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Analysis and Risk Estimation of High Priority Unstable Rock Slopes in Great Smoky Mountains National Park, Tennessee and North Carolina

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Analysis and Risk Estimation of High Priority Unstable Rock Slopes in Great Smoky Mountains National Park, Tennessee and North Carolina

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A thesis

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In partial fulfillment

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Master of Science in Geosciences, Geospatial Analysis

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by

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Keywords: geospatial analysis, Ordinary Kriging, rockfall, susceptibility, QRA

ABSTRACT

Analysis and Risk Estimation of High Priority Unstable Rock Slopes in Great Smoky Mountains National Park, Tennessee and North Carolina

by

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Great Smoky Mountains National Park (GRSM) received 12.5 million visitors in 2020. With a high traffic volume, it is imperative roadways remain open and free from obstruction. Annual unanticipated rockfall events in GRSM often obstruct traffic flow. Using the Unstable Slope Management Program for Federal Land Management Agencies (USMP for FLMA) protocols, this study analyzes high priority unstable rock slopes through 1) creation of an unstable slope geodatabase and 2) generation of a final rockfall risk model using Co-Kriging from a preliminary risk model and susceptibility model. A secondary goal of this study is to provide risk estimation for the three most traveled transportation corridors within GRSM, as well as investigate current rockfall hazard warning sign location to ultimately improve visitor safety with regards to rockfall hazards.

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CHAPTER 1. INTRODUCTION

Each year, Great Smoky Mountains National Park (GRSM) experiences unforeseen rockfall failure events that often obstruct traffic flow. This has a significant impact on GRSM as it is the most visited US National Park, and flow of traffic is vital to maintaining visitor safety.

Unstable slopes along transportation corridors are a continuous concern for GRSM park officials and maintenance personnel because of the potential transportation disruptions and associated economic and social costs. There have been several notable rockfalls that have made local news (WBIR News 2020; WBTV 2020) this past year, 2020. The rockfalls mentioned in the articles closed one or both lanes of traffic on the busiest roadway in GRSM, the Gatlinburg Spur. Luckily, a detour was able to be created in one of the slides, and rock debris was removed from one lane of traffic so it could begin flowing again in the other failure event. A rapid response team from GRSM maintenance staff cleaned up the rock debris and re-opened the transportation corridors in a timely manner. After nearly eighty years of use on some roads, GRSM's transportation corridors require effective long-term geotechnical asset management (Anderson 2016). Anderson (2016) also suggested that creating a database of geotechnical assets including unstable slopes within GRSM is the first step towards evaluating the risks, then mitigating them, which will help lowering the life-cycle costs of the corridors. National Park Services has recognized this need and has collaborated with East Tennessee State University (ETSU) to utilize the Unstable Slope Management Program for Federal Land Management Agencies (USMP for FLMA) protocols to create an inventory of unstable slopes and their current conditions along the primary transportation corridors within GRSM. This inventory will contribute to a digital geodatabase that will enable park officials to take steps towards prioritizing maintenance and mitigation efforts using cost-benefit analyses based on short- and long-term budgets.

Therefore, this research involved two studies. Study 1 focused on objectives: (1) create an inventory of unstable slopes, (2) produce a susceptibility model, (3) prepare a preliminary roadway risk map using USMP scores, (4) combine the susceptibility model and risk map to create a final risk map for GRSM. Study 2 utilized the final risk map from study 1 to 1) develop a quantitative risk estimate based on the most unstable slopes of the three most traveled corridors in the park (Gatlinburg Spur [Spur], Little River Gorge Rd. [LRG], and Newfound Gap Rd. [NFG]) using USMP QRA, and 2) identify locations of existing rockfall hazard warning signs throughout GRSM and suggested locations for potential new signs.

To highlight a few of the objectives in Study 1, a geodatabase of unstable slopes throughout paved primary roads of GRSM was created using USMP for FLMA slope rating protocols. Within the Slope Rating form are three categories: a preliminary rating, a total hazard rating, and a total risk rating. The mentioned three categories summed together create a total stability score, which is ranked as <200pts signifies a 'good' (stable) slope, 200-400pts indicates a 'fair' slope, and >400pts represents a 'poor' (unstable) slope.

The unstable slope inventory data was further used to identify areas prone to rockfalls by creating a susceptibility model using Maximum Entropy. A preliminary risk estimate was created using Ordinary Kriging model, utilizing the USMP total risk rating scores. The susceptibility and preliminary risk models were used as co-variates in a final risk estimate to provide a more realistic risk model to be utilized in future studies.

In Study 2, the final risk model was used in risk estimation of the ten highest rated slopes along the three most traveled transportation corridors, as well as investigating rockfall hazard warning sign locations throughout the park. In risk estimation, the USMP Quantitative Risk Assessment (QRA) protocol was used. The USMP QRA tool considers speed limit, occurrence time, boulder size, number of boulders, occupancy time, vulnerability, earthquake triggered probability, and non-earthquake triggered probability. The resulting annual individual risk is compared with other well-known societal risks, such as, U.S. Homicides, incidence of cancer, and U.S. motor vehicle fatalities. A risk estimation of the transportation corridor can provide useful information to decision-makers when coupled with the geodatabase of unstable slopes. This can allow decision-makers to more easily grasp estimated annual individual risk of a slope or slopes along a transportation corridor and make decisions accordingly.

The current locations of rockfall hazard warning signs throughout the park was explored. The goal of locating the rockfall hazard warning signs locations was to understand where they fit within the unstable slope database, and the risk map, to see if they were truly warning visitors of potential rockfall hazard. In future studies, the current rockfall hazard warning sign location information could be used to conduct a more in-detail study and suggest the re-location of several signs to a more suitable area. Overall, the goal of this study, is to improve visitor safety in the most visited US National Park.

CHAPTER 2. ANALYSIS OF HIGH PRIORITY UNSTABLE ROCK SLOPES IN GREAT SMOKY MOUNTAINS NATIONAL PARK, TENNESSEE AND NORTH CAROLINA

by

Samantha Farmer

Abstract

Great Smoky Mountains National Park (GRSM), situated on the Tennessee and North Carolina border, is the most visited national park. Unanticipated rockfalls occur within GRSM annually, and often obstruct traffic flow and pose significant risk to visitor safety. This project focuses on 1) developing a rockfall inventory database, 2) creating a rockfall susceptibility model using Maximum Entropy, 3) preparing a rockfall risk model using Ordinary Kriging, and 4) producing a final risk model using Co-Kriging. Unstable slope data were collected using Unstable Slope Management Program for Federal Land Management Agencies (USMP for FLMA) slope rating protocols. Unstable slopes (284) were rated based on a preliminary rating, total hazard score, and total risk score. This study aims to provide an understanding of current slope conditions and ultimately improve visitor safety.

Keywords: unstable rock slopes, Maximum Entropy, Ordinary Kriging, Co-Kriging, rockfall risk

Introduction

Great Smoky Mountains National Park (GRSM) and East Tennessee State University (ETSU) partnered to create an inventory of unstable slopes along paved roads within the park boundaries including Tennessee and North Carolina sections of the park. Approximately 151 miles of paved, primary roadways were assessed in this study.

Knowledge of current slope conditions, previous failures, their locations, and severity of hazard allows GRSM officials to prepare for future rockfall related risks, ultimately improving roadway safety. In this study, an inventory of unstable slopes along roadways in GRSM was prepared and risk maps were created, which utilized in two applications: 1) quantitative risk assessment and 2) potential rockfall hazard warning sign locations.

Rockfall Risk Estimation

The general framework in rockfall risk estimation consists of the following steps (Mayrouli 2011): (1) consolation of previous studies, reports from historical events, and field surveys to prepare a database of rockfall inventory that provides the spatial distribution of locations of existing rockfalls and (2) preparation of a rockfall susceptibility map showing the probability that an event (i.e. rockfall) will occur in a specific area based on surrounding environmental conditions (such as, geology, hydrology, geomorphology, and landuse pattern). Rockfall susceptibility is estimated either by an empirical assessment of susceptibility to failure or by a data-driven quantitative approach using statistical models.

A synthesis of the available data-driven statistical methods, and their applicability and limitations, can be found in a wide range of literature (Ko Ko et al. 2004; Castellanos and Van Western 2007; Michoud et al. 2012; Mignelli et al. 2012; Wang et al. 2013; Capps et al. 2017).

Ecological niche models (ENMs) can be used to create susceptibility models but are less explored in rockfall susceptibility model analysis. ENMs link occurrence (event) data with environmental variables based on several algorithms (Escobar et al. 2016). For rockfall susceptibility models, the commonly used ENM technique is Maximum Entropy (MaxEnt) (Kornejady et al. 2017; Azareh, et al. 2019). MaxEnt is a presence-only machine learning model which is beneficial for isolated and inaccessible areas and provides a more robust model by using both continuous and categorical data without needing to reclassify continuous layers (Kornejady et al. 2017).

The sequential steps to risk estimation include (1) hazard analysis, containing the analysis of the intensity, and probability of failure of the potential rockfall event, (2) identification of the elements at risk, including their number, value, and degree of exposure, (3) vulnerability analysis, and (4) calculation/estimation of risk. Rockfall hazard refers to the probability of occurrence of a rockfall of a given volume or intensity energy within a given area, which has the potential for generating an undesirable consequence (Vanes 1984; Crosta et al. 2003; Guzzetti et al. 2003).

Rose (2005) described risk as the probability and severity of something causing an adverse effect to health, property, or the environment. Rockfall related risk is defined as the outcome of the occurrence of a rockfall and is expressed qualitatively or quantitatively in terms of loss, damage, injury, or fatality. Risk analysis investigates the likelihood of a rockfall and associated consequences, with the goal of identifying potential failure that represent “unacceptable” risk (Cova and Conger 2003). The analysis also provides a numerally calculated risk value for a certain area, concluding if mitigation techniques should be implemented to reduce potential for failure (Mignelli et al. 2012).

Rockfall Rating Systems

The Rockfall Hazard Rating System (RHRS) was one of the first approaches to estimate rockfall related hazard along roadways. The RHRS is a qualitative method that is based on a preliminary screening step used to identify high hazard areas, which are then evaluated in detail. Pierson (1991) designed the first RHRS in Oregon to assess rockfall hazard along highways. Oregon RHRS provided a tool for managing rock slopes along transportation corridors through a rational method by making informed decisions on where and how to spend construction funds. The Oregon RHRS consists of six major parts: uniform method for slope inventory, preliminary hazard rating of all slopes, detailed rating of hazardous slopes, preliminary design and cost estimate for most serious slopes, project identification and development, and annual review and update.

RHRS uses various parameters like, slope height, geologic characteristics, block size, climate, presence of water on the slope, roadway and traffic conditions, ditch effectiveness, average vehicle risk, sight distance, and roadway width. Several states within the USA have adopted rockfall rating systems modified from Oregon RHRS, like New York (Rock Slope Rating Procedure), Missouri (MORFH RS), Ohio (ORHRM), Colorado (CRHRS), and Tennessee (TRHRS). Many methods have mixed the hazard and risk related parameters. Ferrari et al. (2016) published a comprehensive review highlighting the advantages and limitations of current practice in various available rockfall rating systems. All methodologies require field observations and measurements, and some require laboratory tests.

Recently, a proactive unstable slope management program for Federal Land Management Agencies (USMP for FLMA) has been adopted by the Federal Highway Administration focusing on unstable slope failure-related threats to infrastructure including roads, parking lots, and buildings, while making strategic use of limited financial resources (Beckstrand et al. 2017; Capps et al. 2019).

Unstable Slope Management Program (USMP)

The USMP was created based on transportation assets management (TAM) for Federal Land Management agencies and low traffic volume agencies to manage unstable slopes (Beckstrand et al. 2019). The program is designed for preliminary hazard and risk ratings for unstable rock slopes. USMP tools are designed to be used by agencies (i.e., maintenance officials or any non-specialist with proper training) to predict likelihood of risk related to rockfall or landslide (Capps et al. 2017). This leads to a better understanding of an unstable slope and its event conditions, and can allow Federal Land Management agencies, like the National Park Service (NPS), to effectively communicate unstable slope hazards with maintenance staff, geotechnical engineers, consultants, and/or visitors. The USMP was designed for lower traffic volume corridors, therefore, some USMP risk categories do not differentiate between high volume and extremely high-volume corridors. For instance, the annual average daily traffic (AADT) category and precipitation category always receive the maximum points allowed in that category (81). Nevertheless, slope ratings are reported through a national USMP database that allows the federal agencies to plan proactive management of unstable slopes.

Research has been done on debris slides and flows (Bogucki 1976; Caine 1980; Ryan 1989), as well as shallow landslides (Caine 1980) in GRSM, but there is no comprehensive inventory of unstable slopes in the park and its roadways. Therefore, the principal goal of this research is to provide realistic rockfall risk estimates of the primary roads in GRSM, focusing on high rated unstable slopes from each road. Results of this research project will be shared with GRSM, in hopes that park maintenance can prioritize mitigation efforts based on unstable slope risk ratings. The specific objectives of this research are: 1) Creating an inventory of unstable slopes, 2) Producing a susceptibility model, 3) Making a preliminary roadway risk map, and 4) Combining the susceptibility model and risk map to create a final risk map of GRSM primary roadway corridors.

Background of Study Area

GRSM is the most visited national park in the USA, receiving approximately 12.5 million visitors in 2019 (Lock 2020). The park is situated on the Tennessee and North Carolina border and consists of 522,427 acres (NPS Statistics 2017). Figure 2.1 shows the study area, as well as nearby cities.

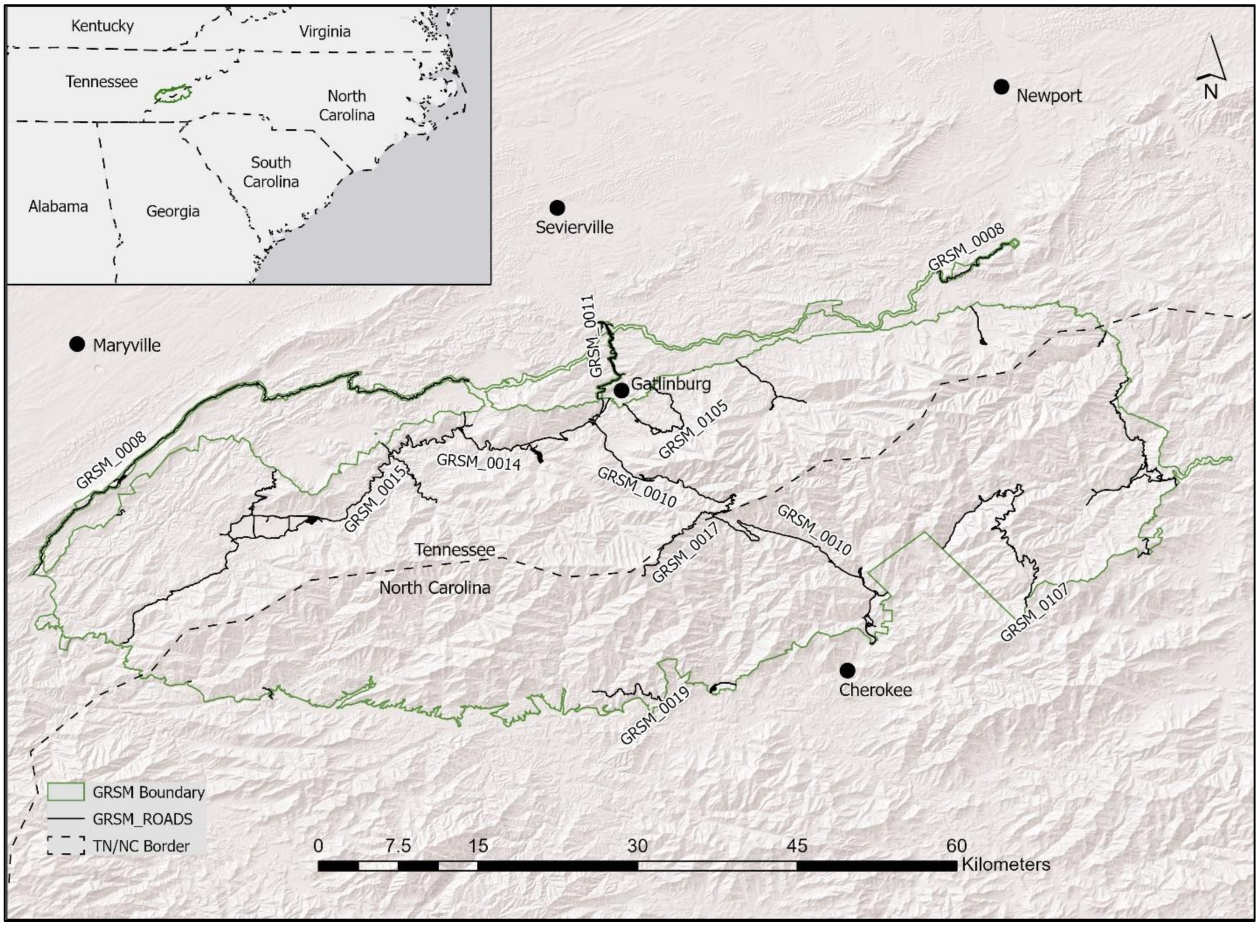

Figure 0.1. Location map of Great Smoky Mountains National Park, located along the border of Tennessee and North Carolina, USA. Roads that are important to this study have been labeled

Significant roads within the park include: GRSM 0008 (Foothills Parkway), GRSM 0010 (Newfound Gap Rd.), GRSM 0011 (Gatlinburg Spur), GRSM 0014 (Little River Gorge Rd.), GRSM0015 (Laurel Creek Rd.), GRSM 0017 (Clingmans Dome Access Rd.), GRSM 0019 (Lakeview Dr. E.), GRSM 0105 (Cherokee Orchard Rd.), and GRSM 0107 (Heintooga Ridge Rd.). These roads are important to this study as they are the roads where there are active rockfalls and/or previous rockfall events.

Geology

Formed approximately 200 – 300 Ma during the Appalachian orogeny, GRSM are some of the oldest mountains in the world and are the highest in the Appalachian Mountains (Thornberry-Ehrlich 2008). GRSM is located within the Blue Ridge physiographic province with a geologically diverse subdivision that contains aspects of three geologic provinces: Piedmont, Blue Ridge, and Valley and Ridge (Thornberry-Ehrlich 2008). The Piedmont is characterized by softer sedimentary rocks to the east, and folded/faulted resistant rocks to the west (Thornberry-Ehrlich 2008). The Blue Ridge province is known for steep terrain, and shallow soils (Thornberry-Ehrlich 2008). The Valley and Ridge province is characterized by long, parallel sandstone ridges that are separated by valleys of easily eroded shale and carbonate rocks (Thornberry-Ehrlich 2008).

GRSM is composed of mainly metasedimentary rock ranging from Proterozoic Y to Holocene; however, all three rock types are found in GRSM (Moore 2002). The oldest rocks in GRSM are Proterozoic Y (4600 Ma) basement rocks known as the Basement complex (Moore 2002). The Grenville "Basement" complex is composed of Mesoproterozoic (1.1 Ba) ultramafic igneous and metamorphic rocks as xenoliths created during the Grenville orogeny (mountain building event) (Thornberry-Ehrlich 2008). The youngest unit within GRSM is alluvium from the Quaternary (Moore 2002). GRSM is dominated by four major thrust faults: 1) Greenbrier fault, 2) Dunn Creek fault, 3) Miller Cove fault, and 4) Great Smoky thrust fault (Thornberry-Ehrlich 2008). Most of the major faults are part of a connected fault system and can be a source of rockslides (Southworth et al. 2005). A GRSM geologic map was used to locate potential geologic units that may affect slope stability (Figure 2.2).

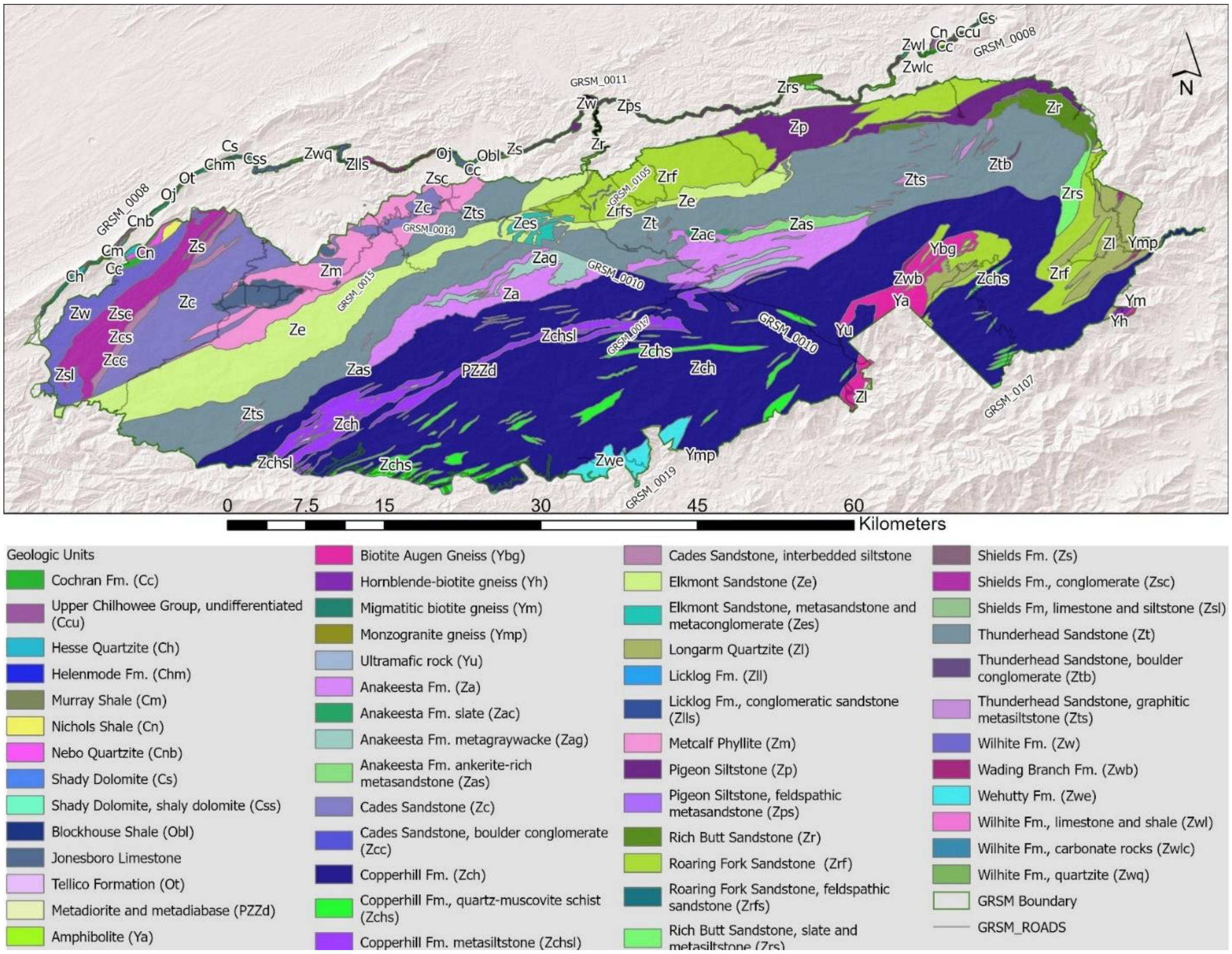

Figure 0.2. Geologic map of Great Smoky Mountains National Park; metasedimentary is the main lithology in GRSM

The lithology at and around Newfound Gap road (NFG) is primarily Proterozoic (4 Ba) (Moore 2002). The Ocoee Supergroup (metasedimentary) (Za, Zac, Zag, Zas, Zc, Zcc, Zch, Zchs, Zchsl, Zcs, Ze, Zes, Zl, Zll, Zlls, Zm, Zp, Zps, Zr, Zrf, Zrfs, Zrs), the Basement complex (granitic gneiss), Thunderhead Formation (Fm.) (metasandstone) (Zt), and Anakeesta Fm. (slate and metasiltstone) (Za) (Southworth et al. 2005) are the primary bedrock formations under NFG (Figure 2.3a). The Anakeesta Fm. (Za) is a prime example of acid producing rock as it contains pyrite, which when mixed with water produces sulfuric acid. Sections of the Anakeesta indicate different levels of oxidation, some stretches show minor oxidation, others are nearly completely oxidized (maroon color). The more oxidized the rock, the greater the potential for it to be acid producing; this can have a negative impact on the environment through acid mine drainage. NFG contains two faults: Greenbrier fault and the Oconaluftee fault (Moore 2002) (Figure 2.4). Moore (2002) notes that there are scars on the road from multiple older landslide and rockfalls; these scars can still be seen today.

Geology at and around the Little River Gorge road (LRG) is composed of Proterozoic Z metamorphic rock and lower Ordovician limestone forming tectonic windows (Moore 2002). The Thunderhead Fm. (metasandstone) (Zt), Metcalf Fm. (phyllite) (Zm), Pigeon Fm. (metasiltstone) (Zp), and Elkmont Fm. (metasandstone) (Ze) (Moore 2002) (Figure 2.3b) make up the geology on LRG. The Greenbrier thrust fault and Great Smoky Mountain thrust fault can be found along LRG (Moore 2002) (Figure 2.4).

The Spur is mainly composed of Neoproterozoic Roaring Fork Fm. (metasandstone) (Zrf) and Pigeon Fm. (metasiltstone) (Zp). (Thornberry-Ehrlich 2008). A small section of the Spur contains the Rich Butt Fm. (metasandstone) (Zr), which is also a part of the Neoproterozoic Snowbird Group (Zm, Zp, Zps, Zr, Zrf, Zrfs, and Zrs, Zwb) (Southworth et al. 2005) (Figure 2.3c).

