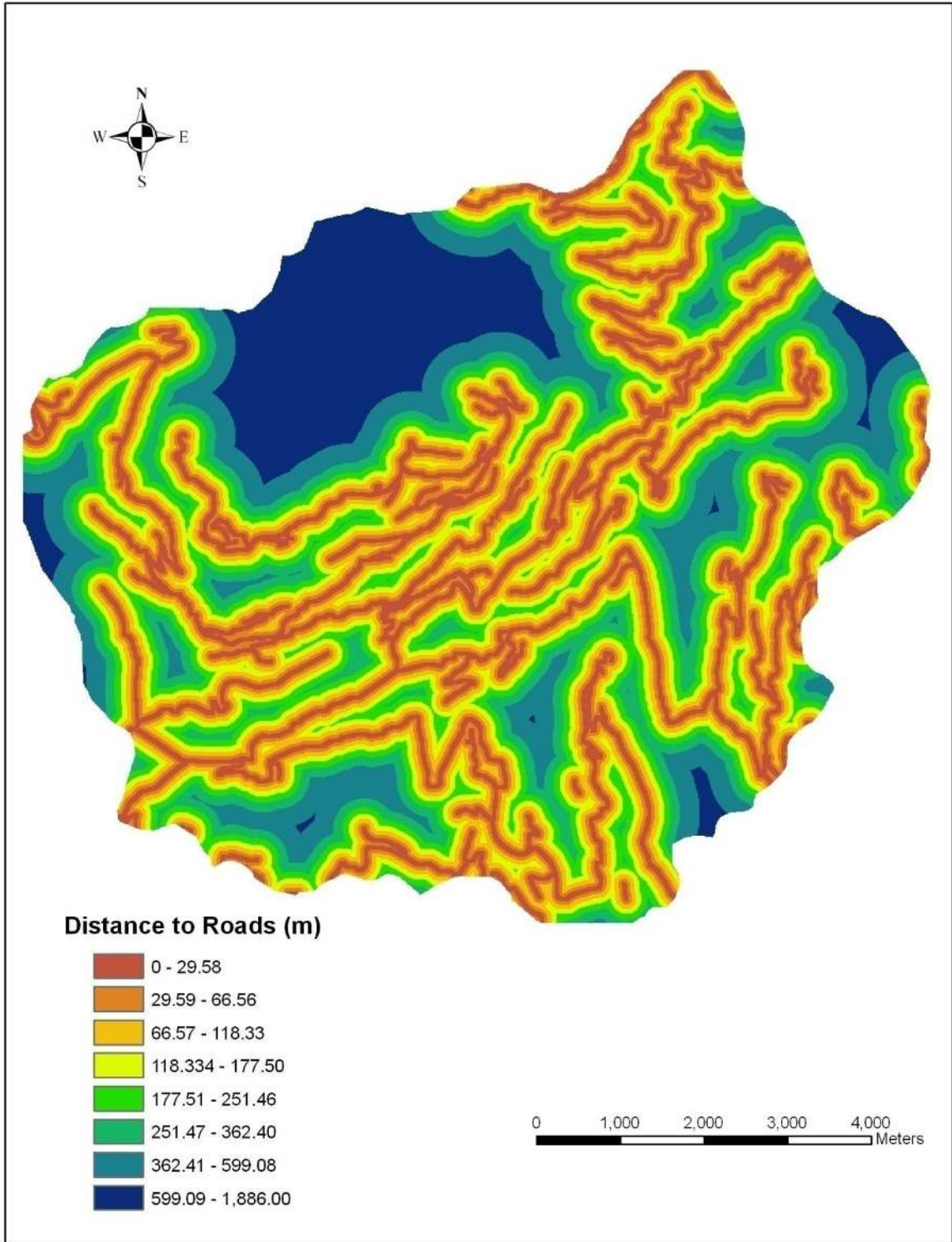
Existing stream and road networks within Forest Service boundaries were obtained from the Mount Baker-Snoqualmie National Forest online GIS database (USDA Forest Service, 2008). Euclidian distance from roads and streams was calculated for each feature. The Euclidian distance determines the shortest path from a source by measuring the minimum straight-line distance for every cell. Figure 9 shows the Euclidian distance to roads while Figure 10 denotes the distance from stream networks. The inclusion of distance information is similar to Lee's (2007) approach, with the exception that straight line distances were used instead of general buffer distances groupings (>100m, >200m etc.).



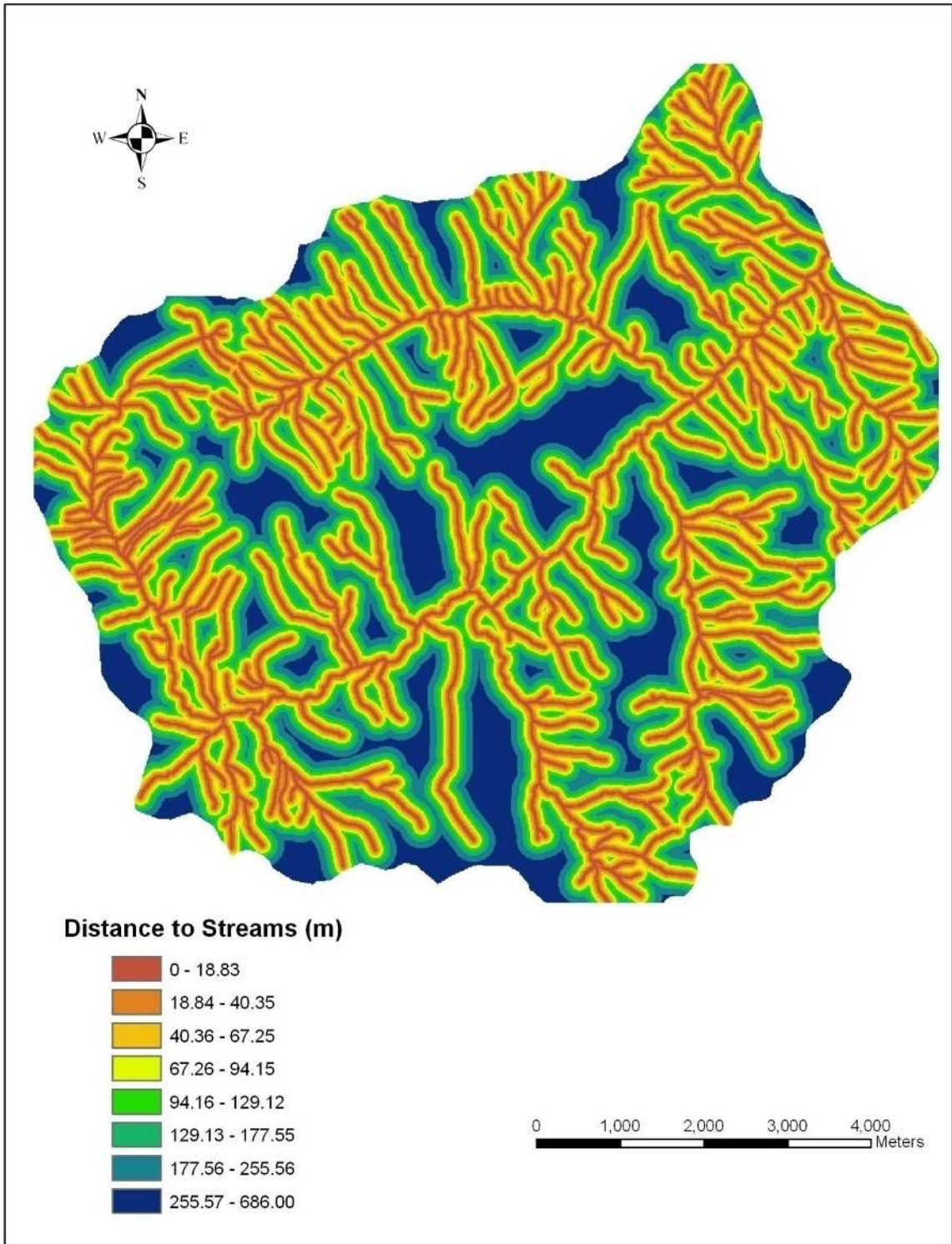
### ***Geology***

The nature of the underlying bedrock or unconsolidated debris strongly influences landslide occurrence as variations in the structure and lithology can lead to differences in material strength, weathering and permeability (Dai and Lee 2001, Gardner 2006).

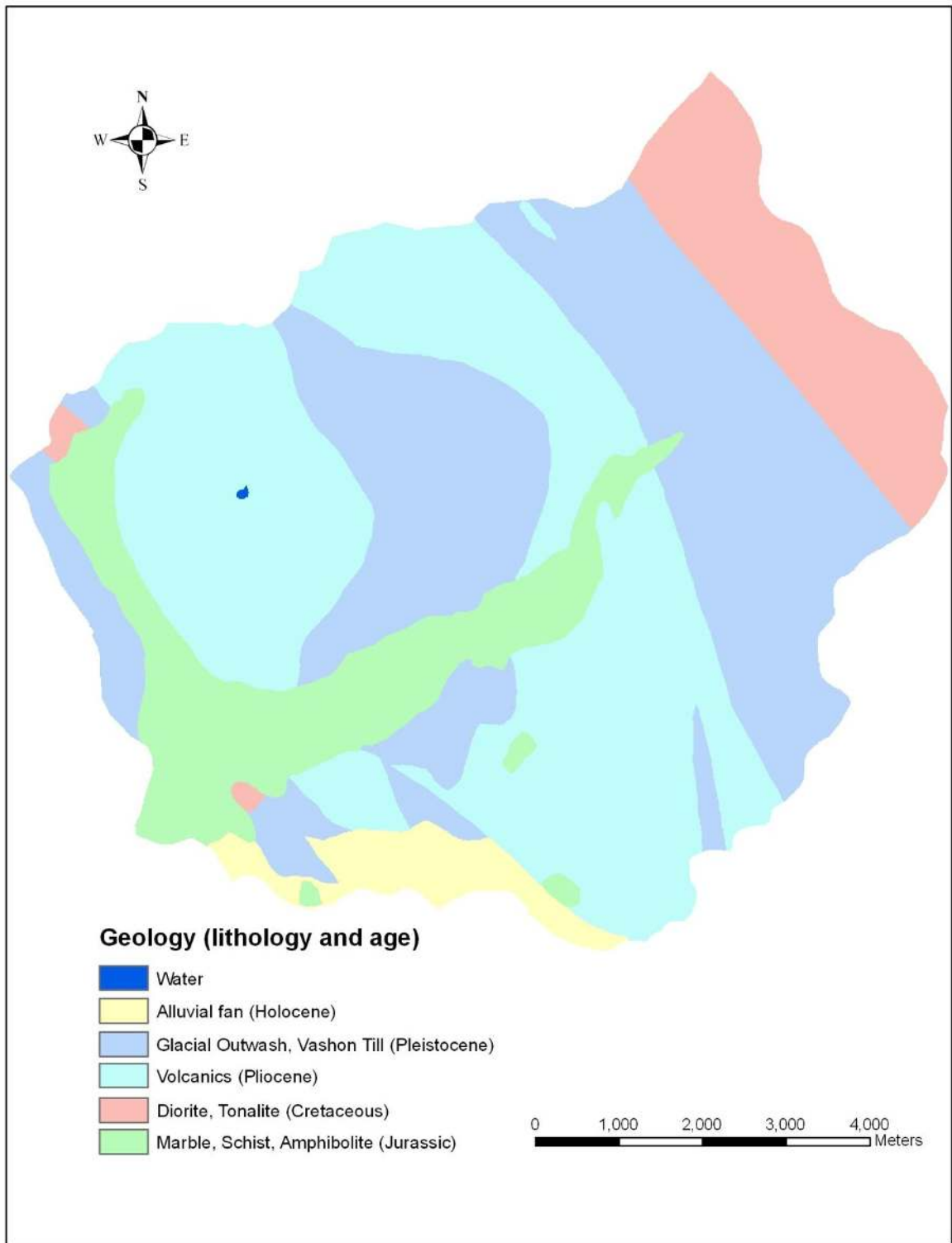
Information regarding underlying geology of the area was obtained via the Washington Division of Geology and Earth Resources' digital geologic map of Washington State (WADGER staff, 2005). This data set included polygon information defining the extent, age, lithology, and geologic name of all units. While this data set also included known fault locations, lineaments were not incorporated as only one fault was found in the western portions of the study area. Approximately twenty four different geologic units were mapped within the Finney Creek subwatershed. These were then grouped and reclassified by age and commonality in formation type, with the purpose of narrowing down terms while maintaining distinctions in geologic properties (Figure 11). Units were reclassified as one of five possible geology types, each with its own age association: 1) alluvial fans [Holocene], 2) glacial outwash and Vashon till [Pleistocene], 3) diorite and tonalite [Cretaceous], 4) marble, schist, and amphibolite [Jurassic], 5) volcanics [Pliocene].