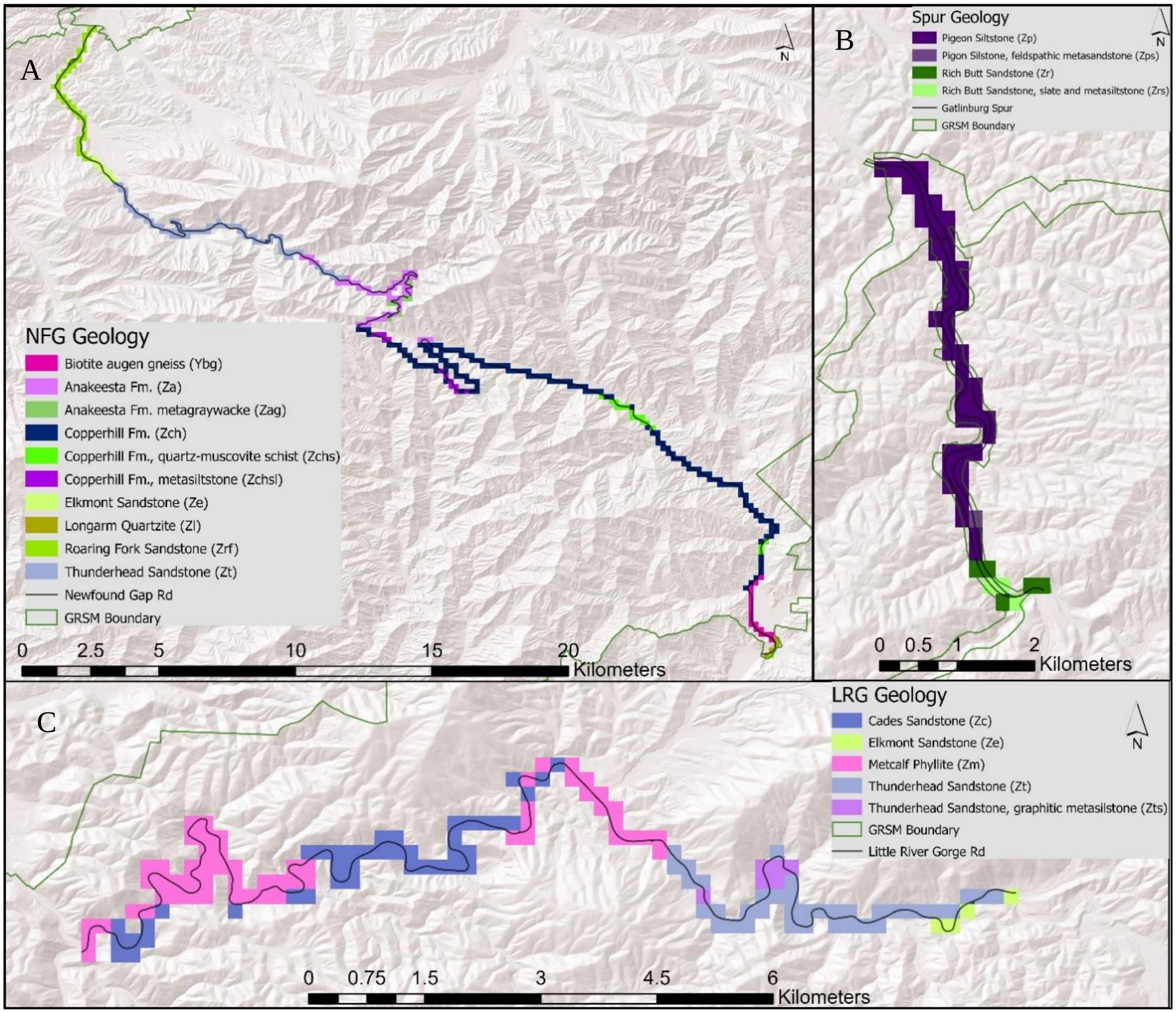

Figure 0.3.A-C. A) Zoomed in geologic map of Gatlinburg Spur (top left); B) Newfound Gap Rd (top right); and C) Little River Gorge Rd. (bottom)

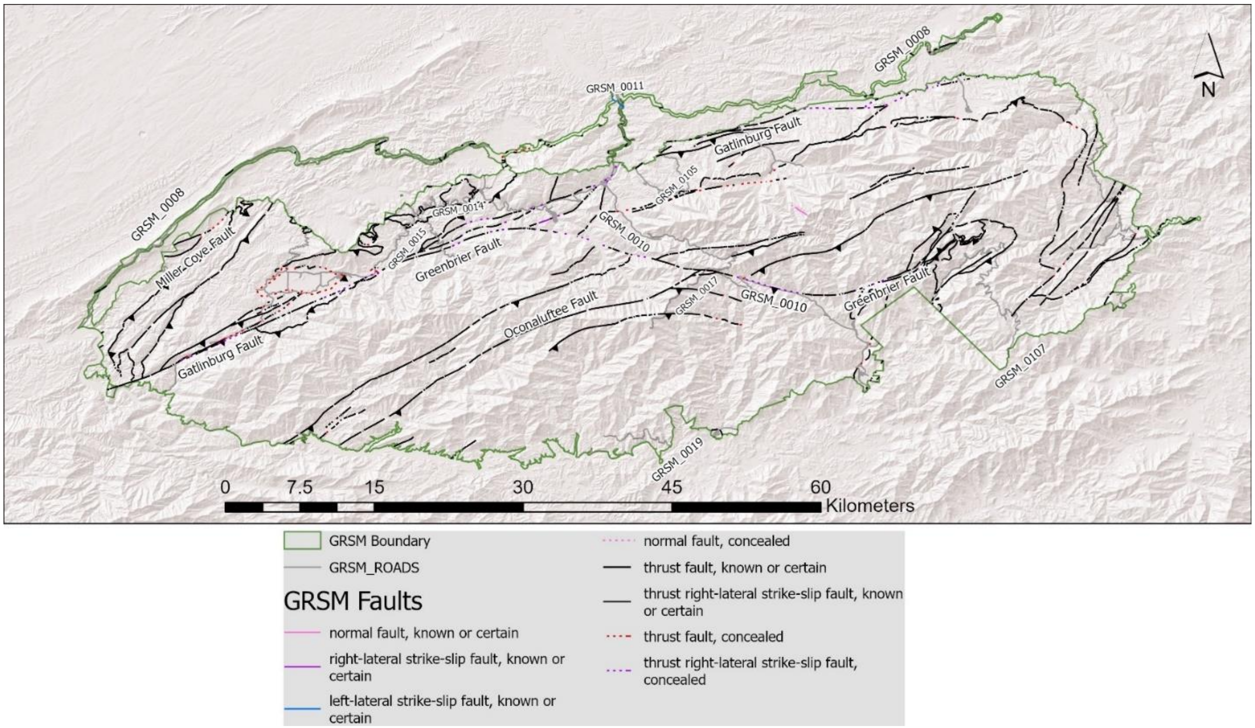

Figure 0.4. Fault map of the Great Smoky Mountains National Park; most fault sin the park are thrust faults or right-lateral strike slip faults. Solid triangles on thrust faults indicate dip direction

Weather and Hydrology

Annual rainfall throughout the park ranges from 1.14 m (45 in) to 2.41 m (95 in). Higher amounts of rainfall occur in higher elevations of the park. Most of the primary roads are in the 1.50 m (59 in) – 2.06 m (81 in) range. More rockfalls are expected to occur during rockfall season (early Spring and late Fall) when frost wedging conditions and large storm events create ideal slide conditions (Snyder 1996; Matsuoka 2001; Sass 2005). It is hypothesized most of the failure events along the roadways are a result of construction, which disturbed the natural slope stability along the hill slopes, undercutting, and potentially blocked culverts, areas of improper water drainage or both. An annual precipitation map was created using 30-year Normal precipitation totals (1981-2010) (PRISM 2020) (Figure 2.5).

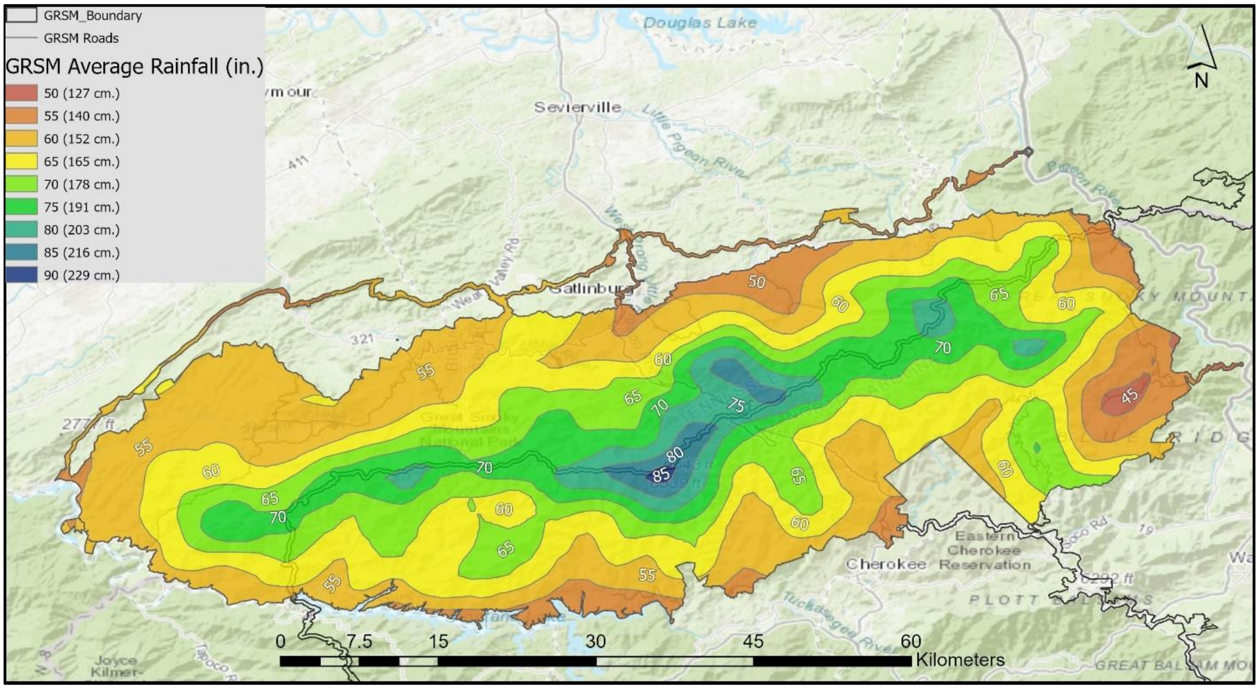

Figure 0.5. Average annual precipitation throughout Great Smoky Mountains National Park using 30-year normals (PRISM, 2020)

Over 2,100 miles of streams and rivers are contained within GRSM, of which 730 miles are fish-bearing and 1,300 miles are tributaries (NPS Statistics 2017). In higher sections of the park, over 85in (2.16m) of precipitation falls annually (NPS Statistics 2015). Tributaries, springs, and aquifers replenish waterfalls and surface streams (McKenna 2007). GRSM streams are vulnerable to acid rain because of nearby power plants, factories, and volume of traffic (McKenna 2007). Water in GRSM can be acidic from pollutants in rain, and from rock formations that have acid-producing potential (i.e., Anakeesta Fm., Copperhill Fm., Wehutty Fm.). These rock types are more prone to rockfalls and landslides, and also have the potential to negatively impact flora and fauna via drinking water.

Methodology

A detailed flowchart (Figure 2.6) describes the methods to accomplish the four objectives of the study: (1) Create an inventory of unstable slopes, (2) Produce a susceptibility model, (3) Prepare a preliminary roadway risk map using USMP scores, (4) Combined the susceptibility model and risk map to create a final risk map for GRSM.

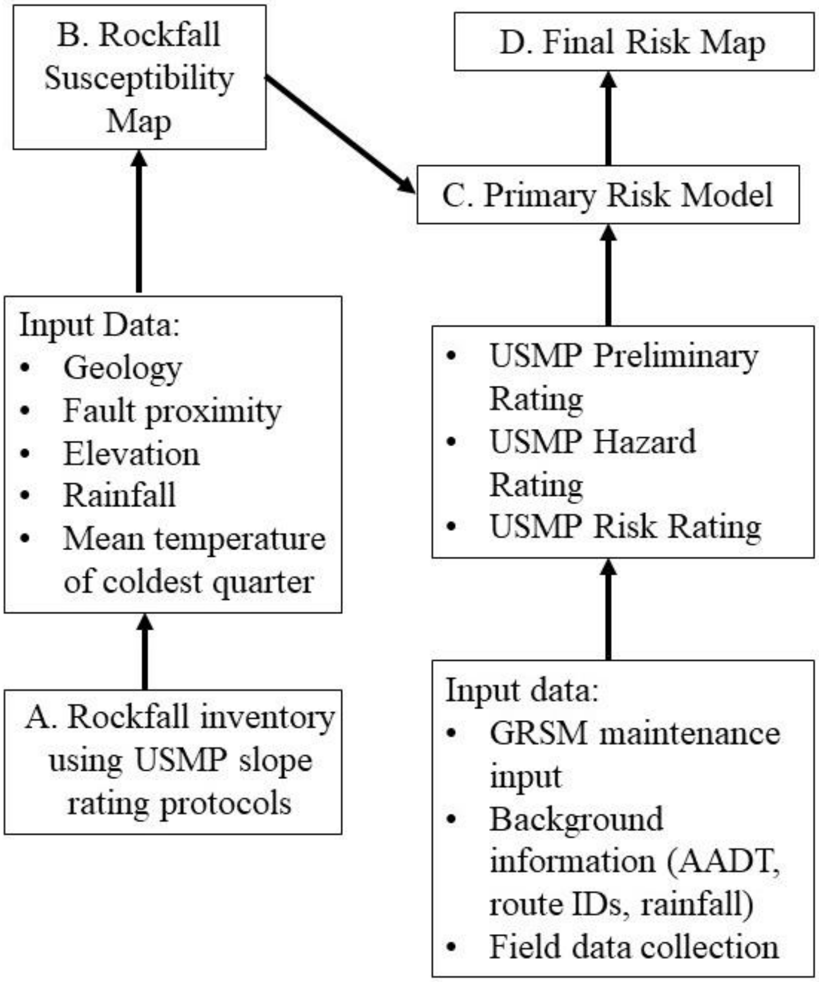

Figure 0.6. Flowchart of the research

A. Data Collection and Inventory Map

For this analysis, the USMP slope rating form was used. The slope rating form provided by the USMP website (Beckstrand et al. 2019) (Appendix A) is split into several sections: site information, preliminary ratings, slope hazard ratings, and risk ratings. Each section contains four to six parameters that were evaluated in the field based on a logarithmic scale (3, 9, 27, or 81). A detailed manual of the rating procedure can be found on the USMP website and is also discussed during training sessions (Beckstrand et al. 2019). Training sessions for this study were conducted in July 2019 with Dr. Eric Bilderback (NPS) where slope rating protocols and the manual were discussed, including a detailed explanation of each parameter and how best to rate the section. The evaluated slope received different rating scores like, preliminary rating, detailed slope hazard rating, detailed risk rating, and total rating.

The input data for the slope ratings include 19 different parameters including ditch effectiveness, rockfall history, block size or volume per event, impact on use, Annual Average Daily Traffic (AADT)/economic significance, slope drainage, annual rainfall, slope height, maintenance frequency, structural condition, rock friction, route width, human exposure factor, maintenance complexity, and event cost. Each slope evaluation site had a unique site ID (GRSM_xxx), so it could be quickly referenced. In real-time, an interactive rockfall risk score along with all input data and site photos are available to NPS at the national level. A screenshot of the dataview is presented in Appendix B.

Site information focuses on collecting measurements and making observations. The hazard category must be defined as rockfall or landslide. Both categories include failure types; rockfall includes planar, wedge, topple, raveling/undermining, rock avalanche, indeterminate rock failures, and differential erosion. There are sections to denote the road number, road class, raters name, beginning and end coordinates (collected with handheld GPS unit: Garmin eTrex Venture HC), what side of the road the hazard is on, weather, and AADT. A laser range finder (TruPulse 360R) was used to measure length of affected road, slope height, slope angle, sight distance, and usable roadway width. Ditch width and depth is observed and recorded, as well as block size/volume of potential hazard. At the end of the site information, there is a place to upload photographs of each site. This allows slopes to be easily referred to when a specific site may need to be considered for further evaluation. One photograph includes the transportation route with the slope in it, the next photo is looking at the rock slope straight on, and the last is taken away from the slope. If the site has any special characteristics (i.e., impact marks on the road), photographs are taken.

The preliminary rating follows site information. The preliminary rating is used for guidance for if the rater should continue the rating assessment and can be used to include or exclude a potential unstable slope location from the database (Beckstrand et al., 2019). If the site falls below 21 points, then it is considered good, and raters may choose to end the slope assessment. Sites rated as fair or poor continue being rated. The preliminary rating section is comprised of ditch effectiveness, rockfall history, block size or volume per event, impact on use, and AADT/usage/economic significance. The detailed slope hazard rating categories include: slope drainage, annual rainfall, slope height, rockfall-related maintenance frequency, and two geologic character cases. The first case is structural condition and rock friction; the second case is structural condition and difference in erosion rates. Only one geologic character case must be completed; in GRSM, Case 1 is generally the section used because structural condition and rock friction are more evident in GRSM compared differential erosion rates in Case 2. The detailed risk rating contains route width, human exposure factor, percent of decision sight distance, right of way impacts, environmental/cultural impacts if left unattended, maintenance complexity, and event cost. The total rating is the summation of the preliminary rating total, rockfall hazard total, and risk totals. The slopes are given a total rating of good (<200 points), fair (200-400 points), and poor (>400 points). All slope related ratings include 18 different parameters including ditch effectiveness, rockfall history, block size or volume per event, impact on use, AADT/economic significance, slope drainage, annual rainfall, slope height, maintenance frequency, structural condition, rock friction, route width, human exposure factor, maintenance complexity, and event cost were also exported in ArcGIS Pro (ESRI, 2020). The longitude and latitude of each rockfall evaluation location, along with every parameter score data, preliminary, hazard, risk, and total rating scores for GRSM were obtained from USMP as .CSV file database and imported into ArcGIS Pro. The database was converted to points using the XY Table to Point tool in ArcGIS Pro. X-field was defined as slope longitude and the Y-field was set to slope latitude. The rockfall inventory database included all rockfall evaluation locations along with the scores from all parameter data collected during the field survey.

B. Susceptibility Model

This study used ArcGIS Pro (ESRI 2021), a Geographic Information Systems (GIS) product, and MaxEnt to create a rockfall susceptibility model of GRSM. The rockfall inventory map was prepared from the USMP database and imported into ArcGIS Pro. GRSM boundary, road centerline, bedrock geology, and 10 m Digital Elevation Model (DEM) layers were downloaded from NPS Integrated Resources Management Applications (IRMA) portal. A GRSM fault layer was extracted from the GRSM geology layer. All mentioned variables were plotted in ArcGIS Pro. Additionally, two bioclimatic variables: 1) mean temperature coldest quarter (bio11), and 2) annual precipitation (bio12) were downloaded from the WorldClim historical climate data site, version 1.4 (1970-2000) (Fick and Hijmans 2017; WorldClim 2020). The variables were downloaded in 30 arc seconds (1 km^2) spatial resolution. Bio11 and bio12 were chosen because they represent the most appropriate climatic variables that trigger rockfalls (Luckman 2013; NPS 2020).

In ArcGIS Pro, bio11 and bio12 were masked to the GRSM boundary using the Extract by Mask tool. Elevation, fault, and geology were snapped and masked to bio12 using the Extract by Mask specifying “snap raster” to bio12 in the environments setting. This ensures each raster has the same cell size.

The bedrock geology was categorical data and was reclassified from 1-4 using the Reclassify tool. Ranking for geology were determined from field notes, geologic maps (Southworth et al. 2005), and maintenance reports with 1 being geologic formations with low risk for rockfall and 4 being units with the highest potential for rockfalls. Geologic units were characterized as follows in Table 2.1:

Table 0.1. Geology Reclassification for GRSM Units to represent the potential for rockfall based on field observations, geologic maps, and maintenance reports. 1 = low risk; 4 = highest risk.

Class	Geologic Unit
4	Anakeesta, Copperhill, Metcalf phyllite, Thunderhead sandstone, Pigeon siltstone
3	Roaring Fork sandstone, Murray shale, Rich Butt sandstone, Cades sandstone, Shields conglomerate, Hesse quartzite, Helenmode
2	Wehutty, Wilhite, Cochran
1	Elkmont sandstone

All other data were continuous data and were not reclassified. Each raster was converted to an ASCII file using the Raster to ASCII tool to run the MaxEnt model. The GRSM USMP total risk data were exported as a CSV file and randomly split into a training set using 80% and testing set using 20% of the data. The training data were used to create the model while the testing data were used to validate the model. The training and testing data were created using the Subset Features tool.

The training data CSV was set as the sample file, and the ASCII files were set as environmental layers. “Do jackknife to measure variable importance” option was selected, output format and output file type were kept as the default. A threshold rule to 10 percentile training presence was chosen meaning if more than 10% of the training data are omitted, the model is considered unacceptable. Default prevalence was kept at 0.5 for all variables. Once the MaxEnt model was successfully completed and validated with the testing data (20%), the output .asc file was uploaded in ArcGIS Pro to better visualize the rockfall susceptibility model results.

C. Rockfall Risk Map Generation

GRSM slope inventory was downloaded as a CSV file from the USMP database. Total stability score (sum of preliminary rating, total hazard rating, and total risk rating) was converted to points using the XY Table to Point tool in ArcGIS Pro. Longitude of slope was defined in the X-field, and latitude of slope was set as the Y-field. GRSM park boundary and road centerlines layers were downloaded from the NPS IRMA portal and imported to ArcGIS Pro. For interpolation, the kriging method was selected in the Geostatistical Wizard of ArcGIS Pro to build the rockfall risk map of the GRSM corridors.

Kriging is a form of probabilistic and local interpolation, where predicted values are assigned to the fields based on values observed in the closest points and statistical relationships based on distance and potentially direction among other variables subject on the type of kriging methodology chosen. Environmental Systems Research Institute (ESRI) defines ordinary kriging as "a kriging method in which the weights of the values sum to unity. It uses an average of a subset of neighboring points to produce a particular interpolation point." Various kinds of kriging methods are available depending on the characteristics of input data. For example, ordinary kriging is best used for stationary and non-parametric data, universal kriging for nonstationary data, and Co-Kriging for data that may be correlated with its underlying environment. In this study, ordinary kriging was chosen because the data is stationary, numerical, exponential, nonparametric, and does not have a linear trend.

In Ordinary Kriging, the data source was set to GRSM Total Score, and the optimized model tool was used. The cross-validation diagnostic was used to determine the accuracy and reliability of the predicted model. Cross validation is defined as a "leave-one-out method" to understand how well the interpolation method fits the data. The predicted value is compared to the measured value after removing a single point from the data and using remaining points to predict the location of the removed point. The cross-validation diagnostics used in this study are Root-Mean-Square (RMS), RMS Standardized (RMSS), and Mean Standardized (MS). RMS demonstrates how closely the model predicts measured values, the smaller the number, the better the model. If the value of RMS Standardized is close to 1, then the model prediction standard errors are valid. For values greater than 1, the model underestimates the variability in the predictions, and vice-versa. Mean Standardized is the average of standardized errors and should be close to 0. The kriging surface was converted to a raster using the Geostatistical Analyst Layer to Rasters (Geostatistical Analyst) geoprocessing tool. This tool exports the kriged layer to multiple raster outputs. After converting the surface to a raster, the Extract by Mask tool was used to mask the surface to a GRSM road centerline buffer surface. A 45.7 m (150 ft) buffer was used for the road centerlines, as the field survey indicated that most rockfall events along the corridors were concentrated within the 45.7 m (150 ft) width of the road centerline.

D. Preparation of the Final Risk Map

To create the most realistic rockfall risk map for the study, the rockfall susceptibility model and kriging surface were used for Co-Kriging. Co-Kriging takes the distribution of a second variable (in this case the susceptibility model) coupled with a primary variable (the rockfall risk map) to create a better interpolation method. Co-Kriging is often used to improve predictions if one variable lacks adequate data, but the second variable is more intensely sampled (ESRI 2020). The rockfall susceptibility model was produced using some important environmental factors like bedrock geology, faults, elevation data, mean temperature coldest quarter, and annual precipitation, which were not part of the risk map. That is why the inclusion of a susceptibility model was reasonable in this study.

Rasters must be in integer rasters format for the Co-Kriging process. The INT tool was used to convert the initial risk map into an integer raster. The susceptibility model was converted from ASCII format to a raster using the Copy Raster tool, and the INT tool was used to convert to an integer raster. Each raster needed to be a polygon before Co-Kriging, so the Raster to Polygon tool was used. After converting the rasters to polygons, Co-Kriging was selected from the Geostatistical Wizard. Ordinary kriging (prediction standard error) was used for Co-Kriging, and the model was optimized with default settings being unchanged.

Results

Rockfall Inventory

From July 2019 to June 2020, a total of 284 slopes were rated. Five slopes were categorized as landslides and have been omitted from this study. Of the 279 rockfalls: 4 received a good rating, 145 received fair, and 130 are considered poor slopes (Figure 2.7). Road cut slopes were considered for the project if: 1) they are above a certain height (3 m.) above the roadway, 2) they show a presence of rocks in ditch (evidence of movement), 3) they show rock impact marks on the road (indicating rocks made it to the road and caused hazard), and/or 4) maintenance officials indicated there have been past slope failures at that location. GRSM covers a large area, therefore, maintenance officials provided some details about: 1) road where a failure occurred, 2) when it occurred, and 3) how difficult it was to clean up. This helped to highlight certain areas that may need to be examined more closely, compared to a site with no recently documented slope failures. The maintenance-flagged sites may lead to detailed, follow-up assessments of the slope to determine factors causing instability.

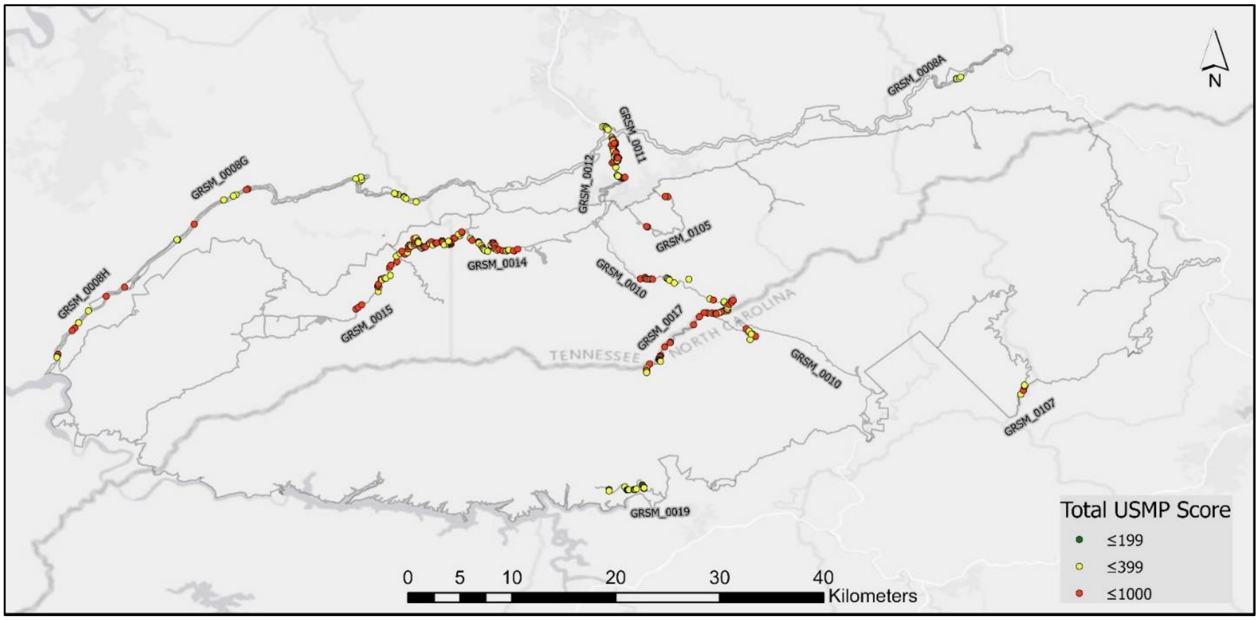

Figure 0.7. Inventory of unstable slopes in Great Smoky Mountains National Park. Four slopes were rated 'good' (green point), 130 rated 'fair (yellow point)', and 130 rated 'poor' (red point).

Rockfall Susceptibility Map

Training Area-Under-Curve (AUC) was 0.749 and testing AUC was 0.873 (Figure 2.8). A score of 0.7 – 0.8 represents a decent model (Bean et al. 2012). Fractional predicted area for 10th percentile training (Commission) is 0.649 (65%), and omission (known areas of predicted presence absence) was 0.080 (8%) meaning 8% of the training data were omitted from the final model, while 65% of the study area was considered suitable for rockfalls.

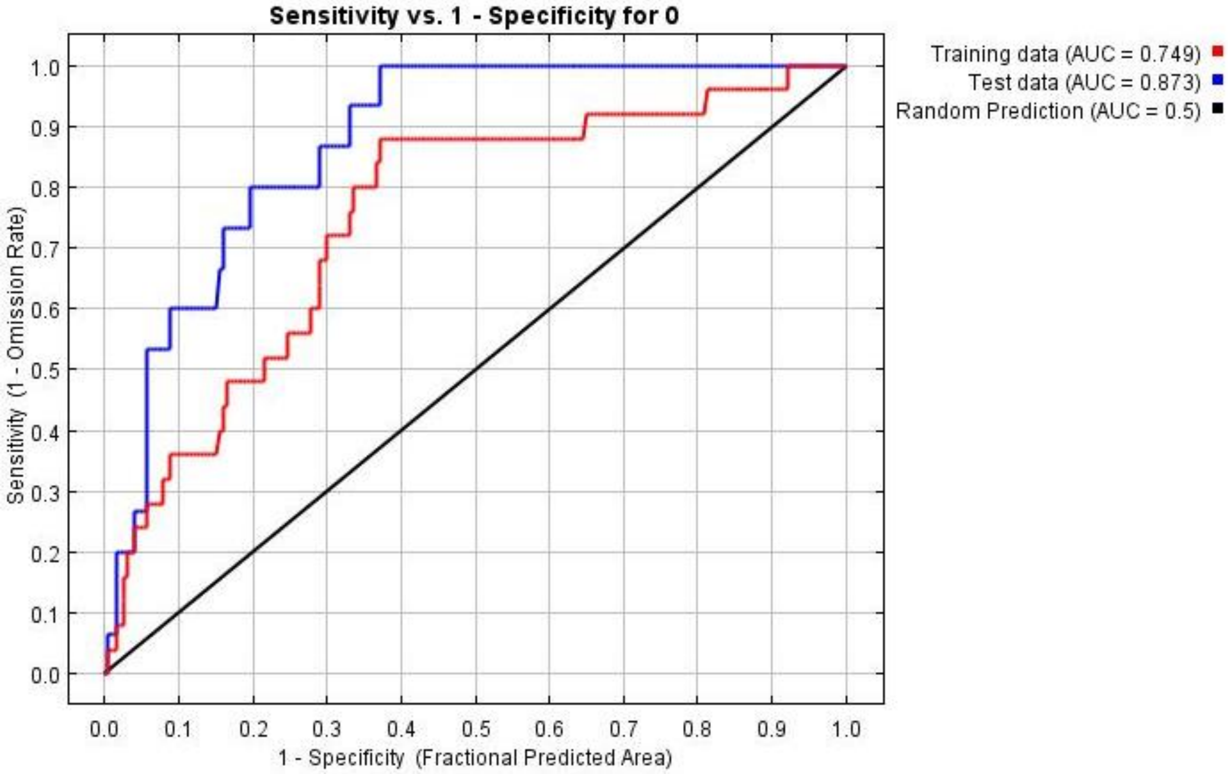

Figure 0.8. Receiver Operating Characteristic (ROC) curve plotting sensitivity vs. specificity. Training AUC was 0.749 (red line) and testing AUC was 0.873 (blue line).

The MaxEnt model created the rockfall susceptibility map with probability of failure ranging from 0.15 to 0.99, and was color-coded from green to red to identify areas with low rockfall susceptibility (green) against areas with high rockfall susceptibility (red) (Figure 2.9). The most contributing variable was the mean temperature of coldest quarter (bio11), followed by elevation, geology, total annual precipitation (bio12), and faults. Output cell size for the susceptibility model was 1km.

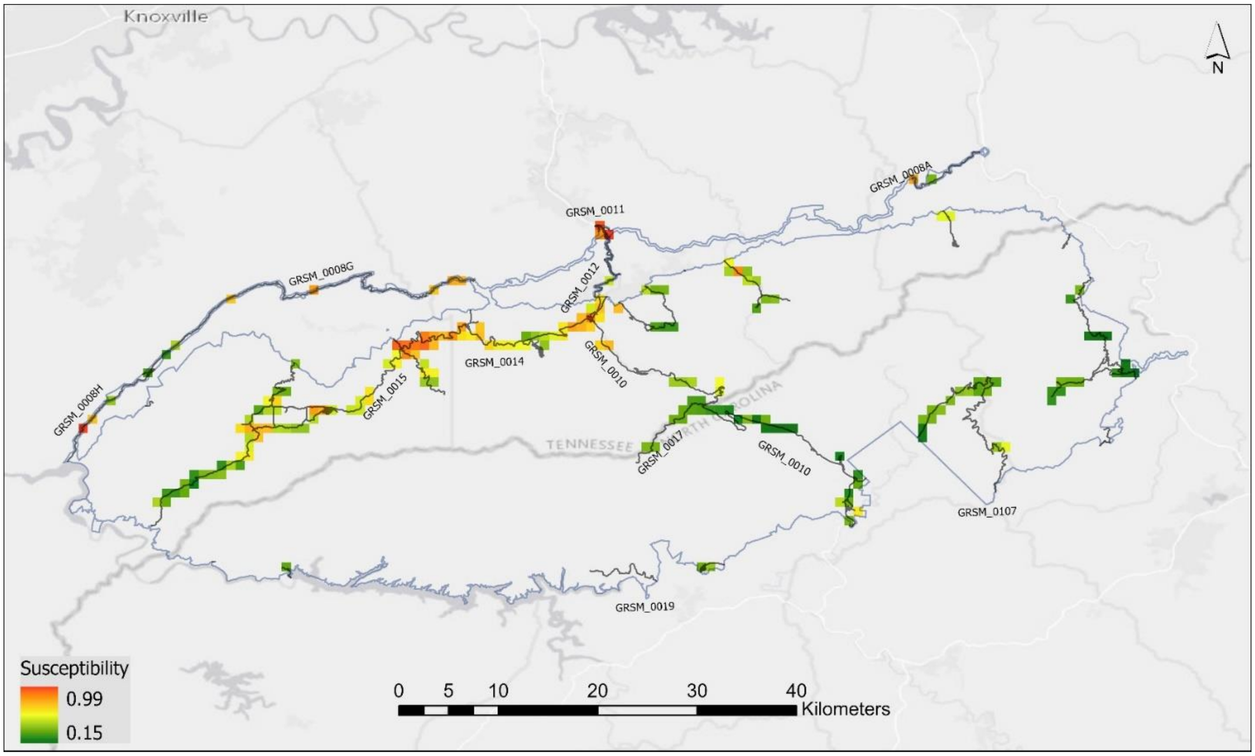

Figure 0.9. Susceptibility model produced from MaxEnt software using geology, faults, elevation, annual precipitation, and mean temperature of coldest quarter. Based on these parameters, red areas are considered more susceptible to rockfalls.

Rockfall Risk Model

The rockfall risk map and the error map were produced using the Ordinary Kriging interpolation method (Figures 2.10 – 2.12). A close-up view of the rockfall risk map (Figure 2.10) and related error map (Figure 2.11) are shown to identify areas of high rockfall risk and high areas of error. RMS was 130.1, RMSS was 1.035, and MS was -0.0235. The cross-validation predicted plot indicates the model is over-predicting with higher values and under predicting with lower values. Cell size of the rockfall risk map was 1.53 m. The rockfall risk map has a smaller cell size than the susceptibility model most likely due to using only rated rockfall locations compared to global data (WorldClim variables).

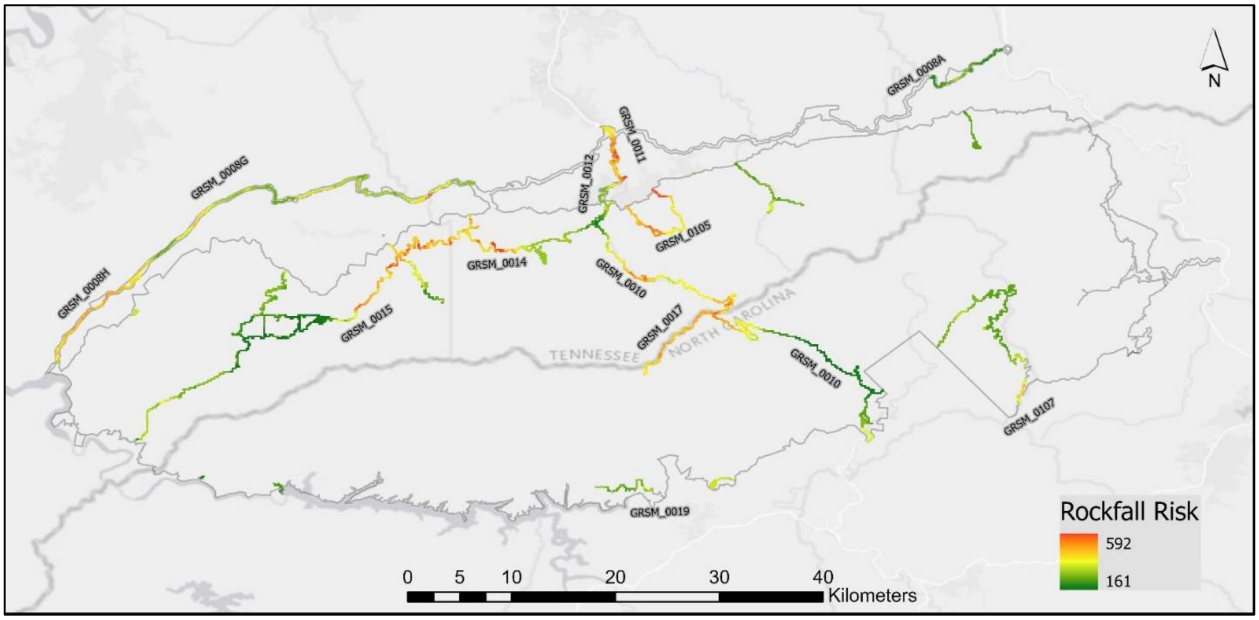

Figure 0.10. Ordinary kriging surface created in ArcGIS Pro using USMP Total Score; green areas indicate low risk while red areas are considered high risk.

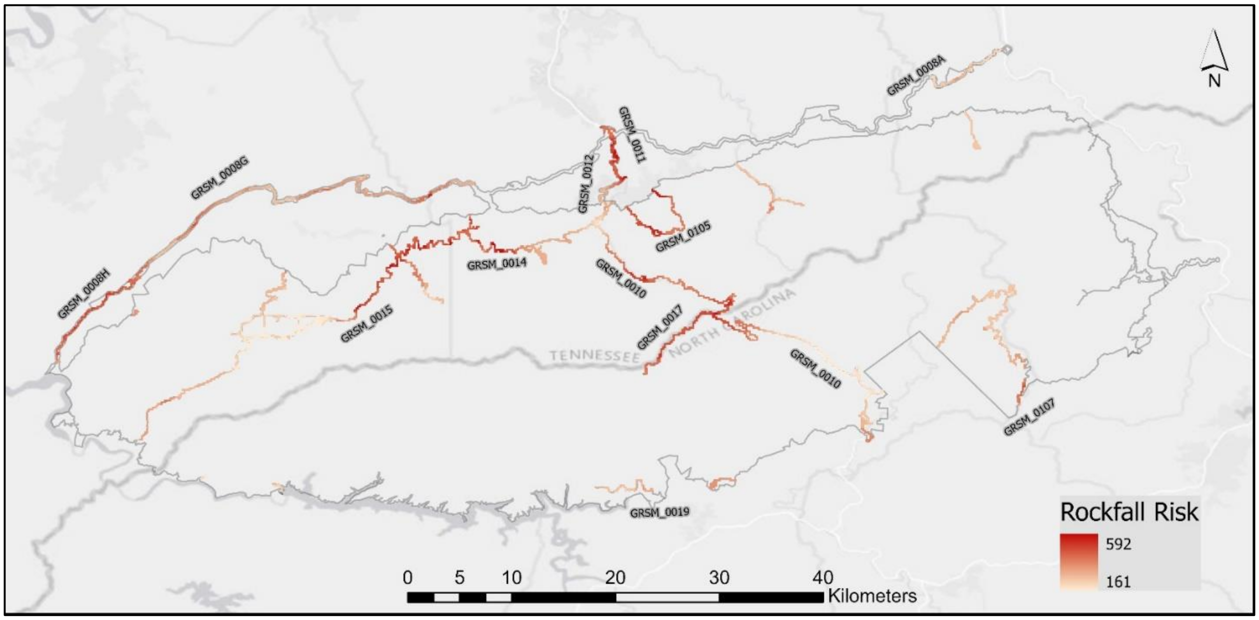

Figure 0.11. Error map of ordinary kriging surface, the higher the error, the more red. Sources of error are likely caused by lack of data along non-primary roadways.

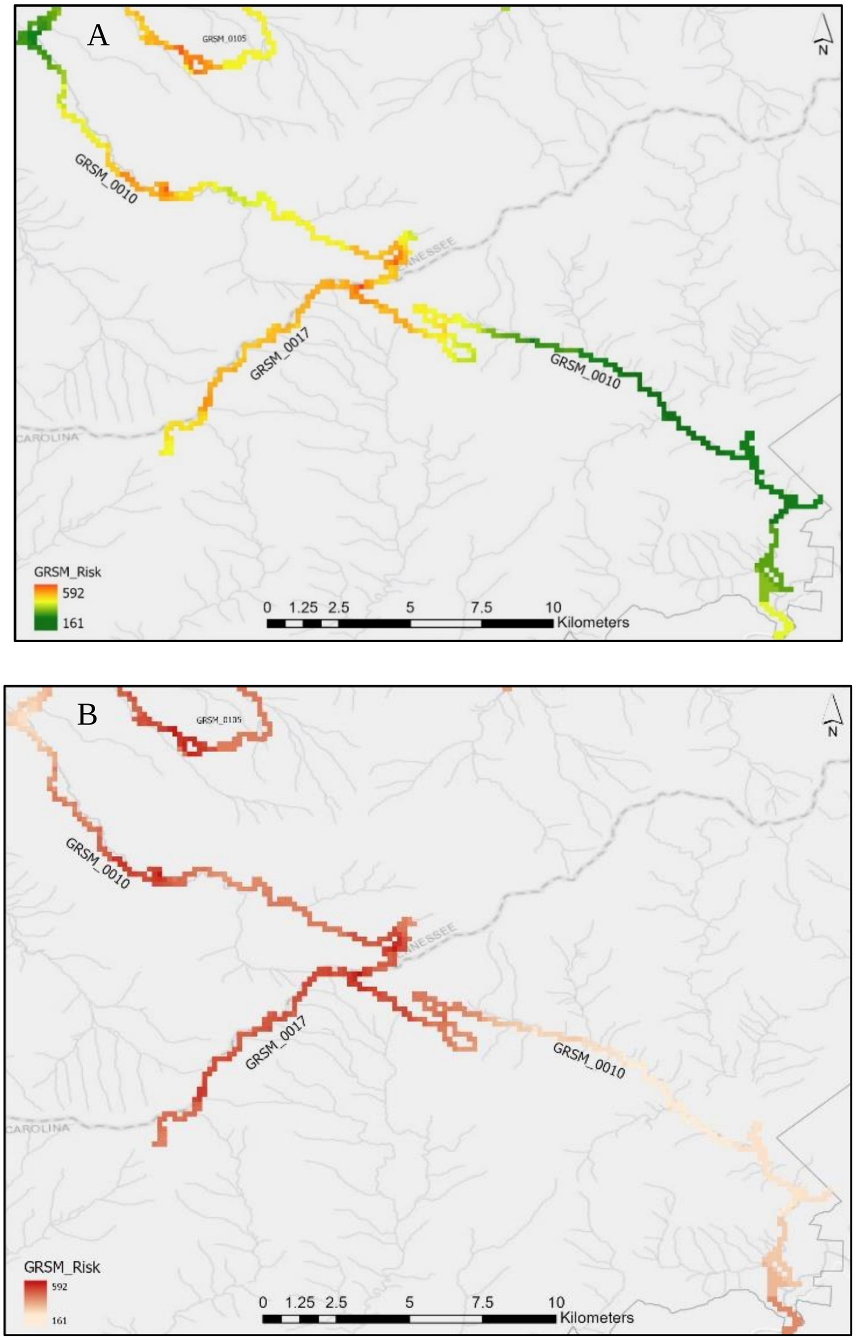

Figure 0.12A-B. A) Ordinary kriging model zoomed in on 0010 (Newfound Gap Rd.) and 0017 (Clingmans Dome Access Rd.) showing different level of risks. B) Error map of the same ordinary kriging model showing levels of error within in the model

Final Risk Model

The final rockfall risk map was produced using the Ordinary Co-Kriging interpolation method (Figures 2.13-2.15) with Risk map and Susceptibility map included as two co-variates. Cell size of the final risk map was 1.52 m. The model diagnostics resulted in a RMS of 15.6, RMSS of 0.937, and MS of 0.00281. The cross-validation graph indicates the model still slightly over predicts but has improved from the original risk model.

Co-Kriging proved to be a better model, as the RMS value dramatically reduced when compared to the ordinary kriging result; the RMSS value decreased and was slightly farther away from 1.0, but the MS value increased and was closer to 0.0 (Table 2.2).

Table 0.2. Model Diagnostics from Ordinary Kriging and Ordinary Co-Kriging

Model	RMS	RMSS	MS
Ordinary Kriging	130	1.035	-0.0235
Ordinary Co-Kriging	15.6	0.937	0.0281

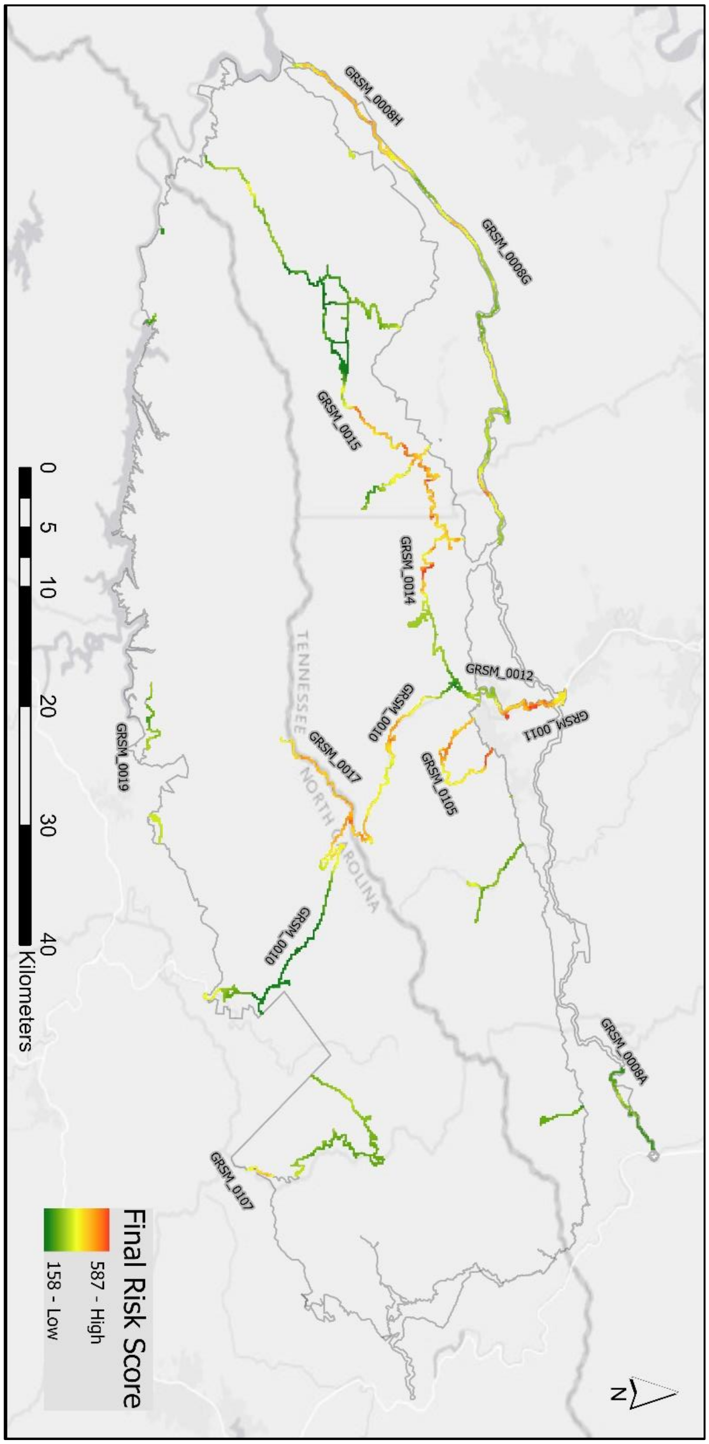

Figure 0.13. Final risk model of GRSM using Co-Kriging. Green areas are considered low risk and red areas are considered more at risk for rockfalls.

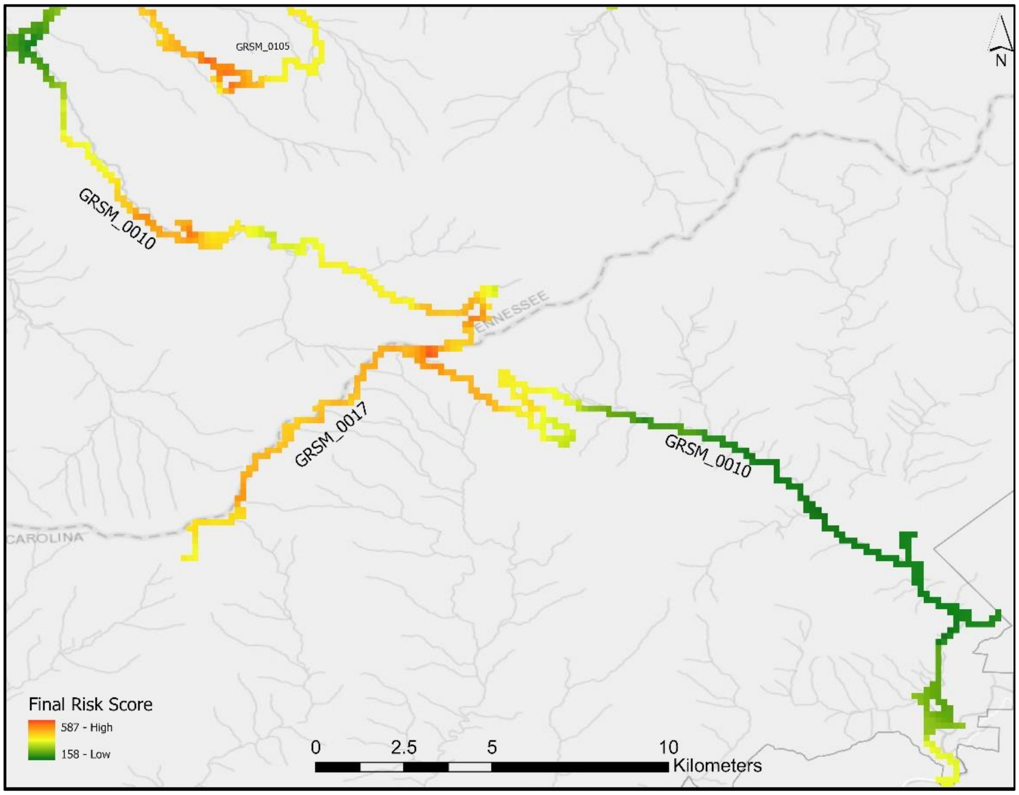

Figure 0.14. Zoomed in final risk map of Newfound Gap Rd. (GRSM_0010) and Clingman's Dome Rd (GRSM_0017).