**Figure 9. Euclidian distance to roads within the Upper Finney Creek subwatershed.**



**Figure 10. Euclidian distance to streams within the Upper Finney Creek subwatershed.**



**Figure 11. Geology of the Upper Finney Creek subwatershed, simplified from WADGER (2005).**

### ***Vegetation***

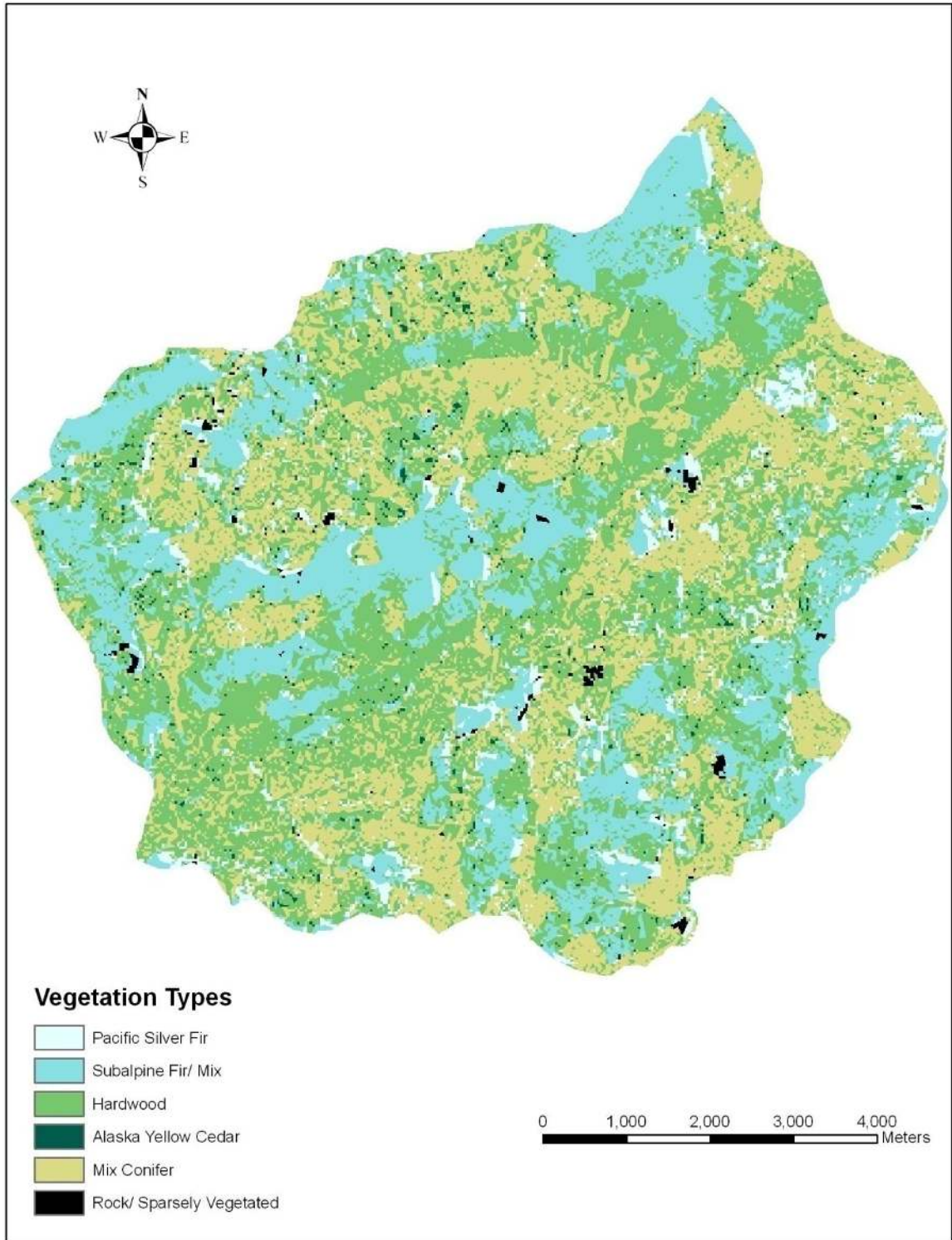
Vegetation has the potential to affect slope conditions, as changes in the size and abundance of forest and ground cover result in different soil binding capabilities of the root structure systems. This is particularly important in logged areas, as the soil-binding power of the root system may reach a minimum years after logging and planting have occurred (Aniya, 1985).

Vegetation data were acquired directly from MBSNF personnel in the form of vegetation input layers created for the FARSITE fire area simulation model. This polygon coverage was originally derived from LANDSAT satellite imagery and depicts the spatial distribution of tree species groupings interpreted by Forest Service personnel. Stand coverage within the study area consisted of six possible types: 1) Pacific Silver Fir, 2) Subalpine Fir/mix, 3) Hardwood, 4) Alaska Yellow Cedar, 5) Mixed Conifer, and 6) rock/sparsely vegetated (Figure 12). While no assumptions are made regarding stand age, vegetation types are intended to generally reflect tree size and coverage, and potential differences in soil binding abilities of these stands. For instance, Fir and Cedar stands are more likely to be larger with more coverage and root structures than Subalpine Fir or sparsely vegetated areas.

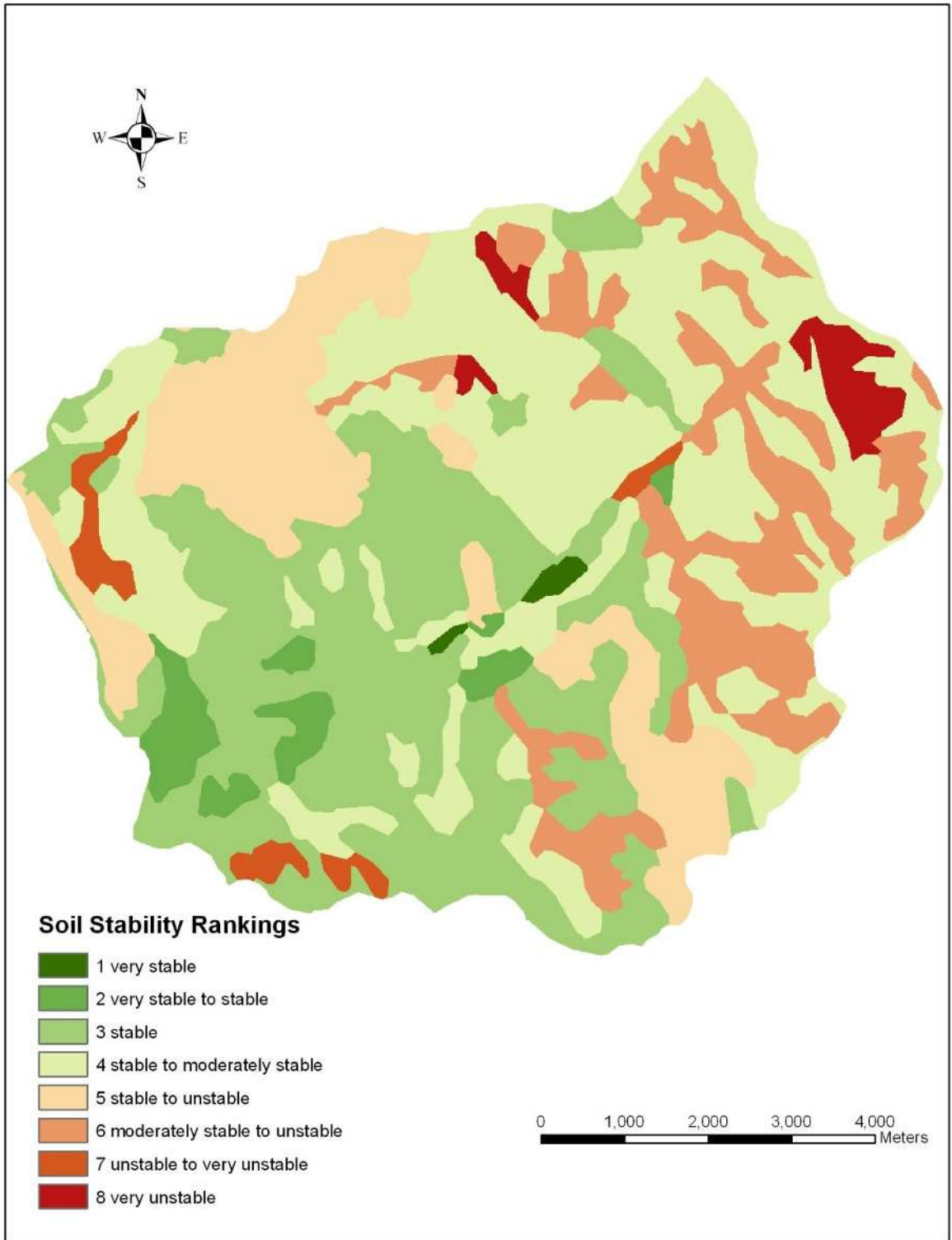
### ***Soil***

Soil properties, such as material type, texture, thickness, and permeability, have the potential to influence susceptibility by altering a slope's relative strength. Poor drainage, combined with thin soils exhibiting poor permeability, will likely decrease a slope's strength (Lee and Min, 2001). Digital soil information for this study was taken from the Mount Baker-Snoqualmie National Forest online GIS database (USDA Forest Service, 2008). This Forest-wide coverage incorporates soil polygons mapped and classified

according to their suitable uses and disturbance limits. These include stability and erosion potential, susceptibility to logging impacts, and seeding and regeneration probabilities. While multiple attributes associated with this soil coverage were related to slope stability (maximum soil depth, permeability, etc.), the Natural Stability Rating attribute was thought to be the most complete and comprehensive and therefore initially selected as the representative attribute for soil mapping. This rating, referred to as the NS rating, ranges from 'very unstable' to 'very stable' and consists of eight soil stability and erosion potential categories heuristically determined by Forest Service personnel (USDAFS, 2008, Figure 13).



**Figure 12. Vegetation types within the Upper Finney Creek subwatershed (Data from MBSNF).**



**Figure 13. USFS soil stability rankings for the Upper Finney Creek subwatershed (Data from USDAFS 2008).**



### 3.3 Determination of Membership Functions

Membership functions graphically represent a series of fuzzy sets that plot the degree to which input values belong to a particular category of a variable. Each fuzzy set within a membership function is composed of two values: a truth value from 0 to 1 inclusive (typically represented along the y axis) and an input value of the variable (with the numerical domain of inputs represented along the x axis). A membership function, representing each particular category of the variable, is defined by the simple plotting of these multiple fuzzy sets. Thus the variable Distance, for example, may have the four membership functions representing the categories “zero” "close" "medium" or "far" over the domain 0 to 30 yards (Figure 14). Such categories are often referred to as terms, with the membership function showing the degree to which a variable is true. For the term “close,” it is true that a distance of 5 yards is “close” to a degree of 1. Thus, the truth value associated with the statement “Distance Is Close” is 1 for a distance of 5 yards.