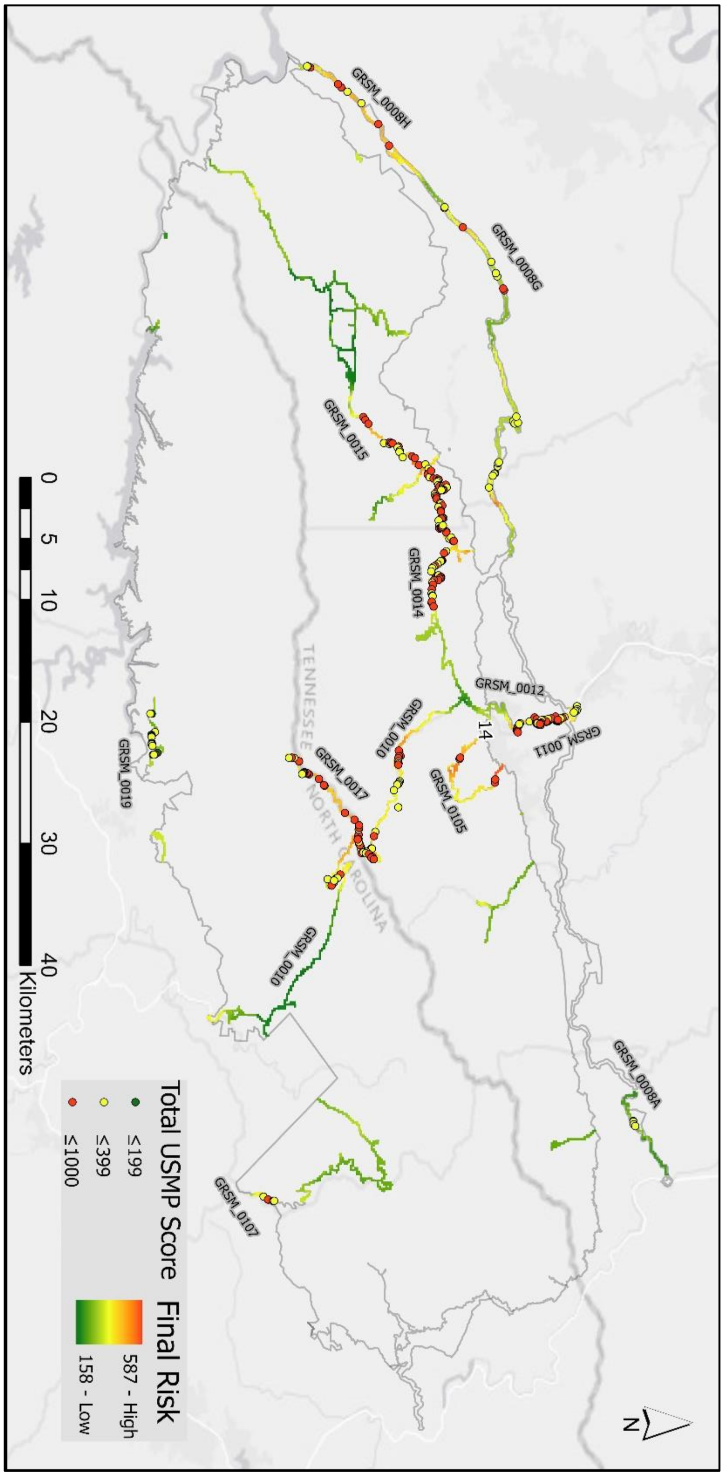

Figure 0.15. Final Risk map of Great Smoky Mountains National Park, as well as inventory of unstable slopes created for this project. Areas of green indicate stable slopes and low risk, orange areas are moderate rockfall risk, and red areas have the highest risk for rockfall.

Discussion

As a result of road construction exposing outcrops to weathering, erosion and natural processes, rockfalls have become a major issue within GRSM. Over the course of Summer 2019 to Summer 2020, 284 unstable slopes were rated in GRSM using the USMP Slope Rating form. The inventory is based on current slope conditions with slopes being rated as ‘good’, ‘fair’, or ‘poor’. This is the first time the park will have an inventory of all current unstable slopes, which allows GRSM to have a better understanding of slope conditions. A probable reason as to why most of the slopes in GRSM were rated so highly is because two categories were ‘maxed’ out at 81 points: AADT and Annual Precipitation. GRSM receives an extreme amount of traffic flow, and much of GRSM receives 152+ cm. (60+ in.) of yearly rainfall.

The susceptibility model indicated that 65% of GRSM roadways are suitable for rockfalls. Mean temperature coldest quarter (bio11) and elevation were the two most contributing factors in this susceptibility model. A possible explanation for mean temperature of coldest quarter (bio11) being the most contributing factor is it represents temperatures during the coldest months (December, January, February) when rockfalls are more likely to occur due to frost wedging (Synder, 1996; Matsuoka, 2001; Sass, 2005). Using Ordinary Kriging to create a rockfall risk map resulted in a slightly over-predicted but overall good model. However, finer temporal resolution (seasonal) precipitation data could improve the model output, but was not used in this study. Based on field observations and maintenance reports, nearly all areas considered by both models to be highly prone to rockfalls have the highest number of unstable slopes per road. Roads indicated to be the highest risk are: 1) Gatlinburg Spur, 2) Newfound Gap Rd., 3) Little River Gorge Rd., 4) Clingmans Dome Access Rd., and 5) Cherokee Orchard Rd. This is due to the poorly rated slopes along each roadway and associated environmental factors. However, the primary corridors, Gatlinburg Spur, Newfound Gap Rd., and Little River Gorge Rd., have the highest risk because they are also the heaviest travelled roads throughout the park. Therefore, keeping them free of rock debris is a priority to maximize visitor safety. The final risk map can offer a proactive first step for GRSM officials to prioritize specific roadways or high-risk areas in the park.

Kornejady et al. (2017) expressed a major limitation being that a failure event, particularly landslides, can be caused by various environmental factors, the same can be said for rockfalls. Also stated is that a landslide inventory should be conducted to better understand landslides in the study area (Ziarat watershed) which would provide a significant platform to decision-makers and authorities, much like the GRSM USMP geodatabase that was created during this research. Unlike the susceptibility model created in this research, Kornjady et al. (2017) used twelve controlling factors: altitude, slope percent, slope aspect, proximity to streams/roads/faults, precipitation, geology, land use/cover, plan/profile curvature, and height above nearest drainage. This provided a more acceptable AUC value (0.906) to this research's susceptibility model (0.749). In the future, the susceptibility model created in this paper could be improved by using more environmental factors, like land use/cover and aspect.

Azareh at al. (2019) used ten environmental factors to model gully erosion using MaxEnt: distance from rivers, geology, land use, slope angle, topographic wetness index, aspect, plan curvature, soil texture, elevation, and drainage density. The model AUC was 0.886 which provides a better model output than this research's susceptibility model (0.749). Azareh et al. (2019) concluded that the model output encouraged future work using MaxEnt or similar machine-learning algorithms to predict gully erosion – the same can be applied to GRSM. Improvement of the GRSM susceptibility model by applying more environmental factors provides opportunity for

GRSM decision-makers to evaluate sections of roadways more likely to experience a rockfall failure event.

Limitations

Project objectives were to create inventory of unstable slopes along primary paved roadways throughout the park. Therefore, unpaved roadways and non-priority roadways do not have data, limiting the data analysis based only on primary roads. It is also important to note that depending on time of year, slopes can be highly vegetated making it difficult to grasp a full understanding of slope stability conditions. Large volumes of traffic, especially on Gatlinburg Spur, make it difficult to cross the road, restricting researchers from getting at the toe of the slope and obtaining accurate slope measurements and distances (i.e., sight distance). In addition, most slope failures are not recorded on paper, only through news articles for large failures, or in the memories of current and past maintenance members. It was a challenge to collect previous slope failure information from maintenance as they have a busy schedule and simply cannot remember every rockfall in GRSM but offered as much assistance as they could.

An additional limitation included using coarser resolution precipitation data. Finer temporal resolution seasonal precipitation data could make the susceptibility model output more successful, as well as the addition of several inputs (e.g., soil type, land use, aspect).

Future Studies

A finer resolution rockfall susceptibility model should be created to include finer resolution precipitation data (seasonal), as well as, land use, aspect, and soil type to improve the model output. A final rockfall risk model should then be created using the updated susceptibility model.

A rockfall risk map can be utilized for several projects such as, prioritization of slope maintenance and emergency planning. In Study 2 of this project, the final rockfall risk map will be used to recommend potential locations for rockfall hazard warning signs and to conduct an annual individual risk estimate of three transportation corridors: 1) Gatlinburg Spur, 2) Newfound Gap Rd., and 3) Little River Gorge Rd.

Conclusion

Rockfalls are often unexpected surprises and can occur at what appear to be stable slopes. Understanding and monitoring current slope conditions can alleviate some of the uncertainty surround potential rockfall events. Using USMP slope rating protocols to create an inventory of unstable slopes in GRSM allows park officials and maintenance to see current conditions and prepare for future rockfall events. Although USMP is not designed for high-volume parks, it served as a great tool to create an inventory of unstable slopes. In the future, this could be an opportunity for the USMP slope rating protocols to be slightly altered.

The rockfall susceptibility map, rockfall risk map, and final risk map created in this study can act as tools to assist GRSM staff identify areas considered highly prone to rockfall failure events and prepare proactive approaches to mitigating those areas. These maps can also provide aid to future researchers and/or maintenance staff as a base to compare how the risk has changed throughout the years as rockfalls continue to occur. Information in this study is beneficial to taxpayers who pay for upkeep of park infrastructure and maintenance of roads and provide insight of the importance of mitigation for slopes with high slope instability ratings, and high-risk estimates. Results may lead to a proactive management approach from GRSM officials concerning specific unstable slopes and the potential to mitigate them.

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CHAPTER 3. RISK ESTIMATION OF HIGH PRIORITY UNSTABLE ROCK SLOPES AND INVESTIGATION OF ROCKFALL HAZARD WARNING SIGN LOCATIONS IN GREAT

Samantha Farmer

Abstract

An inventory of unstable rock slopes in Great Smoky Mountains National Park (GRSM) was utilized for two objectives: 1) create a transportation corridor quantitative risk analysis (QRA) using the Unstable Slope Management Program for Federal Land Management Agencies (USMP for FLMA) protocol and 2) identify and recommend locations ideal for additional rockfall hazard warning signs in GRSM. QRA for the corridors was based on the ten most unstable slopes from each of the three busiest roadways: 1) Gatlinburg Spur, 2) Newfound Gap Rd., and 3) Little River Gorge Rd. Results from the QRA indicated Little River Gorge Rd. had the highest risk (1.58E-07). 9 of 21 rockfall hazard warning signs do not appear to be near an unstable slope. Suggestions for additional hazard sign locations were based on current sign locations and active slopes.

Introduction

A task grant between the National Park Service (NPS), Great Smoky Mountains National Park (GRSM) and East Tennessee State University (ETSU) recognized a need to create an inventory of unstable slopes along primary roadways of GRSM to identify high rockfall risk areas, for emergency planning purpose, budget preparations, and public safety.

The Unstable Slope Management Program for Federal Land Management Agencies (USMP for FLMA) slope rating protocols were used to produce a catalog of unstable slopes in GRSM. Several products have been generated from the unstable slope data: 1) inventory of unstable slopes in GRSM, 2) rockfall susceptibility model using Maximum Entropy (MaxEnt), 3) rockfall risk map using Ordinary Kriging, and 4) final rockfall risk map by combining the susceptibility model and risk map using CoKriging. The final rockfall risk map identified sections of GRSM transportation corridors that are most prone to rockfall hazard. Details of the risk map and slope inventory can be found in Study 1 of this report.

Background

Rockfall hazard refers to the probability of occurrence of a rockfall event of a given volume or intensity over a predefined period within a given area (Varnes 1984). This includes probable location of a rockfall event, its temporal frequency, and magnitude or energy involved in the rockfall (Ferrari et al. 2016). Rockfall risk is referred to as the probability and severity that an event will happen and what the consequences could be to the public (Varnes 1984; Corominas et al. 2014; Ferrari et al. 2016; Capps et al. 2017). Castellanos and Van Westen (2007) state more research needs to be done in relation to visualization of risk and how effective it is with decision makers.

Rockfall hazard and risks have been evaluated using quantitative (Mignelli et al. 2012; Stock et al. 2012; Wang et al. 2013; Corominas et al. 2014; Capps et al. 2017) methods and qualitative (KoKo et al. 2004; Budetta and Nappi 2013) methods. A qualitative site evaluation is a basic requirement for rockfall hazard and risk assessment because it considers ground in situ parameters, natural triggers, as well as societal factors (Ko Ko et al. 2004; Capps et al. 2017; Beckstrand et al. 2019). The analysis produces results in terms of weighted indices, relative ranks (e.g., low, moderate and high) or numerical classification (Corominas et al. 2014).

Quantitative Risk Assessment (QRA) quantifies the probability of loss and the uncertainties related to a hazard. The consequence of rockfall hazards are always challenging to estimate using a QRA (Corominas et al. 2014). QRAs are vital to as they allow risks to be quantified in a reproducible manner so the results can be more easily compared from one site to another (Corominas et al. 2014). Corominas et al. (2014) describes the general framework of a QRA as evaluating risk assessment and risk control, which generally involves identifying and assessing the hazard, creating an inventory of elements (in this particular study, elements refers to vehicles and passengers within the vehicle) at risk, and producing a risk estimation using a risk equation (Varnes 1984; Fell 2005).

The QRA protocol is a standardized form within the Unstable Slope Management Program (USMP) suite that follows the rockfall hazard and risk evaluation for individual unstable slopes of concern (Capps et al. 2017; Beckstrand et al. 2019). The USMP QRA aims to assist decision-makers to better grasp the concept of rockfall risk when it is compared to a well-known risk, like the probability of being killed by cancer (Capps et al. 2017). The USMP QRA was utilized in Denali National Park on Denali National Park Road (Capps et al. 2017) and found the highest rated unstable slope is not necessarily the slope with the highest QRA score. This allowed park officials, stakeholders, geoscientists, and other parties to not assume the worst first, but to also conduct a QRA to understand and put an estimate to the risk involved at a slope or along a roadway.

There are several uncertainties in rockfall risk analysis: lack of accurate slope location and failure volume data, site-specific rockfall nature, measuring vulnerability of different elements, like tourists at risk and temporal variability (Michoud et al. 2012; Wang et al. 2013). The risk equation presented in Michoud et al. (2012) for their annual rockfall risk assessment, which focused on vehicles, was an adaptation of Fell et al. (2005): $R(E,x_p)=H(E,x_p)\times Exp(x_p)\times N_c(x_p)$ where

- R is risk expressed as number of direct impacts of blocks on cars annually based on hazard (H) and exposure (Exp);
- E,x_p represents the magnitude (E) at cell x_p
- And N_c is the number of vehicles threatened annually

Michoud et al. (2012) states the simplified Rockfall Hazard Rating System (RHRS) by Pierson et al. (1990), which the USMP Slope Rating System resembles, requires too high resolution datasets (i.e., Digital Elevation Models) and too many parameters to be practically used on large areas. Castellanos and Van Westen (2007) noted several drawbacks to existing landslide systems particularly in completeness in space, the databases are often not updated regularly, and are mostly biased to landslides if they have affected roads and other infrastructure. Corominas et al. (2014) noted limitations and sources of error when using QRA: 1) accurately determining spatial variability, measurement accuracy, and temporal variability. Improvement could be made by categorizing hazards into two groups: 1) conditional hazards (e.g., slope angle, land use, geology, soil, geomorphology, slope length, drainage density, and internal relief) and 2) triggering factors (e.g., precipitation and seismicity) (Castellanos and Van Westen 2007). Castellanos and

Van Westen (2007) continue to add that vulnerability indicators like physical indicators (e.g., housing condition and transportation), social indicators (e.g., population), economic production, and environmental indicators (e.g., protected areas) should also be considered, but can mostly only be applied at the municipal level within political-administrative borders.

Aucote et al. (2010) examined the public's behavior and knowledge about rockfalls in a questionnaire and found high-risk behavior is observed when the person does not believe the hazardous area is dangerous. Aucote et al. (2010) also noted the people who show high-risk behavior have negative attitudes towards hazard signs and doubt the validity of those signs. DeChano and Butler (2001) conducted a survey study in Glacier National Park concerning the public's perception about the likelihood of a mass movement event or debris flow in the park and the danger it poses to them. Unsurprisingly, most people discounted the likelihood of a mass movement event occurring during their visit but did state landslides were the highest risk to self. On July 28, 1998, a series of debris flows occurred and trapped several cars for 24 hours in Glacier National Park. The same survey given to visitors ten days prior to the debris flow was given to the visitors that experienced the debris flow to investigate potential change to public perception. The results indicated no significant changes in public perception of danger to self from landslides (DeChano and Butler 2001).

Ronay and Kim (2006) studied how different genders perceive risk and their attitudes towards them. The authors found males in a group are the most likely to disregard hazard warning signs as they tend to involve themselves in high-risk situations. Ultimately, the person, male or female, makes the decision to obey or disobey warning signs, called choice dilemma, based on the parameters that involve that choice (Ronay and Kim 2006).

NPS Management Policies (2006) states the following about identifying and managing geologic hazards:

"Naturally occurring geologic processes, which the Park Service is charged to preserve unimpaired, can be hazardous to humans and park infrastructure. These include earthquakes, volcanic eruptions, mudflows, landslides, floods, shoreline processes, tsunamis, and avalanches. The Service will work closely with specialists at the U.S. Geological Survey and elsewhere, and with local, state, tribal, and federal disaster management officials, to devise effective geologic hazard identification and management strategies. Although the magnitude and timing of future geologic hazards are difficult to forecast, park managers will strive to understand future hazards and, once the hazards are understood, minimize their potential impact on visitors, staff, and developed areas. Before interfering with natural processes that are potentially hazardous, superintendents will consider other alternatives." Section 4.8.1.3 Geologic Hazards.

Recent Rockfalls in GRSM

In Study 1 of this research, 284 unstable rock slopes were rated in GRSM, of which 130 were rated poor. GRSM maintenance noted nine rockfalls have occurred on Gatlinburg Spur, Newfound Gap Rd., and Little River Gorge Rd. within the past six years, with one slope on Newfound Gap requiring clean-up four times per year. Based on the maintenance notes, three roads appear consistently and happen to be the busiest roads in the park: Gatlinburg Spur, Newfound Gap Rd., and Little River Gorge Rd. It is likely several unrecorded, small-scale rock debris cleanups have occurred in GRSM since July 2019 (start of research), however, there have been some recent rockfalls that have made local news due to road closures. Because of the extremely high traffic volume of GRSM, re-opening roadways is vital.

The most recent slope failure occurred on February 12, 2021, on the southbound lanes of Gatlinburg Spur and closed one lane of traffic. Not much information was provided, other than a stability investigation was ongoing and could close both lanes if the slope were deemed still unstable (WBIR News 2021). Based on the single photo from the news article (Figure 3.1), it is assumed this is slope GRSM_219. If correct, this slope received a ‘poor’ rating (554) and was noted that this was the site of a previous wedge failure. The rockfall was likely caused by heavy rainfall and possibly freeze/thaw conditions from the fluctuating weather.

Figure 0.1. Top right: GRSM_219: the slope suspected to be the one that failed on February 12, 2021 on the Gatlinburg Spur. This slope received a poor rating (554) and was noted that previous wedge failures had occurred here. Bottom left: Google Earth image of GRSM_219 before failure. Bottom right: GRSM_219 shown on the interactive USMP database.

Another, recent recorded slope failure occurred on February 11, 2020 after the park experienced heavy rains. The slope failure happened in the northbound lanes of the Gatlinburg Spur, the busiest road in GRSM, and closed it for several hours. It was estimated that the failure was approximately 500 cubic yards of debris in a 100-foot-long and 70-foot-tall area (WJHL News 2020). According to WJHL News (2020), GRSM officials expected 45 dump truck loads would be required to remove the material. It should be noted that this slope was rated (GRSM_233) and received a ‘fair’ rating (386) (Figure 3.2). Traffic was able to be detoured to small side roads.

Figure 0.2. Left: Landslide that occurred on February 11, 2020 on Gatlinburg Spur in Great Smoky Mountains National Park. It was estimated by GRSM officials it would take 45 dump trucks to remove the estimated 500 cubic yards of material from the road. This slide did block both northbound lanes of the Spur. Photo: WJHL News (2020). Right: Samantha Farmer (researcher) in the process of rating GRSM_233, the mentioned above slope that failed. GRSM_233 received

a 'fair’ rating, and likely failed due to heavy precipitation. Photo credit: Thomas O’Shea (ETSU). Bottom: GRSM_233 shown on USMP interactive database.

On February 24, 2019, a rockfall occurred on the Spur due to heavy rainfall. This rockfall also closed the Spur temporarily, but detours were in place (WVLT News 2019). No information seems to be available that describes the actual location, volume of the rockfall, how long it took to clean up, or what actions were taken to stabilize the slope.

Objectives

Objectives in this study are to: 1) Develop a quantitative risk estimate based on the most unstable slopes of the three most traveled corridors in the park (Gatlinburg Spur [Spur], Little River Gorge Rd. [LRG], and Newfound Gap Rd. [NFG]) using USMP QRA, and 2) identify locations of existing rockfall hazard warning signs throughout GRSM and suggest locations for potential new signs based on a final rockfall risk map from study 1, and QRA analysis in the current study.

Methodology

To achieve the two objectives of the study a methodology was developed and is summarized in the following flowchart (Figure 3.3).

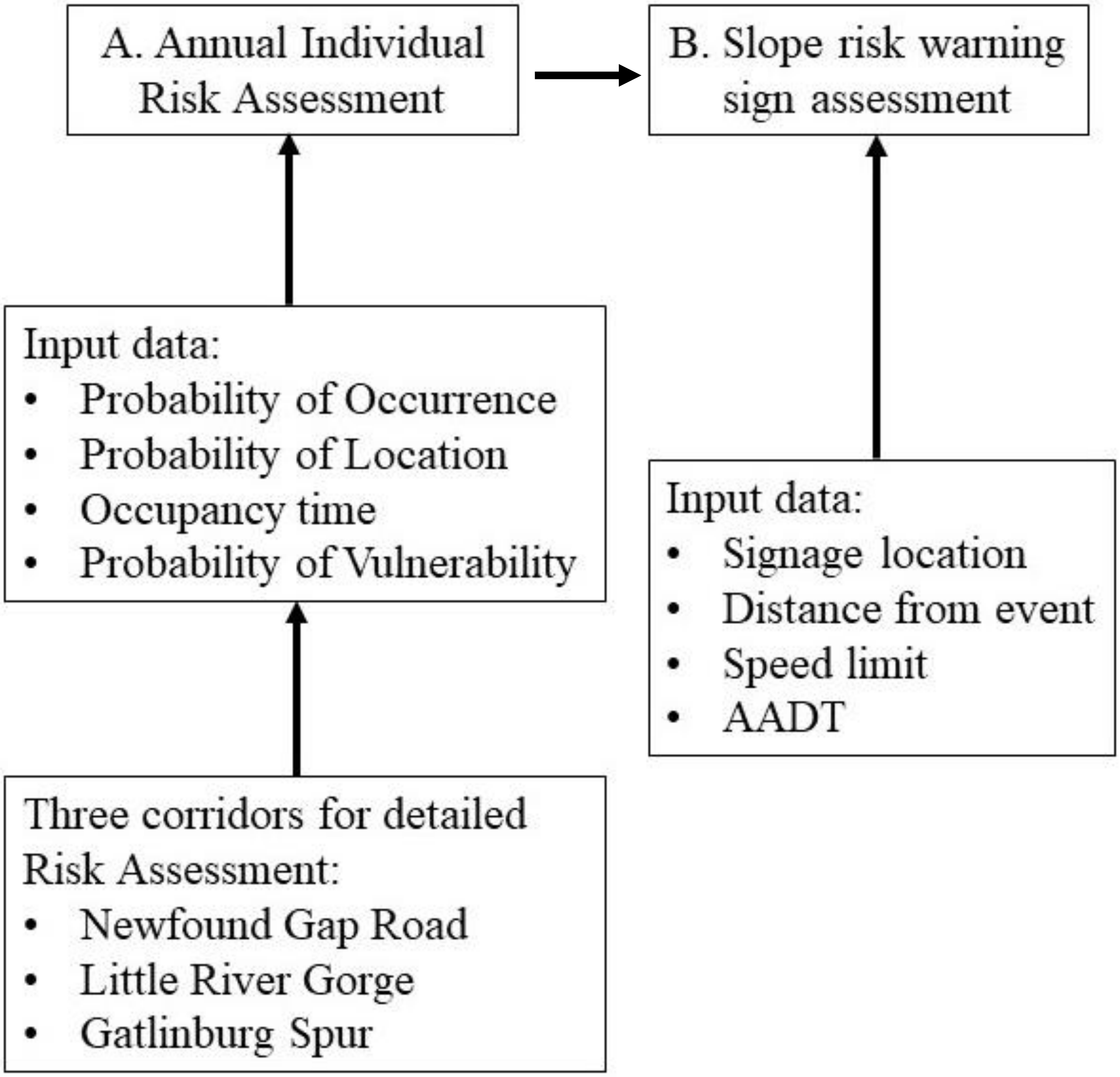

Figure 0.3. Flowchart used to achieve the objectives for Study 2

A. Quantitative Risk Analysis

Of the 284 total rockfall slopes rated, 183 slopes are on LRG, NFG, and the Spur – these slopes were the focus of the QRA (Figure 3.4). Ten of the highest rated slopes on each of the three mentioned roadways were used for the study. To estimate risk within the park, the USMP QRA technique (Appendix A) was used to evaluate annual individual risk and compared that with other well-known societal risks.