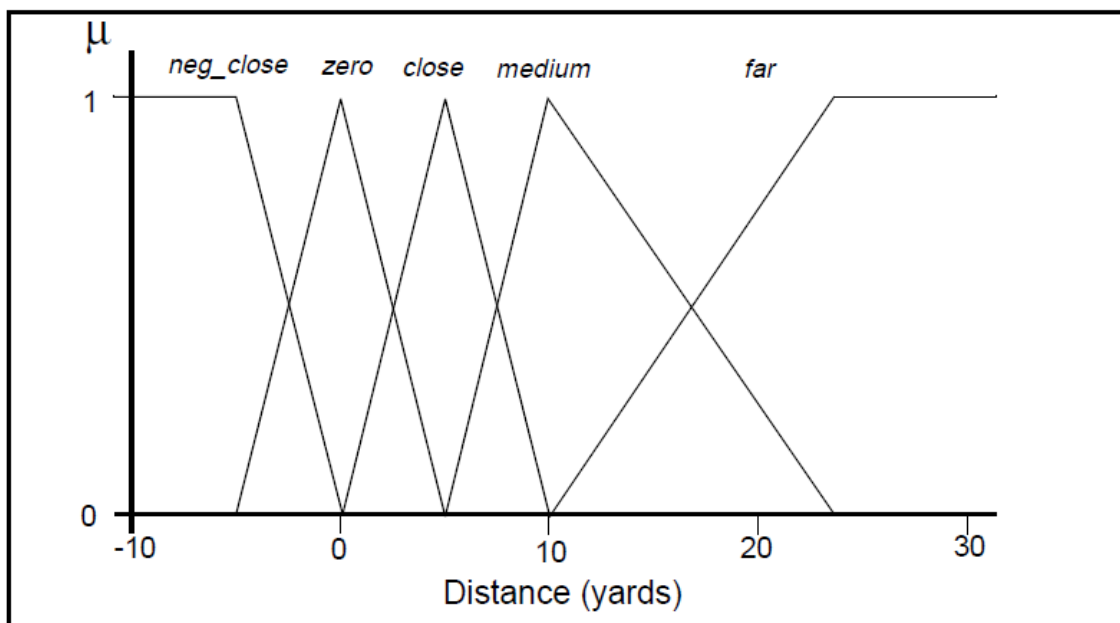


Figure 14. Membership Functions for “Distance” Example, adapted from FuzzyTech®

In designing the membership functions for the landslide susceptibility model, each distinct fuzzy set is determined by the relationship between landslide occurrence and the considered model variables. Thus, the fuzzy sets are calculated by the strength of the correlation between the landslide inventory and the variables. This relationship is essentially established by quantifying different landslide concentrations within various bin ranges for each variable. To accomplish this task, landslide ratios were utilized as a measure of landslide concentrations. The landslide ratio is simply a ratio between the occurrence and absence of landslides in a given area. This quotient relates the percent of the land area for the variable in question (say for instance 20% of the total area is classified as “steep”) to the percent of landslides occurring within that area. (Thus, if 20% of all the total landslides occurred within the “steep” land area, the ratio would be 1.)

In order to set up membership functions, preliminary analysis of the parameters was performed in GIS. All input layers were first clipped to the Upper Finney Creek subwatershed and rasterized. The mapped landslide raster set was reclassified with cells given a value of 0 (if landslide not present) or 1 (landslide present) for ease in calculating the landslide ratio for the various terrain parameters. Layers with nominal information (vegetation, soil, and geology) were re-coded numerically, giving a corresponding numerical value for each linguistic term of the variable. All input layers were then classified into 8 bins (or classes) using a quantile classification, where each bin contains an equal number of pixel cells. The number of classes (8) was chosen because it allows for ample categories of linguistic terms and prevents information from being lost, while still being manageable for visual depiction and naming schemes. For example, 20 classes for a variable like slope would make it extremely difficult to distinguish these on a map,

in addition to being troublesome to associate names with each class. Conversely, downsizing to only 2 classes of slope may improve communicative powers (mapping and easy naming of 'low' and 'high' slope), but such few groupings reveals less about the data's distribution (as features with widely different values can be lumped into the same class) and greatly diminishes the statistical significance of the analysis. Quantile classification was chosen over other classification methods in order to best represent the ranges of the data. Attempts were first made to use the equal interval method, but this approach resulted in significantly high kurtosis and a largely disproportionate amount of cells within the value ranges. For example, dividing the curvature values in equal ranges results in 97% of the cells occurring within the single range of -7 to 15.

Once all layers were classified and rasterized, the spatial relationships between landslide location and landslide-related factor were analyzed. For each factor, the following process was executed. First, the total number of pixels contained in each bin was counted (as seen in column D of Table 1). This was then divided by the total number of pixels in the study area in order to get a percentage of the area (column E). Next, the landslide pixels occurring in each class was calculated using the reclassified landslide raster (column F). This was divided by the total number of landslide pixels in the study area to get a percentage of landslide occurrences (column G). A landslide frequency ratio between the occurrence and absence of landslides in each cell was finally calculated (column H) by dividing the percentage of landslide occurrences by the percentage of the area. If the landslide ratio is greater than 1, the correlation between landslides and the factors is stronger. If the ratio is less than 1, the relationship between landslides and the factor is lower (Lee 2001). A ratio value of 1 would represent the variable having a

neutral effect on landslide occurrence. The calculated landslide ratio was then normalized between the minimum value and 1.00 to create the fuzzy truth value (column I). This was accomplished by dividing each frequency ratio by the largest frequency ratio value within the factor class. 0 values were not “forced” in the normalization process as was done in Lee 2007, as such a value may falsely indicate that that particular element or class of the parameter has no influence on landsliding.

**Table 1. Relationships between variables and fuzzy membership values.**

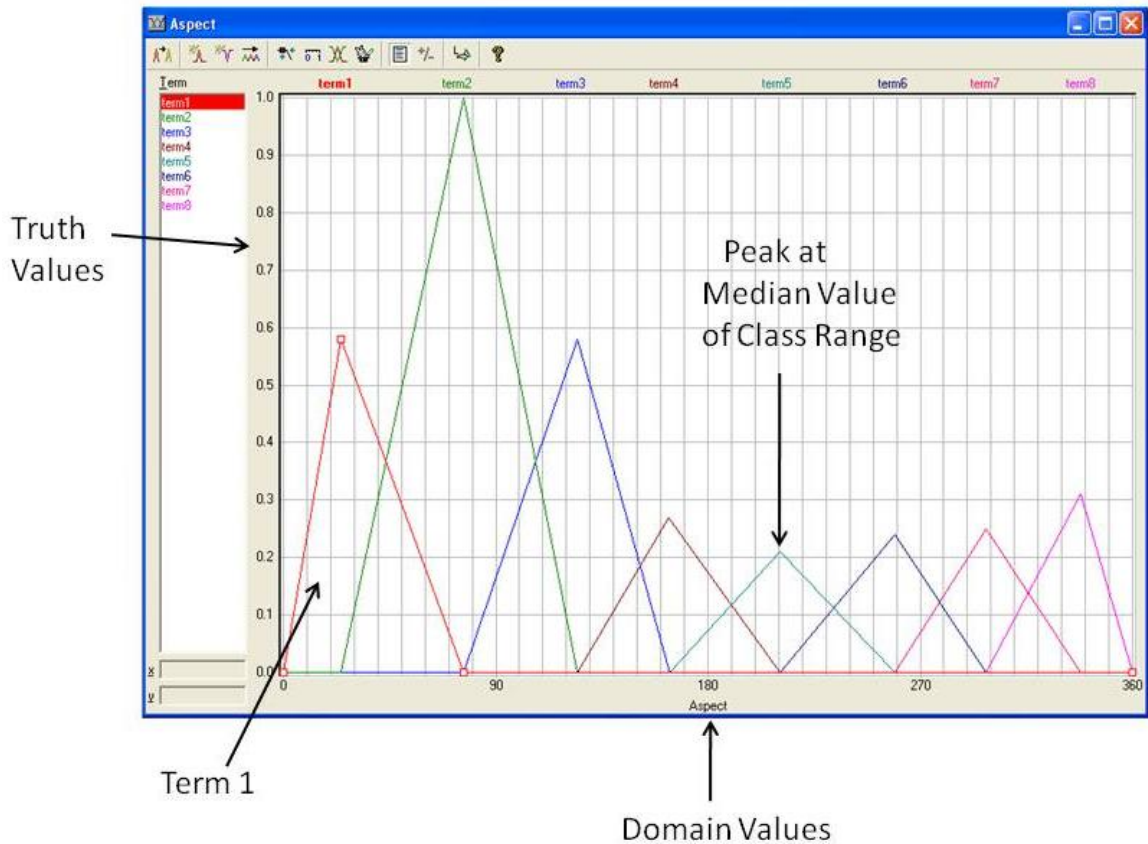
Factor (A)	Bin Ranges (B)	Class mid point (C)	No. of Pixels in range (D)	% of entire area (E)	No. of LS Pixels (F)	% of LS (G)	Frequency Ratio (H)	Truth Value (I)
<b>Aspect</b>	0- 49.8	24.4	86535	12.00	7881	16.42	1.37	0.58
	49.8- 103.4	76.6	88669	12.30	14041	29.26	2.38	1.00
	103.4- 145.7	124.5	89380	12.40	8190	17.07	1.38	0.58
	145.7- 182.3	163.9	90511	12.55	3861	8.05	0.64	0.27
	182.3- 238.7	210.5	88111	12.22	2911	6.07	0.50	0.21
	238.7- 279.6	259.2	86460	11.99	3349	6.98	0.58	0.24
	279.6- 316.3	297.9	88721	12.31	3525	7.35	0.60	0.25
	316.3- 360.0	338.1	85527	11.86	4228	8.81	0.74	0.31
<b>Curvature</b>	75.10 - -3.06	39.0	72096	10.24	7816	16.29	1.59	0.86
	-3.06- -1.65	-2.4	48910	6.95	3898	8.12	1.17	0.63
	-1.65- -0.94	-1.3	45007	6.39	3060	6.38	1.00	0.54
	-0.94- -0.24	-0.6	97252	13.82	5337	11.12	0.81	0.43
	-0.24- 0.47	0.1	182495	25.93	8224	17.14	0.66	0.36
	0.47- 1.88	1.2	146819	20.86	8448	17.61	0.84	0.45
	1.88- 4.00	2.9	65366	9.29	5387	11.23	1.21	0.65
	4.00- 105.7	54.9	45969	6.53	5816	12.12	1.86	1.00
<b>Elevation</b>	893.4- 1878.5	1385.9	89994	12.78	1811	3.77	0.30	0.18
	1878.5- 2298.5	2088.5	93253	13.25	2745	5.72	0.43	0.27
	2298.5- 2686.1	2492.3	89721	12.75	5502	11.47	0.90	0.56
	2686.1- 3041.4	2863.7	90173	12.81	7051	14.69	1.15	0.71
	3041.4- 3332.1	3186.7	87577	12.44	5278	11.00	0.88	0.55
	3332.1- 3622.8	3477.4	85384	12.13	7835	16.33	1.35	0.83
	3622.8- 3994.3	3808.5	82192	11.68	8327	17.35	1.49	0.92
	3994.3- 5027.9	4511.1	85620	12.16	9437	19.67	1.62	1.00
<b>Geology</b>	Holocene		22165	3.15	264	0.55	0.17	0.14
	Pleistocene		252653	35.89	17147	35.73	1.00	0.79
	Cretaceous		61084	8.68	1037	2.16	0.25	0.20
	Jurassic		94251	13.39	5923	12.34	0.92	0.73
	Pliocene		273612	38.87	23615	49.21	1.27	1.00

<b>Slope</b>	0- 12.90	6.5	86684	12.31	2955	6.16	0.50	0.19
	12.90- 18.77	15.8	85398	12.13	2900	6.04	0.50	0.19
	18.77- 22.87	20.8	90252	12.82	3175	6.62	0.52	0.19
	22.87- 26.39	24.6	88873	12.63	3784	7.89	0.62	0.23
	26.39- 30.21	28.3	92361	13.12	4726	9.85	0.75	0.28
	30.21- 34.31	32.3	85033	12.08	5762	12.01	0.99	0.37
	34.31- 40.18	37.2	88406	12.56	8734	18.20	1.45	0.54
	40.18- 75.07	57.6	86907	12.35	15950	33.24	2.69	1.00
<b>Soil (NS Rating)</b>	Very stable		2918	0.41	75	0.16	0.38	0.11
	Very stable- stable		24491	3.48	152	0.32	0.09	0.03
	Stable		212445	30.19	3805	7.93	0.26	0.07
	Stable-mod stable		229098	32.55	10142	21.24	0.65	0.18
	Stable-unstable		109381	15.54	26460	55.14	3.55	1.00
	Mod unstable- unstable		96089	13.65	5119	10.67	0.78	0.22
	Unstable- very unstable		13996	1.99	682	1.42	0.71	0.20
	Very unstable		15365	2.18	1551	3.23	1.48	0.42
<b>Vegetation</b>	Pacific Silver Fir		38138	5.42	3708	7.73	1.43	0.61
	Subalpine Fir/mix		166473	23.65	14692	30.62	1.29	0.56
	Hardwood		274081	38.94	17026	35.48	0.91	0.39
	Yellow Cedar		7140	1.01	896	1.87	1.84	0.79
	Mix Conifer		214513	30.47	11099	23.13	0.76	0.33
	Rock/sparsely veg.		3569	0.51	565	1.18	2.32	1.00
<b>Dist. to Roads</b>	0- 29.58	14.8	86723	12.35	2620	5.51	0.45	0.16
	29.58- 66.56	48.1	88530	12.61	3106	6.53	0.52	0.19
	66.56- 118.34	92.5	102095	14.54	4032	8.48	0.58	0.21
	118.34- 177.51	147.9	95363	13.58	3970	8.35	0.61	0.22
	177.51- 251.47	214.5	89517	12.75	4331	9.11	0.71	0.26
	251.47- 362.41	306.9	81967	11.67	6959	14.64	1.25	0.45
	362.41- 599.08	480.8	79712	11.35	7820	16.45	1.45	0.52
	599.08- 1886.00	1242.5	78175	11.13	14693	30.91	2.78	1.00
<b>Dist. to Streams</b>	0- 18.83	9.4	81848	11.65	10542	22.10	1.90	1.00
	18.83- 40.35	29.6	99876	14.21	9988	20.94	1.47	0.78
	40.35- 67.26	53.8	102235	14.55	7841	16.44	1.13	0.60
	67.26- 94.16	80.7	82227	11.70	5098	10.69	0.91	0.48
	94.16- 129.13	111.6	86481	12.30	4745	9.95	0.81	0.43
	129.13- 177.55	153.3	88739	12.63	3846	8.06	0.64	0.34
	177.55- 255.57	216.6	81723	11.63	2896	6.07	0.52	0.28
	255.57- 686.00	470.8	79697	11.34	2742	5.75	0.51	0.27

After membership values were calculated, the membership functions were constructed in the fuzzy systems development software, FuzzyTech™. This software facilitates model construction, allows easy export in various programming languages, and integration with commercial software (Miles and Keefer 2009). Utilizing FuzzyTech™, the membership function of each input parameter was constructed using a basic triangular piece-wise linear function, as this is one of the simplest and most common mathematical definitions used in such applications (Miles and Keefer 2007) (Figure 15). Within the functions, the y-axis represents the truth value for each term of the variable and therefore ranges from 0 to 1. In every term, the peak of the function denotes the corresponding truth value. The x-axis represents the given range in values for each variable. For ordinal variables, the domain range of the 8 terms was established using the quantile classification bin ranges. The peak of each term was placed in the middle of the term's original bin range, with the bounding minimum and maximum values always starting at the middle of the adjacent terms. Thus, the first term in Aspect ranges from 0 to 76.56 degrees, with the peak at 24.4 as this is the median of the first quartile class range of 0 to 49.76. Term peaks were placed at the class midpoint to best represent the potentially large range in the element's values. In summary, each variable received 8 membership functions which are defined fuzzy sets (determined by the bin range midpoint and the normalized landslide ratio).

Nominal variables were structured with slight variations to the membership functions. For the geology, soils, and vegetation fuzzy sets, the number of membership functions was limited to the amount of terms associated with each parameter. For example, only 6 types of vegetation existed within the study area, so that parameter's

domain ranged from 0 to 7, allowing each class an equally spaced term boundary to accommodate for the categorical nature of the data. Truth values were still mapped at peak centers of each term in the same manner as ordinal terms. It can be noted that the assigning of each nominal category to term number is arbitrary and inconsequential, as the order of the nominal categories has no effect on calculating the truth values.



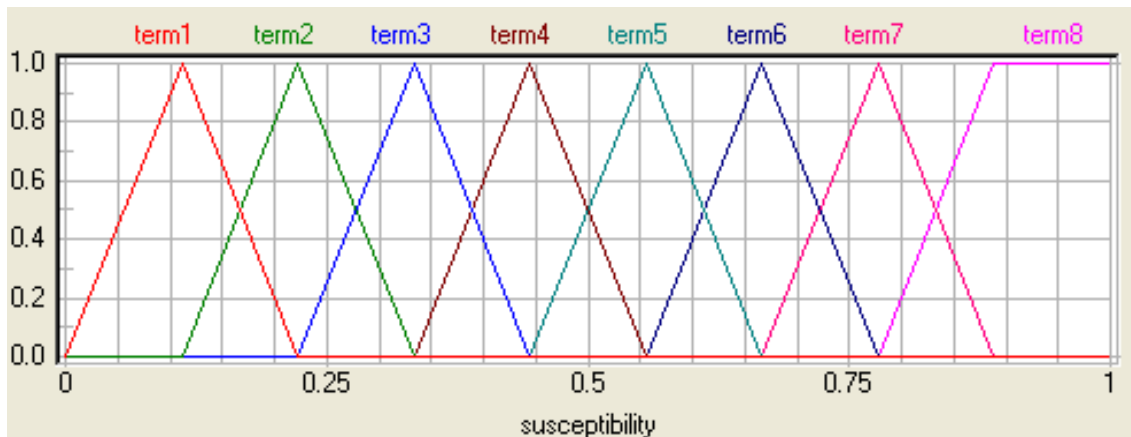
**Figure 15. Example of basic Fuzzy Membership structure.**

### ***3.4 Construction of Fuzzy Rules***

With the antecedent inputs already structured in the form of membership functions, an output function was constructed in FuzzyTech™ for use with fuzzy rules. The output consisted of one membership function to represent landslide susceptibility, with a numerical domain range of 0 to 1 (0 being lowest susceptibility and 1 being



highest). This final output function was divided up into 8 terms of equal shape and size for easy inference with the inputs, with each term representing a numerical range of susceptibility (Figure 16). With this structure, fuzzy rules could then be constructed that link the inputs (variables) to the output (value between 0 and 1 as a relative indicator of landslide susceptibility).



**Figure 16. Membership functions for landslide susceptibility.**

Rules for all possible input terms were elicited and structured in a rule block (Table 2). For each input term, a rule was built to relate it to the appropriate output term (i.e. degree of susceptibility) depending on the term's truth value. To do this, the input membership functions were ordered from 1 to 8 with respect to the truth value and then assigned to the output membership function of equal rank, which was ranked by relative susceptibility. Thus, the input membership function with the highest truth value was assigned to the output membership function with the highest susceptibility; the membership function with the second highest truth value assigned to the second highest susceptibility, and so on. A total of 75 rules were defined in order to produce output considering possible combinations of inputs.

As mentioned previously, more complex IF-THEN rules can be constructed by combining multiple membership functions via operators like AND or OR (Miles and Keefer 2007). This input aggregation is necessary as multiple factors act upon an area simultaneously. If for example, a grid cell exhibits high slope in combination with very unstable soil and close proximity to streams, its membership value could be higher compared with individual membership values of slope or soil type. This effect is referred to as “increasive” and could be calculated by fuzzy algebraic sum. Likewise, if the presence of a set of parameters has a “decreasive” effect, it can be calculated by fuzzy algebraic product (see Dewitte et al. 2006 for further explanation of these algebraic equations). Perhaps the most popular operator for rule aggregation is fuzzy gamma, which is defined as:

$$\mu_{\text{combination}} = (\text{Fuzzy algebraic sum})^{\lambda} * (\text{Fuzzy algebraic product})^{1-\lambda},$$

where  $\lambda$  is a chosen value between 0 and 1. This operator produces output values that ensure a flexible compromise between the “increasive” trends of fuzzy algebraic sum and the “decreasive” effects of fuzzy algebraic product (Champati ray et al. 2007). As such, the gamma operator was selected as the method for input rule aggregation. A gamma value of 0.975 was specifically used because it appeared the most often in previous works and routinely showed the highest prediction accuracy (Aksoy and Ercanoglu 2006, Lee 2007, Champati ray et al. 2007). While Lee (2007) also tested a range of other operators, only the one with the highest success rates (0.975) was employed for this study.

**Table 2. Fuzzy Rule Block with IF-THEN rules for each input.**

IF									THEN
Aspect	Curvature	Elevation	Geology	Soil Rating	Roads	Slope	Streams	Vegetation	Output
term1									term6
term2									term8
term3									term7
term4									term4
term5									term1
term6									term2
term7									term3
term8									term5
	term1								term7
	term2								term5
	term3								term4
	term4								term2
	term5								term1
	term6								term3
	term7								term6
	term8								term8
		term1							term1
		term2							term2
		term3							term4
		term4							term5
		term5							term3
		term6							term6
		term6							term7
		term8							term8
			Holocene						term4
			Pleistocene						term7
			Cretaceous						term5
			Jurassic						term6
			Pliocene						term8
				term1					term3
				term2					term1
				term3					term2
				term4					term4
				term5					term8
				term6					term6
				term7					term5
				term8					term7
						term1			term2
						term2			term1
						term3			term3
						term4			term4
						term5			term5
						term5			term6
						term7			term7
						term8			term8

IF									THEN
Aspect	Curvature	Elevation	Geology	Soil Rating	Roads	Slope	Streams	Vegetation	Output
								Pacific silver	<b>term6</b>
								subalpine firmix	<b>term5</b>
								hardwood	<b>term4</b>
								Alaska yellow	<b>term7</b>
								Mix conifer	<b>term3</b>
								Rock Sparse veg	<b>term8</b>
					term1				<b>term1</b>
					term2				<b>term2</b>
					term3				<b>term3</b>
					term4				<b>term4</b>
					term5				<b>term5</b>
					term6				<b>term6</b>
					term7				<b>term7</b>
					term8				<b>term8</b>
							term1		<b>term8</b>
							term2		<b>term7</b>
							term3		<b>term6</b>
							term4		<b>term5</b>
							term5		<b>term4</b>
							term6		<b>term3</b>
							term7		<b>term2</b>
							term8		<b>term1</b>

### 3.5 Model Integration with GIS

The fuzzy system was exported into Microsoft Visual Basic code to integrate it with ESRI's ArcGIS. The fuzzy system is compiled and exported as a single binary file (FINNEY.ftr) that is used by the FuzzyTech™ Runtime DLL ("Ftrun32.dll") for integrating fuzzy systems in Windows-based software. (These and other necessary files are further described in Table 3.) In Microsoft Visual Basic, a module can then be set up with the appropriate code to use the FuzzyTech runtime libraries to pass input data values of all cells in the raster extent to the model and then back to ArcGIS with the

corresponding output value (Figure 17). Model integration with ArcGIS was based on Miles and Keefer (2007). Within the ArcMap document, each original input variable raster for the study area was added and labeled systematically to correspond to the appropriate input names used in the code during model processing.

After completion of the steps outlined in the previous chapter, the model was run with the appropriate Finney Creek inputs: elevation, slope, aspect, curvature, geology, soil, vegetation, distance to roads, and distance to streams. A final landslide susceptibility map of the region was produced that represents numerical output for susceptibility. The resultant map expresses values ranging from 0 (lowest susceptibility) to 1 (highest susceptibility) with 8 equal interval classes corresponding to the output membership functions (as seen previously in figure 16). The spatial distribution of these susceptibility results can be seen in Figure 18. Visual overlay of the mapped landslide locations with the calculated outputs indicated a relatively strong spatial concurrence between the landslides and higher susceptibility regions (Figure 19). Such visual congruence suggests a relatively good model performance. In order to better assess the accuracy and reliability of the model, however, further evaluation of the results was performed.

**Table 3. Description of FuzzyTech files for integration with ArcGIS. Adapted from Miles and Keefer (2007).**

***FuzzyTech Runtime DLL Files***

Ftrun32.dll

The actual DLL file. Must be copied into ".../Windows/System32" folder and registered using regsvr32.exe.