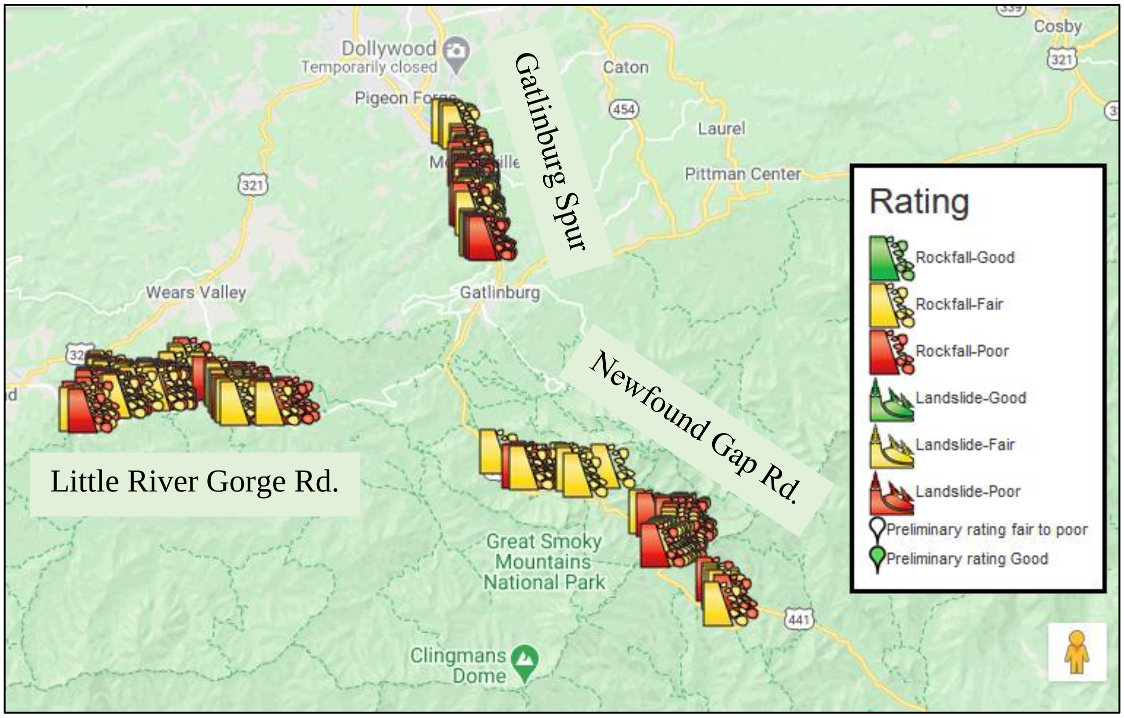

Figure 0.4. USMP rated slopes on the three most traveled corridors in GRSM: 1) Gatlinburg Spur, 2) Newfound Gap Rd, and 3) Little River Gorge Rd. These slopes account for 183 out of 284 total unstable slopes in the park. Along these roadways, zero slopes were rated ‘good’, 92 were rated ‘fair’, and 91 were rated ‘poor’.

The QRA is divided into several sections to allow for approximations of risk associated with a hazard (Beckstrand et al. 2019). These parameters include probability of occurrence, probability of location, occupancy time, and probability of vulnerability. The QRA uses the following equation:

$$R(AIR) = P(occ) \times P(loc) \times P(pres) \times P(vul)$$

- R(AIR) is the annual individual fatality risk (modified to be width of standard vehicle (1.7 m));
- P(occ) is the annual probability of an unstable slope event affecting the area of interest, the probability of occurrence;
- P(loc) is the probability of a person, if present, being in the path of one or more rocks at a given location. This is specific for hazards such as rockfall where the entire hazard zone is not necessarily affected by every event;
- P(pres) is the occupancy rate or rate of presence, the amount of time spent by an individual in the affected area; and
- P(vul) is the vulnerability, or probability of a person being killed or injured by the event.

The QRA tool also provides a comparison with other well-known societal risks such as southern California earthquakes, the incidence of cancer, and U.S. automobile accidents. Many planners and decision-makers in the GRSM are not geoscientists; the overall risk evaluation when compared to the other societal risk will help grasp the significance of slope instability in a comparative scale (Capps et al. 2017).

Data Collection

The inventory of unstable slopes in GRSM was collected along paved primary roadways, and it has been assumed that most people would drive continuously along the corridor and not stop. To evaluate the annual individual risk of rockfalls to vehicle traffic of the three mentioned corridors, the width of a car (1.7m) was used. It was also assumed that each car would pass by all of the unstable slopes along the transportation corridor to get from the beginning of the road to the end. Therefore, vulnerability is considered to be 100%. Likewise, it was assumed that each car holds four people, and each person's risk is equally high due to the driver's reaction in the event of a rockfall or rock debris in the roadway.

The QRA contains two probability categories: 1) probability of a rockfall failure event not triggered by an earthquake (referred to as background risk), and 2) probability of a rockfall failure event being triggered by an earthquake. Earthquake hazard is described as a disruption to normal activities of people because of anything associated with an earthquake (USGS, 2021). Earthquake hazard depends on magnitudes and locations of likely earthquakes, frequency, and the lithology and sediments of surrounding areas that earthquake waves travel through. Earthquake ground shaking will vary, and the United States Geological Survey (USGS) has created an Earthquake Hazard map to show the probability of a given amount of ground motion in 50 years (USGS 2021).

Earthquake ground motion is described as movement of earth's surface from earthquakes or explosives and is created by waves that are produced by sudden flip of a fault or sudden pressure of an explosive and travel through earth along the surface (USGS 2021). For this study, the annual rate of exceedance for peak ground acceleration (g) were found using USGS Unified Hazard tool by inputting the latitude and longitude of one of the highly rated unstable slopes on said corridor. The g values of 0.203 (20% gravity) and 0.103 (10% gravity) were recorded as evidence suggests a 10-20 Kilojoule rockfall is likely to be fatal (Grant et al. 2016).

B. Slope Risk Warning Sign Assessment

A secondary objective of this study is to evaluate usefulness of the existing slope hazard signage in the park. Field data collection for signage were conducted using a hand-held GPS unit (the same unit used for rock slope stability data in Study 1), and the same range-finder unit used for collecting accurate slope stability measurements. Detailed notes at each signage location were taken, and a brief observation of present slope conditions were noted. Evidence of cars going into the ditch (tire marks were present within the dirt in the ditch) and rock impact marks on the road were also noted. A qualitative judgement was made based on locations of the rockfall hazard warning signs, highest risk slopes, and the QRA values.

Results

QRA of Gatlinburg Spur

The Gatlinburg Spur had an approximate Annual Average Daily Traffic (AADT) of 49,000 (annual (365 days) = 17,885,000) in 2019 (reported by GRSM maintenance staff) making it the most traveled road in the park, as well as the road with some of the most devastating and frequent rockfall events. The ten highest rated slopes on the Spur were selected (Table 3.1; Figure 3.5), information for each slope was taken from the USMP Slope Rating form and included into the QRA equation. Values for a slope failure event not triggered by an earthquake were called background (BK) risk. Next, ground motion (g) values of 0.103 and 0.203 for each slope were identified using the USGS Unified Hazard Tool. The annual frequency of exceedance values for corresponding g values were put into the QRA form to recognize the impact an earthquake could have on a slope (EQ).

Table 0.1. Ten Highest Rated Unstable Slopes on Gatlinburg Spur; * denotes where rockfall event has been reported by GRSM maintenance (more slopes could have experienced failure, but no reports were available for this study); # represents rockfall hazard warning sign location.

Slope	**Total USMP Score**	**BK Risk**	**EQ Risk (0.103)**	**EQ Risk (0.203)**	**BK + EQ (0.103)**	**BK + EQ (0.203)**
GRSM_204*	775	3.15E-08	4.43E-10	1.66E-10	3.19E-08	3.17E-08
GRSM_207*	765	2.08E-08	3.81E-10	7.78E-11	2.12E-08	2.09E-08
GRSM_215*	762	2.68E-08	3.73E-10	1.39E-10	2.72E-08	2.69E-08
GRSM_218*	743	1.54E-08	3.50E-10	1.31E-10	1.58E-08	1.55E-08
GRSM_211	683	4.53E-09	3.82E-10	1.43E-10	4.91E-09	4.67E-09
GRSM_225$^\#$	677	1.99E-08	4.57E-10	1.17E-10	2.04E-08	2.01E-08
GRSM_244	648	6.21E-09	3.82E-10	1.58E-10	6.59E-09	6.37E-09
GRSM_239*	624	3.89E-08	3.83E-10	1.34E-10	3.93E-08	3.90E-08
GRSM_214$^\#$	420	4.48E-09	3.35E-10	1.25E-10	4.82E-09	4.61E-09
GRSM_254$^\#$	361	3.60E-09	2.99E-10	1.15E-10	3.90E-09	3.72E-09
SUM		1.72E-07	3.79E-09	1.36E-09	1.76E-07	1.73E-07
Mean		1.72E-08	3.79E-10	1.36E-10	1.76E-08	1.73E-08
Minimum		3.60E-09	2.99E-10	7.78E-11	3.90E-09	3.72E-09
Maximum		3.89E-08	4.57E-10	1.71E-10	3.93E-08	3.90E-08

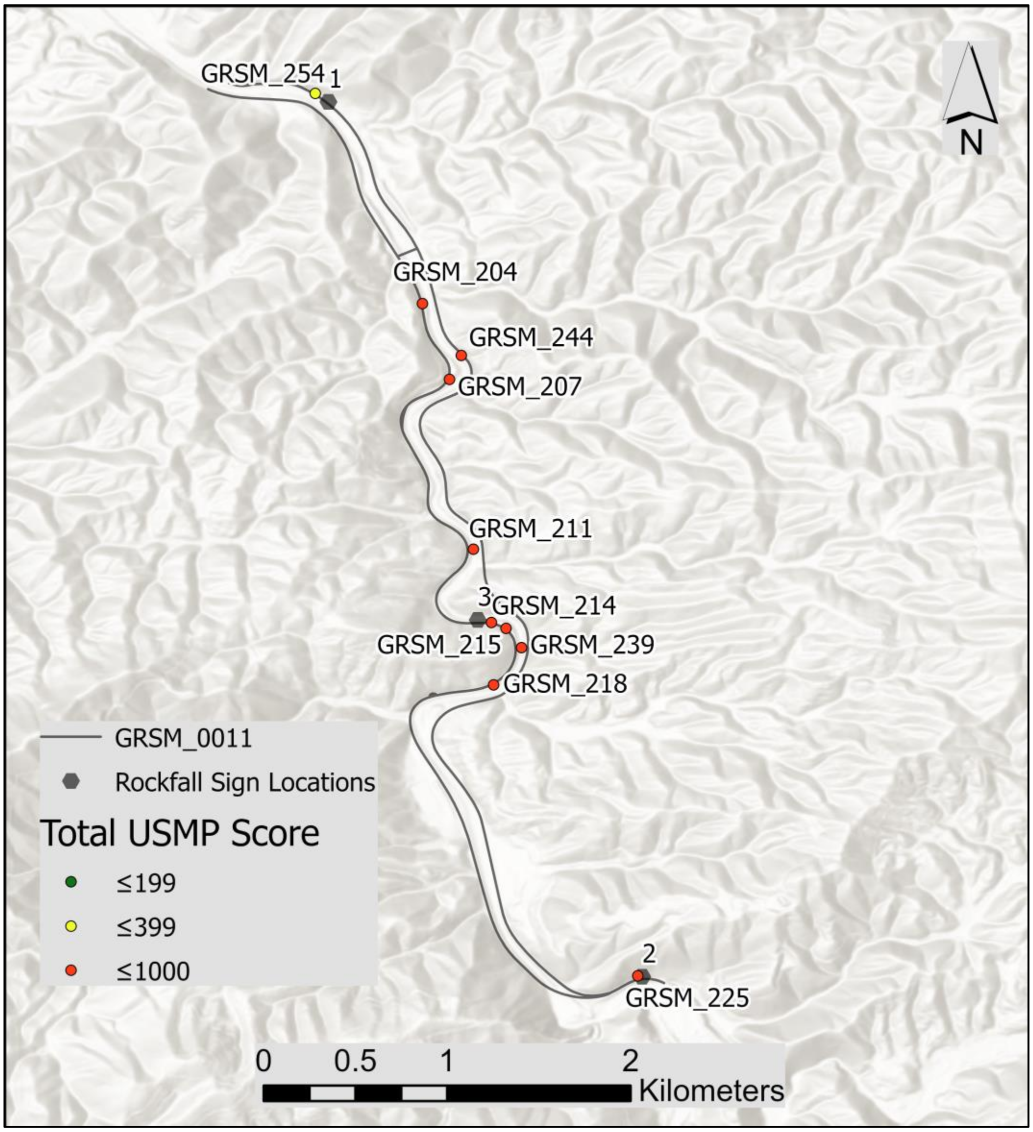

Figure 0.5. Ten highest rated unstable slopes along Gatlinburg Spur (GRSM_011) used for QRA. Rockfall hazard warning signs found along the Spur are also marked.

Newfound Gap Road

Newfound Gap Road received an estimated AADT of 4400 (annual = 1,606,000) in 2019 (GRSM park staff). Unlike the one-way travel of the Spur lanes, visitors driving on Newfound Gap Rd would pass potentially hazardous slopes twice, once going up and once coming down. In the USMP QRA, there is a selection for two-way travel, which does increase the individual risk.

The ten highest rated unstable slopes on Newfound Gap were identified, put into the QRA form, and corresponding g values of 0.103 and 0.203 were found for each slope (Table 3.2; Figure 3.6).

Table 0.2. Ten Highest Rated Unstable Slopes on Newfound Gap Rd; * denotes previous rockfall failure recorded by GRSM staff (although more sites could have had slope failures and were not reported to us); # denotes a rockfall hazard warning sign location.

Slope	**Total USMP Score**	**BK Risk**	**EQ Risk (0.103)**	**EQ Risk (0.203)**	**BK + EQ (0.103)**	**BK + EQ (0.203)**
GRSM_002[#]	756	5.53E-07	1.31E-09	4.74E-10	5.66E-08	5.58E-08
GRSM_020	711	2.58E-08	8.41E-10	3.08E-10	2.66E-08	2.61E-08
GRSM_013	641	2.37E-08	1.20E-09	4.35E-10	2.49E-08	2.41E-08
GRSM_011	609	2.68E-08	9.84E-20	3.57E-10	2.78E-08	2.72E-08
GRSM_010	580	2.42E-08	1.45E-09	5.27E-10	2.57E-08	2.47E-08
GRSM_047	511	1.38E-08	7.89E-10	2.85E-10	1.46E-08	1.41E-08
GRSM_021	466	2.48E-08	1.50E-09	5.49E-10	2.63E-08	2.53E-08
GRSM_034	457	2.29E-08	8.74E-10	3.17E-10	2.38E-08	2.32E-08
GRSM_024	455	1.61E-08	9.88E-10	3.62E-10	1.71E-08	1.65E-08
GRSM_005[*]	447	1.13E-08	6.23E-10	2.26E-10	1.19E-08	1.15E-08
SUM		2.45E-07	1.06E-08	3.84E-09	2.55E-07	2.49E-07
Mean		2.45E-08	1.06E-09	3.84E-10	2.55E-08	2.49E-08
Minimum		1.13E-08	6.23E-10	2.26E-10	1.19E-08	1.15E-08
Maximum		5.53E-08	1.50E-09	5.49E-10	5.66E-08	5.58E-08

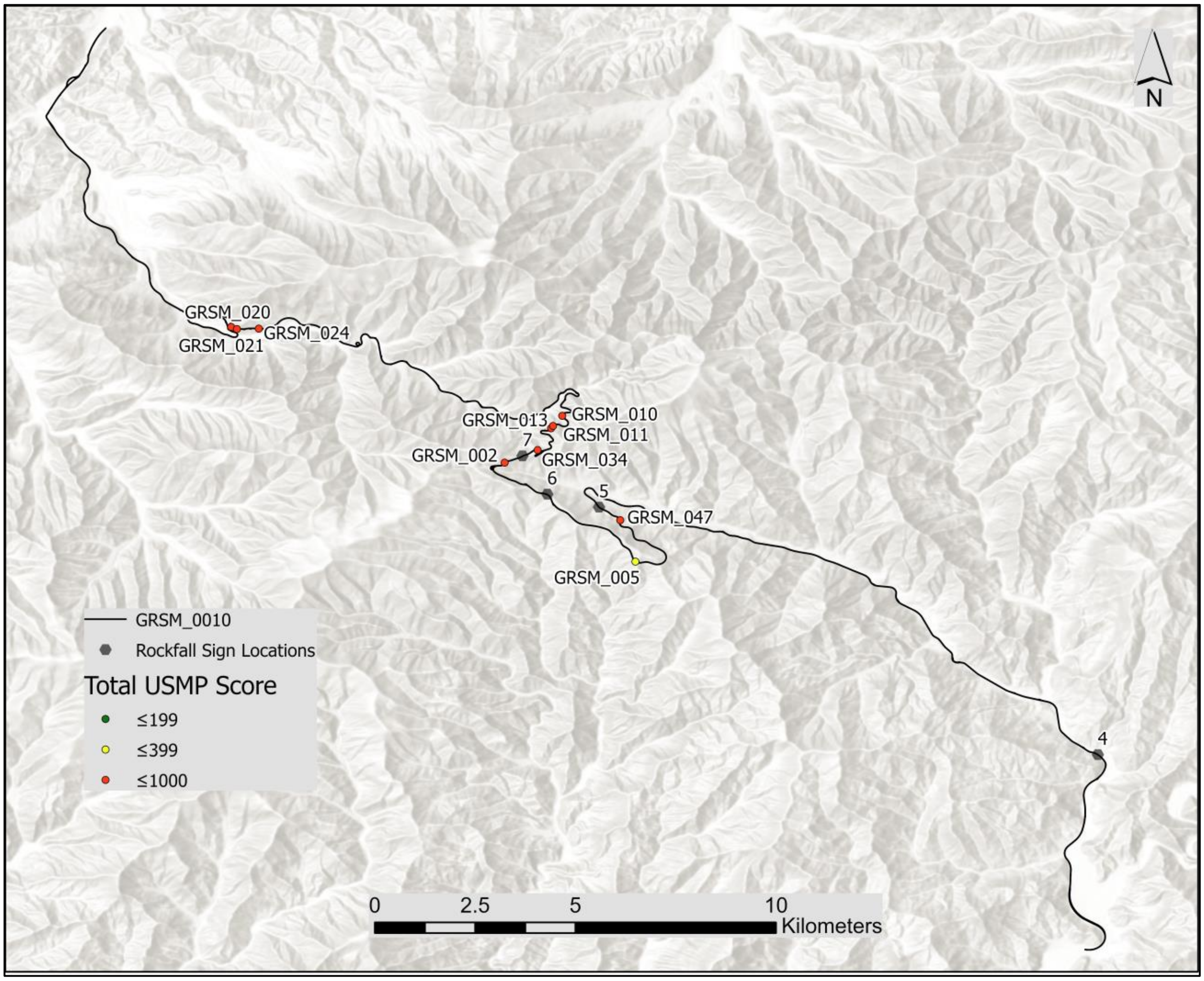

Figure 0.6. Ten highest rated unstable slopes along Newfound Gap Rd (GRSM_0010) used for QRA. Rockfall hazard warning sign locations along Newfound Gap Rd are also indicated.

Little River Gorge

Little River Gorge Road received a projected AADT of 3900 (annual = 1,423,500) in 2019 (GRSM park staff). Like Newfound Gap Rd, visitors driving on Little River Gorge would pass potentially hazardous slopes twice, once going up and once coming down, increasing the individual risk. The two-way travel section of the USMP QRA was selected which increases the amount of individual risk. The ten highest rated unstable slopes on Little River Gorge were identified, put into the QRA form, and corresponding g values of 0.103 and 0.203 were found for each slope (Table 3.3; Figure 3.7).

Table 0.3. Ten Highest Rated Slopes on Little River Gorge Rd; * denotes where previous rockfall failure has been recorded by maintenance (although some slopes could have previously failed and were not reported to us); there are no rockfall hazard warning signs on this roadway.

Slope	**Total USMP Score**	**BK Risk**	**EQ Risk (0.103)**	**EQ Risk (0.203)**	**BK + EQ (0.103)**	**BK + EQ (0.203)**
GRSM_109	984	9.24E-09	1.33E-09	5.24E-10	1.06E-08	9.76E-09
GRSM_051*	819	9.29E-08	1.30E-09	4.97E-10	1.06E-08	9.79E-09
GRSM_066	791	1.89E-08	1.47E-09	5.56E-10	2.04E-08	1.95E-08
GRSM_110	762	1.81E-08	1.14E-09	4.44E-10	1.92E-08	1.85E-08
GRSM_070	751	1.81E-08	1.15E-09	3.79E-10	1.93E-08	1.85E-08
GRSM_125	716	1.88E-08	1.61E-09	6.29E-10	2.04E-08	1.94E-08
GRSM_069	699	1.86E-08	1.30E-09	4.94E-10	1.99E-08	1.91E-08
GRSM_090	699	1.57E-08	1.06E-09	4.09E-10	1.68E-08	1.61E-08
GRSM_101	678	1.57E-08	1.09E-09	4.24E-10	1.68E-08	1.61E-08
GRSM_088	675	1.56E-08	1.01E-09	3.92E-10	1.66E-08	1.60E-08
SUM		1.58E-07	1.25E-08	4.75E-09	1.70E-07	1.63E-07
Mean		1.58E-08	1.25E-09	4.75E-10	1.70E-08	1.63E-08
Minimum		9.24E-09	1.01E-09	3.79E-10	1.06E-08	9.76E-09
Maximum		1.89E-08	1.61E-09	6.29E-10	2.04E-08	1.95E-08

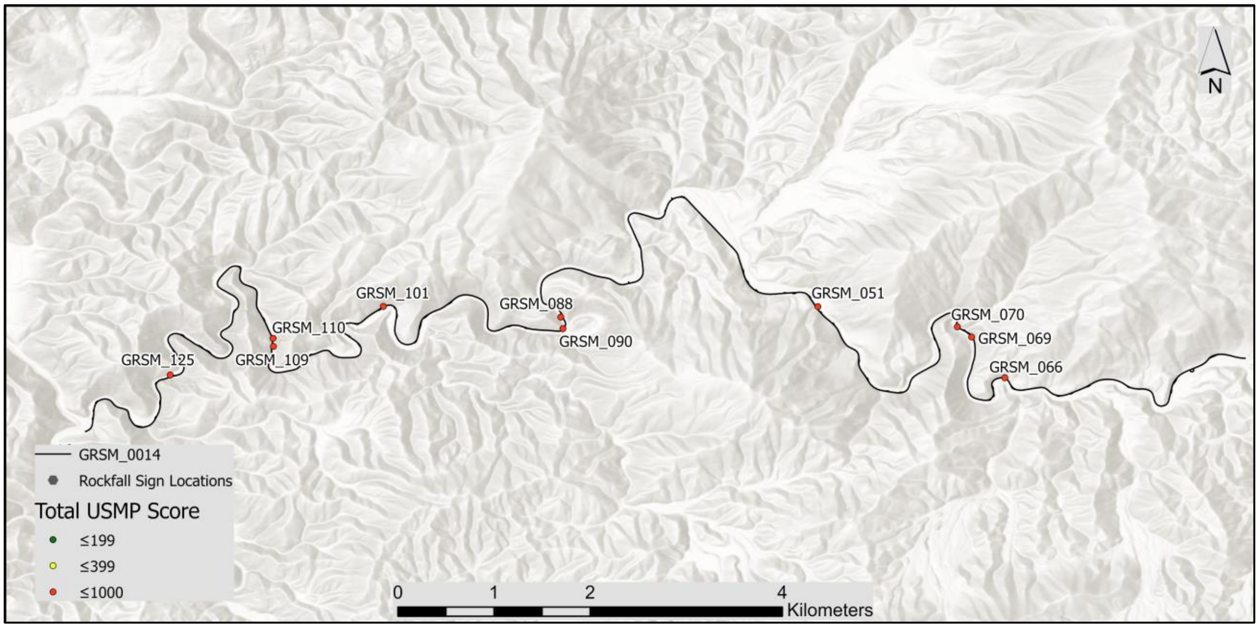

Figure 0.7. Ten highest rated unstable slopes along Little River Gorge Rd (GRSM_0014) used for QRA.

Based on the USMP QRA protocols for each of the slopes on the corridors, background risk and earthquake risks were plotted together in conjunction with total score to provide a better understanding of the risk of the corridor (Figures 3.5-3.7). A graph was created for each roadway to provide visual context on annual individual risk, as well as the impact of background risk in addition to earthquake risk when the peak ground acceleration is 10% and 20% at a specific slope.

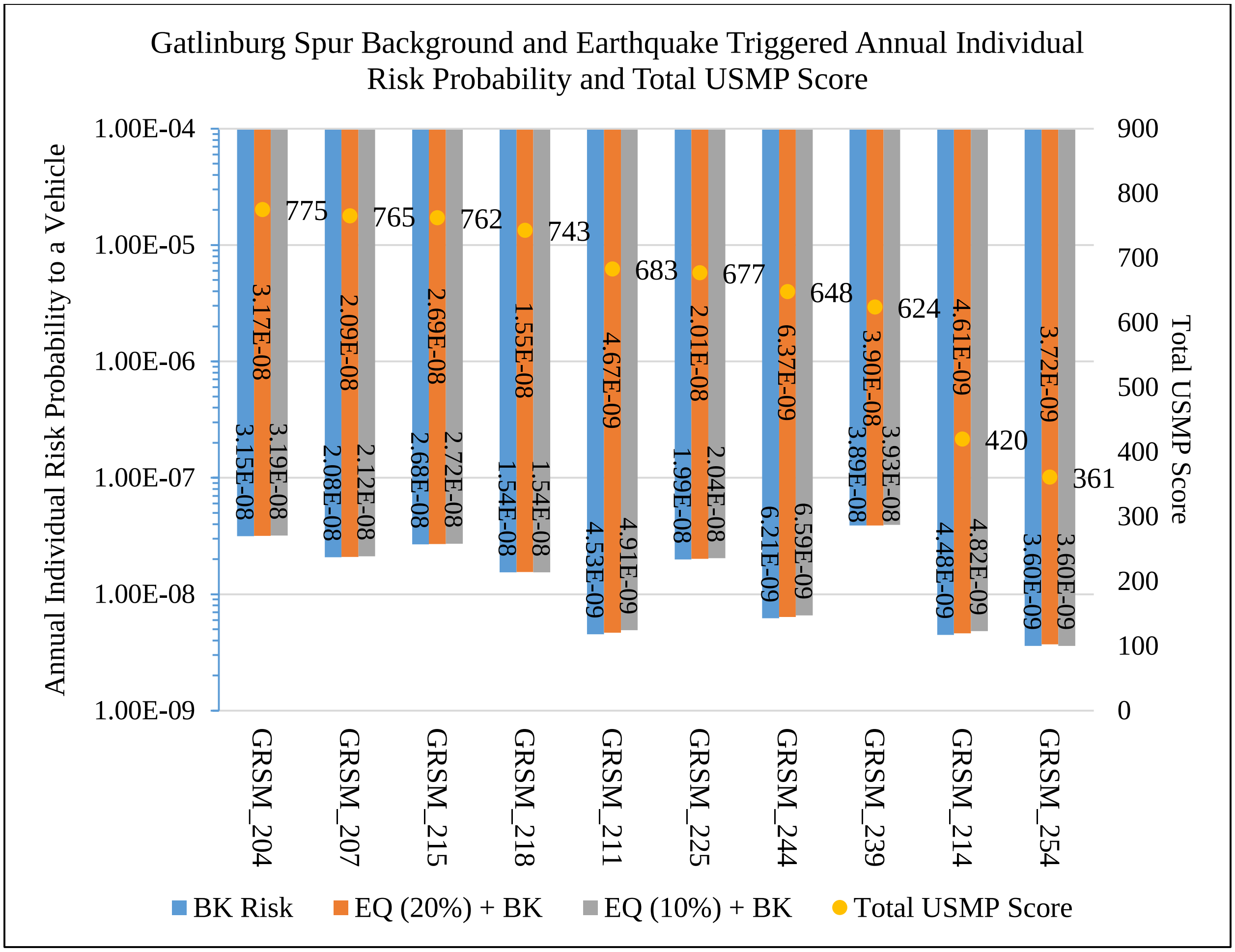

Figure 0.8. Gatlinburg Spur earthquake and non-earthquake triggered annual individual risk probability coupled with the corresponding slope’s total USMP score. The blue bar represents background risk, orange is earthquake risk when g = 10%, grey is earthquake risk when g = 20%, and the yellow point represents total score.