Ftrun32.ini

Must be copied into ".../Windows" folder. A text file for modifying settings of the Runtime DLL. Instructions for use in "Ftrun32.hlp"

Ftrun32.hlp

Help file; typically installed in the same folder as "Ftrun32.dll". Double-click to open and read with Microsoft Help system.

Ftrun.bas

Visual Basic module file for use of "Ftrun32.dll" within Visual Basic or Visual Basic for Applications™ (VBA) code.

***MODEL Files For FuzzyTech Runtime DLL***

FINNEY.ftr

Fuzzy system (binary file) for use with "Ftrun32.dll." Any modifications to the fuzzy system require exporting a new .ftr file.

FINNEY.io

Text file describing input and output variables for accessing "FINNEY.ftr."

FINNEY.cls

Visual Basic class file for use of "Ftrun32.dll" within Visual Basic or Visual Basic for Applications™ (VBA) code.

```

Microsoft Visual Basic - Finney_CAMEL2.mxd - [Finney (Code)]
File Edit View Insert Format Debug Run Tools Add-Ins Window Help
Project - Project (General)
Normal (Normal.mxt)
Project (Finney_CAMEL2)
  ArcMap Objects
  Modules
    Finney
    ftrun32
    Functions
    StringParseUtil
  Class Modules
  References

Properties - Finney
Finney Module
  Alphabetic | Categorized
  (Name) Finney

'Get output raster suffix before i/o and calculations
Dim sSuffix As String
sSuffix = InputBox("Enter output filename suffix:")

'***OPEN INPUT RASTERS***
'Specifiy workspace objects
Dim pRWS As IRasterWorkspace2
Dim pWSF As IWorkspaceFactory
Set pWSF = New RasterWorkspaceFactory

'### q_diststreams ###
'Get handle to RasterLayer based on name
Dim pq_diststreamsRL As IRasterLayer
Dim strLayerName As String
strLayerName = "q_diststreams"
Set pq_diststreamsRL = GetLayer(strLayerName)

'Make sure the layer is valid
If Not CheckRasterLayer(pq_diststreamsRL, strLayerName) Then Err.Raise vbObjectError + 17

'Get filename and path from RasterLayer
Dim sq_diststreamsPath As String
Dim sq_diststreamsFileName As String
sq_diststreamsPath = FileDir(pq_diststreamsRL.FilePath)
sq_diststreamsFileName = GetFileName(pq_diststreamsRL.FilePath)

If Not pWSF.IsWorkspace(sq_diststreamsPath) Then Exit Sub
Set pRWS = pWSF.OpenFromFile(sq_diststreamsPath, 0)
Dim pq_diststreamsRDS As IRasterDataset
Set pq_diststreamsRDS = pRWS.OpenRasterDataset(sq_diststreamsFileName)

' Get RasterBand from the input raster and QI raster
' properties interface from input raster dataset
Dim pq_diststreamsBand As IRasterBand
Dim pq_diststreamsBandCol As IRasterBandCollection
Set pq_diststreamsBandCol = pq_diststreamsRDS
Set pq_diststreamsBand = pq_diststreamsBandCol.Item(0)
Dim pq_diststreamsRasProps As IRasterProps
Set pq_diststreamsRasProps = pq_diststreamsBand

' Create a default raster from input raster dataset
Dim pq_diststreamsRaster As IRaster
Set pq_diststreamsRaster = pq_diststreamsRDS.CreateDefaultRaster

'Use q_diststreams raster properties as the basis of output rasters and analysis FOR loop
'!!!Probably want to eventually change this to use the smallest height and width of input rasters
Dim pInputRasProps As IRasterProps
Set pInputRasProps = pq_diststreamsRasProps

' Create a DblPnt to hold the PixelBlock size
'!!!pSizePnt is used by all subsequent input and output rasters!!!
Dim pSizePnt As IPnt
Set pSizePnt = New DblPnt
pSizePnt.SetCoords pInputRasProps.Width, pInputRasProps.Height

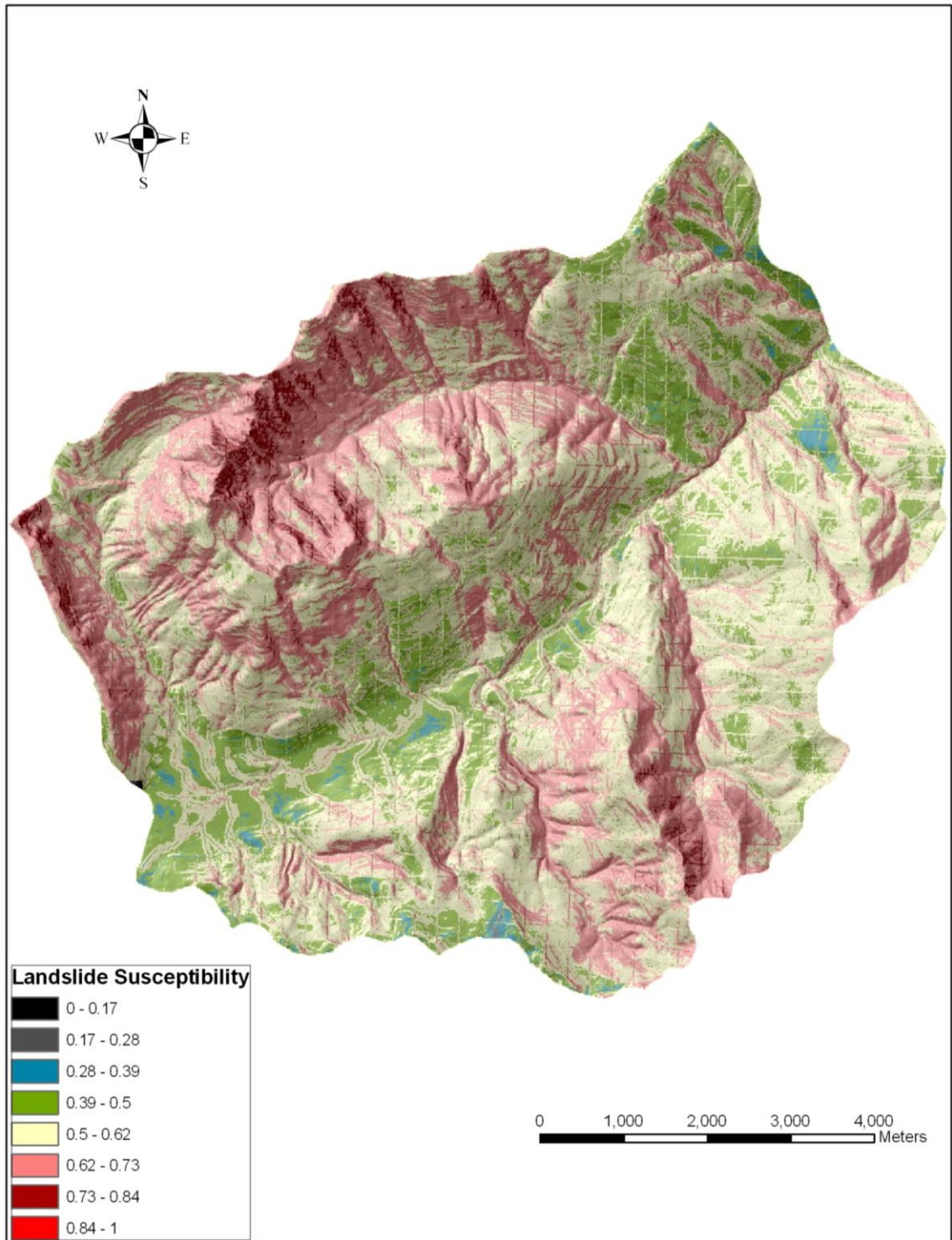
' QI RawPixel interface for input
Dim pq_diststreamsRawPixel As IRawPixels
Set pq_diststreamsRawPixel = pq_diststreamsBand

' Creates PixelBlock of input with defined size
Dim pq_diststreamsBlock As IPixelBlock3
Set pq_diststreamsBlock = pq_diststreamsRawPixel.CreatePixelBlock(pSizePnt)

' Read input PixelBlock

```

Figure 17. Example segment of Microsoft Visual Basic Code used for ArcGIS integration.



**Figure 18. Final landslide susceptibility outputs combined with a hillshade of the Upper Finney Creek subwatershed.**



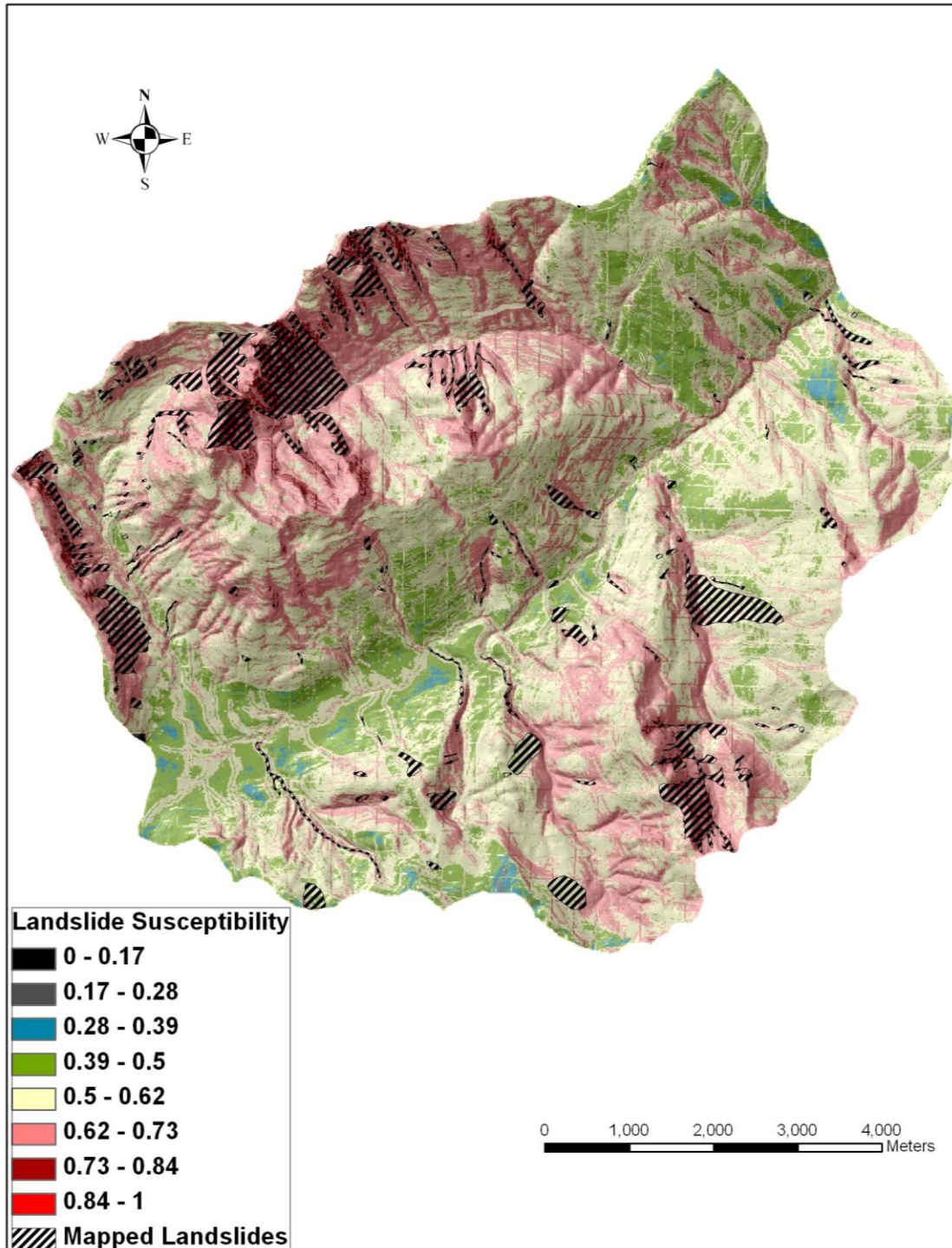


Figure 19. Landslide susceptibility (with hillshade) and mapped landslides within the Upper Finney Creek subwatershed.