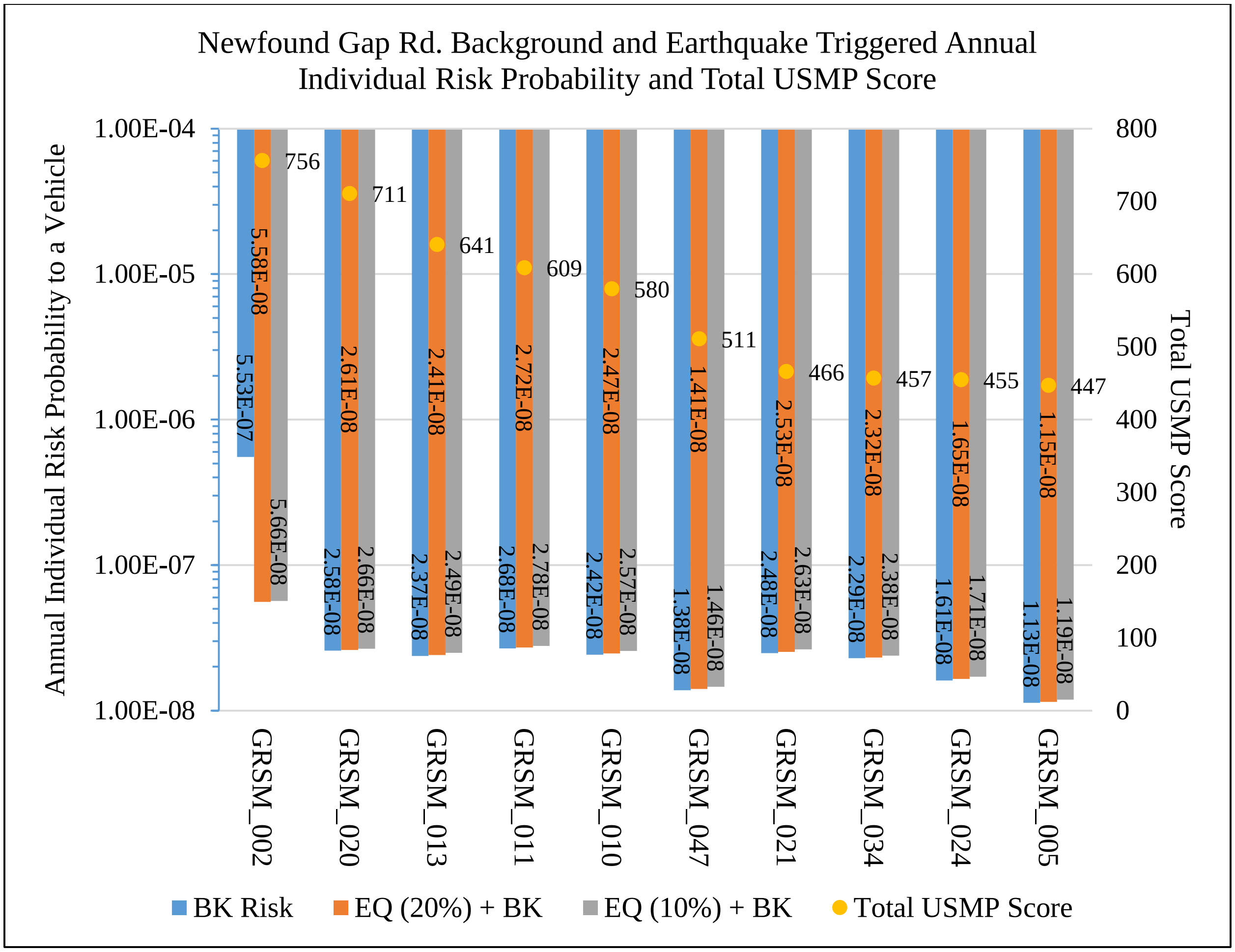

Figure 0.9. Newfound Gap Rd. earthquake and non-earthquake triggered annual individual risk probability coupled with the corresponding slope’s total USMP score. The blue bar represents background risk, orange is earthquake risk when g = 10%, grey is earthquake risk when g = 20%, and the yellow point represents total score.

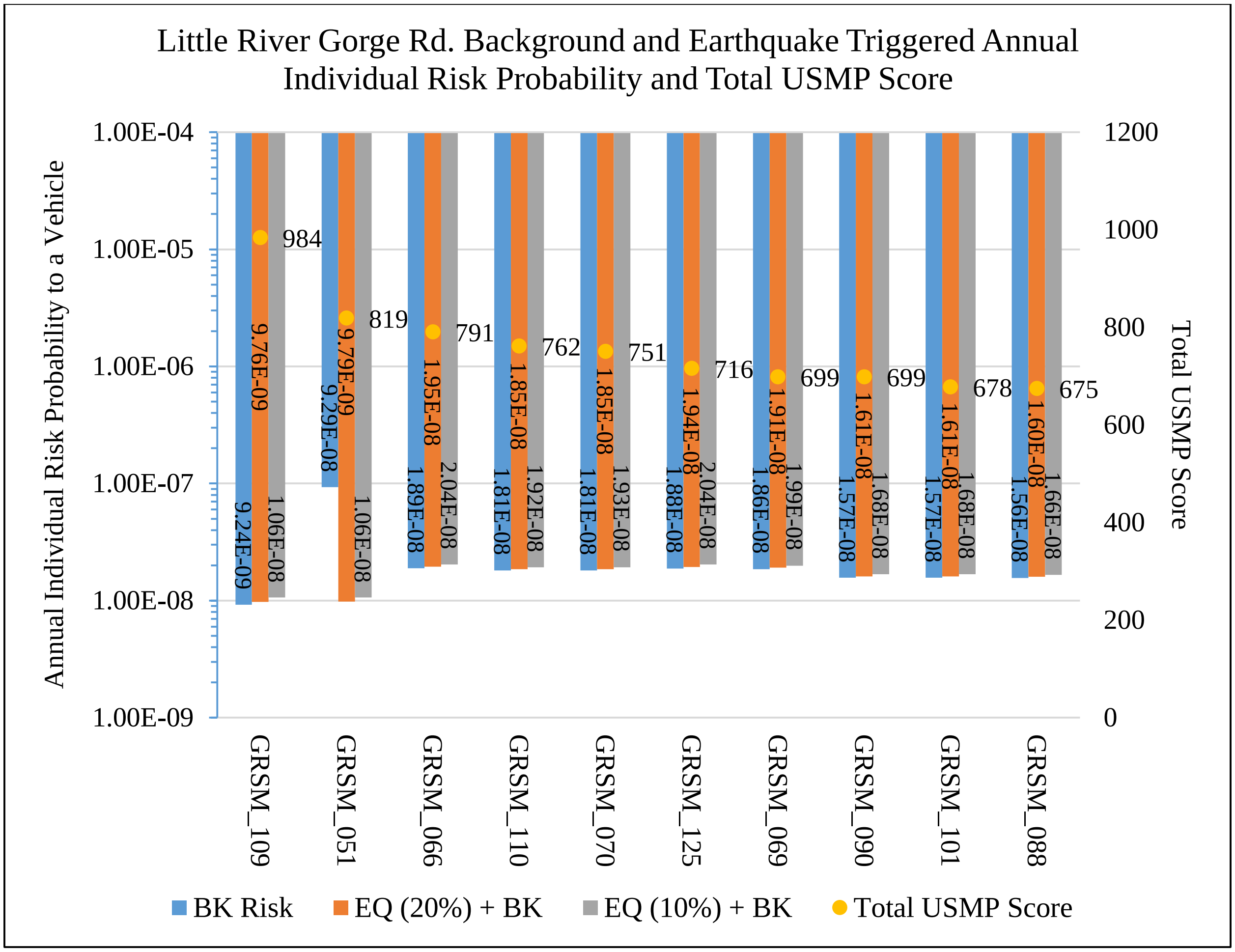

Figure 0.10. Little River Gorge Rd. earthquake and non-earthquake triggered annual individual risk probability coupled with the corresponding slope's total USMP score. The blue bar represents background risk, orange is earthquake risk when g = 10%, grey is earthquake risk when g = 20%, and the yellow point represents total score.

Gatlinburg Spur had the highest spread of numerical risk values while Little River Gorge Rd. did not have as big of a difference. Figure 3.8 shows the Spur being the roadway with the greatest risk variability, followed by Newfound Gap Rd., and Little River Gorge Rd. Outliers are present in on Little River Gorge Rd and Newfound Gap Rd. The outliers for Newfound Gap Rd. are from the maximum value of risk (refer to Table 3.2), while the outliers for LRG are from the minimum risk values (refer to Table 3.3). GRSM_021 has the highest BK risk on Newfound Gap Rd., while GRSM_002 has the highest risk to vehicles when EQ risk is added to BK risk. On Little River Gorge Rd., GRSM_066 received the maximum risk score in BK risk, and BK + EQ risks identifying it has the slope with the most risk to vehicles. Finally, on Gatlinburg Spur, GRSM_239 had the highest risk value in BK risk and BK + EQ risks. Based on the comparison graph of the three roads QRAs, it appears the Spur is the corridor with the highest annual rockfall risk to vehicles.

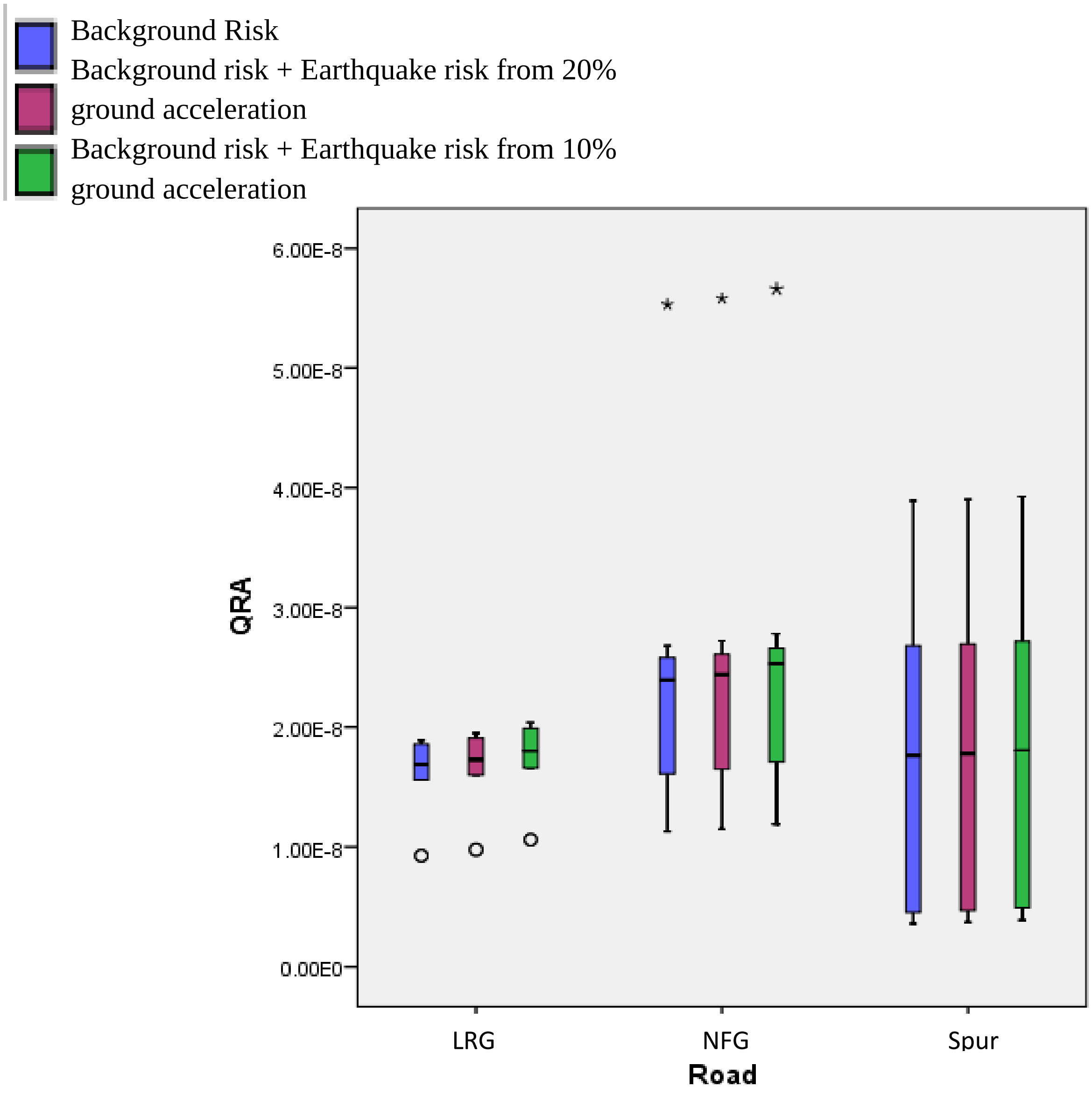

Figure 0.11. Comparison graph of Gatlinburg Spur, Newfound Gap Rd., and Little River Gorge Rd. QRAs. Outliers are shown on LRG (open circles) and NFG (asterisks).

Sum of BK risk, EQ risk 0.103, and EQ risk 0.203 for each of the three corridors were recorded and compared to other well-known societal risks, like cancer, homicide, and vehicle motor accident fatalities (Figure 3.9). This allows non-specialists, like maintenance staff, to gain a better visual understanding of the annual risk of the three most traveled corridors.

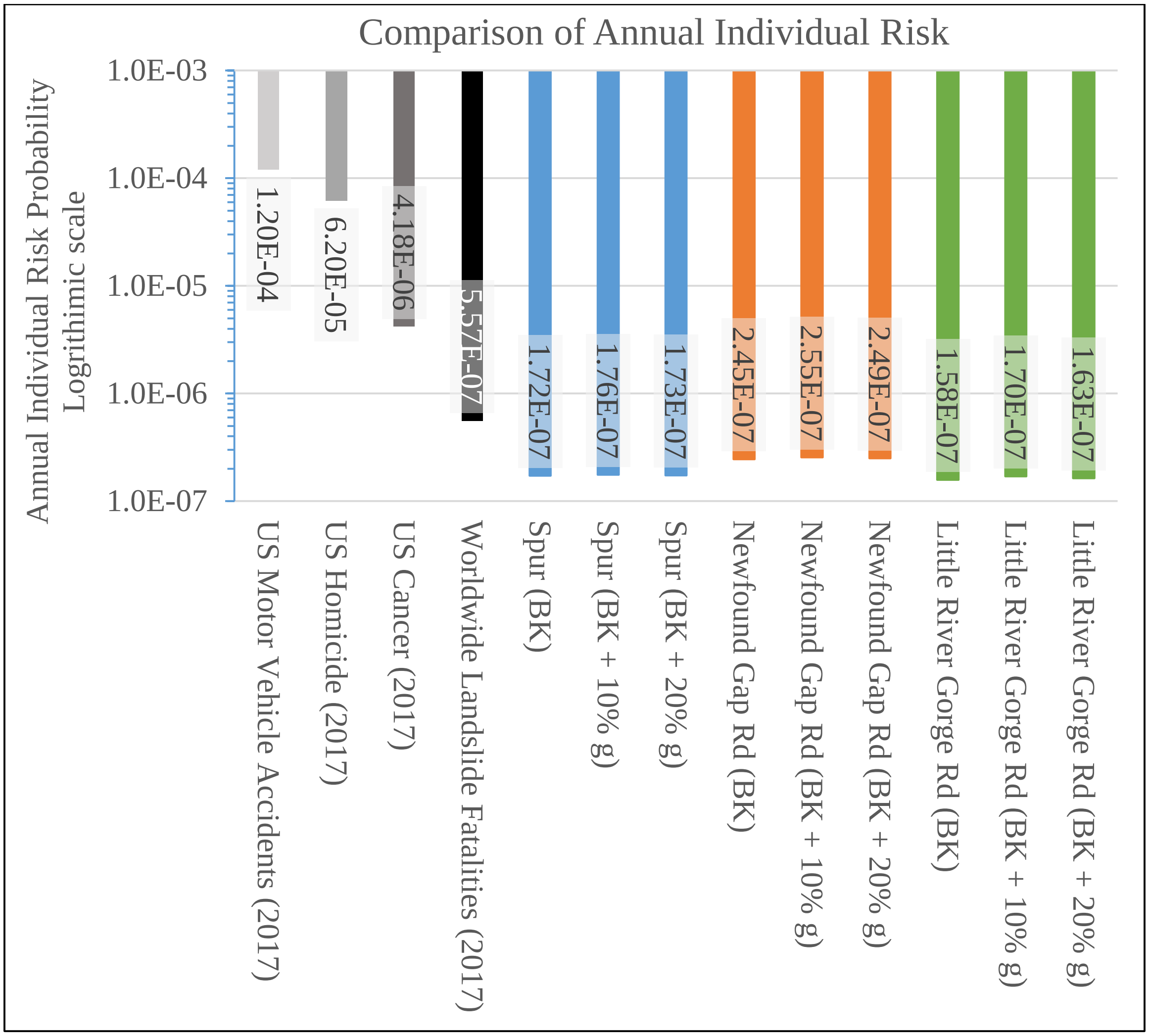

Figure 0.12.GRSM Gatlinburg Spur, Newfound Gap Rd, and Little River Gorge Rd annual individual risk probabilities being compared to other well-known societal risks to allow non-specialists a better understanding of the risk.

Large earthquakes are not common in GRSM and the probability of an earthquake triggering a rockfall is relatively small in the park. However, they are possible as USGS recorded a 2.4 magnitude earthquake on November 11, 2020 (USGS 2020).

Environmental factors, such as precipitation and freeze/thaw conditions, contribute more to slope failures in GRSM. Of the three corridors in this study, Gatlinburg Spur, is the most likely to experience rockfalls, but does not have the highest annual individual risk. Little River Gorge Rd. has the highest background annual individual risk per car (1.58E-07), followed by Gatlinburg Spur (1.72E-07), and Newfound Gap Rd. (2.45E-07). The risks for each corridor are most similar to World Landslide Fatalities (5.57E-07) which is not surprising.

B. Slope Risk Warning Signs

Results

Most visitors will pass one of the 21 rockfall hazard warning signs throughout GRSM with some being in rockfall prone areas and some being in seemingly stable areas (Figure 3.10; Table 3.4). For example, sign locations on Newfound Gap (GRSM_0010) (signs 4 & 5) do not appear to have any unstable or stable slope nearby. These signs could have warned of previous slope failures that have occurred, been cleaned up, and been stabilized. However, no immediate slope failure exists, and the signage location should be re-evaluated. The catalog of unstable slopes provides an opportunity for GRSM to assess the current placement of signs. Each road in GRSM should be separately evaluated for potential rockfall hazard sign locations. There are hazard warning signs in prime areas where rockfall events happen often, like on Gatlinburg Spur, but there are still active failures (GRSM_051) in the park that do not have warning signs.

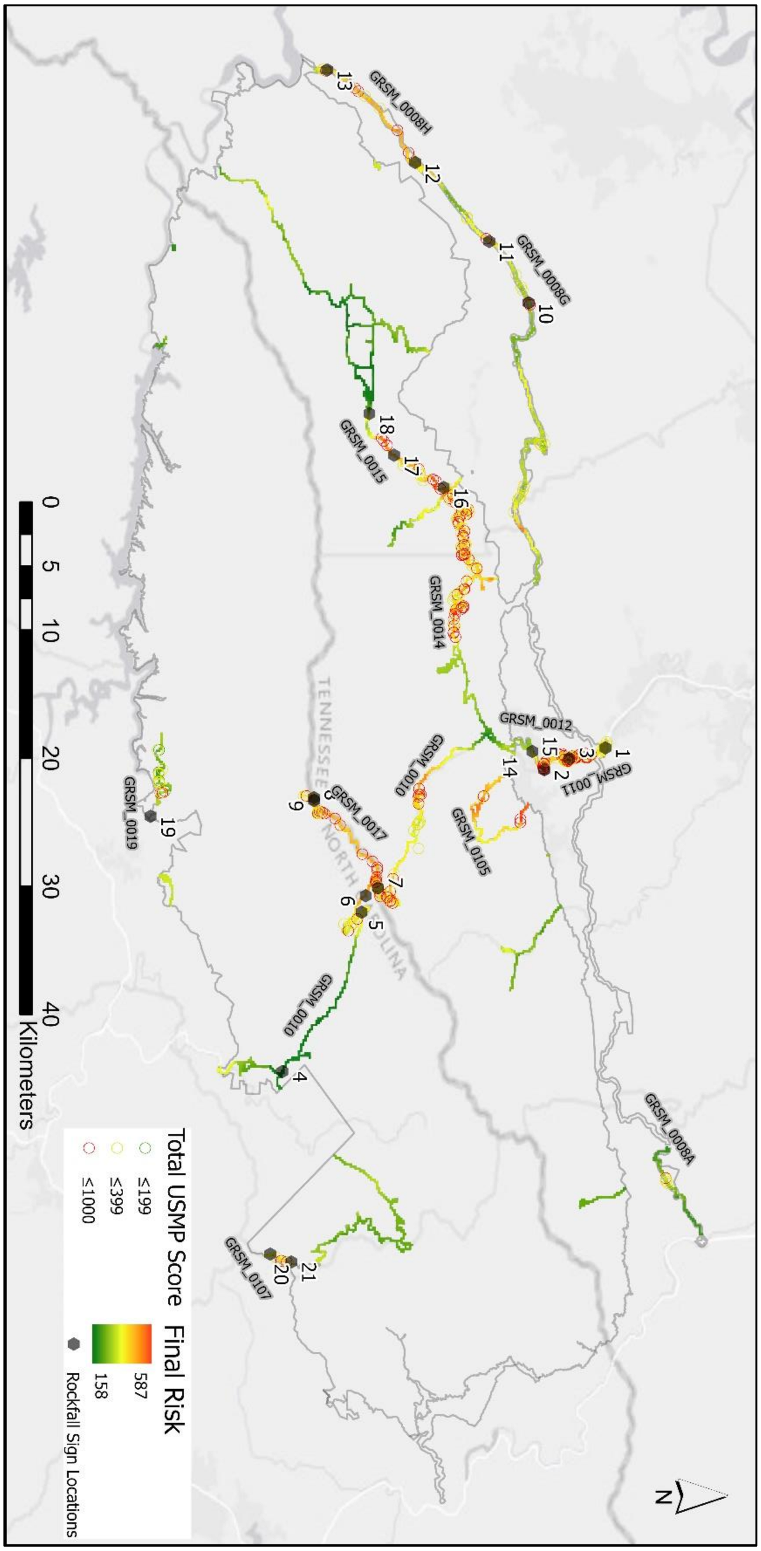

Figure 0.13. Rockfall hazard warning signs throughout GRSM. Rockfall hazard warning signs are mainly found in high rockfall risk areas, but some are found in relatively low rockfall risk zones.

Table 0.4. Locations of Rockfall Hazard Warning Signs throughout Great Smoky Mountains National Park. Several signs do not have unstable slopes present.

Rockfall Hazard Sign Number	Rockfall Hazard Sign (Road)	Corresponding Unstable Slope(s) in GRSM	USMP ID	AADT	Speed Limit (mph)	USMP Score
1	Gatlinburg Spur N	GRSM_254 & GRSM_255	6523 & 6524	49,000	45	361 & 372
2	Gatlinburg Spur N	GRSM_225, GRSM_226, & GRSM_227	6480, 6481, & 6482	49,000	45	677, 590, & 588
3	Gatlinburg Spur S	GRSM_214, GRSM_215, & GRSM_216	6000, 6001, & 6002	49,000	45	420, 7622, & 493
4	Newfound Gap (NC side)	No unstable slope present				
5	Newfound Gap (NC side)	No unstable slope present				
6	Newfound Gap (NC side)	GRSM_042	5374	4,400	35	362
7	Newfound Gap (NC side)	GRSM_036 – GRSM_040	5347, 5350, 5352, 5353, & 5373	4,400	35	325, 437, 378, 391, & 377
8	Clingmans Dome	GRSM_261	7120	2,200	30	412
9	Clingmans Dome 2	GRSM_260	7119	2,200	30	347
10	Foothills Parkway (0008G)	GRSM_132	5596	45	2,000	410
11	Foothills Parkway (0008G)	No unstable slope present				
12	Foothills Parkway (0008H)	No unstable slope present				
13	Foothills Parkway (0008H)	No unstable slope present				
14	Gatlinburg Bypass	No unstable slope present				

15	Gatlinburg Bypass	No unstable slope present				
16	Laurel Creek Rd	GRSM_185	5919	35	3,900	556
17	Laurel Creek Rd	GRSM_200	5938	35	3,900	624
18	Laurel Creek Rd	No unstable slope present				
19	Lakeview Drive E	GRSM_152 – GRSM_155	5712, 5713, 5714, & 5720	35	250	124, 485, 275, & 414
20	Heintooga Ridge Rd	No unstable slope present				
21	Heintooga Ridge Rd	GRSM_159 & GRSM_160	5718 & 5719	35	200	656 & 357

Recommendations

Newfound Gap Rd. (0010) has four rockfall hazard warning signs: #4, #5, #6, and #7 (Figure 3.10). Of these four signs, only two, #6 and #7, are in the vicinity of unstable slopes, GRSM 032 and GRSM_036 – GRSM_040 respectively. Signs #4 and #5 do not appear to be in the presence of unstable slopes and should be re-evaluated and potentially relocated to a better, more practical location. If there are no unstable slopes present after a rockfall hazard warning sign, the likelihood of the public trusting in future signs in GRSM may be slim because more people are likely to believe all rockfall signs are not going to have an unstable slope nearby.