### ***3.6 Model Evaluation***

To execute the evaluation, a prediction rate curve was constructed for area-under-the-curve (AUC) analysis. AUC is a measure of model performance (Miles and Keefer, 2008) where a value of 0.5 indicates model performance no better than randomness and a value of 1.0 represents perfect performance. AUC analysis compares susceptibility classes and actual landslide occurrence. AUC analysis (figure 21) calculates the cumulative percentage of landslides pixels in the sample (y- axis) with respect to susceptibility classes (expressed as portion of the study area above a given susceptibility value, from higher to lower along the x- axis) (Remondo et al. 2003). The larger the area under the curve and the steeper the curve, the greater the predictive performance as more landslides are occurring in areas mapped with the highest susceptibility.

Several steps were taken to complete the AUC analysis. First, the susceptibility map was reclassified into 50 equal intervals between the minimum and maximum output values. The number of landslide pixels falling within each area was then summed. This can be represented using a histogram showing these 50 predicted susceptibility bins vs. the number of landslide pixels as in Figure 20. For the AUC plot, the number of pixels in each interval of predicted values is plotted as a proportion of the total study area (x- axis). These values are then plotted against the proportion of landslide pixels falling within those zones (y-axis). The area under the curve for the model was calculated to be 0.76 (Figure 21), indicating reasonable predictive capabilities that are comparable to other landslide susceptibility models (Miles and Keefer 2008, Lee 2007).

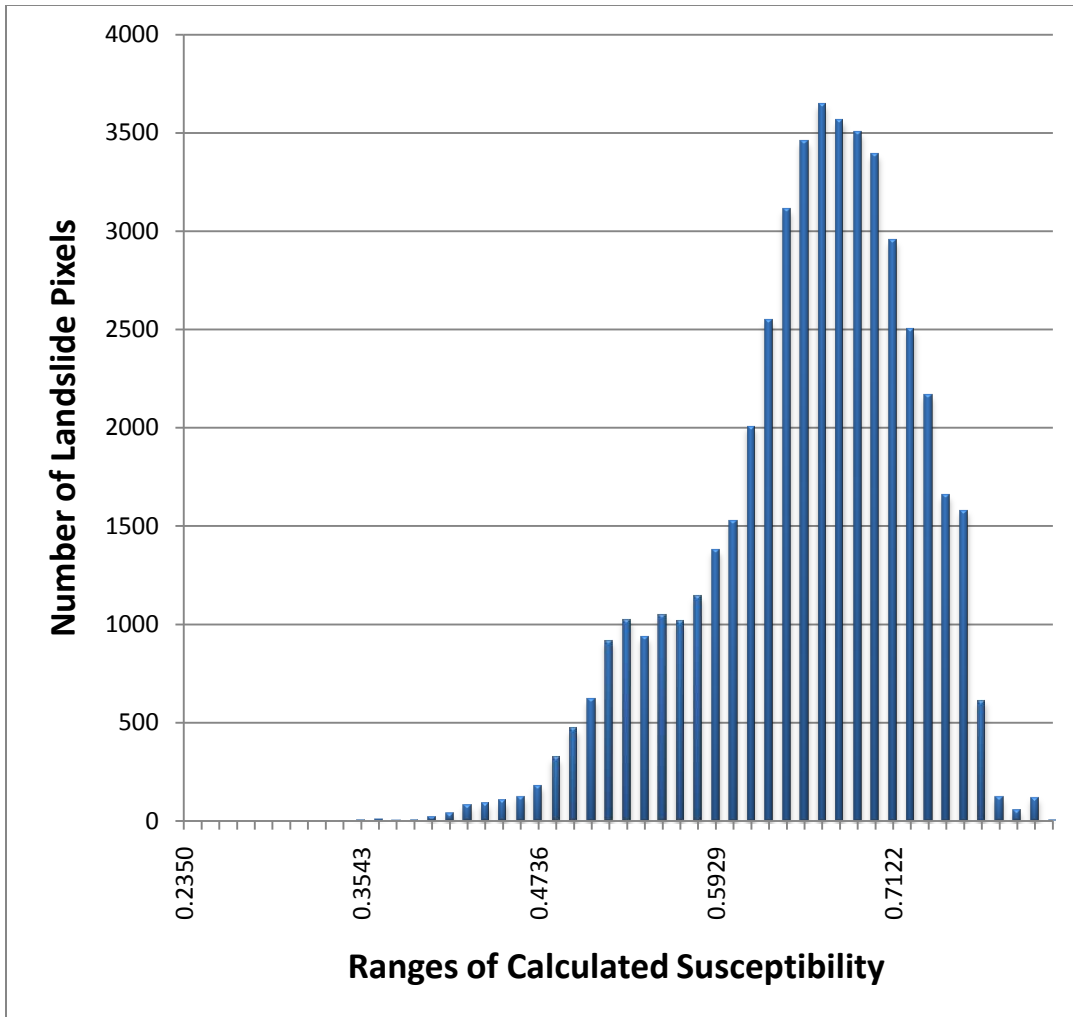
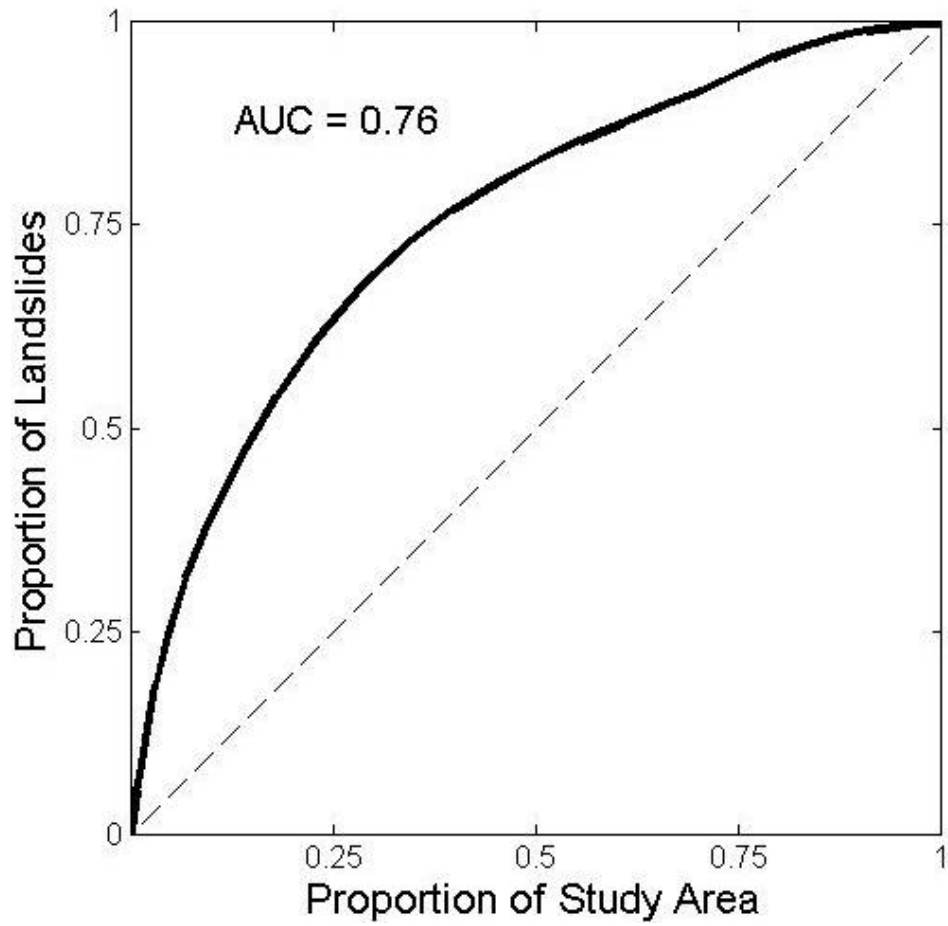


Figure 20. Histogram of mapped landslide pixels occurring within 50 susceptibility bins.



**Figure 21. Area Under the Curve (AUC) chart representing model performance for application to the Upper Finney Creek region.**

## Chapter 4: Discussion

Previous chapters have described the model development, application, and evaluation. Further discussion, however, is needed to understand how such information may best be used within current USFS' decision processes related to roads. In order to meet this objective, it is important to appraise what information can be gained from the model, as well as model limitations. This chapter thus begins with a discussion of model limitations and sources of error. The subsequent section includes observations of model results and discussion of the utility and implications of these results from a management perspective. Lastly, current USFS road policy and procedures are reviewed and recommendations made for model use within this context.

### ***4.1 Model Limitations and Sources of Error***

With AUC evaluation showing model results comparable to similar studies, reasonable confidence levels can be seen in the model's predictive abilities. Like any model, however, certain inherent limitations and sources of error exist and should not be overlooked. One such drawback is that that model is data-driven and relies on other sources for landslide mapping. Given the fact that landslides are a non-static phenomenon, the model assumes the record of mass wasting events has captured an adequate representation of the temporal and spatial variability in the region. Because the model is dependent on landslide locations to determine membership functions of variables, inaccuracies in landslide mapping will directly affect the reliability of the modeling processes. Due to the large number of slide features throughout the region, it is possible there are mapping errors in the WA DNR landslide database used for this study.

Any improvements made to mapping accuracy will only help the model's representation of the physical conditions present.

Another potential for model uncertainty is the level of detail related to DEM-derived input information. Several input factors (slope, aspect, elevation, curvature) are obtained directly from the DEM raster. Thus the resolution of the DEM will directly affect the precision of these input layers. A 10-meter DEM was used for this study as it was the best resolution available. If more precise elevation data (such as 3 meter DEM or LIDAR data) are obtainable for use, improvements will likely be seen in the DEM-related input factors.

One fundamental limitation with the outputs of this model is the lack of temporal information associated with landslide occurrence. While model outputs signify where landslides are likely to occur, the frequency with which they occur over time is not addressed. This is primarily due to the complexities and uncertainties involved in determining the probabilistic component of such assessment. Inclusion of information identifying the causes, triggering factors, and historic rate of incidence would theoretically enable the forecasting of both where and when landslides will occur over time. At present though, no assumptions can be made about probabilities of future landslide events.

Additionally, the model does not predict the type of landslide event, nor the failure's size or length of run out. As a result of many types of landslides being incorporated from the WA DNR dataset, no distinctions are made in the model outputs between types of landslides such as shallow-rapid, deep-seated, and debris slides. While the model output indicates where failure is likely to originate, the length of run out for

events such as debris flows are not predicted, as this would depend on topographic morphology as well as flow, velocity, and entrainment zones.

Like most other empirical models, this work is not immune to the effects of statistical outliers. While mapping results and simple distance queries show many landslides occur in proximal distance to the road networks, the size and distribution of these features may act as a possible source for discrepancy between model inputs and such “observable” relationships. According to the frequency ratios and subsequent truth values for distance to road networks, landslide pixels proportionally increase with increased distance from roads. While this appears to go against the visible pattern of more failures close to roads, it is likely due to a few large “outlier” landslide features located in the western portion of the study area. These include several large landslides to the north and east of Gee Point where no roads are present (Figure 22). As a result, the large slides increase the percentage of landslide pixels occurring far from roads.