The Gatlinburg Spur (0011) has three rockfall hazard warning signs (#1, #2, and #3), is the most travelled transportation corridor in GRSM, and has annual rockfall events that often block traffic flow. All three warning signs are in the area of unstable slopes. However, several more warning signs could be added along both the Northbound lane and Southbound lane of the Spur. Sign #1 is located at the Northbound entrance of the Spur, sign #2 is located at the Northbound entrance of the Spur, and sign #3 is located in a cluster of unstable slopes on the Southbound lane of the Spur. It is recommended that an in-depth study be conducted to determine best places to add rockfall hazard warning signs.

Sections of the Foothills Parkway (0008H and 0008G) require attention as three of the four rockfall hazard warning signs do not appear to have an unstable slope present. Sign #10 (GRSM_132) is the only one that is in the presence of an unstable slope; it is unclear as to what signs #11, #12, and #13 is warning of in concerns to rockfall.

Little River Gorge Rd. (0014) is a major artery to GRSM and does not have any rockfall hazard warning signs. There is an active, ongoing wedge failure (GRSM_051 (Figure 3.11)) where the addition of a rockfall hazard warning sign would be extremely beneficial. There are clusters of highly rated unstable slopes along Little River Gorge Rd. where a hazard warning sign would also be beneficial (GRSM_068 to GRSM_073 and GRSM_086 to GRSM_090). These clusters are especially significant as comments were made at each slope indicating evidence of rock debris hitting the road (impact marks), and evidence of previous rockfall (GRSM_090). Knowledge of previous slope failure events would assist in pinpointing a location for an additional rockfall hazard warning sign. Potential rockfall hazard warning sign locations should be near GRSM_051 (Figure 3.11) on Little River Gorge Rd which is an active wedge failure, and GRSM_013 (Figure 3.12) on Newfound Gap Rd which is near a popular overlook area and had recent wedge failure. A more detailed study should be conducted to prioritize rockfall signs for more unstable slopes that have a history of frequent rockfall events that impact the road.

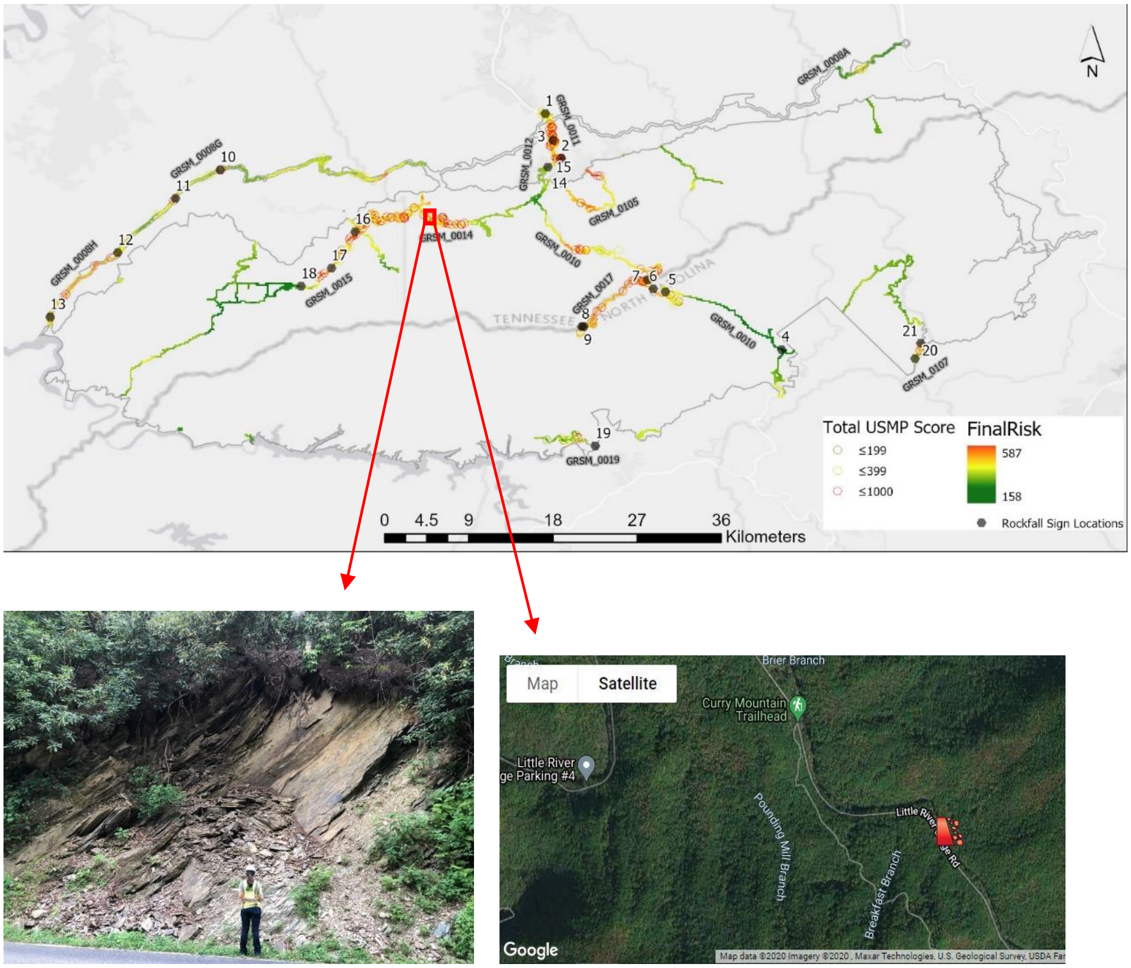

Figure 0.14. GRSM_051 located on Little River Gorge Rd is an ongoing wedge failure that is cleaned up annually. The red box indicates where this slope is in relation to the rest of the USMP inventory. Rock debris is continuously cleaned up and deposited on the opposite side of the road. Bottom Left photo credit: Thomas O'Shea, ETSU.

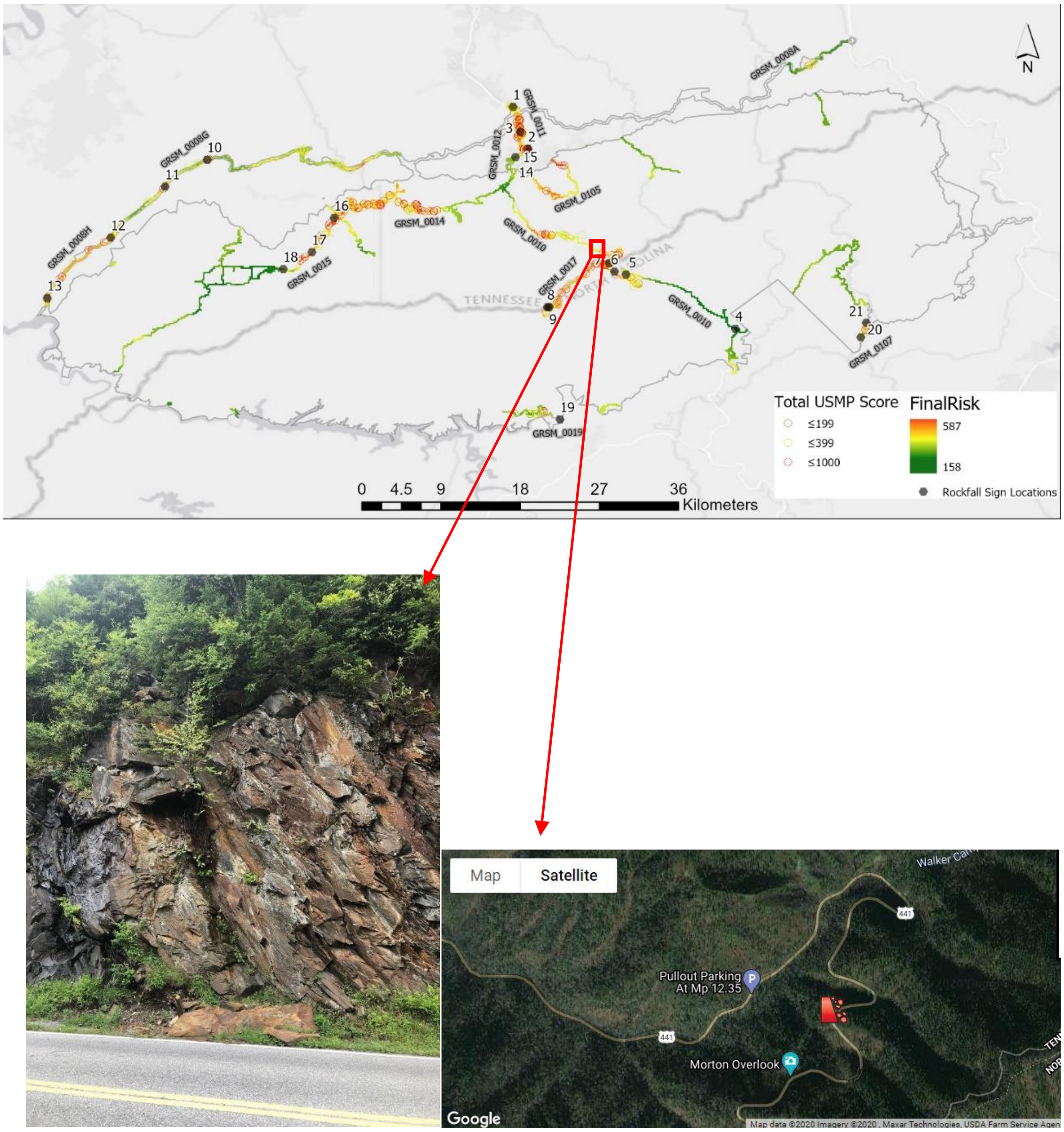

Figure 0.15. GRSM_013 on Newfound Gap Rd, located near Morton Overlook, a popular tourist spot. A 1.2m (4ft) rock can be seen in the ditch, that almost hit the road. Had this rock hit the road, traffic would have had to be diverted or closed as this is the only way up and down the mountain until Clingmans Dome. The red box indicates where the GRSM_013 is located. Bottom Left photo credit: Thomas O’Shea, ETSU.

Discussion

The USMP QRA tool provided an overall annual individual risk estimation for Gatlinburg Spur, Newfound Gap Rd., and Little River Gorge Rd. Comparing the overall risk of the corridors to other well-known societal risks, like cancer and homicides, offers context about the degree of risk associated with that roadway. This allows non-geoscientists to grasp the amount of risk more easily and can allow communication to be more fluid and proactive actions to be taken. Overall, annual individual risk for the three GRSM roadways is most like the World Landslide Fatalities risk, which signifies these roadways to be of moderate risk.

The USMP QRA protocol was also used for Denali National Park Road (Capps et al. 2017) and the QRA ten highest ranked sites ranged from 2.08E-08 to 4.2E-08. The study identified the highest risk slope as a poorly rated slope, but not the most unstable slope (9th highest ranked QRA score = 2.8E-06). Similarly, in GRSM, the highest rated slope (GRSM_109 (984)) does not have the highest risk, in fact, it received one of the lower risks (1.06 E-08). The low risk is likely due to the slope having mitigation present (Shotcrete at the base of the slope) along with a reasonable sight distance of 50.6m (166ft). Outliers are found on Newfound Gap Rd. and Little River Gorge Rd.; outliers for Newfound Gap Rd. are from the maximum value of risk (refer to Table 3.2), while outliers for LRG are from the minimum risk values (refer to Table 3.3). A different QRA protocol was used by Corominas et al. (2014) in which they state probability may be estimated based on personal judgement but does enable conversations between geoscientists and decision-makers. The QRA results from this study for GRSM hope to spark those conversations amongst geotechnical managers, geoscientists, future researchers, and GRSM staff.

The inventory of unstable slopes provides an opportunity for GRSM to examine current sign placement, as most visitors will pass at least one hazard warning sign. Currently, there are 21 rockfall hazard warning signs throughout the park, nine of which do not appear to be associated with an unstable slope in the vicinity. There are a few poorly rated slope sites on Little River Gorge Rd. and Newfound Gap Rd. that could benefit from additional rockfall hazard warning signs as they are active slopes and do not have adequate ditches to contain rock debris. Queensland National Park conducted a study that was initiated by challenges associated with park safety signage and a heavily crowded communication environment (i.e., injuries and fatalities associated with visitors not following safety signs) (Saunders et al. 2019). The study concluded that it is impossible to eliminate injury; the study stated the best approach to safety signage is to be clear, consistent, and coordinated (Saunders et al., 2019). The same signage guidelines can be applied to GRSM rockfall hazard warning signs to more effectively get the message across to the public.

Limitations

The USMP QRA tool is not meant for high-volume parks, nor is it strictly meant for roadways. However, the QRA can be slightly altered so the width accounts for a standard car (1.7 m) and not a person (0.7 m). This allows for the scope of work done in this study to be a more realistic. A QRA tool that is used specifically for transportation corridors and assesses annual risk of cars would be a more useful solution to obtaining a better risk estimate.

Lack of officially recorded notes concerning rockfall events and rockfall debris cleanup in GRSM limits the knowledge provided to researchers about previous failures. In this study, this led to questioning locations of rockfall warning signs and recommending re-evaluation of rockfall signs along most roadways throughout the park. In the future, better documentation can immensely help future studies, along with detailed reports or notes about the rockfall or debris cleanup (e.g., volume, how much did it cost to clean up, is it an annual cleanup, block size).

Conclusion

Visitor safety is one of the top priorities of GRSM, and this study aims to provide tools to assist in improving safety concerning rockfalls. Utilizing the USMP QRA allowed for a numerical risk for the three main roadway arteries of GRSM that can be helpful for non-geoscientists and in budget preparations. Understanding the risk associated with the corridors, coupled with rockfall risk maps, creates a base for a proactive approach for rockfall stability projects throughout GRSM. Comparing the QRA results for GRSM with other well-known societal risks gives context for what the annual individual risk numbers mean.

There are 21 rockfall hazard warnings signs throughout the park, nine of which do not appear to be associated with an unstable slope in the vicinity. However, visitors will pass at least one hazard warning sign during their visit. GRSM lacks rockfall hazard warning signs throughout vital sections along Little River Gorge Rd. and Newfound Gap Rd. (on the Tennessee side). Additionally, there are rockfall hazard warning signs on Heintooga Ridge Rd. and Newfound Gap Rd. (on the North Carolina side) that could be relocated as there is no unstable slope present at sign locations. The inventory of unstable slopes could be used to evaluate current sign positions.

There were two recommendations for several additional rockfall hazard warning signs in the park, but more signs could be added along Little River Gorge especially. Based on current slope conditions, the signs on Little River Gorge Rd. and Newfound Gap Rd. appear to be the most important and unstable, and further investigations should be conducted to determine if a sign should be there. Creating a catalog of rockfall hazard warning signs throughout GRSM allows GRSM staff to identify areas lacking hazard warning signs and areas that no longer need signs. Increasing the number of rockfall hazard warning signs would further improve visitor safety in the park.

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CHAPTER 4. CONCLUSION

Results of Study 1 focused on the creation of an unstable slope geodatabase using the USMP slope rating form which formed the foundation of a rockfall susceptibility model using MaxEnt, a preliminary rockfall risk model applying Ordinary Kriging, and ultimately creating a final rockfall risk model using Co-Kriging.

The geodatabase of unstable slopes in GRSM is comprised of 284 slopes, 5 of which were classified as landslides and were omitted from the study. Of the 279 remaining slopes, 4 were characterized as a ‘good’ rating, 145 as ‘fair’, and 130 as ‘poor’. This provides insight to GRSM officials about current slope conditions and can lead to discussions about a proactive approach to maintaining and prioritizing specific slopes.

Utilizing the geodatabase, a susceptibility model was created using MaxEnt, which allows the user to input environmental and climatic variables. In this study, environmental variables included: GRSM geology, GRSM faults, and GRSM 10m LiDAR Digital Elevation Model, and climatic variables being mean temperature of coldest quarter and annual precipitation. The climatic variables used to create this model were selected because they represent conditions best suited from rockfall season, which is often in late fall/early spring when temperatures fluctuate (freeze/thaw) coupled with high amount of precipitation. An 80/20 model was used in which 65% of the data was appropriate for rockfalls with the highest risk areas being along the most traveled roadways in GRSM: Newfound Gap Rd., Little River Gorge Rd., and Gatlinburg Spur.

Continuing to use the geodatabase, a preliminary rockfall risk model was produced employing Ordinary Kriging. Ordinary Kriging was chosen because the data are nonlinear, stationary, and numerical. The preliminary rockfall risk model indicated highly suited rockfall areas are along portions of the three busiest roadways.

Using Co-Kriging, the susceptibility model and preliminary risk model were used as co-variates to produce a final rockfall risk model. The final risk model provides realistic risk estimations and can be utilized in future studies. The final risk model confirms the three busiest roadways in GRSM do have the highest risk related to rockfall, which validates field observations, GRSM maintenance reports, and local news articles. The final risk model would be a beneficial asset to decision-makers as it better illustrates current slope conditions and the risk they could pose on visitor safety.

In Study 2, the final rockfall risk model was applied in two manners: 1) conducting a QRA of the three most traveled transportation corridors in GRSM, and 2) investigating rockfall hazard warning sign locations throughout the park.

Using the USMP QRA tool, the ten highest rated slopes from each of the three busiest roadways were used: 1) Gatlinburg Spur, 2) Newfound Gap Rd., and 3) Little River Gorge Rd. In this study, the QRA focused on annual individual risk per vehicle, as it is assumed every person in the vehicle has the same amount of risk throughout the corridor. The USMP QRA tool allows geoscientists and non-geoscientists the ability to communicate and understand the estimated amount of risk per site, or in this study an entire corridor, by quantifying the risk and comparing that to other well-known societal risks, like US cancer incidence (1.20E-04), US homicides (6.20E-05), or US automobile accidents (4.18E-06). Of the three corridors, Little River Gorge Rd. had the highest annual individual risk to vehicles (1.58E-07), followed by Gatlinburg Spur (1.72E-07), and Newfound Gap Rd. (2.45E-07). It should also be noted that 183 unstable slopes out of 284 are located on these three roads with zero rated as ‘good’, 92 as ‘fair’, and 91 as ‘poor’.

Continuing into Study 2, the locations of rockfall hazard warning signs were examined. There are 21 signs throughout the park, located on both the Tennessee side and North Carolina side. Of the 21 signs, 9 locations do not appear to be warning visitors of imminent rockfall hazard. Most of the signs that do not appear to be in the vicinity of an unstable slopes were found on the North Carolina side of the park. Data collected for this portion of the study included signage coordinates, brief observations of a slope (if one was present), and evidence of rocks impacting the roadway via marks in the road.

Two recommendations were suggested for the re-location of hazard signage: one on Newfound Gap Rd. where the unstable slope is on a hair-pin turn and near a popular tourist overlook, and secondly on Little River Gorge Rd. where there is an ongoing active wedge failure that is cleaned up at least four times per year. However, a more detailed study is needed to truly evaluate the effectiveness of the rockfall hazard warning sign locations. As previous studies (Dechano and Butler (2001); Aucote 2010) indicate, the public will ultimately make their own decisions and often distrust the validity of hazard signage. Rockfall hazard warning signs should not be located where there appears to be no significant rockfall risk but should be placed in a location where a potentially unstable slope has the ability to impact the roadway and visitor safety.

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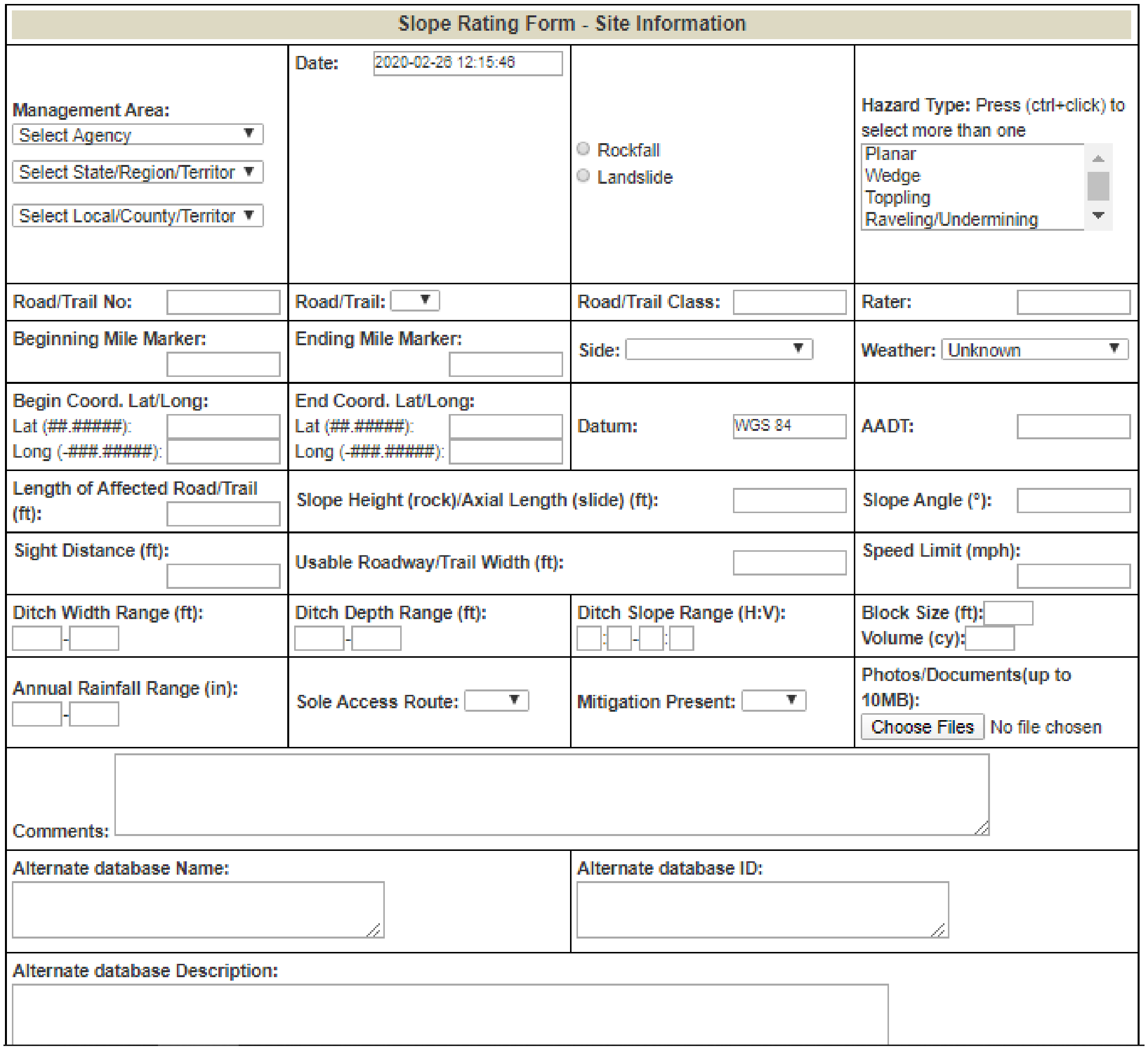
APPENDICES

Appendix A: USMP Slope Rating Form



Slope Rating Form - Site Information

Management Area:
Select Agency ▼
Select State/Region/Territor ▼
Select Local/County/Territor ▼

Date: 2020-02-26 12:15:46

○ Rockfall
○ Landslide

Hazard Type: Press (ctrl+click) to select more than one
Planar
Wedge
Toppling
Raveling/Undermining

Road/Trail No:
Road/Trail: ▼
Road/Trail Class:
Rater:

Beginning Mile Marker:
Ending Mile Marker:
Side: ▼
Weather: Unknown ▼

Begin Coord. Lat/Long:
Lat (##.#####):
Long (-###.#####):

End Coord. Lat/Long:
Lat (##.#####):
Long (-###.#####):

Datum: WGS 84
AADT:

Length of Affected Road/Trail (ft):
Slope Height (rock)/Axial Length (slide) (ft):
Slope Angle (°):

Sight Distance (ft):
Usable Roadway/Trail Width (ft):
Speed Limit (mph):