#### ***4.2 Case Study Observations: What can be learned from model results***

While keeping in mind the possible shortcomings related to output generation, it is possible to make observations regarding the spatial relationships of the data. One of the most relevant of these is the link between mapped landslide susceptibility and roads. By overlaying the Forest Service road layer on top of a semi-transparent susceptibility map and hill shade, we are able to see which road segments are located in steep topography and/or areas of high susceptibility (Figure 22). Such mapping allows for easy identification and delineation of road segments that may pose future problems. For instance, roads like FS 1700 located along flat, low elevation flood plains appeared to pose less risk to slope failure than compared with higher elevation switchback roads like

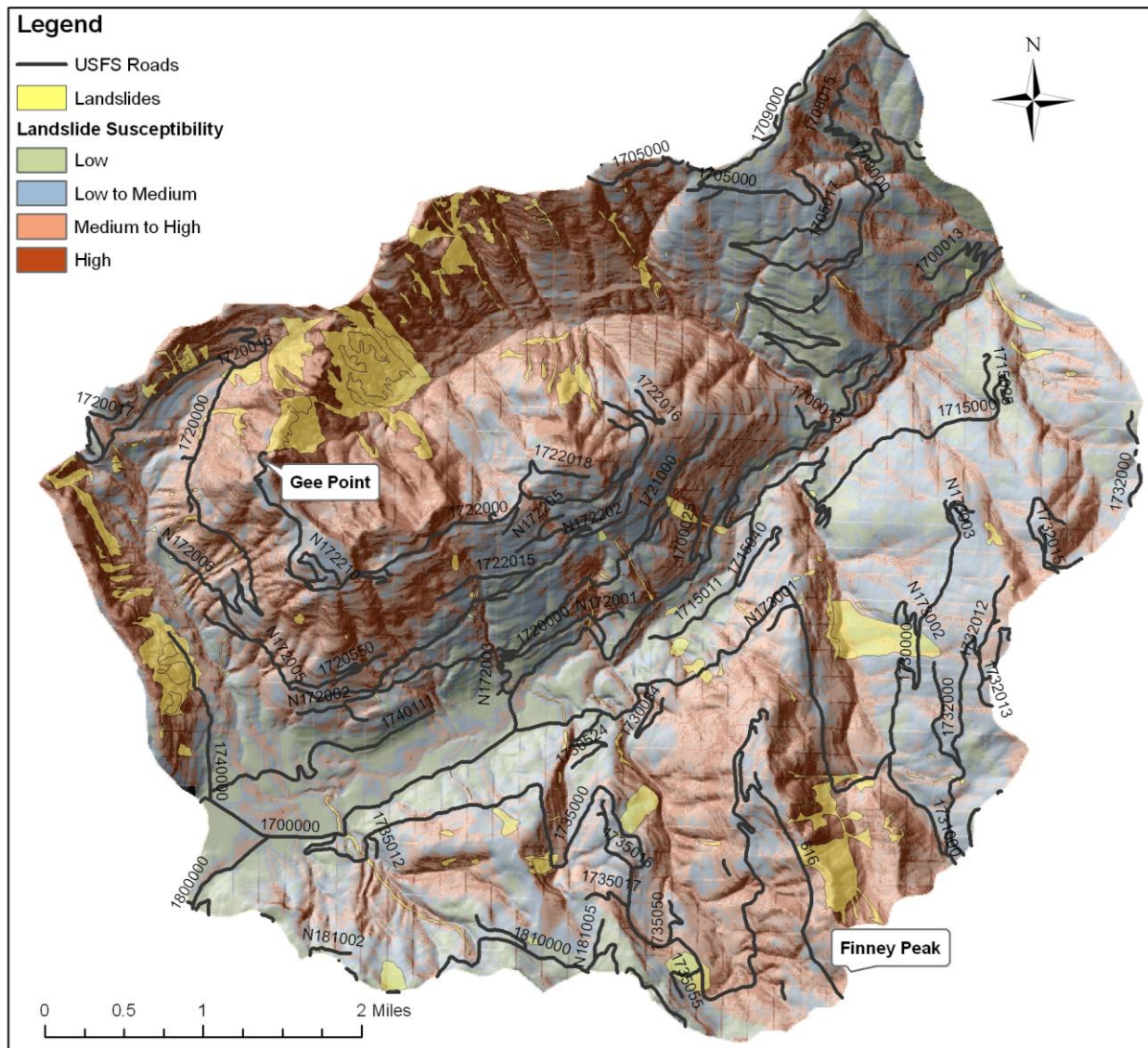
those located near Gee Point (FS 1720, 1722, etc.). Simple querying also allows for more regional road assessment, as one can query the total number of road segments occurring within each susceptibility zone. This would allow a manager to say a certain percentage of roads within the given area can be classified as “high susceptibility,” for example.

The ability to delineate roads located within areas susceptible to landslides is directly related to enhanced economic forecasting for the USFS road network. When dealing with roads in steep terrain, managers are constantly balancing budget and liability concerns with an interrelated and complex set of environmental factors (Allison and Tait, 2000). Identifying unstable, high risk roads allows for setting geographical priorities and targeted resources. Rather than spending portions of the finite budget on long-term upkeep of roads that are likely to fail, decommissioning or similar strategies may then become a preferred management option. Decommissioning can encompass several levels of access, ranging from gate closure to complete removal of the road and re-contouring the slope.

Identifying susceptible areas can also support the evaluation of past road-related decisions. For sites where previous decommissioning has occurred, susceptibility mapping may help confirm (or refute) closure actions. For example, multiple roads within the Finney Creek area have been closed in recent years as part of the MBSNF’s efforts to reduce existing road mileage. In areas near Gee Point, roads that traversed the south flanking slopes above Gee Creek were decommissioned and permanently removed from the road inventory (Figure 22). The distribution of high landslide susceptibility values in this region provides further support that these roads were potentially prone to future stability problems.



Another additionally potential useful aspect of landslide susceptibility mapping is improved planning and management of road drainage. Assessing the likelihood of failure events at stream crossing locations (Figure 23) allows managing personnel to more accurately plan appropriate drainage measures. Drainage issues commonly encountered include determination of culvert size and placement for both new and replacement culverts. A significant percentage of the MBS road maintenance fund is allocated to cleaning, repair, and replacement of the forest's 40,000 culverts (USFS, 1998). If a high potential exists for failure on a slope above the road's stream crossing, then a wider culvert may be more appropriate to accommodate the large flow (debris and water) in the event of slope failure. Such preventative measures have been identified by USFS personnel as an important means of avoiding costly blow-outs of culverts, which may damage or destroy a road segment.



**Figure 22. Map showing landslide susceptibility and locations of USFS road segments within the Upper Finney Creek subwatershed.**

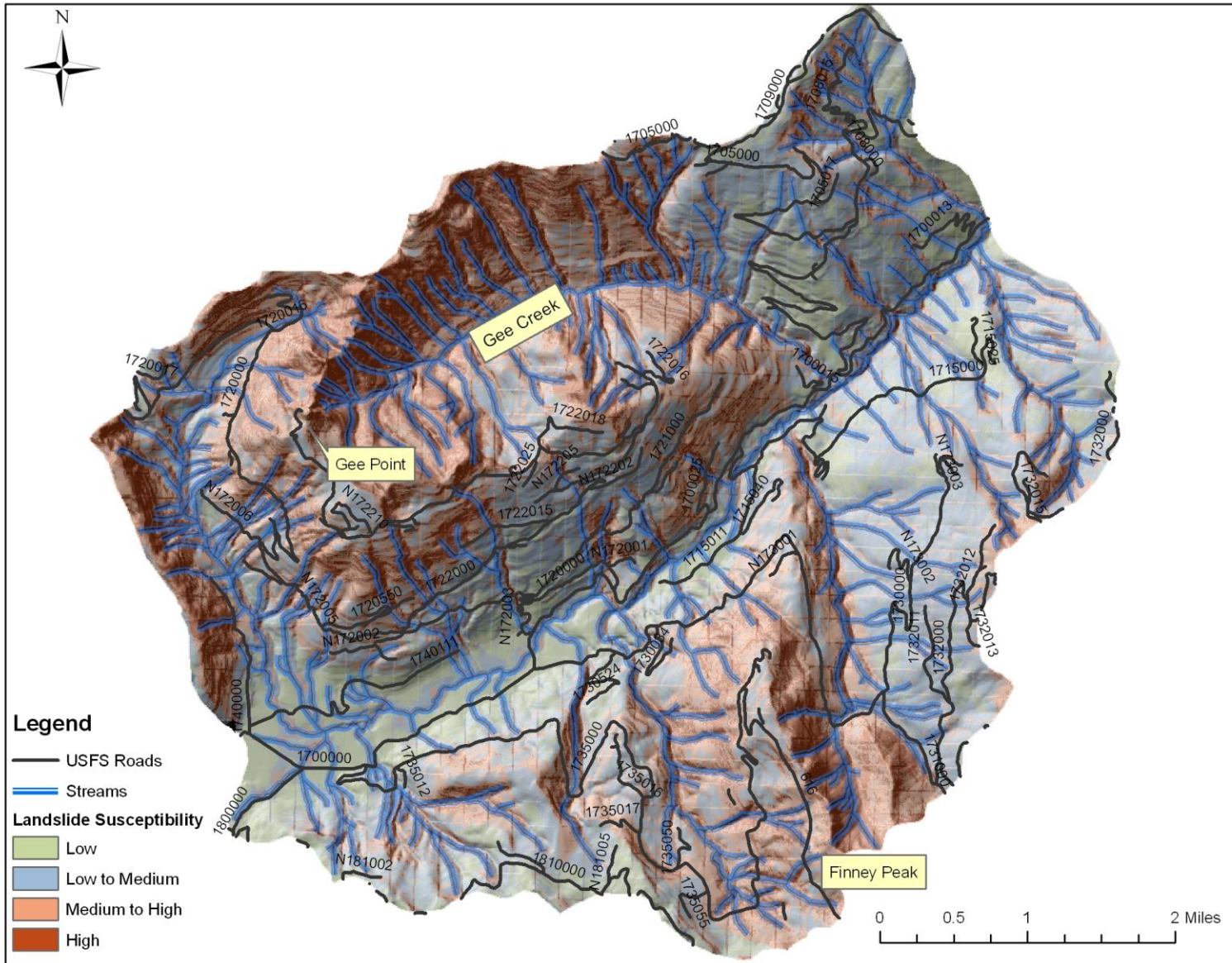


Figure 23. Map showing landslide susceptibility and stream crossings within the Upper Finney Creek subwatershed.

### ***4.3 Model Applications within current USFS practices***

As shown in previous sections, a range of specific and practical information can be garnered from model results. This information can, and arguably should be, incorporated into current practices for road-related decision development. Several practices and tools are presently in place for facilitating road management decisions in the country's national forests, including the Roads Maintenance Management System and Roads Analyses Procedures.

#### **4.3.1 Road Maintenance Management System**

One of the tools currently employed by the USFS for road management is the Road Maintenance Management System (RMMS). The objective of the RMMS is to “maintain the forest transportation system to support resource programs’ to protect the investment, environment, and adjacent resources; to meet applicable air and water quality standards; and to provide for user economy and convenience” (USDAFS, 1995). The RMMS assigns levels of maintenance to roads in attempts to address concerns over how to identify and manage critical roads, as well as managing non-critical roads. These levels are based on criteria considering adjacent resources, season for use, volume and type of traffic, and road operation and management strategies (Grace and Clinton, 2007). Five levels of maintenance are used:

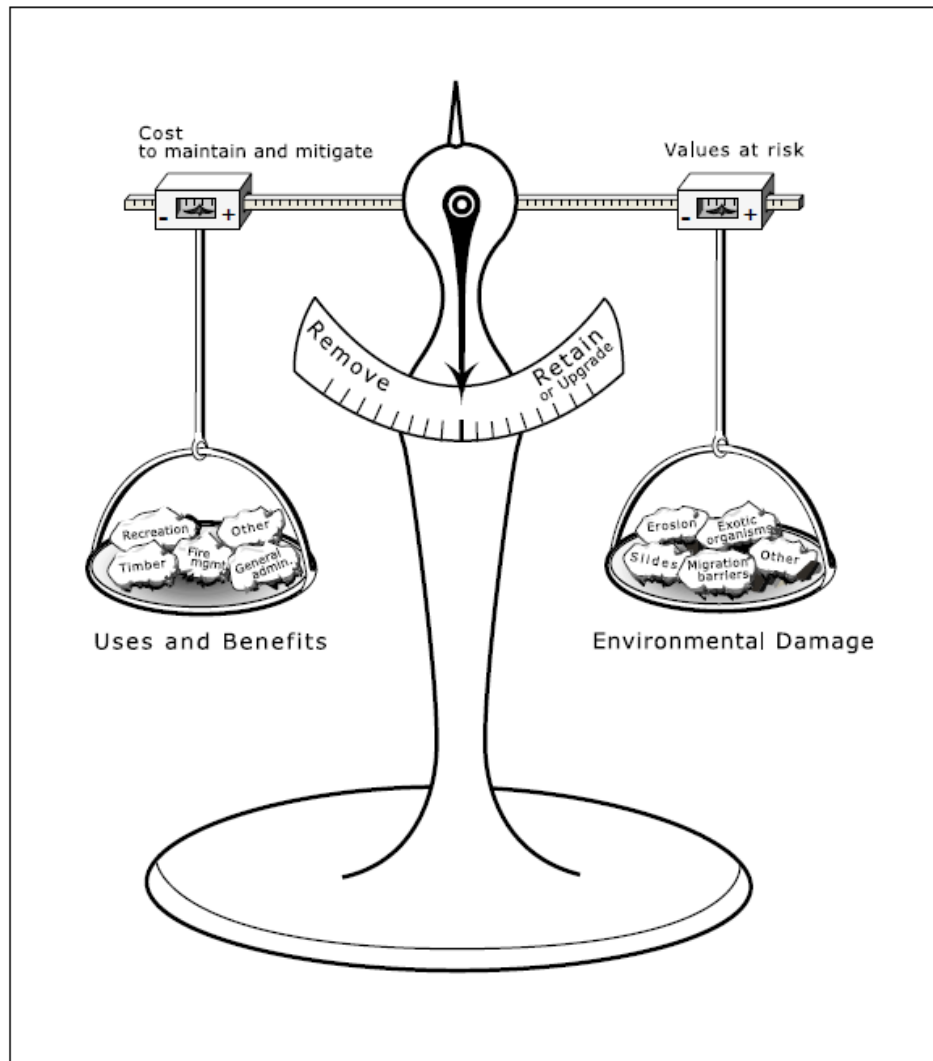
- Level 1: Intermittent service roads of any type that are closed to vehicular traffic and receiving custodial maintenance (storage).
- Level 2: Roads open for minor use by high-clearance vehicles
- Level 3: Roads open and maintained for travel by passenger car. Typically single lane.
- Level 4: Roads that provide moderate convenience and comfort. Typically double lane and aggregate surface.
- Level 5: Roads that are typically double-lane and paved, with a high degree of convenience and comfort.

The RMMS helps identify roads that are non-essential for both USFS forest management and public recreation access, as these are often closed off in storage and classified as Level 1. Because maintenance is typically less rigorous and frequent on these unneeded roads, they may have the greatest environmental impacts and the potential to cause mass failures (Grace and Clinton, 2007). Treatment is necessary to prevent such impacts, as weather conditions and steep terrain often preclude closing or abandoning roads without treatment (USDAFS 1998). The preferred solution for unneeded roads is typically decommissioning as it eliminates maintenance cost and the chance for degradation. While ideally all Level 1 roads could be decommissioned, the costs for such action far exceed annual forest maintenance budgets. Thus, only select roads may be eligible for decommissioning treatment. To assist with the prioritization of road treatment (i.e. which roads are the best candidates for decommissioning), the landslide susceptibility map may be used as an additional input into the decision process. For instance, Level 1 roads located in highly susceptible regions should logically be decommissioned before Level 1 roads that are less susceptible. Such prioritization is key to efficient use of maintenance funds and ensuring unneeded roads exhibiting the greatest risk to human and ecosystem health are removed.

#### **4.3.2 The “Roads Policy” and Roads Analysis Procedures**

Another set of practices that could benefit from landslide susceptibility modeling is the USFS Roads Policy (Forest Transportation System Management Policy previously introduced in Chapter 2). The Roads Policy (USDA Forest Service 2000) requires

interdisciplinary, science-based roads analyses for all new construction, reconstruction, and decommissioning activities. These analyses are designed to consider the ecological, social, and economic aspects of road management in an effort to balance risk and access issues with usage impacts (Figure 24). The product of the analyses includes documentation and maps for managers that identify opportunities, changes, and priorities for existing and future road systems.



**Figure 24. Depiction of components that are incorporated into the complex decision matrix of road management (from USDAFS 1999).**

Procedures for conducting these scalable analyses are outlined in “Roads Analysis: Informing Decisions about Managing the National Forest Transportation System” (USDA Forest Service 1999). In this report, six fundamental steps are described: 1) setting up the analysis (planning), 2) description of the situation, 3) issue identification, 4) benefits and risk analysis, 5) description of opportunities and setting priorities, and 6) reporting. For each of these steps, a set of possible road-related issues and questions are provided that can inform choices made about future road systems. The analysis team can determine the relevance of these questions though as the analysis is deliberately customized to local situations- landscape and site conditions coupled with public issues, forest plan land allocations, and management constraints (USDAFS 1999). Because the process is not specific to a geographic scale or a particular set of issues, current and relevant existing data and studies can be used directly or with minimal modification wherever possible (USDAFS 1999). Landslide susceptibility modeling is a key example of relevant data that can be easily incorporated into the roads analysis.

Specifically, information on landslide susceptibility is most appropriate for inclusion in step 4 of the analysis process: Assessing benefits, problems, and risks. In this step, a range of questions are suggested to assess the potential uses and socioeconomic gains (i.e. benefits), as well as likely future losses in environmental, social, and economic attributes (i.e. risks) if roads remain the same. These queries are meant to be comprehensive and thus cover a range in topics such as: Ecosystem Functions and Processes, Aquatic Riparian Zone and Water Quality, Terrestrial Wildlife, Economics, Commodity Production, Public Transportation, Recreation, Social Issues, etc. Assessment of mass wasting currently is placed within the ‘Aquatic, Riparian Zone, and

Water Quality' section where suggested questions include "how and where does mass wasting affect the road system, and how do roads affect mass wasting?" Model results will obviously help answer such queries, with landslide susceptibility maps assisting the assessment of mass wasting processes in roaded environments. By facilitating a better understanding of the potential problems and risks for roads from a slope stability perspective, landslide susceptibility results can be utilized within this part of the roads analysis.

Furthermore, specific suggestions of use in the appendix of the Roads Analysis Report substantiate the utility of landslide modeling technology in addressing road-related questions. In particular, the appendix notes many watersheds have a unique combination of factors that can be used in a GIS to: 1) address where mass wasting is most likely, and 2) rate the relative susceptibility of road segments to mass wasting failures (USDA Forest Service 1999, p. 52). Additionally, the document suggests queries surrounding roads and mass wasting effects may benefit from "the use of outside indicators like maps, GIS queries, statistical summaries, and other information displays...Even the best indicators will not answer questions directly but may assist in discerning and quantifying important interactions" (USDA Forest Service 1999, p. 25). Thus, while road-related determinations are not limited to solely using landslide susceptibility information, understanding the potential for slides clearly has a needed and definitive role in ensuring that the most comprehensive road analyses are made possible.



## Chapter 5: Conclusions and Future Work

The arena of federal road management is a multifaceted and complicated domain. With thousands of miles of USFS roads of varying age, surface material, and maintenance conditions, stewardship of the USFS transportation network becomes an increasingly challenging endeavor. When contending with roads in steep forested terrain like that of the Pacific Northwest, managers balance access, safety, and budget considerations together with an interrelated and complex set of environmental and geophysical factors (Allison and Tait, 2004). Regional slope stability problems are a significant factor that compound problems for personnel making deliberations and management decisions within this environment. Landslides can lead to costly infrastructure damage and road closures, causing hazard to travelers while impeding forest access for recreation and management. Additional consequences also include environmental damage, as failures may destroy vegetation, impact riparian environments and road-stream crossings, and degrade water quality by sedimentation.

Understanding the likelihood of landslide events is an essential component in pursuits to better manage road liabilities, assess changes in access, and achieve effective use of maintenance budgets. By identifying areas exhibiting the greatest risk, landslide susceptibility information becomes vital for agency personnel to prioritize road treatments and plan management strategies at various scales. As such, it was initially questioned whether fuzzy-based methods for generating and disseminating landslide susceptibility information could be used for USFS road management applications. To fully answer this inquiry, this research has been centered around two objectives: 1) developing a fuzzy-based landslide susceptibility model for use as a decision support tool

in prioritizing USFS road management activities, and 2) determining how such information may best be used within current USFS' decision processes related to roads.

The research performed to date reflects that these objectives have been successfully met. A new fuzzy-based landslide model for areas of the Mount Baker-Snoqualmie National Forest was constructed and implemented. The application of the model successfully resulted in a discernable output product of relative landslide susceptibility. The second objective was accomplished by researching procedures and tools currently in place for guiding the management of Forest Service roads. Such examination allowed for the contextualizing of modeling technology within this procedural framework, thereby enabling specific suggestions for model use to be made. Through the fulfillment of these objectives, the conclusion has been supported that landslide susceptibility modeling is an effective and viable decision tool for incorporation into the decision analysis matrix of road management. Due to the inherent complexity and difficulty associated with road related decisions, modeling results obviously should not be the sole decider in determining verdicts. Rather, this work has demonstrated landslide susceptibility modeling can be an effective and valuable addition to other considerations involved in the decision making processes.

The results and recommendations surrounding this modeling work are fairly consistent with findings presented in existing literature. Comparison with past quantitative studies of landslide modeling in forested regions revealed general similarities in working scale (medium) and selection of input data (landslide inventory and parameter maps). Additionally, most fuzzy methods reviewed appeared to use similar fuzzy operators (such as the fuzzy gamma operator) and all displayed results in the same

manner (landslide susceptibility map). Lastly, output verification was most commonly executed in the form of AUC evaluation, as was accomplished in this study.

While literature regarding forest service road management commonly highlighted a need for sound decision making amidst present circumstances, no decision tools were found available that are similar in nature to the one presented in this work. At present, this modeling effort appears to be one of the best methods for assessing conditions at a medium scale (like watersheds and basins). While the Forest Service has extremely qualified engineers and staff whose knowledge of local areas enable site specific evaluation, it becomes difficult for such deterministic analysis to be tiered to the broad forest scale. The fuzzy-based model, however, uses readily available data to show details over a larger area, thus displaying more opportunities for adjusting the road system. An advantage of the model is that it has a relative short processing time; because time-intensive field work is eliminated, the model can produce susceptibility outputs for a region in days to weeks as opposed to longer timeframes. Once the user is acquainted with the procedural steps for model implementation, the modeling process is also relatively straightforward and enables use by non-technical staff as well.

The perceived efficacy of the model should not indicate the model is perfect by any means; future work is still needed for model refinement. Varieties of other possible input factors exist for model inclusion that may add to model robustness. For instance, remote sensing information such as NDVI (Normalized Difference Vegetation Index) can be used as another source for representing vegetation and land cover. This measurement quantifies the density of green leaf vegetation and has been applied to other GIS models in the past. Hydrologic tools could also be an additional input to the model; a wetness

index like the topographic convergence index (TCI), which uses slope and contributing areas to indicate soil wetness, would characterize a slope's ability to retain soil moisture. Additionally, factors like the type of road construction and the proximity to inner gorges could be explored, as both elements may show correlation with initiation of slope failure. Additionally, the selected input factors could be weighted individually within the model. If certain variables are found to have increased relevance in facilitating slope failure for an area, then these inputs may be weighted appropriately within the FuzzyTech system.

Regardless of the variables chosen, future sensitivity analysis of the input factors will help improve accuracy and identify superfluous components. One of the easiest methods for this may be a sampling-based sensitivity analysis, where model sensitivity is evaluated by changing combinations of variables one at a time (Helton et al. 2006). Thus, the model could be run 9 times, with one of the inputs absent in each run. If no notable change in the AUC occurs, then the absent variable is likely non-essential in predicting landslide susceptibility. By performing such sensitivity analysis, one may be able to reduce the number of inputs while ensuring reasonable predictive capabilities are still maintained.

Future options for model adjustment could also include refining the focus of the model specifically to road locations. Currently, the model uses distance to roads as an input while simultaneously using roads as the subject matter for decisions. However, the model could be changed to simply examine slope failure along roads if the user is interested only in areas proximal to roads. By applying the model within a certain buffer from roads, the distance to roads input would be eliminated and susceptibility outputs would be limited to the roaded areas in question.

With such potential for improvements, the future applications of this predictive technology are promising. As the model is applied to more case studies and physical environments, operational modifications may take place and comparisons with new fuzzy-based models can be made to reveal further uses. Equally important, insight may be gained regarding new ways for restructuring decision support systems for forest planners and managers and integrating this tool into decision-making, particularly in roaded areas where little is known about slope stability.

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