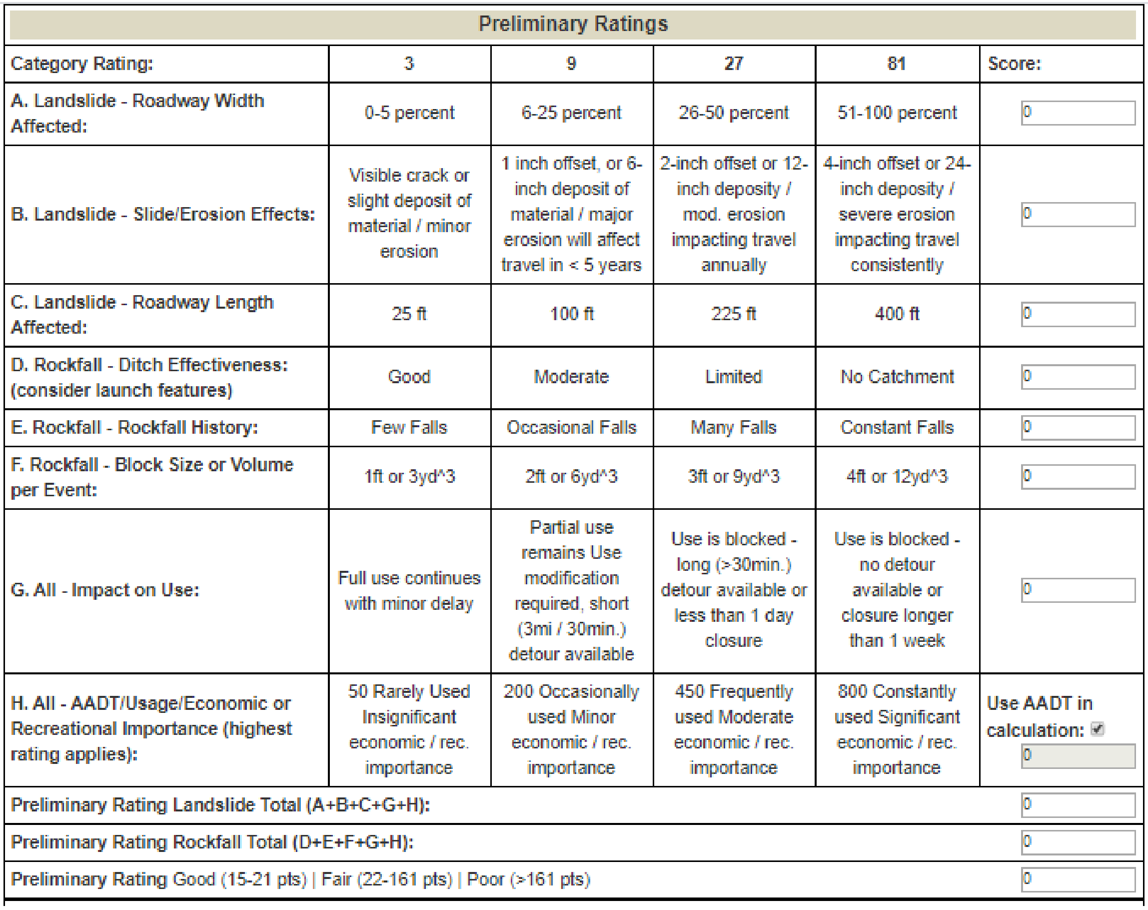
Ditch Width Range (ft): -
Ditch Depth Range (ft): -
Ditch Slope Range (H:V): : - :
Block Size (ft):
Volume (cy):

Annual Rainfall Range (in): -
Sole Access Route: ▼
Mitigation Present: ▼
Photos/Documents(up to 10MB):
Choose Files No file chosen

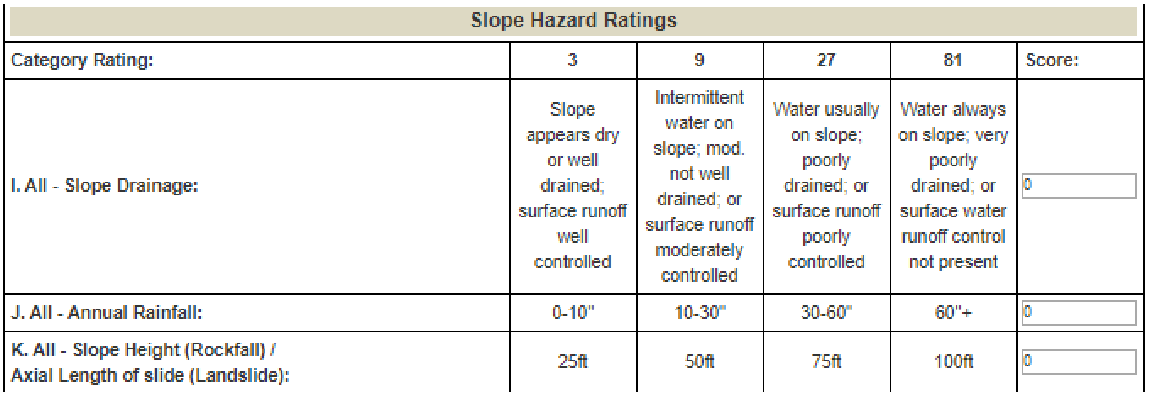
Comments:

Alternate database Name:
Alternate database ID:

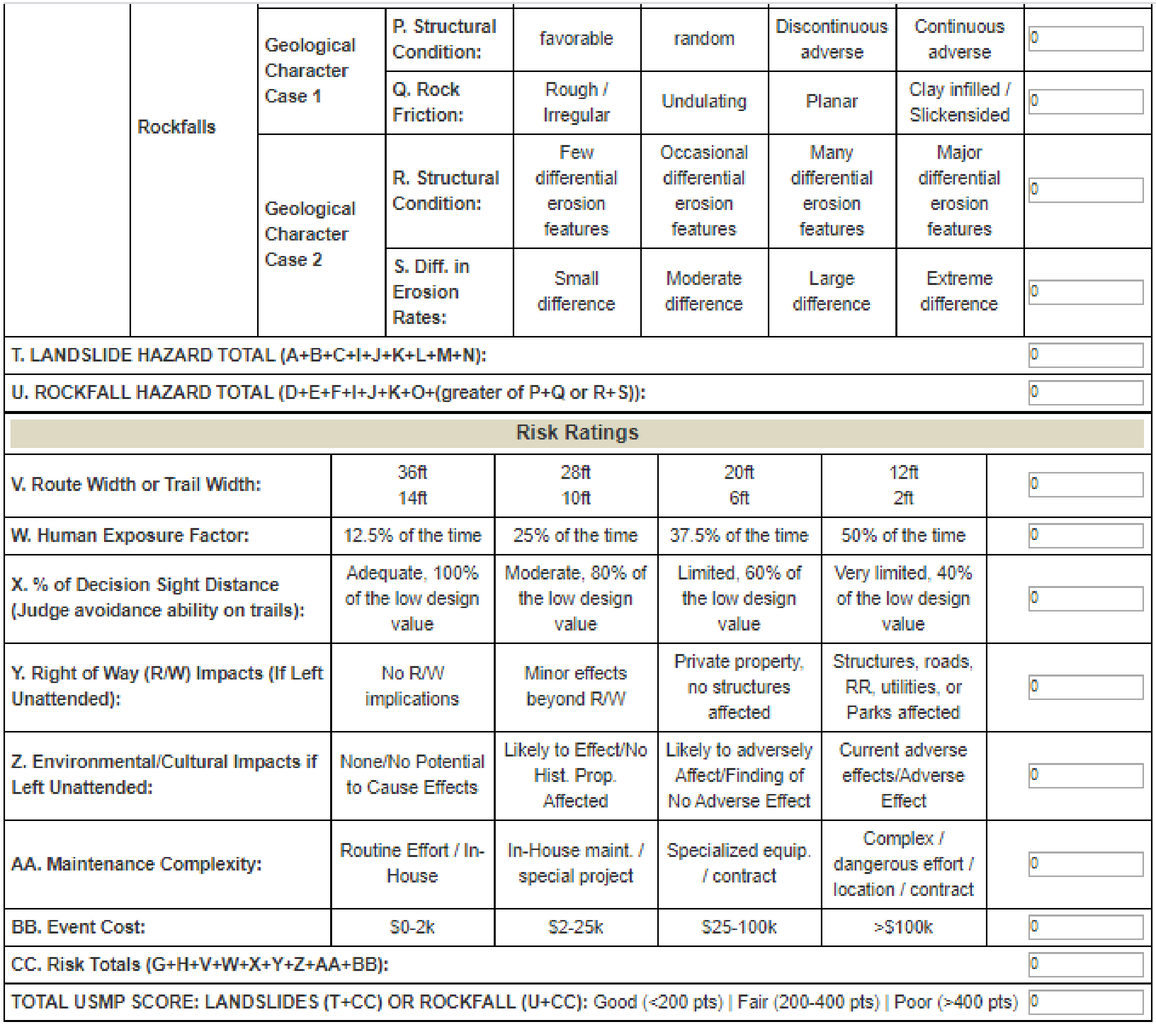
Alternate database Description:



Preliminary Ratings					
Category Rating:	3	9	27	81	Score:
A. Landslide - Roadway Width Affected:	0-5 percent	6-25 percent	26-50 percent	51-100 percent	0
B. Landslide - Slide/Erosion Effects:	Visible crack or slight deposit of material / minor erosion	1 inch offset, or 6-inch deposit of material / major erosion will affect travel in < 5 years	2-inch offset or 12-inch deposity / mod. erosion impacting travel annually	4-inch offset or 24-inch deposity / severe erosion impacting travel consistently	0
C. Landslide - Roadway Length Affected:	25 ft	100 ft	225 ft	400 ft	0
D. Rockfall - Ditch Effectiveness: (consider launch features)	Good	Moderate	Limited	No Catchment	0
E. Rockfall - Rockfall History:	Few Falls	Occasional Falls	Many Falls	Constant Falls	0
F. Rockfall - Block Size or Volume per Event:	1ft or 3yd^3	2ft or 6yd^3	3ft or 9yd^3	4ft or 12yd^3	0
G. All - Impact on Use:	Full use continues with minor delay	Partial use remains Use modification required, short (3mi / 30min.) detour available	Use is blocked - long (>30min.) detour available or less than 1 day closure	Use is blocked - no detour available or closure longer than 1 week	0
H. All - AADT/Usage/Economic or Recreational Importance (highest rating applies):	50 Rarely Used Insignificant economic / rec. importance	200 Occasionally used Minor economic / rec. importance	450 Frequently used Moderate economic / rec. importance	800 Constantly used Significant economic / rec. importance	Use AADT in calculation: ☑ 0
Preliminary Rating Landslide Total (A+B+C+G+H):					0
Preliminary Rating Rockfall Total (D+E+F+G+H):					0
Preliminary Rating Good (15-21 pts) | Fair (22-161 pts) | Poor (>161 pts)					0



Slope Hazard Ratings					
Category Rating:	3	9	27	81	Score:
I. All - Slope Drainage:	Slope appears dry or well drained; surface runoff well controlled	Intermittent water on slope; mod. not well drained; or surface runoff moderately controlled	Water usually on slope; poorly drained; or surface runoff poorly controlled	Water always on slope; very poorly drained; or surface water runoff control not present	0
J. All - Annual Rainfall:	0-10"	10-30"	30-60"	60"+	0
K. All - Slope Height (Rockfall) / Axial Length of slide (Landslide):	25ft	50ft	75ft	100ft	0

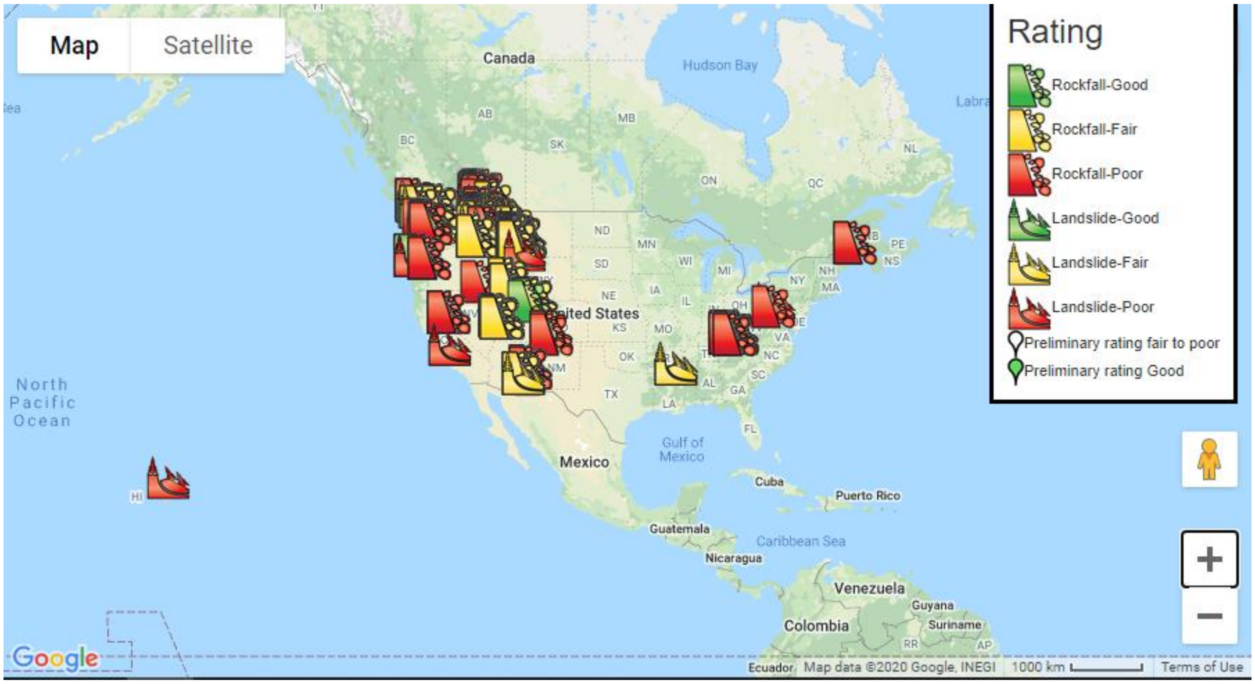


	Rockfalls	Geological Character Case 1	P. Structural Condition:	favorable	random	Discontinuous adverse	Continuous adverse	0
			Q. Rock Friction:	Rough / Irregular	Undulating	Planar	Clay infilled / Slickensided	0
		Geological Character Case 2	R. Structural Condition:	Few differential erosion features	Occasional differential erosion features	Many differential erosion features	Major differential erosion features	0
			S. Diff. in Erosion Rates:	Small difference	Moderate difference	Large difference	Extreme difference	0
T. LANDSLIDE HAZARD TOTAL (A+B+C+I+J+K+L+M+N):								0
U. ROCKFALL HAZARD TOTAL (D+E+F+I+J+K+O+(greater of P+Q or R+S)):								0

Risk Ratings					
V. Route Width or Trail Width:	36ft 14ft	28ft 10ft	20ft 6ft	12ft 2ft	0
W. Human Exposure Factor:	12.5% of the time	25% of the time	37.5% of the time	50% of the time	0
X. % of Decision Sight Distance (Judge avoidance ability on trails):	Adequate, 100% of the low design value	Moderate, 80% of the low design value	Limited, 60% of the low design value	Very limited, 40% of the low design value	0
Y. Right of Way (R/W) Impacts (If Left Unattended):	No R/W implications	Minor effects beyond R/W	Private property, no structures affected	Structures, roads, RR, utilities, or Parks affected	0
Z. Environmental/Cultural Impacts if Left Unattended:	None/No Potential to Cause Effects	Likely to Effect/No Hist. Prop. Affected	Likely to adversely Affect/Finding of No Adverse Effect	Current adverse effects/Adverse Effect	0
AA. Maintenance Complexity:	Routine Effort / In-House	In-House maint. / special project	Specialized equip. / contract	Complex / dangerous effort / location / contract	0
BB. Event Cost:	$0-2k	$2-25k	$25-100k	>$100k	0
CC. Risk Totals (G+H+V+W+X+Y+Z+AA+BB):					0
TOTAL USMP SCORE: LANDSLIDES (T+CC) OR ROCKFALL (U+CC): Good (<200 pts) | Fair (200-400 pts) | Poor (>400 pts)					0

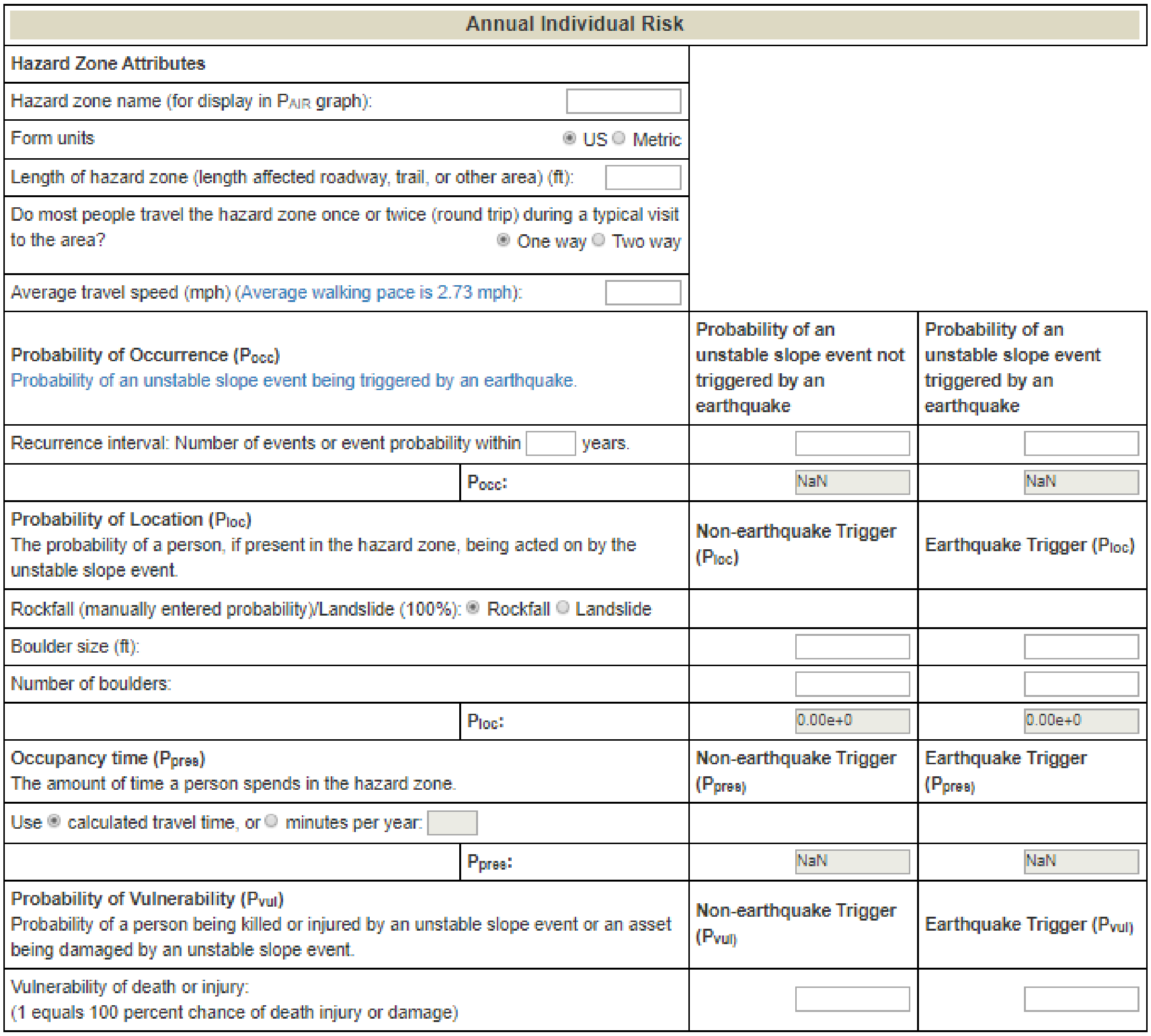
Appendix A. Unstable Slope Management Program (USMP) Slope Rating form used to collect quick assessments of rock slopes throughout the park.

Appendix B: USMP Unstable Slope Interactive Map

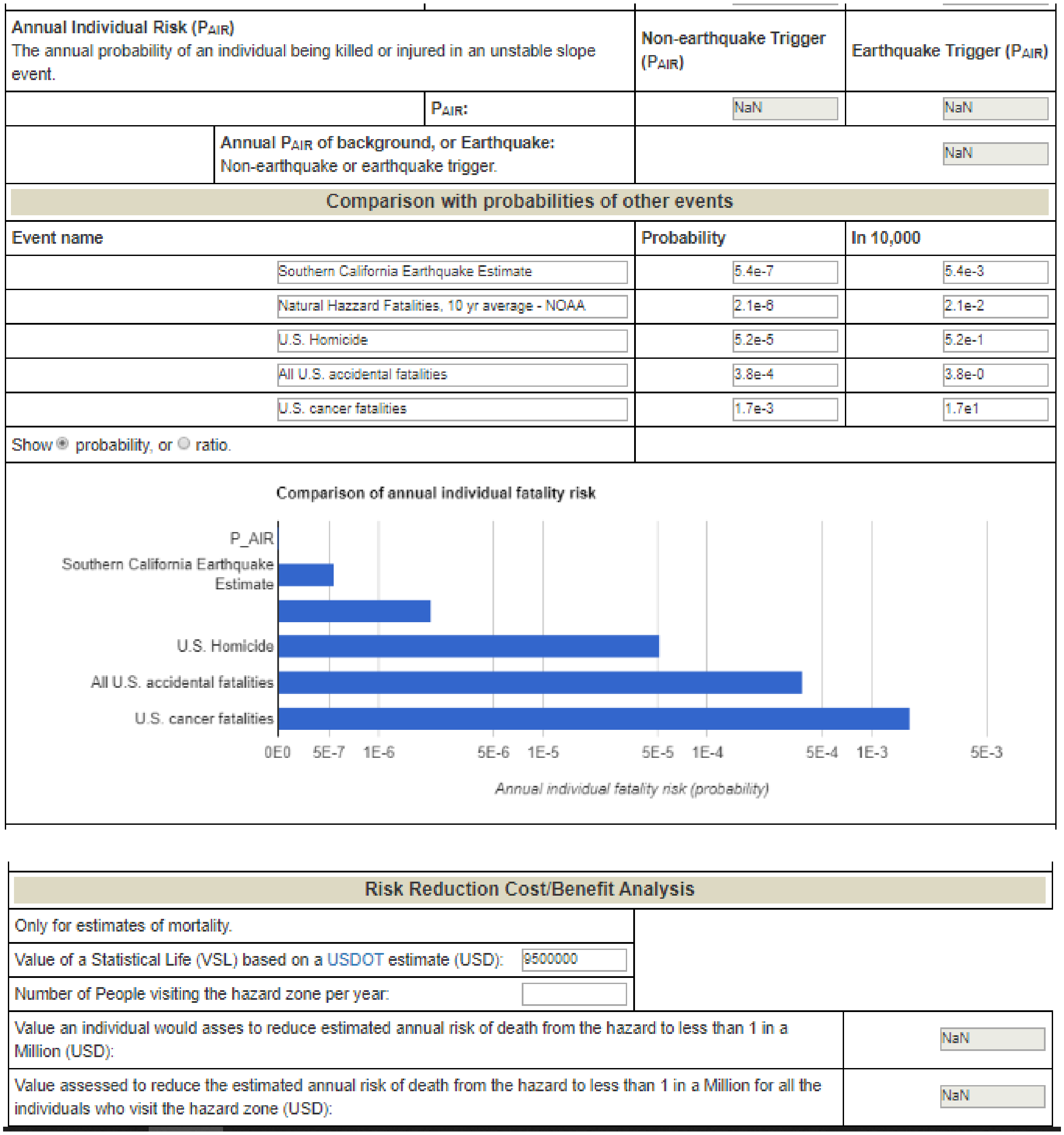


Appendix B. USMP map showing unstable slopes that have been submitted throughout the United States. 284 slopes were rated (including 5 categorized as landslides); 4 slopes were rated ‘good’, 147 ‘fair’, and 133 ‘poor’.

Appendix C: USMP QRA Form



Annual Individual Risk		
Hazard Zone Attributes		
Hazard zone name (for display in P_{AIR} graph): ☐		
Form units ● US ○ Metric		
Length of hazard zone (length affected roadway, trail, or other area) (ft): ☐		
Do most people travel the hazard zone once or twice (round trip) during a typical visit to the area? ● One way ○ Two way		
Average travel speed (mph) (Average walking pace is 2.73 mph): ☐		
Probability of Occurrence (P_{occ}) Probability of an unstable slope event being triggered by an earthquake.	**Probability of an unstable slope event not triggered by an earthquake**	**Probability of an unstable slope event triggered by an earthquake**
Recurrence interval: Number of events or event probability within ☐ years.	☐	☐
P_{occ}:	NaN	NaN
Probability of Location (P_{loc}) The probability of a person, if present in the hazard zone, being acted on by the unstable slope event.	**Non-earthquake Trigger (P_{loc})**	**Earthquake Trigger (P_{loc})**
Rockfall (manually entered probability)/Landslide (100%): ● Rockfall ○ Landslide		
Boulder size (ft):	☐	☐
Number of boulders:	☐	☐
P_{loc}:	0.00e+0	0.00e+0
Occupancy time (P_{pres}) The amount of time a person spends in the hazard zone.	**Non-earthquake Trigger (P_{pres})**	**Earthquake Trigger (P_{pres})**
Use ● calculated travel time, or ○ minutes per year: ☐		
P_{pres}:	NaN	NaN
Probability of Vulnerability (P_{vul}) Probability of a person being killed or injured by an unstable slope event or an asset being damaged by an unstable slope event.	**Non-earthquake Trigger (P_{vul})**	**Earthquake Trigger (P_{vul})**
Vulnerability of death or injury: (1 equals 100 percent chance of death injury or damage)	☐	☐



Annual Individual Risk (P_{AIR}) The annual probability of an individual being killed or injured in an unstable slope event.	**Non-earthquake Trigger (P_{AIR})**	**Earthquake Trigger (P_{AIR})**
P_{AIR}:	NaN	NaN
Annual P_{AIR} of background, or Earthquake: Non-earthquake or earthquake trigger.		NaN

Comparison with probabilities of other events

Event name	Probability	In 10,000
Southern California Earthquake Estimate	5.4e-7	5.4e-3
Natural Hazzard Fatalities, 10 yr average - NOAA	2.1e-6	2.1e-2
U.S. Homicide	5.2e-5	5.2e-1
All U.S. accidental fatalities	3.8e-4	3.8e-0
U.S. cancer fatalities	1.7e-3	1.7e1

Show ● probability, or ○ ratio.

Risk Reduction Cost/Benefit Analysis

Only for estimates of mortality.	
Value of a Statistical Life (VSL) based on a USDOT estimate (USD):	9500000
Number of People visiting the hazard zone per year:	
Value an individual would asses to reduce estimated annual risk of death from the hazard to less than 1 in a Million (USD):	NaN
Value assessed to reduce the estimated annual risk of death from the hazard to less than 1 in a Million for all the individuals who visit the hazard zone (USD):	NaN

Appendix C. Quantitative Risk Assessment (QRA) form created by NPS on the USMP website. This form assesses the probability of someone being in the path of a rockfall or landslide at the time they occur. This form also compares the fatality risk estimate of the study site to other fatalities, such as, cancer fatalities and homicides.

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	Robert C. & Brenda Lark Whisonant Scholarship, 2018